Unconfined Compressive Strength of Rehabilitated Road Base via Polymer-Modified Cold In-Place Recycling (CIPR)

Poi-Cheong Tan¹*, Chee-Ming Chan²
¹, ²Faculty of Engineering Technology, Universiti Tun Hussein Onn, Malaysia.

E-mail: hn180028@siswa.uthm.edu.my

Abstract. Cold In-Place Recycling (CIPR) is a road maintenance technology, which chemically stabilize, recycle and improve existing asphalt concrete together with road base underneath. Cement is the most common chemical for CIPR adopted in Malaysia. However, shrinkage crack remains as unresolved technical drawback of cement stabilization, road practitioners are always seeking alternative materials to replace cement in CIPR. A proprietary product, Polymer Modified Cementitious (PMC) chemical binder was identified as the research object to verify the suitability in CIPR application and to study the strength-gain over time, through laboratory testing. To replicate CIPR process, Crusher run (CR) and Recycled Asphalt Pavement (RAP) were mixed at various ratio to study the effect of CR to RAP ratio on strength gained; with PMC added in dosage between 2-4% per dry weight of the materials to compare strength gain at different dosage. Samples were compacted and cured for 7 days then subjected to Unconfined Compressive Test where the strength UCS ($q_u$) was recorded. Strength-gain over time from 1 day to 28 days, for a specific CR-RAP ratio at fixed PMC dosage was also studied. It was found that UCS was directly proportionate to PMC dosage and amount of CR component in the mixture. This study concluded that at various combination of CR-RAP ratio, with varying PMC dosage, minimum requirement of UCS (7-day) of 2 MPa for road base application specified by local authority is achievable. The correlation between strength and curing duration obtained serves as guideline to extrapolate long-term strength from short-term strength.

1. Introduction

Soil stabilization is a common engineering method to treat unsuitable materials or recycle existing materials, and turn into usable materials, with desirable properties. In general, soil stabilization can be categorized into mechanical stabilization and chemical stabilization [1]. Means of mechanical stabilization includes compaction (densification), drainage [2], altering particle size distribution, replacement, consolidation/dewatering and reinforcement [3]. Chemical stabilization is the method to stabilize soil through chemical reaction. In general, soil properties such as strength, stiffness soil permeability, compressibility, plasticity and swelling/shrinkage potential of soil can be improved through chemical stabilization.

History of applying chemical stabilization for road construction in Malaysia was as early as 1980’s. In Malaysia civil construction industry context, in-situ chemical stabilization process involving stabilization of existing asphalt concrete together with underlying materials with addition of stabilizing agent, is often known as Cold In-Place Recycling (CIPR). Cement is a most common chemical used in CIPR in Malaysia. However, with shrinkage crack inherited as natural characteristic of cement stabilized
bases, overall performance of cement stabilized base is remain a concern [4]. Therefore, there is a need to evaluate other potential chemical binder as alternative.

This study aims to evaluate a proprietary polymer modified cementitious (PMC) chemical, and verify as the alternative chemical binder in CIPR process in terms of mechanical strength. Through laboratory experiments optimum chemical dosage is verified, and thus serves a guideline for field application. Besides, Unconfined compressive strength (UCS) with various curing during is also studied to understand strength development pattern over time.

2. Design of Experiment

Unconfined compressive strength is a direct indication of a material’s strength to resist deformation under unconfined condition. It is one of the common design criteria of chemical stabilization adopted by Malaysia Public Works Department (JKR Malaysia). Therefore in this study, unconfined compressive strength is only criteria to evaluate the technical feasibility of the PMC in road base stabilization. UCS tests are carried out using cylindrical sample in accordance to BS 1924:1990 (Part 2).

This study is carried out in two stages, namely Stage I-Verification Technical Suitability of PMC, and Stage II-Strength-Gain Over Time. Stage I experiment aimed to determine the PMC dosage and crusher run-RAP mixing ratio, which attain minimum strength required. During stage I, curing duration was kept constant at 7-day. Duration of 7-day was chosen as the reference because this is the standard curing duration specified in requirement of Unconfined Compressive Strength Test (UCS) in Standard Specification for Road Works Section 4: Flexible Pavement and Section 18: Soil Stabilization published by JKR Malaysia [5]. Nevertheless, as opposed to cylindrical samples used in this study, cube UCS samples were specified as test specimen in both specification. Therefore, UCS of both cylindrical and cube samples prepared at a specific condition, were first tested to verify correlation of UCS results between both types of sample.

Table 1 summarizes ratio of various CR to RAP mixture, ranging from 100% CR to 100% RAP, to study the effect of mixing ratio. PMC dosage was set at 2%, 3% and 4%, to investigate correlation of strength development against dosage.

| Sample Reference | Crusher Run Percentage (%) | RAP Percentage (%) |
|------------------|---------------------------|--------------------|
| C100R0           | 100                       | 0                  |
| C75R25           | 75                        | 25                 |
| C50R50           | 50                        | 50                 |
| C27R75           | 25                        | 75                 |
| C0R100           | 0                         | 100                |

Stage II experimental work aimed to study time-dependency of strength development with the PMC chemical stabilization. Adopting the optimum PMC dosage mixing and specific ratio of crusher run-RAP and obtained in Stage I where these two factors were set as constants, the curing duration was varied between 1-day, 3-day, 14-day and 28-day. From the strength development pattern obtained in Stage II, the short-term strength could be extrapolated to predict the long-term strength.

Since this study is limited to laboratory experiment, recycle asphalt pavement (RAP, as knows as milling waste) and crusher run were used to replicate asphalt concrete layer and crusher road base layer in road rehabilitation. The PMC used is a commercialised product, supplied by industrial collaborator from Malaysia. The product has been applied in Malaysia road construction for more than five years. This proprietary product consists of cementitious chemical, ionic chemical and polymeric fiber.

3. Results and Discussions
In order to relate UCS obtained in this study, which was using cylindrical sample, to the requirement specified by JKR Malaysia, correlation between UCS cylindrical \( q_u \) sample and UCS cube \( q_{u,\text{cube}} \) sample, is to be obtained. Refer to BS EN1992-1-1:2004, the strength of cylindrical concrete approximates 80% of cube concrete. Unconfined compressive strength test was carried out on 2 sets C100R0 with 3% PMC dosage samples, in cylindrical (100 mm diameter, 200 mm height) and cube samples (100 mm x 100 mm x 100 mm) respectively to verify the correlation. The samples were cured for seven days prior to the tests. Table 2 summaries results of the UCS tests of both sets samples. The ratio of \( q_u/q_{u,\text{cube}} \) was found to be 0.78, close to the ratio found in BS EN1992-1-1:2004. The minimum requirement of UCS (7-day) stipulated by JKR Malaysia in the aforementioned specification was 2 MPa using cube sample. Therefore one can estimate the minimum UCS (7-day) required is 80% of 2 MPa, which equals to 1.6 MPa.

Table 2. Comparison of UCS Using Cylindrical and Cube Sample

| Sample No | \( q_u \) (MPa) | \( q_{u,\text{cube}} \) (MPa) | Ratio \( q_u/q_{u,\text{cube}} \) |
|-----------|----------------|-----------------------------|-------------------------------|
| S1        | 2.38           | 3.22                        | 0.75                          |
| S2        | 2.58           | 3.10                        | 0.82                          |
| Average   | 2.48           | 3.18                        | 0.78                          |

\( a \) due to experimental error, \( f_{ck} \) of S1 was not considered in the calculation for average \( q_u \)

3.1. Stage I – Verification Technical Suitability of PMC

Figure 1 shows the relationship between UCS and PMC dosage for various CR-RAP ratio. It was found that UCS attained is direct proportionate to PMC added in linear model. With 2% of PMC dosage, UCS (7-day) of 1.6 MPa was not achievable for all CR-RAP ratio. Therefore, dosage of 2% or below is not advisable for road base rehabilitation. Nevertheless, UCS of C100R0 at 2% dosage obtained were 1.50 MPa, 1.39MPa and 1.51 MPa, which were close to 1.60 MPa, more study is required to further verify suitability to apply 2% dosage for C100R0.

Figure 1. UCS vs PMC dosage at 7-day curing.
By comparing trendlines obtained in Figure 1, trendline for C100R0 series has highest magnitude of gradient, which indicated effect of increasing of dosage on increment of UCS is higher for C100R0. A decreasing trend of the trendline gradient is observed as ratio of CR is decreasing. The gradient decreased greatly after C50R50 series, indicated PMC is less effective to improve UCS when RAP ratio is more than 50%. In order to further study relationship of UCS and CR-RAP ratio, the data was rearranged and presented in Figure 2. It is apparent that with PMC stabilization, resultant UCS is directly proportionate to percentage of CR component in the mixture in linear model. By comparing the two factors, PMC dosage and CR ratio, which affect UCS, CR ratio is more dominant factor. Average UCS of C100R0 at 2% PMC dosage was 1.47 MPa, while C0R100 even at higher dosage of 4%, average UCS of 0.64 MPa was recorded.

Besides, with increasing of PMC dosage, the effect on increasing of UCS, in terms of both absolute value and percentage, is more prominent at higher CR ratio. For C100R0 samples, by increasing PMC dosage from 2% to 4%, average UCS increased from 1.47 MPa to 3.38 MPa, an increment of 1.91 MPa or equivalent to 131%. With same increment of PMC dosage from 2% to 4%, average UCS of C0R100 increased from 0.34 MPa to 0.64 MPa, an increment of 0.30 MPa or equivalent to 90%. From technical point of view, it is advisable to maximize the CR ratio in order to maximize the resultant strength achievable. On the other hand, from environmental and sustainability point of view, it is more beneficial to recycle more RAP in the mixture. Therefore one has to strike the balance to decide CR-RAP ratio with the PMC dosage, in order to optimize resultant UCS.

![Figure 2. UCS vs Crusher Run Percentage at 7-day curing.](image)

Figure 2 showed that UCS requirement of 1.6 MPa is achievable with various CR-RAP ratio, applying different PMC dosage. Depending on thickness of existing asphalt concrete layer to be rehabilitate, the ratio of CR to RAP is known. Then the PMC dosage required can be estimated from Figure 2. In Stage II time-dependent of UCS development, the ratio 60% CR to 40% RAP (C60R40) was selected as the experiment standard, in order to replicate the situation where in-situ chemical stabilization involves mixing of 120mm of existing asphalt concrete layer and 180mm existing crusher run road base. With the correlation established, the PMC dosage of 3% is required to meet UCS (7-day) requirement of 1.6 MPa.

It was suggested that participle size distribution of CR and RAP would affect resultant UCS. Sieve analysis was carried out for both pure CR and pure RAP respectively verify this hypothesis, by studying difference in particle size distribution between both samples. Sieve analysis was presented against sieve
envelop on road base materials approved by JKR Malaysia, plotted as the lower and upper limits in Figure 3.

RAP is the by-product of asphalt concrete milling process, which the cutting drum rotates the cutting tools in high speed across existing asphalt concrete surface and breaks the asphalt concrete with mechanical force. Therefore grain size distribution of RAP is uncontrolled. Refers to Figure 3, for C0R100, particles passed 0.118mm sieve and below did not meet the lower limit of the acceptable sieve envelop. The finding implied C0R100 lacked of fines which filled up the voids in between particles during compaction, leading to poor bonding, less mechanical interlocking between particles, and lower compactability. During compressive test, more voids within the sample act as failure surface, resulting in lower resultant UCS. Unlike RAP, CR is purposely crushed and mixed with better grain size distribution, to achieve certain requirement of sieve envelop. The more CR percentage in the mixture, the better overall grain size distribution is, and thus improve resultant UCS after PMC stabilization.

![Figure 3. Sieve Analysis for C0R100 and C100R0 Plotted Against Acceptable Sieve Envelop](image)

To study effect of grain size distribution on UCS, a set of C0R100 samples, treated with PMC at dosage of 3%, was prepared, by artificially remix the particles from difference sieve size, in accordance to grain size distribution of C100R0. The samples were compacted and cured for 7 days, then subjected to unconfined compressive test. Table 3 summarizes and compares UCS results of remix C0R100 against C0R100 of original grain size distribution, as well as C100R0, with same PMC dosage and curing duration. It was found that, by changing the grain size distribution of RAP, resultant UCS results were improved. However, even with identical grain size distribution with CR, UCS attained by RAP were still lower CR. This finding implies there is/are intrinsic difference(s) between RAP and CR which affect(s) resultant strength after PMC treatment.

| Sample No | C100R0 (MPa) | C0R100 (original) (MPa) | C0R100 (remix) (MPa) |
|-----------|--------------|------------------------|---------------------|
| S1        | 1.86         | 0.30                   | 0.64                |
| S2        | 2.38         | 0.39                   | 0.47                |
| S3        | 2.52         | 0.33                   | 0.65                |
3.2. **Strength-Gain Over Time**
UCS attained against curing duration was presented in Figure 4. Strength of PMC stabilization develops over time in logarithmic model, which is similar to strength-gain curve of a concrete. With the strength development equation obtained, the relationship of UCS at various curing duration against UCS at 7-day curing and 28-day curing is summarized in Table 4. Curing duration of 7-day is always used as design requirement. With the relationship established, UCS can be tested at early stage to estimate the UCS achievable at 7-day. Thus, any non-conforming work can be identified and thus rectified at earlier stage.

![Figure 4. Strength Development Over Time](image)

**Table 4. Ratio of UCS at Various Curing Duration Against UCS 7-day and UCS 28-day**

| Curing Duration | Ratio \( \frac{q_{u\text{ 7-day}}}{q_{u\text{28}}} \) | Ratio \( \frac{q_{u\text{ 7-day}}}{q_{u\text{7}}} \) |
|-----------------|----------------|----------------|
| 1-day           | 33%            | 45%            |
| 3-day           | 55%            | 76%            |
| 7-day           | 72%            | 100%           |
| 14-day          | 86%            | 119%           |
| 28-day          | 100%           | 140%           |

4. **Conclusions**
Unconfined compressive strength of PMC stabilized CR-RAP mixture is a direct proportionate to PMC dosage added, as well as the ratio of crusher run component in the mixture. Ratio of crusher run in the mixture is the more dominant factor deciding resultant UCS. It is verified that, min UCS (7-day, cube sample) requirement of 2 MPa stipulated by JKR Malaysia for road base chemical stabilization usage is achievable with various combination of CR-RAP ratio, and PMC dosage. With 40% substitution of CR by RAP (C60R40), PMC dosage of 3% is adequate to comply to JKR Malaysia requirement. From this study, strength-gain over time for C60R40 is established, to serve as guideline to extrapolate and estimate long term strength. With correlation obtained in this study, one has to optimize the CR-RAP ratio (existing pavement design an condition) and PMC dosage (commercial consideration), which is technically, commercially and environmentally viable.
References
[1] Patel A and Patel A 2019 Soil Stabilization Geotechnical Investigations and Improvement of Ground Conditions 19-27
[2] Kitazume M and Terashi M 2013 The Deep Mixing Method (London: CPC Press) 6
[3] Makusa G P 2013 State of the Art Review Soil Stabilization Methods and Materials in Engineering Practice (Luleå: Luleå University of Technology) 1
[4] Louw S, Jones D and Hammack J 2016 Pavement Recycling: shrinkage crack mitigation in cement-treated pavement layers - Phase 1 Laboratory Testing (Davis: Institute of Transportation Studies, University of California)
[5] Malaysian Public Works Department 2019 Section 18: Soil Stabilization. In Standard Specification for Road Works S18-8, Firoozi A, Guney Olgun C, Firoozi A, Baghini M S 2017 Fundamentals of soil stabilization International Journal of Geo-Engineering 8