Sustainability Assessment of Hydrated Cement Treated Crushed Rock Base (HCTCRB)

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1 Introduction

From 2000 – 2004 alone, $7.73 billion have been spent on road rehabilitation in Australia (BITRE 2008) with 1250 Mt CO_2 equivalent emission released and 13.9 terajoule of energy consumed for road constructed in the reported year (Hendrickson et al. 2006). Though with the abundance of natural aggregates in Australia, crushed rock used in road construction are nevertheless non-renewable resources and should be efficiently utilised. This invokes an economical and sustainable urgency to select optimum base course materials to reduce the environmental and economical footprint of road construction.

Mroueh et al. (1999) highlighted that the most significant environmental burden in road construction is caused by the manufacturing and transport of road construction materials where the dominant environmental loading is the consumption of natural materials. This reaffirms the pivotal step of optimising pavement material selection to improve the sustainability of road construction. The increase of number and sizes of road vehicles also require higher performing pavements and the use of higher quality but scarce pavement materials.

Stabilisation allows the use of otherwise mechanically inadequate materials for heavier traffics (Nikraz 2009), therefore, in consideration for logistics and resources availability, stabilisation has been deemed as a viable solution to improve sustainability of the transport industry (Ministry for the Environment 2003). The use of cement stabilised base course materials to increase the service life of pavements potentially reduces the economical and environmental footprint of Australia’s road network.

In Western Australia, a relatively new engineering advance product known as Hydrated Cement Treated Crushed Rock Base was developed as a form of modified cement treated base by Main Roads Western Australia to provide a solution for increased performance requirements of heavily trafficked pavements. It has since been used at Reid Highway, Tonkin Highway, and major freeways, at a total estimate of 250,000 tonnes (Kelley 2009) to date and is seeing further increase of application.

1.1 Hydrated Cement Treated Crushed Rock Base (HCTCRB)

HCTCRB was a brainchild of Main Roads in light of premature failures caused by excessive deflection of the base course layers between South Street and Forrest/Yangebup Road on the Kwinana Freeway in 1992 (Butkus 2004).

It is a product of cement treated crushed rock which is stockpiled to allow hydration for a period of days and disturbed/retreated to form cement coated crushed rocks, ultimately used as a form of unbound granular material. It was identified that the cement treatment of the crushed rock base provided increased mechanical performance (Butkus 2004; Jitsangiam and Nikraz 2007) and extended pavement serviceability.

In comparison to HCTCRB, Cement Treated Base (CTB) is predominantly unfavoured in Western Australia because it undergoes shrinkage cracking during hydration (Chakrabati and Kodikara 2007) which eventually results in the early distress of pavements. However, studies have provided other mitigation measures for shrinkage cracking, such as, material proportioning, using additives, construction control and other physical alterations (George 2002; Adaska and Luhr 2004 ; Scullon et al. 2005). Among them is the successful practice of micro-cracking applied in the United States developed by the Portland Cement Association (2005). Microcracking basically forms miniscule networks of fine cracks right after initial curing to prevent the formation of wider and more severe cracks (PCA 2005).

Nevertheless, with its prematurity in the industry, not only are the mechanical properties of HCTCRB has yet to be fully understood, but more importantly the economical and environmental impact of its use has yet to be studied.

1.2 Sustainability assessment of pavements

With the severe impacts of road construction, studies on sustainability and the selection of pavement materials or technology have been undertaken extensively around the world. This section discusses briefly on approaches for sustainable pavement selection.

The predominant approach in assessing sustainability had been focused on Life Cycle approaches, i.e. to evaluate the complete life cycle of pavements to determine best practices and options. With the triple bottom line in mind, assessments have been generally conducted to ascertain environmental and economical impacts of road construction. Life Cycle Cost (LCC) analysis has been the prominent tool utilised to determine whole of life cost and have been utilised to assess environmental impacts by taking into account the factor on a monetary model as shown in Chan (2007).

In relation, Life Cycle Inventory Analysis (LCIA or LCA) as per ISO14040:1998 which is established based on inputs and outputs of each life cycle stages have been a well received and widely used tool in the evaluation of environmental loadings caused by construction material. The Built Research Establishment (1998) had been a proponent of the use of LCA in construction, establishing a database of environmental performance of building products in 1998. Moreover, LCA has been recognised by industries as an accepted tool for asphalt products and laying processes (Bird et al 2004). Specific LCI studies had been undertaken by Eskola et al. (2004) and Birgisdóttir (2005) to develop LCI models for the determination of environmental impacts. Chiu et al. (2007) was also utilised LCI to ascertain areas of improvement for the production of pavement materials.

Nonetheless, Life Cycle Inventory assessments have potential for misuse as it is open for interpretation by the analyser (Jacquetta et al. 1994), leading to biased and erroneous results, however, it was also iterated that with proper control and standardised approached, it is a significant tool serve as a base line for making decisions.

2 Objective of study

The concept of sustainable development, as presented in the Brundtland Commission, has identified the pivotal role engineers have in designing for the future. In reflection to the issues presented on pavement materials and stabilisation, the objectives of this report are

i. determine the sustainability of HCTCRB and CTB with microcracking based on their economical and environmental performance through a Life Cycle approach
ii. determine the applicability of HCTCRB and CTB based on sustainability considerations
iii. provide recommendation to the engineering and road planning community on the improvement of the supply and production of HCTCRB to achieve improved sustainability

As is the case in Western Australia, this research assumes a scenario where the use of stabilisation for increased mechanical performance is required and crushed rock is the choice of material.

3 Assessing the sustainability of pavement materials

As discussed in Section 2, the application of life cycle assessments allows a more holistic and acceptable approach in engineering to determine the sustainability of materials. A pilot study based on Life Cycle Analysis (LCA) is therefore undertaken to determine the sustainability of HCTCRB and CTB, focusing on the environmental and economical implications of utilising either of the pavement materials.

The results are then used as performance indicators to perform a multi criteria analysis (MCA). The approach to the evaluation undertaken by this paper is shown in Figure 1 below.

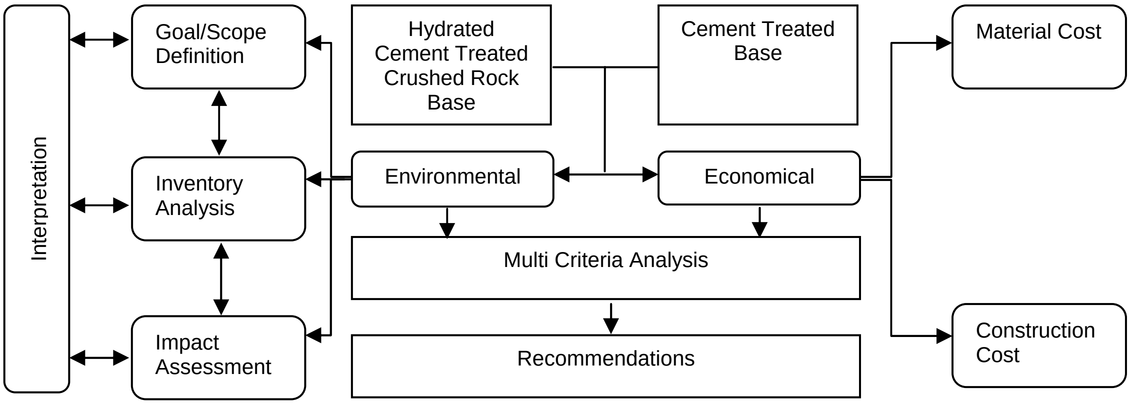

Figure 1. Methodology diagram of sustainability assessment

The LCA is conducted as per ISO 14040:1998 which involves a four phase approach, i.e. goal definition, inventory analysis, impact assessment and interpretation. Following that, an economical evaluation is determined from material, construction and maintenance cost incurred from the selection of the material. The two factors are then weighted and evaluated based on a multi criteria analysis.

3.1 System boundary

The system boundary to evaluate the sustainability performance between HCTCRB and CTB encompasses the critical life cycle stages that more apparently distinguishes the two materials namely, batching and construction. Figure 2 below showcases the system boundary and the major input parameters and relevant consequential impacts.

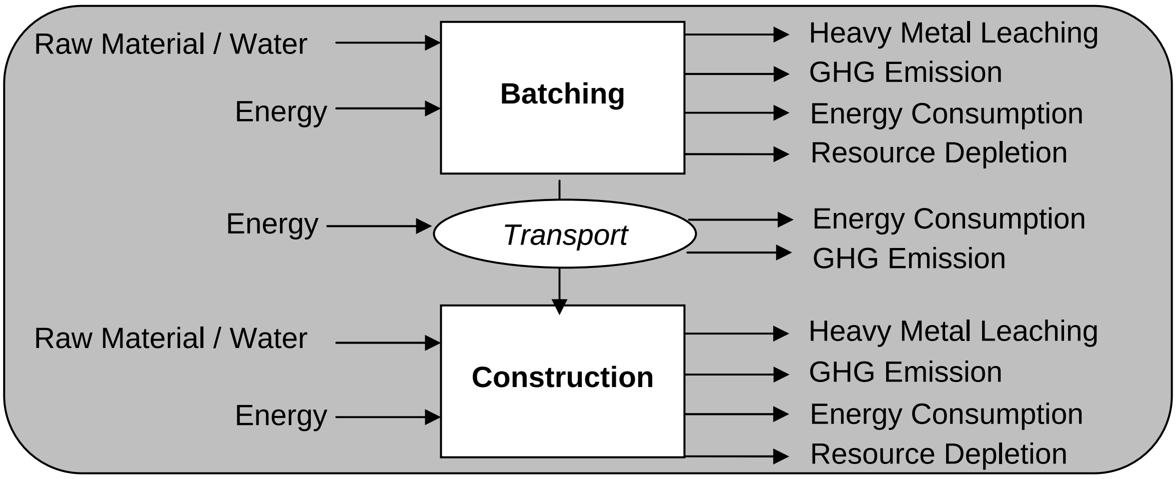

Figure 2. System boundary of assessment

The system boundary is narrowed to the two life cycle stages based on a gate to gate assessment as the loadings associated to sourcing of raw materials is reflected its consumption. Furthermore, stages beyond construction are discounted as pavement maintenance primarily involves resurfacing of the wearing surface. As for issues with frequency of maintenance, the design service life is standardised. Finally, the end of life of the pavements are not directly considered in this paper but are touched briefly in Section 4.2.5, where the potential for material recycling based on material selection is discussed.

The output environmental loadings have been also limited to in this pilot study based on existing studies of road construction life cycle analyses (Eskola et al. 2001) where the significant environmental impacts of road construction are atmospheric emissions, energy and resource depletion as well as chemical leaching. Similarly, Mroueh et al. (1999) has presented the key environmental loading of road construction based on expert groups and its corresponding scale. The top 5 items of the list and the equivalent generalised environmental loading assessed in this paper are shown in Table 1 below:

Table 1. Top 10 environmental loading of road construction

	Averaged score	*Generalised assessment*
Consumption of natural materials	10.0	Resource Depletion
Heavy metal to soil	9.4	Leaching
Fuel consumption	7.5	Energy Consumption
NO_x to atmosphere	7.0	GHG Emission
Energy consumption	6.9	Energy Consumption

As for the economical considerations, the associated material, transportation, storage and labour costs are accounted for throughout the two life cycle stages based on typical Bill of Quantities used for the construction of the designed pavements. As discussed in the following section, the service life of the pavements will be designed to similar number of years as to provide a better comparison, and hence will predominantly evaluate the initial capital cost, which reflects studies undertaken for stabilising techniques of road rehabilitation (Smith and Vorobieff 2005).

3.2 The functional unit

The sustainability evaluation applies the *functional unit* of one kilometre highway designed by applying standard pavement design procedures as per Main Roads design guideline (Butkus 2004) used in the Reid highway test sections. The choice of functional unit allows provisions of the effects of individual mechanical properties of the pavement materials to be evident governing material consumption. The cross section of selected pavement designs applied for evaluation are designed to allow optimum usage of the pavement materials as shown on Figure 3 below.

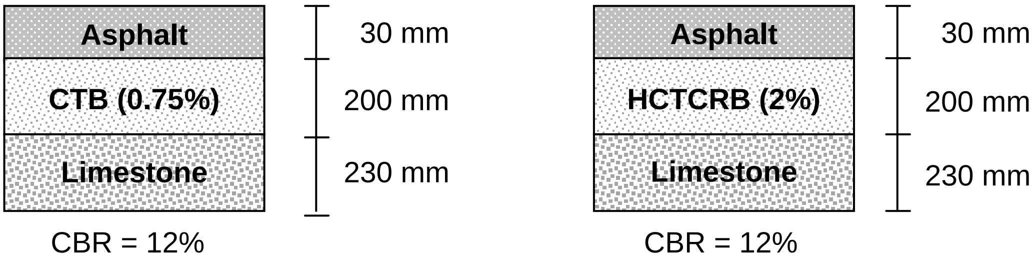

Figure 3. Pavement design

3.3 Production and construction process of pavement materials

This section details the batching and construction processes of the two different pavement materials. The investigation into the two life cycle stages determines the magnitude of input and output parameters of over each life cycle stage.

3.3.1 HCTCRB production and construction

Hydrated Cement Treated Crushed Rock Base is pre-mixed at quarries with typically 2% cement by using a loader. The premix is then passed through a pugmill at OMC. Following, the cement treated crush rock is then set in prepared forms and stockpiled at the quarry to allow for hydration to occur, with interim remixes to prevent setting up (Butkus 2004). After 24 - 48 days (Kelley 2009), the materials are then put through a mill to be disturbed and ultimately used as typical base course granular materials, i.e. the materials are trucked to site and spread on the subgrade with a grader.

3.3.2 CTB with microcracking production and construction

Cement treated base for this evaluation are assumed to be batched from plants. The production of CTB is similar to the typical batching processes of concrete where the required amount of cement which ranges from 0.5% to 10% is mixed with crushed rock and loaded onto concrete trucks. Once transported to site, CTB is poured onto the pavement and allowed to cure for 48 to 72 hours by sprinkling. Following, the microcracking process is undertaken by a minimum 12-ton vibratory roller travelling at 3.2km/h to 4.8km/h (PCA 2005). Upon satisfactory completion of microcracking, the base layer is further moist cured by sprinkling for an additional 72 hours.

3.4 Applied sustainable assessment

In view of the current practices in sustainability assessment, a pilot gate to gate life cycle inventory analysis based on the system boundary defined allows the fulfilment of objectives defined. References are sought based on life cycle inventory database where applicable. The following section discusses the investigation results and its interpretation thereof.

4 Assessment results

From the methodology set out in previous section, a pilot life cycle inventory analysis was undertaken based on the inputs and outputs as shown in Figure 2 for the pavements sections presented in Figure 3. The selected outputs of the pavement material batching and construction and its interpretation thereof is discussed as follow.

4.1 Pavement score

The pavement scores based on the LCI are presented in Table 2.

Table 2. Relative pavements loading percentage

	CTB			***HCTCRB***		
	Batch	Construct	**Life**	Batch	Construct	**Life**
Environmental (30%)						
Resource Depletion				+0.9%		**+0.9%**
Energy Consumption		+5.5%		+41.4%		**+16.7%**
GHG Emission		+4.6%	**+2.6%**	+2.6%		
Chemical Leaching		+	**+**	+		
Economical (70%)						
Direct Cost		+50.0%	**+6.1%**	+18.8%		
Sustainability score						
Relative %						**+3.0%**

The table shows the relative % difference of each assessment criterion over the two assessed life cycle stages, i.e. batching and construction and the whole life cycle. The values indicate the % higher sustainable loading imposed by the pavement at the corresponding life cycle stage.

Environmentally, HCTCRB incurs a higher loading in terms of resource depletion at +0.9% and energy consumption +16.7%, while CTB imposes a higher loading in terms of green house gas emission at +2.6% and chemical leaching into soil. Data for chemical leaching into soil are limited and site oriented, and hence is evaluated based on qualitative assessment.

The construction of CTB incurs an economical loading that is significantly higher than HCTCRB, i.e. at +50.0%. The direct cost of the CTB pavement is 13.7% higher than the HCTCRB pavement.

Overall, the weighted sustainable score shows the HCTCRB has a 3% better performance.

4.2 Interpretation and discussion of results

With the results presented in Section 4.1, this section provides interpretation of the data and provide discussions of the processes of the life cycle stages involved in the construction of stabilised pavements using HCTCRB and CTB. It discusses the environmental and economical loadings determined from the assessment while touching on issues of transport, storage, construction timeline and the afterlife of each pavement.

4.2.1 Environmental loading

Based on the system boundary and constraints as discussed in Section 3.1, it is inferred from the relative scores presented in Table 2 that the use of HCTCRB results in the depletion of resources. The total required tonnage of material for CTB is marginally lesser than HCTCRB as the cement forms mortar during hydration of the material. The remixing of HCTCRB in its batching also potentially results in a lost of cement material during to milling, which is a due cause for production improvements of HCTCRB as discussed in Section 5.

The construction of CTB layers require more passes by compactors to apply the microcracking, which results in an increase of energy consumption, cost and GHG emission. On the other hand, as the production HCTCRB requires additional remixing through a pugmill which is relatively more significant than the GHG emission caused by microcracking procedures. The total energy use through the life cycle of the pavements is therefore primarily governed by the energy use during batching. The energy requirements noted from the study allows the identification of improvement processes as discussed in Section 5.

The inventory analysis also noted that the predominant contributor to GHG emission is governed by transportation of materials and use of diesel fuelled plants. The additional construction works required for microcracking as discussed in Section 3.3.2 causes more GHG emission relative to the typical grading of HCTCRB. Moreover, the total tonnage deliverable by a dump truck is relatively higher than standard cement trucks, resulting in more trips required for the delivery of batched CTB. With transport being a major factor, further discussion is provided in Section 4.2.4 with regards to delivery distances.

Since the mixing of cement and the hydration process for the production of HCTCRB is conducted at the quarry, which is assumed to be in a more controlled environment, the chemical leaching of the cement paste to soil is better mitigated. In contrast, CTB is laid on site to be cured which may cause significant infiltration of toxicity into soil. Based on physical bonding between the aggregates, the moisture susceptibility of HCTCRB is believed to be higher compared to CTB which may potentially result in the “washing out” of cement into the soil. Further studies are required to understand this characteristic of both HCTCRB as discussed in Section 5.

Nonetheless, in overall the environmental loading is identified to be not majorly significant as shown in Table 2. As the assessment is conducted under specific constraints other factors such as distance, rehabilitation potential, material availability, delivery efficiency, etc will affect the outcome of the environmental loadings of the pavement materials.

4.2.2 Economical loading

As reviewed in Section 3.1, the economical loading is principally determined from the direct cost as maintenance of the base course layer is generally limited throughout the life cycle of the pavement. The cost associated to maintaining pavements to reach its full service life is largely associated to rehabilitation of the wearing surface.

In this assessment, the direct cost incurred by CTB is primarily due to the construction costs associated to site supervision and prolonged risk to wet weather with extended construction on site as a result of i) the extended construction time to allow CTB to cure on site before microcracking, ii) the additional compaction effort required to perform microcracking after CTB has set. The batching cost, although more significant for HCTCRB, is dominated by the cost of cement which does not outweigh the construction cost of CTB. For discussion purposes, the application of microcracking in Australia would also run a risk in over compaction, causing excessive cracking, due to the limited knowledge of the technology.

4.2.3 Multi criteria analysis and sensitivity analysis

The final sustainability assessment from the results has been undertaken using a multicriteria analysis of weighting the environmental loadings as per the rankings established in Table 1 and then weighing the economical and environmental loadings. The pilot study of this paper takes into account a 70% economical and 30% environmental weighting which results in an indicative result of HCTCRB being 3.0% more sustainably sound.

To further evaluate the weighting selected, a sensitivity analysis was undertaken. The analysis allows the estimation of a convergence point between the weighting to evaluate a scenario where CTB would be deemed as sustainable to HCTCRB. This would in turn verify the selected economical to environmental rating as well as to assist in identifying scenarios where CTB would be a more plausible choice. Figure 4 below shows the sensitivity analysis, where the convergence point is estimated to be at the weighting of 59% economical and 41% environmental under the constraints studied.

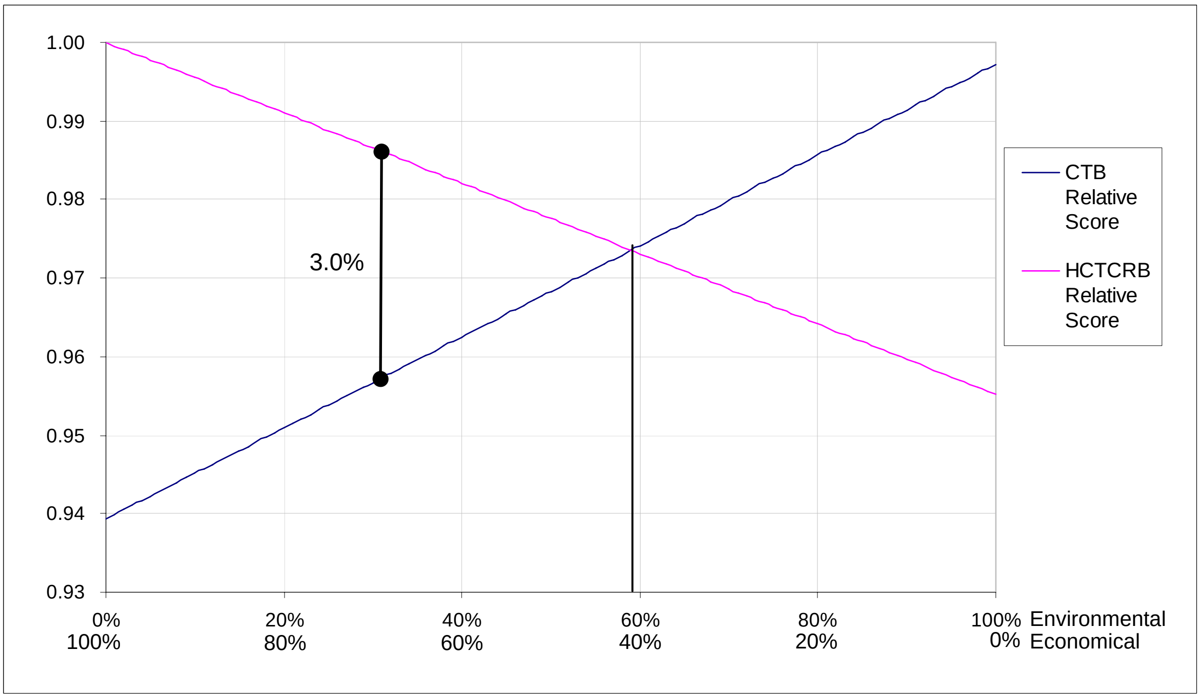

Figure 4. Sensitivity analysis

It is therefore inferred from the multicriteria analysis that HCTCRB is a more sustainable solution in stabilising pavement. The sensitivity analysis also shows that HCTCRB would be in general circumstances a more sustainable solution with the applied weighting.

4.2.4 Transportation and in-situ mixes

The delivery distance of the materials reflects as a significant factor in the determination of the sustainability assessment. With different characteristic densities of CTB and HCTCRB, the total number of trips varies resulting in more GHG gas emissions and fuel consumption for HCTCRB at the batching life cycle stage.

However, the delivery of batched CTB is significantly limited by the setting period, which hence limits the use of CTB within a confined proximity where a batching plant is available. In-situ CTB mixes can be used as an alternative, but would require an increase in thickness and more advanced equipments as provisions for quality assurance.

4.2.5 Afterlife rehabilitation potential

The rehabilitation potential of both pavements is deemed highly plausible with existing CTB pavements requiring two times more reclamation effort compared to HCTCRB (Austroads 2007). However, rehabilitation of pavements through Full Depth Reclamation (FDR) techniques which grinds and mixes existing pavements with cement to form new layers of CTB has been identified in numerous literatures as being a sustainable solution. Under these circumstances, an in-situ recycled CTB base course layer would therefore greatly outweigh the use of HCTCRB.

5 Conclusion and recommendation

In summary, this paper has discussed the application of life cycle analysis combined with a multi criteria analysis to act as a pilot study in determining the sustainability of engineering modified base course materials, i.e. Hydrated Cement Treated Crushed Rock Base (HCTCRB) and Cement Treated Base (CTB) with microcracking.

The use of HCTCRB in pavements consumes more material and energy. However a pavement with CTB will result in higher green house gas emissions, increased potential for chemical leaching, and higher costs. Through a multicriteria analysis, and considering the constraints and circumstances studied in this paper, HCTCRB has been identified as being a more sustainable solution compared to CTB. Nonetheless, delivery distance, rehabilitation potential and availability of resources remain key factors in determining the right base type for road construction.

More importantly, the following assessment has been successful in identifying potential improvements in the production and construction of road pavement with HCTCRB and CTB with microcracking as follow:

i. Improve recovery of cement lost in the remixing processes of HCTCRB
ii. Investigate and improve remixing sequences of HCTCRB to reduce total energy used for the production
iii. Ensure hydration of HCTCRB at quarries are duly controlled to prevent chemical leaching
iv. Understand the moisture susceptibility characteristics of HCTCRB to determine potential chemical leaching
v. Utilise CTB with microcracking as part of Full Depth Reclamation road rehabilitation.
vi. Improve CTB and microcracking knowledge base in Western Australia to optimise its use
vii. Plan CTB pavements to minimise construction cost.

As a final point, stabilisation of base course materials to improve otherwise mechanically inadequate materials for heavily trafficked pavements are essential for sustainable road construction, nevertheless, more studies are required to understand the characteristics of HCTCRB and CTB in order to optimise the sustainability of the transport industry.

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