RESEARCH ARTICLE | DECEMBER 26 2023

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AIP Conf. Proc. 2624, 030079 (2023)
https://doi.org/10.1063/5.0132373

A Comparative Investigation into Pavement Thickness and Cost of Construction Materials of Stabilised Flexible Pavement with Crumb Rubber-modified Asphalt

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Abstract. The economic feasibility of soil chemical stabilisation and asphalt crumb rubber (CR) modification in flexible pavement has not been investigated in recent research. It had been accomplished in this paper by comparing a conventional section comprised of unbound sub-base, unbound roadbase and conventional hot-mix asphalt (HMA) wearing course with a non-conventional section comprised of chemically-stabilised sub-base, unbound roadbase and CR-modified (CRM) HMA wearing course. The thickness of each layer in the two sections was determined using California bearing ratio (CBR) design chart and the cost of construction material was determined using the layer thickness and local material unit cost. The investigation concluded that sub-base stabilisation with 3% Portland composite cement (PCC) and wearing course modification with 1% CR resulted in the thinnest and most economical non-conventional section when compared to the conventional section. Sub-base stabilisation with 1% styrene-butadiene latex copolymer (TP) resulted in the thickest and costliest non-conventional pavement section.

INTRODUCTION

There are numerous factors that influence the cost of road construction [1]. Material cost typically accounts for between 40% to 60% of the road construction cost [2, 3]. In principle, the cost of road construction is influenced by: 1) the pavement design method, which could be either empirical (e.g., American Association of State Highway and Transportation Officials (AASHTO) design method and CBR design charts), mechanistic (finite element modelling (FEM)) or mechanistic-empirical; 2) the type of construction material, such as local or imported aggregate, marginal- or high-quality aggregate; 3) the type of soil stabilisation, which could be either mechanical (compaction), physical (geosynthetics) or chemical (additives); and 4) the type of asphalt modification, such as conventional HMA, CRM HMA and polymer-modified HMA.

Ref. [4] showed that pavement design using Indian Road Congress-37, AASHTO-93, AUSTROADS and Design Manual for Roads and Bridges resulted in 4 different asphaltic surface thicknesses. In addition, Ref. [5] showed that pavement design using Asphalt Institute, British and Egnatia Odos design methods resulted in 3 different pavement thicknesses. Ref. [6] found that the initial cost of traditional flexible pavement using bitumen/asphalt (₹3.70 crores/km) was less than that of reinforced flexible pavement using non-woven geotextile (₹4.05 crores/km). Ref. [7], on the other hand, concluded that conventional flexible pavement, composed of granular sub-base and wet mix macadam roadbase, had less durability and strength than non-conventional flexible pavement, composed of cement-

International Scientific and Practical Conference "Railway Transport and Technologies"
AIP Conf. Proc. 2624, 030079-1–030079-7; https://doi.org/10.1063/5.0132373
Published by AIP Publishing. 978-0-7354-4706-6/$30.00

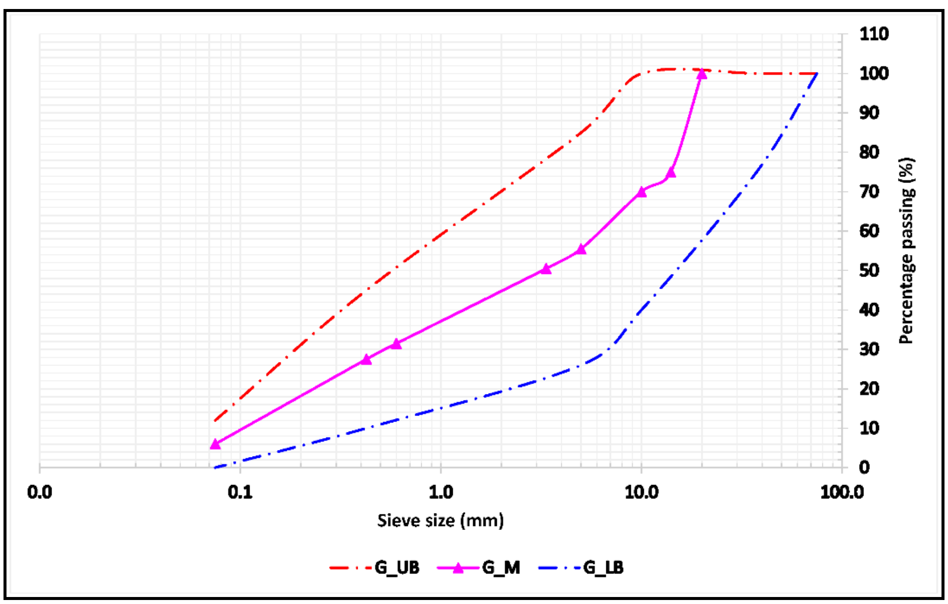
treated sub-base or cement-treated roadbase), and thus the long-term cost of conventional flexible pavement (₹1,96,79,760/km) was more than that of non-conventional flexible pavement (₹1,54,18,080/km). Furthermore, the thickness of non-conventional flexible pavement was 100mm less than that of conventional flexible pavement. In another example, Ref. [8] found that conventional asphaltic road with a wearing course of unmodified bitumen has a cost of less than non-conventional asphaltic road that had a wearing course of modified bitumen; the additional cost (₹25,600/km) was incurred when waste plastic was used to modify the bitumen.

It is common for subsidies of state-owned road infrastructure to be under-funded, and road engineers and contractors often resort to cost-effective construction approaches that do not compromise pavement performance and lifespan. If available local aggregate, such as sandstone, is of low strength, this would result in the construction of thick pavement sections, which may not be cost effective. As an alternative that can reduce pavement thickness, recent research has investigated the use of chemical stabilisation of sandstone [9] and CR modification of HMA for road construction. However, the additional cost of stabilisation and CR modification may escalate the construction cost of pavement. Recent research has not compared the construction cost of these two alternatives. Moreover, there is a shortage in research on the identification of the most cost-effective option for sandstone's chemical stabilisation.

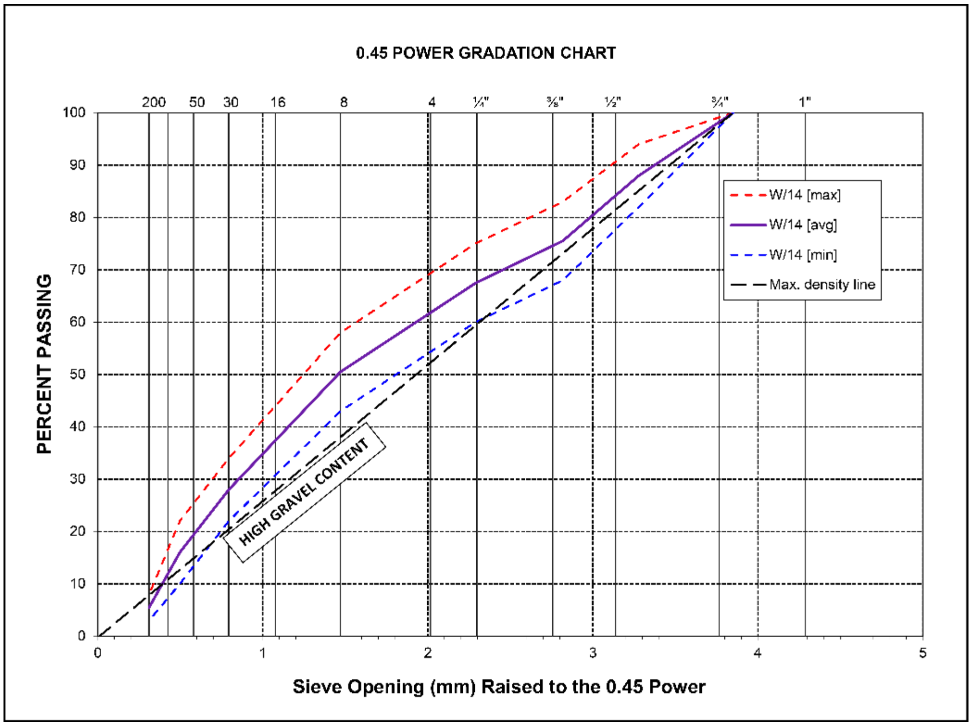
Based on the aforementioned gap in previous research studies, the objective of this paper is to compare the cost of construction materials of a conventional flexible pavement section, comprised of unbound sandstone sub-base layer, unbound imported roadbase aggregate layer and conventional HMA wearing course, to that of a non-conventional flexible pavement section, comprised of chemically-stabilised sandstone sub-base, unbound imported roadbase and CRM HMA wearing course. Three different options of sandstone stabilisation are investigated in the non-conventional pavement section: polymer stabilisation, cement stabilisation and polymer plus cement stabilisation. This is to highlight the monetary utility of aggregate stabilisation and asphalt modification in flexible pavement construction, thus, encourage road professionals to shift from conventional to non-conventional construction of flexible pavement. The thickness of each layer in the conventional and non-conventional pavement sections was determined using the CBR design chart method. This study excludes the costs of labour, equipment and post-construction pavement maintenance and rehabilitation.

MATERIALS, SAMPLE PREPARATION AND TEST METHODS

FIGURE 1 (a) and (b) show the gradation curves for the local sandstone aggregate mixture used for the sub-base construction and imported diorite aggregate mixture used for the wearing course construction respectively. Both gradation curves are the median curves of their respective gradation envelopes specified in the local specification in Brunei Darussalam, i.e., GS 1 [10].



(a)



(b)

FIGURE 1. Gradation curves for (a) local sandstone aggregate mixture used in sub-base and (b) imported diorite aggregate mixture used in wearing course.

For the construction of the non-conventional pavement section, the sandstone samples were stabilised with PCC – CEM II/A-V (C2), which is produced locally. C2 is rarely used in soil stabilisation but has several benefits. C2 can limit alkali-silica reaction [11] and losses in compressive, tensile and flexural strengths which are due to alkali-silica reaction [12]. C2 can also provide higher strength and durability than ordinary cement in the long term [13]. Cement content less than 3% produces low tensile strength for the cement-stabilised soil samples whereas cement content greater than 5% causes the samples to be stiff and brittle, resulting in transverse and longitudinal cracks [14]. To investigate another option for the chemical stabilisation of sandstone, the sandstone samples were treated with TP (tradename: T-PRO® 500), which is imported. It is a non-ionic and hydrolysis-resistant white colour water-based dispersion of a latex copolymer [9]. The experimental TP contents used by Ref. [15] were 0.5%, 0.75%, 1% and 2% by mass of clay-sand-gravel samples and it was found that the optimum TP content for the highest UCS was 0.75%. The experimental TP contents used by Ref. [16] were 0.5%, 0.75%, 1% and 2% by mass of sand-gravel samples and it was found that the optimum TP content for maximum dry density and optimum moisture content was 0.75%. Since cement causes the cement-aggregate mixture to be brittle [17] and develops drying shrinkage cracking [18], a co-additive is recommended. The addition of polymer creates polymeric film that bridges microcracks resulted from drying shrinkage, thus, inhibiting crack propagation and simultaneously giving additional adhesion bond between aggregate particles and cement hydrates as well as filling the air voids with polymer-cement matrix [19, 20]. Since it was determined by Refs. [15] and [16] that the optimum TP content was 0.75% by mass of aggregate for polymer plus cement stabilisation of sandstone, where TP was used as co-additive to 2%, 3% and 5% C2 (all by mass of aggregate). The test method for punching shear to determine the CBR of the stabilised sandstone in this study was performed in accordance to BS 1377-4 [21]. It was determined that 1% TP, 3% C2 and 0.75% TP+2% C2 (all by mass of aggregate) were the minimum chemical stabiliser contents for the sandstone samples to meet the CBR requirement for sub-base stabilisation, i.e., CBR ≥ 30% for TP-stabilised and CBR ≥ 80% for C2- and TP+C2-stabilised samples. Therefore, these three stabilisation options were adopted in this study for the chemically-stabilised sub-base of the non-conventional pavement section.

The CR used in this investigation was imported and was derived from truck and passenger car tyres. Previous investigations [22-26] had shown that the optimum CR content was 1% – 2% by mass of asphalt mixture and the optimum CR size was 0.1mm – 1.0mm. Therefore, the experimental CR contents in this study were 1%, 2% and 4%

by mass of aggregate. CR retained on the 0.71mm BS sieve was used to replace the diorite aggregate retained on the 1mm BS sieve in order to prepare the CRM asphalt of the non-conventional pavement section. As recommended by Ref. [27], the experimental HL content adopted in this study was 2% by mass of aggregate to act as an anti-stripping agent and as a filler. The HL was also imported. Locally-sourced bitumen 60/70 penetration grade was used as the asphalt binder. The range or target bitumen content stipulated by Ref. [10] is 5.5% – 6.5% for the wearing course gradation, thus, the experimental bitumen content (range) adopted for this investigation was 5.0% – 7.0% at 0.5% interval by mass of asphalt mixture (± 0.5% from the stipulated range). The test method to determine the volumetric and Marshall properties of the modified samples was performed in accordance to ASTM 1559 [28]. It was determined that by replacing 1% of imported diorite aggregate with 0.71mm sized CR and using 2% HL, both by mass of aggregate, and mixing with 5.5% bitumen penetration grade 60/70 by mass of asphalt mixture, the volumetric and Marshall properties of the CRM asphalt satisfied international standards. The Marshall stability (S) and flow (F) for unmodified wearing course were 17.8kN and 3.92mm respectively while the F and S of CRM wearing course were 17.52 and 3.37mm respectively.

RESULTS AND DISCUSSION

The CBR design chart is used to estimate pavement thickness above a certain pavement layer using the CBR value of this layer for either light, medium or heavy traffic condition. Assuming the worst possible sub-grade (CBR = 2%) and traffic overloading (heavy traffic) conditions, using the sub-grade's CBR and the CBR design chart, the total thickness (T) of the conventional pavement section was determined as 680mm. Using the CBR results from 4-day unsoaked condition at the top surfaces of the unstabilised sandstone samples, as shown in TABLE 1, and assuming a CBR of 80% for the roadbase, the thicknesses of sub-base ($t_{sb,design}$), roadbase ($t_{b,design}$) and surface layer ($t_{s,design}$) of the conventional pavement section were estimated from the CBR design chart, as shown in TABLE 2. Other strength properties of the unstabilised and stabilised sub-bases, such as unconfined compressive strength (UCS) and indirect tensile strength (ITS), for the 7-day air-dried sandstone samples are also shown in TABLE 1.

TABLE 1. 4-day unsoaked CBR and 7-day air-dried UCS, ITS and ρ_b for unstabilised and stabilised sub-base.

Layer	Unstabilised sub-base	Stabilised sub-base (1% TP)	Stabilised sub-base (3% C2)	Stabilised sub-base (0.75% TP+2% C2)
CBR (%)	46	49	126	106
UCS (MPa)	0.95	2.06	5.04	2.64
ITS (MPa)	0.00	0.16	0.43	0.20

The aforementioned design process was repeated for the non-conventional pavement section, in which the sub-base was stabilised with 1% TP, 3% C2 and 0.75% TP+2% C2 contents and the wearing course was modified with 1% CR content of 0.71 mm. Since the CBR design chart method only considers the CBR value of pavement layer without any consideration for the structural strength of layers above the layer of interest, the thickness of the chemically-stabilised sub-base ($t_{sb\_stabilised}$) in the non-conventional pavement section was unrealistically higher than that of the unstabilised sub-base ($t_{sb\_unstabilised}$) in the conventional pavement section. To rectify this issue, the ratio of $t_{sb\_stabilised}$-to-$t_{sb\_unstabilised}$ was assumed proportional to $CBR_{sb\_unstabilised}$-to-$CBR_{sb\_stabilised}$. TABLE 2 shows the resultant design layer thicknesses of the non-conventional pavement section. According to Refs. [29] and [30], the AASHTO-recommended minimum thicknesses for surface, roadbase and sub-base under the heavy traffic condition are 90mm ($t_{s,new}$), 150mm ($t_{b,new}$) and 150mm ($t_{sb,new}$) respectively. The new pavement thicknesses (T_{new}) were accordingly determined as shown in TABLE 2.

TABLE 2. Pavement thickness for $t_{sb,new}$, $t_{b,new}$, $t_{s,new}$ and T_{new}.

Pavement section	Conventional	Non-conventional		
Property	**Unstabilised sub-base**	**Stabilised sub-base (1% TP)**	**Stabilised sub-base (3% C2)**	**Stabilised sub-base (0.75% TP+2% C2)**
$CBR_{sub\text{-}base}$ (%)	46	49	126 (> 80%)	106 (> 80%)
$t_{sb,design}$ (mm)	560	530	205	245
$t_{b,design}$ (mm)	40	30	20	20
$t_{s,design}$ (mm)	80	80	80	80

TABLE 2. Continued

$t_{b,new}$ (mm)	150	150	150	150
$t_{s,new}$ (mm)	90	90	90	90
$t_{sb,new} + t_{b,new} + t_{s,new} = T_{new}$ (mm)	800	770	445	485

Using the current construction costs of Brunei Darussalam for this study, the unit rates of sandstone, C2 and TP are BND35/m^3, BND0.16/kg and BND5/L respectively, while the unit rates of diorite, CR, HL and bitumen are BND45/m^3, BND1/kg, BND0.40/kg and BND0.95/kg respectively. The unit cost (BND/m^2) for the whole layer thickness for the unstabilised sub-base, stabilised sub-base, unstabilised roadbase, unmodified wearing course and modified wearing course are shown in TABLE 3, TABLE 4 and TABLE 5.

TABLE 3. Unit cost per the whole pavement thickness for unstabilised sub-base, stabilised sub-base and unstabilised roadbase.

Layer	**Unstabilised sub-base**	**Stabilised sub-base (1% TP)**	**Stabilised sub-base (3% C2)**	**Stabilised sub-base (0.75% TP+2% C2)**
$t_{sb,new}$	BND19/m^2 (560mm)	BND74/m^2 (600mm)	BND9/m^2 (205mm)	BND30/m^2 (245mm)
$t_{b,new}$ (unstabilised)	BND7/m^2 (150mm)	BND7/m^2 (150mm)	BND7/m^2 (150mm)	BND7/m^2 (150mm)

TABLE 4. Unit cost per the whole pavement thickness for unmodified wearing course, modified wearing course and unmodified binder course.

Layer	**Unmodified wearing course**	**Modified wearing course (1% CR)**
Wearing course (t_{wc})	BND8/m^2 (40mm)	BND10/m^2 (40mm)
Binder course (t_{bc}) (unmodified)	BND9/m^2 (50mm)	BND9/m^2 (50mm)

TABLE 5. Total unit cost per the whole thickness of conventional and non-conventional flexible pavement sections.

Pavement section	**Conventional**	**Non-conventional**		
Sub-base Layer	**Unstabilised (A)**	**Stabilised with 0.75% TP (B)**	**Stabilised with 3% C2 (C)**	**Stabilised with 0.75% TP+2% C2 (D)**
Total cost per the whole depth of pavement	BND43/m^2	BND100/m^2	BND35/m^2	BND56/m^2

TABLE 5 shows that the lowest total unit cost of construction materials and pavement thickness were related to Section C, for which the UCS and ITS were the greatest among all investigated sections. The second lowest total unit cost of construction materials was related to Section A in which the sub-base was unstabilised; however, its total pavement thickness was 1.8 times that of Section C. In addition, the unstabilised sub-base had the poorest UCS and ITS. The highest total unit cost of construction materials was related to Section B, which was 3 times that of Section C. Moreover, the total thickness of Section B was 1.7 times that of Section C. At almost the same total pavement thickness, the total unit cost of construction materials related to Section B was 2.3 times that of Section A. At almost the same total pavement thickness, the total unit cost of construction materials related to Section D was 1.6 times that of Section C. Generally, polymers are more expensive than Portland cement [31]. Although the cost of the CR-modified wearing course was higher than that of the conventional wearing course by BND2/m^2, the former showed significant improvement in F and slight regression in S.

CONCLUSION AND RECOMMENDATIONS

The investigation has clearly proven that non-conventional flexible pavement, in particular when the sub-base was stabilised with 3% C2 and wearing course modified with 1% CR, is thinner and has a lower construction material cost than conventional flexible pavement. It is also demonstrated that sub-base stabilisation reduces the sub-base and roadbase thicknesses but not necessary the unit cost of pavement construction materials. This is evident for the non-conventional pavement section with 1% TP-stabilised sub-base, for which the unit cost of construction materials was the highest among all investigated pavement sections. As the results in TABLE 5 were based on short-term curing periods, it is recommended that longer curing periods, i.e., 7 days for CBR and 14 and 21 days for UCS and ITS be conducted for different curing conditions. Alternative CBR design charts from Refs. [32] and [33] can be used to determine the pavement thickness and compare with that in TABLE 5. Other performance tests to determine the flexural strength, stress-strain behaviour and material moduli (in particular, the resilient modulus (M_r)) after long curing periods under different curing conditions are also recommended for future research. With M_r and other moduli, pavement thicknesses can be determined and validated using more sophisticated pavement design methods, such as AASHTO method and FEM. In addition to the cost of construction materials, the costs of labour, construction time, equipment and post-construction pavement maintenance and rehabilitation are recommended for consideration in future research.

ACKNOWLEDGMENTS

The Authors gratefully acknowledge the grant bestowed by UTB (UTB/GSR1/2019(4)) and the material supports provided by SWEE Sdn. Bhd. and Terratech Earth Solutions.

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