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An Investigation into the Relationship between Strength Properties of Sandstone Aggregate Stabilised with Cement and Polymer Emulsion for Road Sub-base Applications

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Abstract. The splitting tensile strengths of cement- and polymer-stabilised road aggregate sub-base of marginal quality are of considerable importance in pavement design. There is still limited information concerning the splitting tensile strengths of polymer- and polymer-cement-stabilised on the sub-base since most of the literature focused on compressive strengths and the relationship between splitting tensile and compressive strengths of cement-stabilised sub-base. This paper models the relationship between the splitting tensile and compressive strengths of sandstone aggregates sub-base samples of marginal quality stabilised with combinations of Portland composite cement (PCC) and styrene-butadiene (SB) latex copolymer (TP). All samples were subjected to 7 days of dry curing before undergoing the splitting and unconfined compression tests. While PCC- and TP+PCC-stabilised samples exhibited linear correlations (R2 > 0.98) with slopes of 8.3% and 10.6% respectively, TP-stabilised samples exhibited a negative 2nd degree polynomial correlation (R2 > 0.95). Researchers and practitioners can use these models to determine the corresponding splitting tensile strengths by using measured values of unconfined compressive strengths without conducting indirect tensile tests and vice versa. This approach reduces cost and time of laboratory testing.

Keywords: *Strength properties; sandstone aggregate; cement; polymer emulsion; road sub-base application*

INTRODUCTION

The ratio between splitting tensile (or indirect tensile) and compressive strengths is an important material property of chemically stabilised soil samples. Unconfined compression test (UCT) is universally a common test used to evaluate the compressive strength of soil samples used in road construction [1, 2]. The indirect tensile test (ITT), on the other hand, is one of the least commonly used tests but it provides one of the most critical design parameters [3]. Generally, the stabilised soils for use in road fail in tension rather than in compression, thus, it is logical to specify tensile strength that is adequate to resist the compression-induced tensile/lateral stresses or strains [4]. It is worthwhile to note that soils are inherently too weak to resist tension, thus, it if often considered that the tensile strength of unbound soils is zero [5-7]. Therefore, pavement design standards usually assume that unbound layers can only resist compressive and shear stresses, but not tensile stresses [8].

Tensile strength is usually indirectly evaluated due to difficulties in conducting direct uniaxial tension test [9, 10]. The drawback of split-tension test is that it does not provide a test-loading condition that resembles field condition nor does it facilitate the determination of tensile strain during loading [10]. The ratio of indirect tensile-to-unconfined compressive strengths is useful for road engineers and contractors to estimate unknown indirect tensile strength (ITS)

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of sub-base aggregate samples by only measuring the samples' unconfined compressive strength (UCS). This saves cost and time spent on additional laboratory tests.

Soil stabilisation using physical methods or chemical additives are used to stabilise the granular layers (i.e., sub-base or roadbase) or sub-grades of flexible pavements [11]. In Brunei Darussalam, the use of cement and polymers are more prevalent than bitumen emulsion. Although there are standard methodologies for UCS, flexural strength (FS), moduli of rupture (MR), elasticity (E) and California bearing ratio (CBR) for chemically stabilised granular layers in local specifications [12, 13] tests are often conducted to determine the UCS and CBR only. There is no standard relationship between ITS and UCS of chemically stabilised granular layers in local specifications [12, 13].

Existing ITS-UCS relationships found in the literature are often based on: (1) soil types and gradations, (2) stabiliser types and dosages and curing periods, (3) sample height/diameter (H/D) ratios and (4) compression loading rates. Despite the differences among these past stabilisation scenarios, the ITS/UCS ratios for cement-stabilised granular samples obtained from past investigations were fairly similar. Ref. [14] found that the ITS/UCS ratios for cement-stabilised granular samples ranged between 10% and 20%. In contrast to cement-stabilised granular samples, there have not been no past investigations that examined the ITS-UCS relationships for sandstone aggregate sub-base stabilised with SB polymer emulsions or SB polymer-cement blend.

Thus, the aim of this paper is to model using regression analysis the relationship between ITS and UCS of cylindrical sandstone aggregate sub-base samples of the same dimensions, stabilised with combinations of PCC and TP, and are subjected to the same loading rate. The samples were prepared using the median gradation of the sub-base grading envelope in GS 1: General specifications for flexible pavement [12]. The strength of correlation between ITS and UCS of the samples was measure using the coefficient of determination (R^2). The samples underwent dry curing for 7 days before testing.

MATERIALS, SAMPLE PREPARATION AND TESTING METHODOLOGY

Local crushed sandstone, sourced from a local quarry in Brunei Darussalam was used as the sub-base samples. The mineralogical composition of the sandstone is mostly quartz. The physical and mechanical properties of the aggregate used marginally complied with the local specification stipulated in Ref. [12]. The median gradation curve (G_M) between the upper and lower boundaries (G_UB and G_LB) of the sub-base grading envelope in Ref. [12], as illustrated in FIGURE 1, was used to prepare the samples.

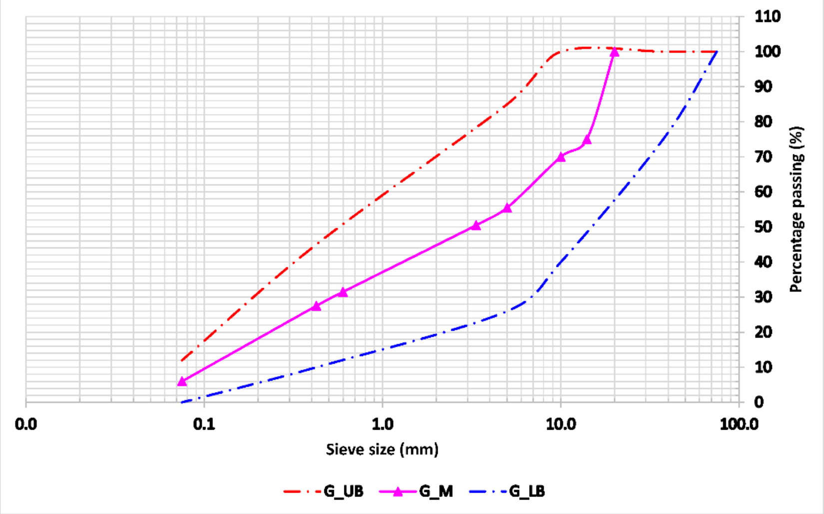

FIGURE 1. *Gradation curve for G_M samples*

PCC (tradename CEM II/A-V) – a blend of clinker (80% – 94%) and Class F fly ash (FA) (6% – 20%) by mass – was procured from a local supplier. PCC, which is rarely used in soil stabilisation, have several benefits over ordinary Portland cement (OPC); the former can limit alkali-aggregate reactions [15] and it can also provide higher strength gain and durability [16]. Ref. [17] cited 30% loss each in compressive and tensile strengths while 60% loss in flexural strengths are due to alkali-silica reaction. Cement content less than 3% does not produce sufficient tensile strength to the cement-modified samples whereas cement content greater than 5% causes the cement-stabilised samples to be stiff and brittle, resulting in transverse and longitudinal cracks [18]. Thus, the experimental cement contents were 3% and 5% by mass of aggregate.

Polymer TP (tradename T-PRO® 500) was selected for use in this paper. It is a non-ionic and hydrolysis-resistant white colour water-based dispersion of a latex copolymer and the main components of this polymer are SB particle (> 50% by weight) and water (< 50% by weight) [9]. The experimental TP contents used by Ref. [19] were 0.5%, 1%, 1.5%, 2% and 2.5% on clayey gravelly sand samples – LCL, LCH and HCH, found the peak TP contents for highest UCS were 0.5%, 1% and 2.5% respectively. The experimental TP contents used by Ref. [20] were 0.5%, 0.75%, 1% and 2% on clayey gravelly sand samples, found the peak TP content for the highest UCS to be 0.75%. The experimental TP contents used by Ref. [21] were 0.5%, 0.75%, 1% and 2% on sandy gravel and gravelly sand samples, found the peak TP content for maximum dry density (MDD) and optimum moisture content (OMC) to be 0.75%. They are all measured as percentage TP by mass of aggregate. Thereafter, the proposed experimental polymer contents to determine the ITS-UCS relationship in this research were 0.5%, 0.75%, 1% and 2%.

Since cement-stabilised soil exhibits brittle behaviour [22] and when exacerbated by transverse shrinkage cracking [23], can lead to other forms of cracking, a co-additive is recommended. The addition of polymer (to cement) creates a polymeric film to bridge the microcracks due to drying shrinkage by cement, thus, inhibiting crack propagation and simultaneously giving a strong adhesion bond between soil particles and cement hydrates as well as filling the in-between voids with polymer-cement matrix [24],[25].

Since the conclusions from Refs. [20] and [21] found that the peak TP content for the stabilisation of sandstone aggregate layers was 0.75% by mass of aggregate, thus, this content of TP was subsequently used as co-additive with the PCC to stabilise sandstone aggregate layers. Ref. [26] stated that the polymer percentage in polymer-cement blend is usually between 10% to 15% and can reach a maximum of 20%. This ensures that ITS and UCS of road sub-base stabilised with polymer-cement blend are within the standard values. Excessive values of ITS and UCS using higher contents of polymer and cement are discouraged to limit the cost of stabilisation and drying shrinkage cracking. Thus, the experimental TP+PCC contents were 0.75%+2%, 0.75%+3% and 0.75%+5% by mass of aggregate.

The test methods for UCT and ITT to determine the UCS and ITS of samples were performed in accordance to BS 1377-7 [27] and BS 1881-117 [28] respectively. In both tests, a constant uniaxial load rate of 0.50MPa/s was applied to the samples. Prior to curing and testing, the samples were compacted using 2.5kg rammer, in accordance to BS 1377-4 [29], to produce samples of height 115.5mm and diameter 105mm (volume = 1000cm3 or 1-L). The samples were then air-dried for 7 days before testing. The compaction characteristics, i.e., MDD and OMC were presented in Ref. [21]. Samples were air-dried for 7 days at 23°C – 26°C and relative humidity of 40% – 50% before testing.

RESULTS AND DISCUSSION

The ITS, UCS and ITS/UCS ratios of PCC-, TP- and TP+PCC-stabilised G_M samples based on the stabiliser contents are shown in TABLE 1.

FIGURE 2 (a) illustrates that the ITS and UCS of PCC-stabilised samples had linear and power relationships with strong correlation ($R^2 \geq 0.98$). This agrees with the findings from Ref. [30] that yielded the ITS-UCS power relationship of $ITS = 0.0685(UCS^{1.1978})$ with $R^2 = 0.9985$ for cement-lime-stabilised samples using 8% to 12% cement content. The slope of the straight line in FIGURE 2 (a) indicated that ITS was almost 8.3% of UCS – slightly below the typical range of 10% – 20%. Presented in the paper as FIGURE 2 (b), the mode of failure presented by PCC-stabilised samples was brittle failure (conical shear). The mechanical property curve for a typical sample stabilised by cement or any other calcium-based stabiliser is nearly linear to failure with very little plastic yielding, i.e., a brittle behaviour [11]. This justified the linear ITS-UCS relationship model in FIGURE 2 (a).

TABLE 1. ITS, UCS and ITS/UCS of PCC-, TP- and TP+PCC-stabilised G_M samples

PCC content (%)	Strength and ITS/UCS ratio	TP content (%)	Strength and ITS/UCS ratio	TP+PCC content (%)	Strength and ITS/UCS ratio
0	ITS = 0.00 MPa UCS = 0.95 MPa ITS/UCS = NA	0.5	ITS = 0.16 MPa UCS = 1.76 MPa ITS/UCS = 9.1%	0.75+2 TP/PCC ratio: 0.375	ITS = 0.20 MPa UCS = 2.64 MPa ITS/UCS = 7.6%
3	ITS = 0.43 MPa UCS = 5.04 MPa ITS/UCS = 8.5%	0.75	ITS = 0.15 MPa UCS = 1.83 MPa ITS/UCS = 8.2%	0.75+3 TP/PCC ratio: 0.25	ITS = 0.36 MPa UCS = 3.96 MPa ITS/UCS = 9.1%
5	ITS = 0.73 MPa UCS = 9.55 MPa ITS/UCS = 7.6%	1	ITS = 0.16 MPa UCS = 2.06 MPa ITS/UCS = 7.8%	0.75+5 TP/PCC ratio: 0.15	ITS = 0.73 MPa UCS = 7.41 MPa ITS/UCS = 9.9%
		2	ITS = 0.19 MPa UCS = 3.43 MPa ITS/UCS = 5.5%		

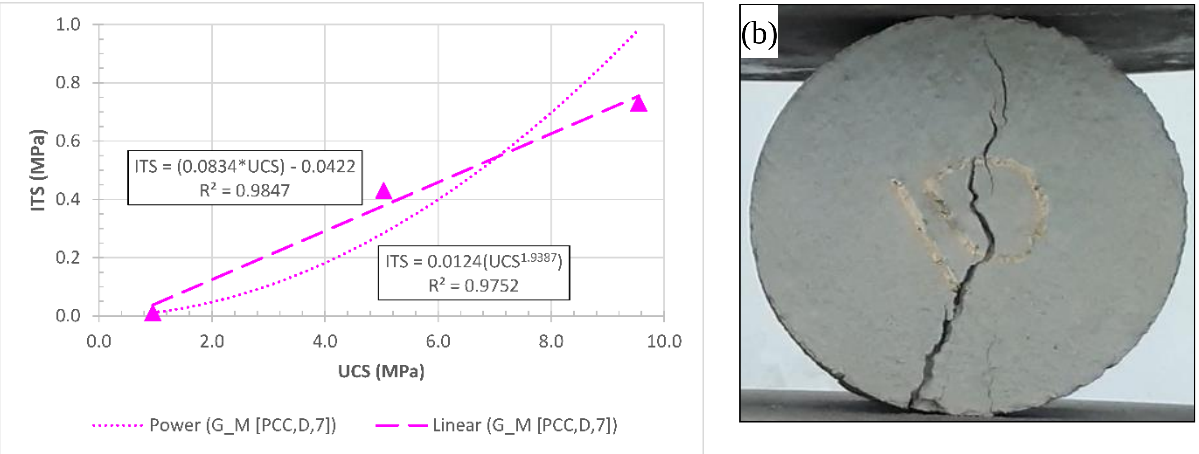

FIGURE 2. *(a) ITS against UCS graphs within the optimum working conditions: 0% < %PCC ≤ 5% and water content = 8%; (b) Split tensile behaviour of 5% PCC-stabilised G_M samples for 7-day dry curing condition (in progress at time approx. 8 seconds)*

FIGURE 3 (a) illustrates that the ITS and UCS of TP-stabilised samples had a negative 2nd degree polynomial relationship with strong correlation ($R^2 \geq 0.98$) and a linear relationship with weak correlation ($R^2 < 0.7$). These disagreed with the findings from Ref. [31] that the ITS/UCS ratios for SB polymer-stabilised granular samples were 10% – 30%, indicating a linear relationship between ITS and UCS. Laboratory observations found that TP content more than 1% may reduce the strength properties and field workability of stabilised sub-base. The TP-stabilised sample in FIGURE 3 (b) suffered more severe transverse cracking than the PCC-stabilised sample in FIGURE 2 (b). This together with the barrel shape upon failure in FIGURE 3 (b) indicated a ductile mode of failure for the TP-stabilised sample. The ductile failure justified the non-linear ITS-UCS relationship model in FIGURE 3 (a).

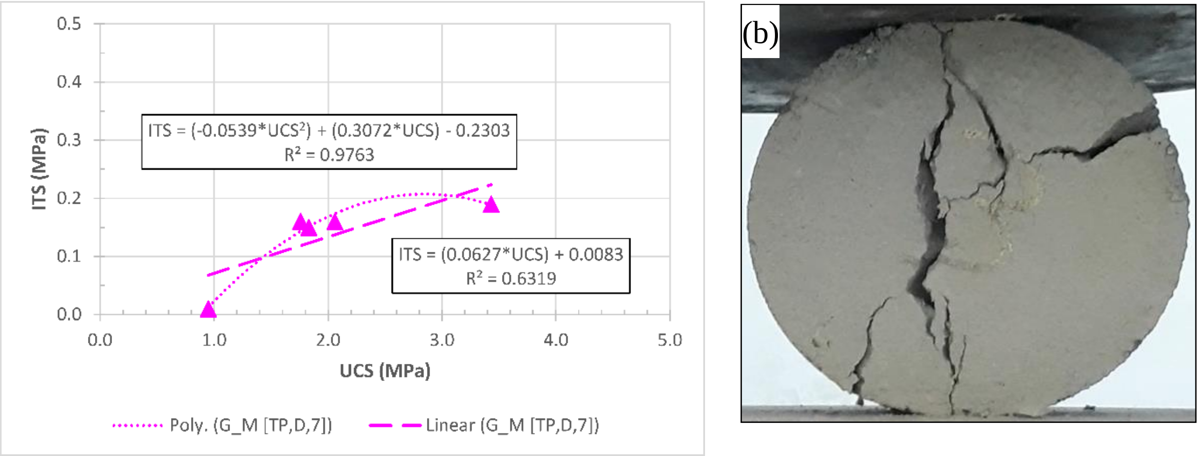

FIGURE 3. *(a) ITS against UCS graphs within the optimum working conditions: 0% < %TP ≤ 2% and water content = 7% (including water content found in TP); (b) Split tensile behaviour of 0.75% TP-stabilised G_M samples for 7-day dry curing condition (in progress at time approx. 4 seconds)*

FIGURE 4 (a**)** illustrates that the ITS and UCS of TP+PCC-stabilised samples had strong linear and power relationships with strong correlation ($R^2 \geq 0.99$), with the linear relationship having slightly higher R^2 than that of the power relationship. FIGURE 4 (a) also shows that ITS was approximately 10.6% of UCS for the TP+PCC -stabilised sub-base samples. This agreed with Ref. [31] who found that the ITS/UCS ratios for SB polymer-cement-stabilised granular samples were between 10% – 20%, indicating a linear relationship between ITS and UCS. It is observed that as the polymer/cement mass ratios increased proportionally from 0.15 to 0.375, the ITS and UCS also increased linearly, which indicates that PCC is more dominant than TP in terms of the strength behaviour of TP+PCC-stabilised sub-base.

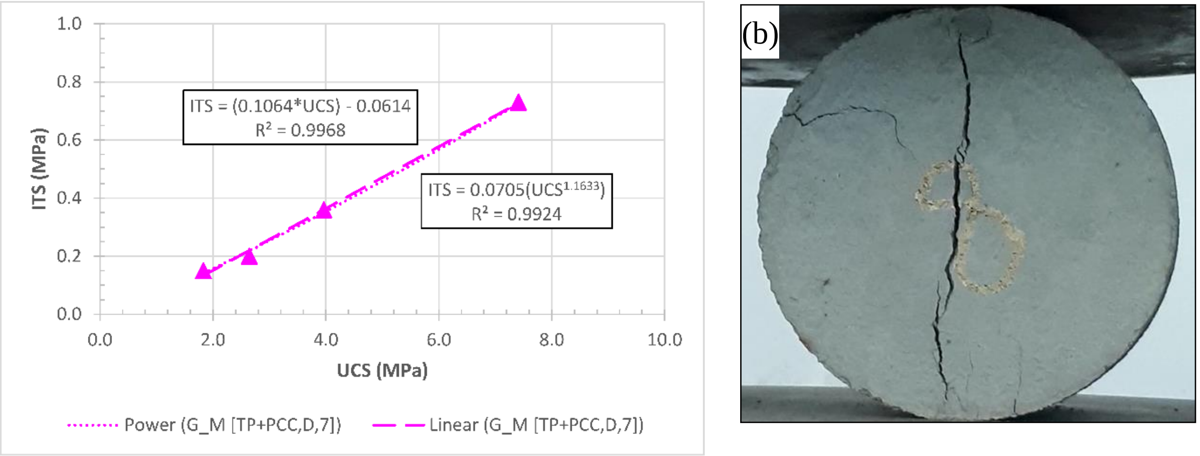

FIGURE 4. *(a) ITS against UCS graphs within the optimum working condition: 0% < %PCC ≤ 5% @ TP = 0.75% and water content = 8% (including water content found in TP); (b) Split tensile behaviour of 0.75% TP + 5% PCC-stabilised G_M samples for 7-day dry curing condition (in progress at time approx. 8 seconds)*

As shown in TABLE 1, for the same PCC contents at 3% and 5%, the ITS and UCS for PCC-stabilised samples were greater than those of TP+PCC-stabilised samples, except for the ITS of PCC- and TP+PCC-stabilised samples at 5% cement content; both have the same ITS of 0.73MPa. The reduction in ITS and UCS when TP is mixed with cement is largely due to the adverse impact of the SB particles on the hydration reaction of cement particles [32]. The mode of failure exhibited by TP+PCC-stabilised samples was a combination of ductile and brittle failures although ductile failure took precedence, which was indicated by the slight transvers cracking of the TP+PCC-stabilised sample upon failure in FIGURE 4 (b).

CONCLUSIONS AND RECOMMENDATIONS

ITT and UCT were test methods used to determine the 7-day (short-term) ITS-UCS relationships of PCC-, TP- and TP+PCC-stabilised sandstone aggregate samples of similar dimensions using loading rates. Using regression analysis on the results obtained from the tests the following conclusions were drawn:

- Stabilisation with PCC, TP and TP+PCC, all within their optimum working conditions, increased the ITS and UCS of the local marginal sandstone aggregate. The ITS and UCS of unstabilised samples were 0 MPa and less than 1 MPa respectively.
- Stabilisation with PCC (PCC content: 3% – 5%) provided the highest ITS and UCS and the ITS-UCS relationship was linear with a slope of 8.3% (R2 = 0.98) **(FIGURE 2)**.
- Stabilisation with TP+PCC (TP+PCC contents: 0.75%+2%, 0.75%+3% and 0.75%+5%) provided the second highest ITS and UCS and the ITS-UCS relationship was linear with a slope of 10.6% (R2 = 0.997). The slight reductions in ITS and UCS were due to the adverse impact of the SB particles on the hydration reaction of cement particles **(FIGURE 4)**.
- Stabilisation with TP (TP content: 0.5% – 2%) provided the least ITS and UCS and the ITS-UCS relationship was a negative 2nd degree polynomial (R2 = 0.98) **(FIGURE 3)**.

Researchers and practitioners can use these models to determine the corresponding splitting tensile strengths by using measured values of unconfined compressive strengths without conducting indirect tensile tests and vice versa. By doing so, it saves both time and cost incurred for additional tests. Further research into ITS and UCS for other curing periods, i.e., 14, 28 and 56 days, is recommended to model the long-term ITS-UCS relationship for PCC-, TP- and TP+PCC-stabilised sandstone aggregate.

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