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Chemically Stabilised Sandstone Sub-base: A Comparative Investigation of the Relationship Between California Bearing Ratios of Top and Bottom Sample Surfaces

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Abstract. There are limited previous investigations on the contributory factors to the relationship between California bearing ratios (CBR) of top and bottom surfaces of chemically stabilised sandstone samples. The aim of this paper is to consider three of these factors: gradation, stabilisation type and soaking condition. Three sandstone gradations of different gravel-to-sand ratios were considered: 2.1, 1.2 and 0.4. Four stabilisation types were inspected: unstabilised, cement-stabilised, polymer-stabilised and polymer-cement stabilised. Two soaking conditions were examined: unsoaked and 4-day soaked. The conclusions from the investigation were: (1) CBR values of samples increased with increasing G:S ratios, (2) cement stabilisation provided the greatest CBR values and this was followed by polymer-cement and lastly, polymer, (3) bottom surfaces of unsoaked samples generally had greater CBR values than those of top surfaces, and the opposite was true for soaked samples and (4) bottom surfaces of the samples were more sensitive to soaking than top surfaces.

INTRODUCTION

Marginal aggregates, such as sandstone, are routinely used as a construction material for sub-base in conventional flexible pavement. Their primary function is to transfer traffic load induced from the surface to the sub-grade. In an unbound-unsoaked state, the marginal strength properties of the sandstone results in relatively thicker sub-base and roadbase. At a saturated condition, the unbound sandstone becomes somewhat friable [1] and its uniaxial (unconfined) compressive strength (UCS) can be as low as 0.5MPa [2]. It often lacks the required strength to withstand load and prevent excessive deformation when subjected to soaking. The design thicknesses of sub-base and roadbase are also dependant on the strength properties of the sub-grade over which the flexible pavement is constructed, the compaction method applied to each aggregate layer as well as the aggregate gradation. A strength-based approach using CBR values (in particular, unsoaked CBR values) is more commonly used in pavement thickness design than stiffness-based approach (e.g., resilient modulus) [3].

When sandstone is chemically stabilised with additives (e.g., cement (C), polymer (P) and P+C blend), the strength properties of the bound sandstone improve but the degree/magnitude of improvement depends on the aggregate gradations, type of additives, curing conditions and curing periods. While soaking clearly reduces the strength properties of unbound aggregate [3], it is expected that soaking has less (negative) impact on bound aggregate. The reduction in CBR value for unbound aggregate after 4-day soaking is attributed to the lack of suction

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in soaked aggregate and the lubricating effect of water, which decreases the interparticle friction in aggregate [3]. High CBR values are achieved when aggregate is compacted at optimum moisture content (OMC) [3].

In the U.S., it is a common practice to soak the soil samples and test their bottom faces as their top faces usually give lower CBR values than bottom faces because soaking significantly softens the top face [4]. Refs. [5] and [6] found, for their sub-grade and sub-base samples respectively, the soaked top surfaces provided less CBR values than those of soaked bottom CBR surfaces. On the other hand, Ref. [7], for their sub-grade samples, found that soaked top surfaces provided greater CBR values than those of soaked bottom surfaces. During the process of soaking, the moisture distribution along the longitudinal section of the sample is not uniform, even after a long soaking period, which causes a variation in soil strength with depth [5]. Some contributory factors that may have caused such contradictory conclusions on the relationship between top and bottom CBR values are soil gradation, soil stabilisation type, compaction method and soaking condition. There is a gap in recent research on studying how these factors can influence the relationship between the top and bottom CBR values.

Hence, the objective of this paper is to evaluate how aggregate gradation, aggregate stabilisation type and soaking condition can impact the relationship between top and bottom CBR values of sandstone samples. Three gradations of sandstones of different G:S ratios were considered in this study: 2.1, 1.2 and 0.4. Four different aggregate stabilisation types were investigated in this paper: non-stabilisation, cement stabilisation, polymer stabilisation and cement plus polymer stabilisation. Two soaking conditions were also investigated in this paper: unsoaked and soaked for 4 days.

MATERIALS, SAMPLE PREPARATION AND TEST METHODS

FIGURE illustrates the three gradations and TABLE presents the mixture properties of sandstone. The aggregate was locally sourced at the alluvial gravel deposits in Brunei Darussalam. The Los Angeles abrasion value, aggregate crushing value and aggregate impact value of the sandstone are 35%, 20% and 29% respectively. These values marginally satisfy the requirements by Ref. [8].

While G_A and G_B are within the limiting gradation envelope, G_C is on the upper boundary of the gradation envelope; the limiting envelope is stipulated by Ref. [8] (figure 1).

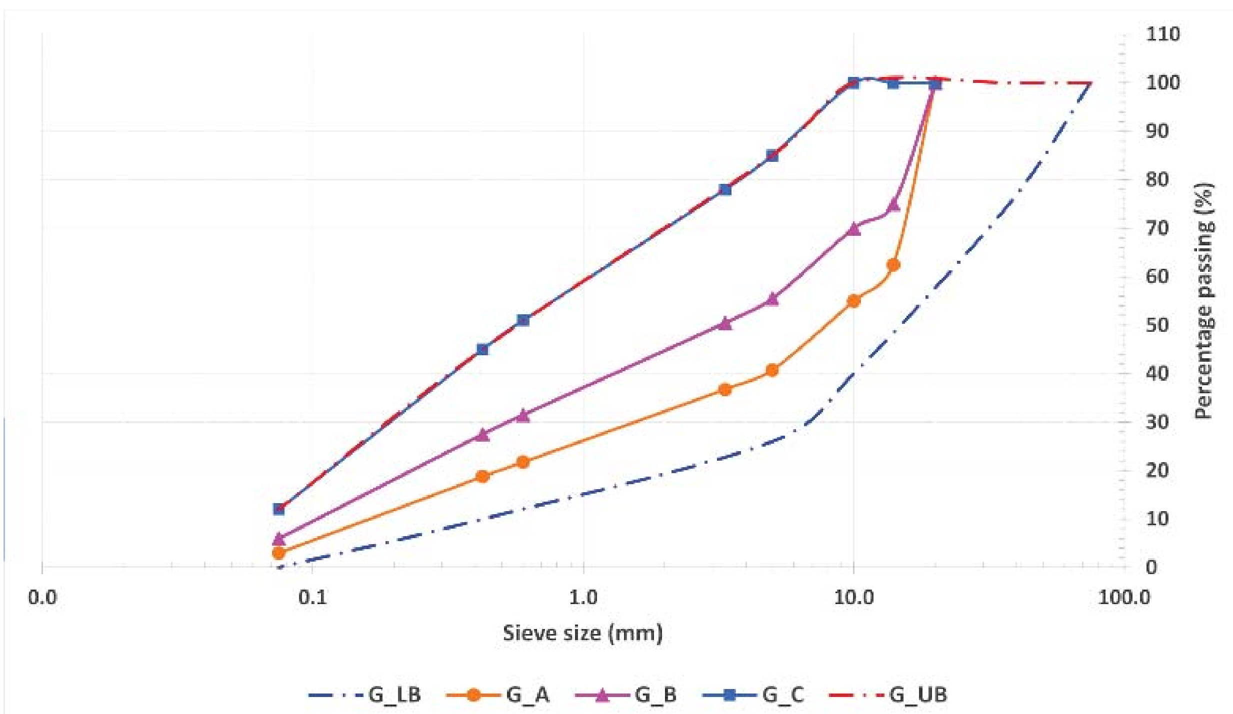


FIGURE 1. Sandstone gradations G_A, G_B and G_C.

TABLE 1. Mixture properties of sandstone gradations G_A, G_B and G_C.

Gradation	G_A	G_B	G_C
Gravel (> 2mm) (%)	68	55	30
Sand (0.06mm ≤ d ≤ 2mm) (%)	32	45	70
Water content (%)	7 ± 1	8 ± 1	9 ± 1

In contrast to ordinary Portland cement (CEM I) (C1), Portland composite cement (CEM II/A-V) (C2) is rarely used in soil stabilisation but C2 has several benefits that outweigh C1. C2 can reduce alkali-silica reaction [9] that is found to cause compressive, tensile and flexural strengths to decrease [10]. Ref. [11] stated that cement content 3% – 5% provides sufficient tensile strength and does not cause severe transverse and longitudinal cracks (due to high stiffness). Therefore, the proposed experimental C2 content for this investigation was 3% by mass of aggregate.

TP is a non-ionic and hydrolysis-resistant white colour water-based dispersion of a latex copolymer [12]. Investigations by Refs. [13] and [14] used 0.5%, 0.75%, 1% and 2% TP contents by mass of clay-sand-gravel and sand-gravel samples respectively and both found that the optimum TP content to be 0.75%, at which UCS was measured in Ref. [13] and OMC was measured in Ref. [14]. Therefore, the proposed experimental TP content for this investigation was 0.75% by mass of aggregate.

The use of cement alone causes soil-aggregate mixtures to be stiff and brittle [15] and the cement-stabilised samples would develop cracking due to drying shrinkage [16]. Polymer, a co-additive, when blended with cement, creates a polymeric film that bridges microcracks resulted from drying shrinkage thus impeding crack propagation and at the same time, providing additional adhesion bond between soil particles and cement hydrates; the polymer-cement matrix fills the air voids (a_v) to provide waterproofness [17, 18]. The polymer also contributes some ductility to the P+C-stabilised sample. Since Refs. [13] and [14] concluded that the optimum TP content was 0.75% by mass of soil, this was used in this investigation as a co-additive to 2% C2 all by mass of aggregate.

All the samples were compacted at their OMC before test. The test method for punching shear to determine the CBR of the unstabilised and stabilised samples was performed in accordance to BS 1377-4 Clause 7.4 Penetration test procedure and the compaction method was performed in accordance to Clause 7.2.3.4 Method (4) Vibrating compaction to a specified density (suitable for granular soils) [19] after air-drying (room temperature range: 23°C – 23°C and relative humidity range: 40% – 50%) and soaking (water temperature: 20°C – 22°C) for 4 days. Since the load exerted by the analogue CBR machine is 4000kg.f (≈ 40kN), the maximum measurable CBR (by the machine) was 400%. Samples without results were those of CBR value greater than 400%.

RESULTS AND DISCUSSION

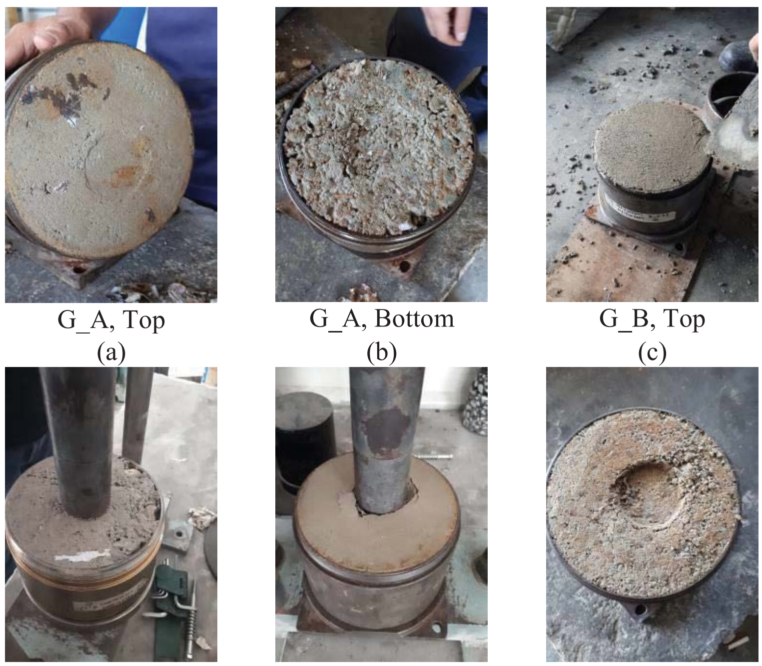
TABLE shows the unsoaked CBR values of top and bottom surfaces for G_A, G_B and G_C samples unstabilised and stabilised with 3% C2, 0.75% TP and 0.75% TP+2% C2. In general, aggregate mixtures with higher content of gravel (e.g., G_A) provided higher CBR values than aggregate mixtures with higher content of sand (e.g., G_C). Aggregate mixture of high G:S ratio has higher inter-granular friction, subsequently higher shearing resistance. For the unstabilised and 0.75% TP+2% C2-stabilised samples, all the top surfaces had lower CBR values than the bottom surfaces. Properly compacted top surfaces like those in **Figure 2** (a), (c) and (e) had low permeability and porosity, which reduced water evaporation from these surfaces while drying. On the other hand, poorly compacted bottom surfaces like those in **Figure 2** (b), (d) and (f) had high permeability and porosity, which increased water evaporation from these surfaces while drying. By the time of CBR testing, excess moisture in the top surfaces resulted in lower CBR values than those of the bottom surfaces. For G_B samples, regardless of the stabiliser types, all the top surfaces had higher CBR values than the bottom surfaces. For C2-stabilised samples, while top surface had lower CBR value than bottom surface for the G_B sample, the opposite was true for the G_C sample. For TP-stabilised samples, while top surface had higher CBR value than bottom surface for the G_A and G_C samples, the opposite was true for the G_B sample.

TABLE 2. Unsoaked CBR values of top and bottoms surfaces for gradations G_A, G_B and G_C using different stabilisers.

Stabiliser type / Gradation	Unsoaked CBR values (%)					
	G_A		G_B		G_C	
	Top surface	Bottom surface	Top surface	Bottom surface	Top surface	Bottom surface
Unstabilised	40.74 (↓)	68.62 (↑)	45.75 (↓)	57.18 (↑)	31.45 (↓)	36.88 (↑)
C2 = 3%	> 400	> 400	125.94 (↓)	142.24 (↑)	246.31 (↑)	185.84 (↓)
TP = 0.75%	65.47 (↑)	45.89 (↓)	42.89 (↓)	44.60 (↑)	35.74 (↑)	20.16 (↓)
TP = 0.75%, C2 = 2%	188.13 (↓)	> 400 (↑)	105.79 (↓)	160.54 (↑)	68.91 (↓)	132.38 (↑)

↓ means CBR value on one surface of the sample is less than the CBR value measured on the other surface of the sample for the same gradation and stabilisation type.

↑ means CBR value on one surface of the sample is greater than the CBR value measured on the other surface of the sample for the same gradation and stabilisation type (figure 2).



G_A, Top (a) G_A, Bottom (b) G_B, Top (c)

G_B, Bottom (d) G_C, Top (e) G_C, Bottom (f)

FIGURE 2. Top and bottom surfaces of compacted, cured and/or tested for G_A, G_B and G_C sandstone.

TABLE shows the soaked CBR values of top and bottom surfaces for G_A, G_B and G_C samples unstabilised and stabilised with 3% C2, 0.75%TP and 0.75% TP+2% C2. For the unstabilised and 0.75% TP-stabilised samples, all the top surfaces had greater CBR values than the bottom surfaces. Properly compacted top surfaces like those in **Figure 2** (a), (c) and (e) had low permeability and porosity, which reduced water intrusion into the surfaces while soaking. On the other hand, poorly compacted bottom surfaces like those in **Figure 2** (b), (d) and (f) had high permeability and porosity, which increased water intrusion into the surfaces while soaking. By the time of CBR testing, the bottom surfaces experienced more lubricating effect of water, which decreased interparticle friction in aggregate [3] and resulted in lower CBR values than those of the top surfaces. For G_A samples, regardless of the stabiliser types, the top surfaces had greater CBR values than the bottom surfaces, except for 3% C2-stabilised samples. For G_B samples, regardless of the stabiliser types, the top surfaces had greater CBR values than the bottom faces, except for 0.75% TP+2% C2 samples. For G_C samples, regardless of the stabiliser types, all the top surfaces had greater CBR values than the bottom surfaces.

TABLE 3. Soaked CBR values of top and bottoms surfaces for gradations G_A, G_B and G_C using different stabilisers.

Stabiliser type / Gradation	Soaked CBR values (%)					
	G_A		G_B		G_C	
	Top surface	Bottom surface	Top surface	Bottom surface	Top surface	Bottom surface
Unstabilised	58.76 (↑)	28.60 (↓)	84.63 (↑)	56.75 (↓)	47.75 (↑)	21.59 (↓)
C2 = 3%	85.77 (↓)	217.44 (↑)	> 400 (↑)	206.29 (↓)	228.62 (↑)	122.80 (↓)
TP = 0.75%	98.50(↑)	53.61 (↓)	52.90 (↑)	25.88 (↓)	50.18 (↑)	27.30 (↓)
TP = 0.75%, C2 = 2%	221.58 (↑)	190.85 (↓)	140.10 (↓)	154.54 (↑)	140.38 (↑)	124.23 (↓)

↓ means CBR value on one surface of the sample is less than the CBR value measured on the other surface of the sample for the same gradation and stabilisation type.

↑ means CBR value on one surface of the sample is greater than the CBR value measured on the other surface of the sample for the same gradation and stabilisation type.

In theory, cement undergoes cementitious hydration reaction to gain strength, while polymer undergoes coalescence to gain strength. Moisture loss by evaporation is required for coalescence to take place. Since the rate of cementitious hydration is faster than the rate of coalescence (or evaporation), cement-stabilised sample gains strength (stiffness) more rapidly than polymer-stabilised sample (ductility). When P+C blend is used for stabilisation, some polymer particles coat some cement particles, thus the efficacy and rate of cementitious hydration are lowered than those in cement-stabilised samples, and thus stiffness get reduced. The strength here refers to compressive, tensile, shear and flexural strengths. Results in TABLE and TABLE show that samples stabilised with 3% C2 overall had higher CBR values than samples stabilised with 0.75% TP+2% C2 and lastly, 0.75% TP.

TABLE shows the soaked-to-unsoaked CBR ratios of top and bottom surfaces for gradations G_A, G_B and G_C using different stabilisers. For unstabilised samples of G_A, G_B and G_C, all the top surfaces were less sensitive to soaking that the bottom surfaces. For G_A and G_B, regardless of the stabiliser types, most of the top surfaces were less sensitive to soaking than bottom surfaces. The bottom surfaces of G_B and G_C were more sensitive to soaking.

TABLE 4. Soaked-to-unsoaked CBR ratios of top and bottom surfaces for gradation G_A, G_B and G_C using different stabilisers.

Stabiliser type / Gradation	Soaked-to-unsoaked CBR ratios					
	G_A		G_B		G_C	
	Top surface	Bottom surface	Top surface	Bottom surface	Top surface	Bottom surface
Unstabilised	1.44	0.42	1.85	0.99	1.52	0.59
C2 = 3%	*	*	*	1.45	0.93	0.66
TP = 0.75%	1.50	1.17	1.23	0.58	1.40	1.35
TP = 0.75%, C2 = 2%	1.18	0.48	1.32	0.96	2.04	0.94

Value > 1.0 indicates that CBR_{SOAKED} > $CBR_{UNSOAKED}$ (LESS SENSITIVE TO SOAKING), Value < 1.0 indicates that CBR_{SOAKED} < $CBR_{UNSOAKED}$ (MORE SENSITIVE TO SOAKING), * CBR > 400% (unmeasurable)

CONCLUSION AND RECOMMENDATIONS

The main conclusions from this investigation were:

- Samples with high gravel contents would have greater CBR values than samples with high sand contents.
- Samples stabilised with 3% C2 overall gave greater CBR values and this was followed by samples stabilised with 0.75% TP+2% C2 and lastly, 0.75% TP.

– For the unsoaked curing condition, bottom surfaces of the samples generally had greater CBR values than those of top surfaces.
– For the 4-day soaked curing condition, top surfaces of the samples generally had greater CBR values than those of bottom surfaces.
– Bottom surfaces of the samples were more sensitive to soaking than the top surfaces.

As the results in **Table 2**, **Table 3** and **Table 4** were based on a 4-day curing period, they could lead to misestimating in-situ shear strength. Therefore, it is recommended that longer curing periods, e.g., 7 and 14 days be considered to further study the relationship between top and bottom CBR values under unsoaked, soaked, unbound and stabilised conditions. It is also suggested that both vertical and radial water flow be allowed during the soaking process to improve uniformity of moisture content surrounding the samples.

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