An investigation into the compaction of sandstone aggregates stabilised with cement and fly ash

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Abstract. This paper experimentally investigated the compaction properties of sandstone aggregate stabilised with a mixture of Portland composite cement and Class F fly ash. This paper determined the influence of fly ash contents on the maximum dry densities, optimum moisture contents and air void contents of the stabilised sandstone using the 2.5kg rammer compaction method. Fly ash contents of 0%, 10%, 20%, 30% and 40% by mass of aggregate were added to sandstone aggregate samples with a constant cement content of 5% by mass of aggregate. The investigation showed that at 5% cement without fly ash, the maximum dry density peaked while the optimum moisture content was the lowest among all investigated fly ash contents. It also showed that for every increment of 10% fly ash with a constant 5% cement content, the maximum dry density decreased linearly, and the optimum moisture content increased exponentially. From 10% to 30% fly ash content, the air void content increased and subsequently decreased from 30% to 40% fly ash content. The investigation concluded that fly ash is an effective stabiliser when cement-to-fly ash ratios are between 1:2 and 1:4 and should not exceed 1:6.

Keywords: Compaction properties, sandstone aggregate, Portland composite cement, Class F fly ash, sub-base construction.

1 Introduction

The roadbase and sub-base layers are typically built with unbound materials [1]. The densification process involves rearranging soil particles into a more tightly packed configuration that results in increased dry density (DD) and decreased air void content

(AVC) in their compacted state. The maximum packing density has a significant effect on the stability of the structure [2]. The highest level of stability is achieved when the materials are compacted to their maximum dry densities (MDD) at the optimal moisture contents (OMC). When all grain sizes are present and distributed uniformly throughout the material (i.e., well-graded), soil interlocking and particle contact will be improved during compaction, resulting in a tightly packed structure [3]. The compaction properties of coarse-grained soils are governed by their gradations [4]. Compaction helps to increase density and stiffness and reduce permeability. Insufficient compaction can lead to settlement, whereas inadequate stiffness can lead to distress [5].

However, when marginal aggregate, such as sandstone, is compacted, the aggregate may be broken down, increasing smaller fragmented aggregate particles. Loads are then transferred to these loose, fragmented aggregate particles, which dominate the aggregate mixture, resulting in reduced stiffness, stability and durability of the roadbase and sub-base layers. Therefore, to use marginal sandstone aggregate as a sub-base material, one option is to chemically stabilise the unbound (loose) aggregate particles to form a bound mass. Chemical stabilisation is achieved by mixing traditional and/or non-traditional chemical stabilisers with soil particles to form stronger composite materials [6]. The selection of type and dosage is a function of soil classification, degree of improvement desired, cost and availability [6, 7]. Examples of traditional chemical stabilisers are cement, lime, fly ash (FA) and bitumen, and examples of non-traditional chemical stabilisers are ionic, enzyme, lignosulfonate, petroleum emulsion, polymer and tree resin [6, 8]. Blends of traditional chemical stabilisers such as cement-FA (CFA), lime-FA (LFA) and cement-lime-FA (CLFA) and blends of traditional-non-traditional chemical stabilisers such as cement-polymer are common in chemical (soil) stabilisation.

FA, also known as pulverised FA (PFA), is the by-product or waste product generated during the combustion process of coal. FA constituted between 70% and 90% of the ash type [9]. The utilisation, rather than disposal, of FA has been found to result in several environmental, technical and economic merits. Therefore, apart from concrete construction, FA is also widely used in the fields of soil improvement and pavement stabilisation. From an economic point of view, using FA in construction projects presents an appealing alternative to disposal. FA can be used with other construction materials to increase the bearing capacity of the soil [10]. This is because when FA is used as mineral filler, it improves soil stability by changing the soil-FA particle size distribution or gradation [9] as FA could act as non-plastic fine silt [11]. As a result, FA presents comparable mechanical properties with those of silt [12]. FA gained popularity as an alternative for soil and pavement base stabilisation due to its ability to enhance the ride quality and serviceability of the road [13], as well as notable improvements in strength and durability [14].

Several soil types are classified using the Unified Soil Classification System (USCS) to well-graded sands, gravelly sands, little or no fines (SW), poorly-graded sands, gravelly sands, little or no fines (SP), SP-clayey sands, sand-clay mixtures (SC), SW-SC, SW-silty sands and sand-silt mixtures (SM), well-graded gravels, gravel-sand mixtures, little or no fines (GW), poorly-graded gravels, gravel-sand mixtures, little or no fines (GP), GP-clayey gravels, gravel-sand-clay mixtures (GC), GW-GC, GP-silty gravels, gravel-sand-silt mixtures (GM), GW-GM, GC-GM and SC-SM can be stabilised with FA [11].

Since FA is a pozzolan that contains siliceous and aluminous compositions as major constituents, it can form cementitious compounds when mixed with water and high-calcium compounds [9]. For instance, when FA is mixed with cement and water, it produces a strong cementitious binder. The two known classes of FA are Class C and Class F, and they are distinguished by the amount of calcium oxide (CaO) and the total amount of silicon oxide (SiO_2), aluminium oxide (Al_2O_3) and iron oxide (Fe_2O_3) found in them. Class C FA has CaO content greater than 10%, whereas Class F FA has CaO content less than 10%. Class C FA has $SiO_2 + Al_2O_3 + Fe_2O_3 \leq 70\%$, normally 50%-70% whereas Class F FA has $SiO_2 + Al_2O_3 + Fe_2O_3 \geq 70\%$. Since the CaO content is less than 10%, Class F FA is devoid of the self-cementing property; thus, it is the least used FA [15]. Class F FA requires high-calcium compounds such as cement and lime to act as activators but not Class C FA as it has self-cementing properties. With CFA blend, in principle, an increase in cement content (constant FA content) gives an increase in strength [7], whereas, with an increase in FA content (constant cement content), the strength may increase then decrease, giving a peak or optimal FA content as presented by Ref. [16]. The ratio CaO-to-SiO_2 is an important indicator of pozzolanic activity [17]. That ratio is very low for a Class F FA.

The most common cement-to-FA ratios (by replacement) used as soil stabilisers are 1:1 and 1:4 [9]. The addition of FA results in decreased MDD due to FA's lower specific gravity and increased OMC due to FA's higher specific surface [9]. When FA is used in excessive (very low cement-to-FA ratio) can cause detrimental effects such as extremely slow strength gain and exceptionally lower strengths (viz., compressive, tensile, shear and bending). Replacement of (Portland) cement with FA effectively dilutes the cement, resulting in a longer hydration period for the hydration products to make interconnections [18]. Excessive use of FA instead of cement reduces the amount of calcium ions (Ca^{2+}) in the cementitious system. Therefore, when cement is partly replaced with FA, the ultimate strengths rarely reach those of untreated samples unless the amount replaced is very low (about 15%) [18].

While past investigations had shown the success of Class F FA on subgrade stabilisation, for instance, stabilising expansive clays as cited by Ref. [19], there remains limited information about the use of Class F FA for stabilising sub-bases and roadbases of road pavements [15]. It has also been identified that the use of a mixture of Portland composite cement (PCC) and Class F FA as an aggregate stabiliser for sub-base construction using sandstone aggregate has not previously been reported. This paper aims to present the quantitative results of the compaction properties of sandstone aggregate treated with PCC and Class F FA. The focus is on the influence of Class F FA on PCC-stabilised sandstone aggregate and to examine the suitability and optimisation of Class F FA content as a suitable mineral filler. The results from this laboratory investigation will then be used to design future laboratory tests – unconfined compression test (UCT), indirect tensile test (ITT) and California bearing ratio (CBR) test. This study is a part of an ongoing research effort aimed at developing more sustainable and economical, as well as mechanically durable, roads.

2 Compaction Methodology

The 2.5kg rammer compaction method outlined in BS1377-4: 1990 Clause 3.3 [20] was used to determine the dry densities and moisture contents of soils with particles up to medium gravel size. No more than 30% of soils (by mass) should be retained on the 20mm and 37.5mm BS sieve (coarse gravels) [20]. Ref. [21] recommended that the ratio of the compaction mould to the largest nominal particle size should not be less than 5 or 6. In this investigation, the ratio is 5.5 (105mm: 19mm). The focus was on normal traffic loading and hence a 2.5kg rammer compaction, equivalent to standard Proctor, was used.

The procedure to obtain the MDD and OMC for the samples is as illustrated in **Fig. 1**. The aggregate, cement and FA are mixed first before water is gradually introduced. The mixture is then compacted and extruded. Small samples from the top, centre and bottom are collected for oven-drying. The calculation, plotting and expression of results are as outlined in BS1377-4: 1990 Clause 3.3.5 [20].

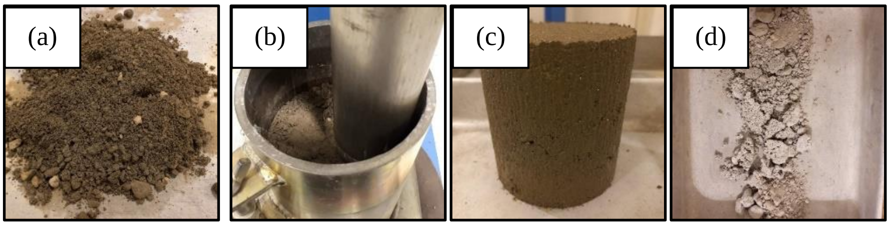

Fig. 1. Procedure to obtain maximum dry density and optimum moisture content: (a) mixing, (b) compaction, (c) extrusion and (d) sample after over-drying.

3 Materials

3.1 Aggregate

The aggregate used in this investigation was crushed sandstone sourced from a local quarry in the Temburong district of Brunei Darussalam. The specific gravity (S.G.) was between 2.3 and 2.5 [2]. This aggregate type is mainly used for sub-base construction in the country. The proposed particle size distribution for the aggregate samples are as shown in **Fig. 2**. The mechanical properties of the aggregate mixture are as shown in **Table 1**.

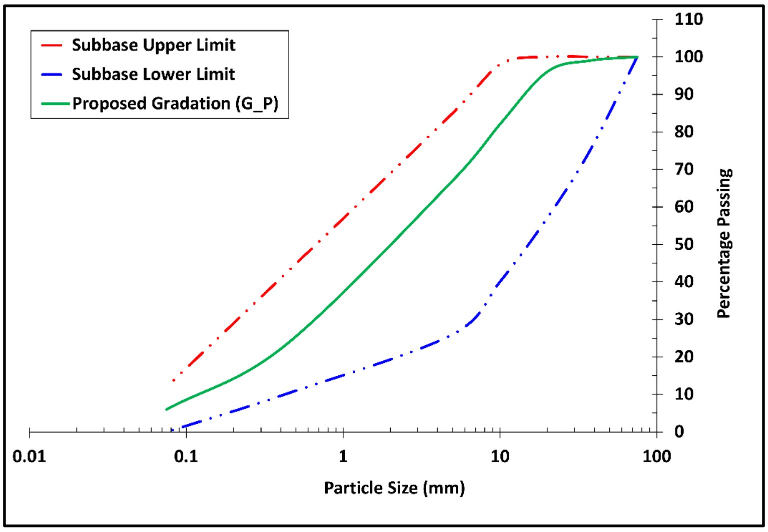

Fig. 2. Proposed gradation for sandstone aggregate mixture and the limits of gradation for subbase [22] and sample of sandstone aggregate mixture.

Table 1. Mechanical properties of sandstone aggregate mixture [22].

Mechanical properties	%	Limit (%)
Los Angeles abrasion value (LAAV)	35	≤35
Aggregate crushing value (ACV)	20	≤25
Aggregate impact value (AIV)	29	–

3.2 Portland composite cement

The PCC used in this investigation was Portland-FA blend CEM II/A-V (52,5N), according to BS EN 197-1: 2000 [23] and it has no ASTM equivalent. It contains between 6% and 20% of FA by mass of PCC. The S.G. was between 3.05 and 3.10. The difference between CEM I, an equivalent to ASTM Type I ordinary Portland cement (OPC) and CEM II/A-V is the clinker replacement by FA between 6% and 20%. Cement content between 3% and 5% by mass of soil is sufficient to bound the soil particles to produce hydraulically bound soil [24, 25]. Cement content less than 3% would provide insufficient tensile strength to the stabilised soil and is essentially unbound [24]. Cement content greater than 6% would begin to cause shrinkage cracking [26]. According to Ref. [27], a 5% or less cement by mass can be used effectively for soil stabilisation of a well-graded soil mixture of stone fragments or gravel, coarse sand and fine sand either with or without small amount of slightly plastic silt- and clay-size soil particles. The proposed PCC content for use in this investigation is at the upper limit of 5% cement content by mass of aggregate mixture.

3.3 Class F fly ash

The mineral filler used in this investigation was a Class F FA. It was supplied from a local coal power generation plant. According to the supplier, the bulk density and S.G. were 556 kg/m^3 and 2.26 respectively. The FA contents with a constant 5% PCC used in this investigation were 10%, 20%, 30% and 40% by mass of aggregate mixture. Therefore, the ratios of PCC-to-FA are 1:2, 1:4, 1:6 and 1:8.

4 Results and Discussion

Fig. 3 illustrates the relationship between DD, Moisture Content (MC) and AVC lines for the compacted soil samples.

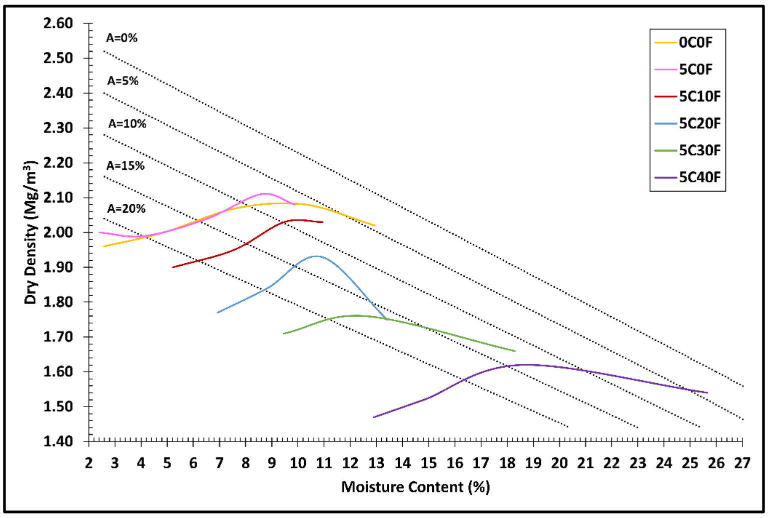

Fig. 3. Relationship between dry density, moisture content and air void content for the compacted soil samples treated with cement and fly ash.

Since the S.G. of cement was greater than the aggregate, the MDD increased slightly from 0C0F to 5C0F. The OMC decreased from 0C0F to 5C0F, as some water would have been lost to the cementitious hydration reaction. The excess heat generated by the cement during the activation process could explain the decrease in the OMC [28].

Fig. 4 illustrates the percentage changes in the OMC and MDD for the cement-FA-stabilised samples with respect to the untreated sample (i.e., 0C0F). It shows that the OMC increased exponentially with increasing FA content. It also shows that the MDD decreased linearly with increasing FA content. The lower S.G. of FA, as expected, reduce the MDD by replacing and occupying the space (void) that could be occupied by larger and denser aggregate particles [29]. The higher specific surface area of the FA particles could have resulted in an increase in OMC [30, 31].

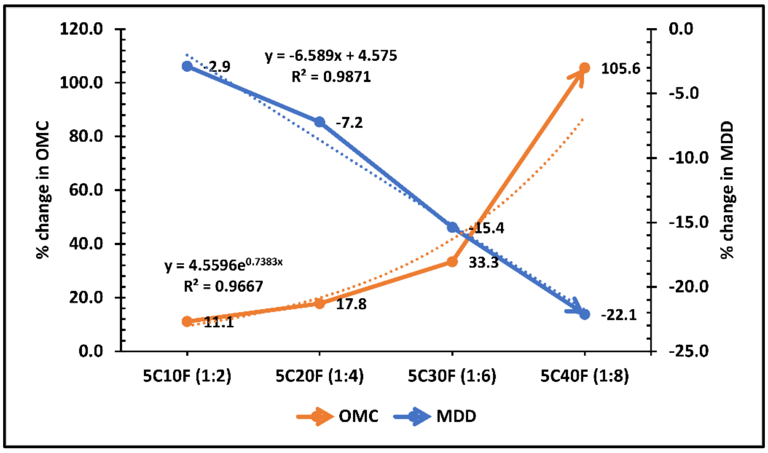

Fig. 4. % changes in optimum moisture contents and maximum dry densities of cement-fly ash-treated samples with respect to untreated sample (0C0F).

Fig. 5 shows the percentage changes in AVC for the cement-FA-stabilised samples with respect to the untreated sample (i.e., 0C0F). It shows that the AVC increased from 10% FA to 30% FA and decreased from 30% FA to 40% FA. The increase in AVC is the result of the increased in FA (silt-sized) content. Higher AVC content in compacted aggregate tends to reduce the strengths. The reduction in AVC from 30% FA to 40% FA indicated that FA has become a more effective mineral filler. The drop in AVC (at 5C30F) is supported by the recommendation of Ref. [12]. Samples with lower MDD and higher OMC have greater porosity [1] and in this case, AVC.

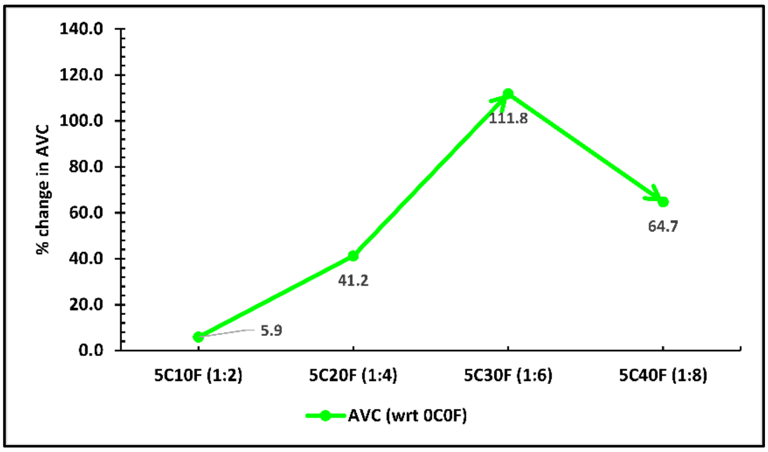

Fig. 5. % changes in air void contents of cement-fly ash-treated samples with respect to untreated sample (5C0F) and cement-treated sample (5C0F).

At 5C30F, **Fig. 4** and show that the OMC and MDD lines intersect each other and they coincide with the peak of % changes in AVC as shown in **Fig. 5**. This is a preliminary indication that the FA content should not be more than 30%, i.e., optimum C:F ratios are between 1:2 and 1:4 and maximum C:F ratio is 1:6. Ref. [12] stated that the typical range for C:F ratio is from 1:3 to 1:4. Investigation by Ref. [28] showed that when C:F ratio increased from 3:5 to 3:15, the MDD decreased and OMC increased; the MDD was highest and OMC lowest when C:F ratio is 3:5 (1:1.67 ≈ 1:2). Investigation by Ref. [16], on the other hand, showed that when C:F ratio increased from 1:1 to 1:2, the MDD decreased and OMC increased whereas when C:F ratio increased from 1:2 to 1:4, the MDD increased and OMC decreased; the MDD was highest and OMC lowest when C:F ratio is 1:4.

Any differences in the trends between this investigation and those of past relevant investigations can be attributed to the differences in aggregate-cement-FA mixtures such as the particle size distributions, aggregate types, cement types and contents and aggregate:cement:FA ratios. However, two consistent observations made in this investigation and those in the past investigations are that the amount of FA does not exceed 30% for sandy and gravelly soil stabilisation and for silty and clayey soil stabilisation, the FA content can exceed 30%.

5 Conclusions and Recommendations

The influence of Class F FA on the compaction properties of PCC-stabilised sandstone aggregate mixtures was evaluated using the 2.5kg rammer compaction method. In this investigation, a constant 5% PCC content was added to the sub-base aggregates with 0%, 10%, 20%, 30% and 40% FA content by mass of aggregate. Based on the results, the following conclusions can be drawn:

- Adding only cement (i.e., 5C0F), the MDD and OMC of the cement-stabilised sample increased and decreased respectively when compared to the untreated sample (i.e., 0C0F) as shown in **Fig. 3**.
- For every 10% of FA added to 5% cement, the MDD decreased linearly and the OMC increased exponentially as shown in **Fig. 4**.
- AVC increase from 10% FA content to 30% FA content and then decreased from 30% FA content to 40% FA content as shown in **Fig. 5**. The decreased in AVC imply that the FA becomes a more effective mineral filler to the aggregate-cement-FA mixture.
- The points of intersection for OMC and MDD lines as shown in **Fig. 4** and the peak of % changes in AVC as shown in **Fig. 5** indicate that the optimum C:F ratios for the sandstone aggregate of gradation as shown in **Fig. 2** are between 1:2 and 1:4 while the maximum C:F ratio is 1:6.

The compaction properties determined in this investigation cannot be used to directly interpret the strengths of sandstone aggregate treated with PCC and Class F FA. Further strength-based laboratory tests such as the following have been designed based on the current findings and will be conducted:

- UCT to determine uniaxial or unconfined compressive strength (UCS),
- ITT to determine indirect tensile strength (ITS) and
- CBR test to determine indirect shear strength in term of CBR value.

The results from the strength-based tests conducted under varying curing conditions (e.g., air-dry, moist-dry, wet, unsoaked and soaked) and periods (e.g., 7, 14, 28, 56, 90 days) will provide better quantitative interpretation on the effects of Class F FA on PCC-stabilised sandstone aggregate mixtures and to support their application in road sub-base construction.

Acknowledgment

The authors are grateful to Universiti Teknologi Brunei for their funding support (UTB/GSR/1/2021(4)) and SWEE Sdn. Bhd. for their material support.

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