Engineering properties of soil-based controlled low-strength materials as slag partially substitutes to Portland cement

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HIGHLIGHTS

• A CLSM was prepared with different sand–soil combinations and GGBFS replacement ratios.
• Increase in slag content may create workability improvement and strength reduction.
• A large amount of soil in mixture would cause strength reduction and flowability increase.
• A pulse velocity–compressive strength correlation has been successfully proposed.

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ABSTRACT

This study aim is to examine on the engineering properties of soil-based controlled-low strength material (CLSM) containing blast furnace slag cement as cement substitute and residual soil as aggregate. By conducting an experimental program, twelve CLSM mixtures made with blast furnace slag partially replace for Portland cement of 10%, 20%, and 30% by weight and three sand–soil combinations, e.g. sand–soil proportion of 6:4, 5:5, and 4:6. The engineering parameters of CLSM, such as slump flow, setting time, ball-drop value, compressive strength, pulse velocity, and modulus of reaction subgrade were determined in accordance with ASTM procedures. Testing results indicate that the proposed mix proportion are almost met the requirements of excavatable CLSM. In addition, with slag replacement to cement would effectively improve the flowability, significantly delay setting time, and noticeably reduce compressive strength, pulse velocity under water-to-binder ratio being fixed. Moreover, the findings also exhibit that an increase in soil content in composition could lead to affect obviously on the CLSM's performances. Furthermore, an exponential formula was also successfully established based on experimental data to express the relationship between compressive strength and ultrasonic pulse velocity, from 01 to 91 days. Finally, as regards geotechnical property, the applied load–deflection curves for CLSM have been plotted and thereby the modulus of reaction subgrade reaction was further estimated.

1. Introduction

Controlled-low strength material (CLSM) has been successfully applied in numerous fields such as wall or trench backfilling, void filling, pavement bases, and subgrades. It is defined as a self-compacting, cementitious material and currently is known as other names, viz. flowable fill, plastic soil–cement or slurry material [1]. In general, CLSM mixtures generally consist of small amount of Type I or II Portland cement (30–120 kg/m$^3$), cementsitious and/or pozzolanic supplementary (optional), and a massive quantity of fine aggregates, as well as mixing water. Coarse aggregate are not often used for producing this kind of slurry material. By definition, CLSM has a compressive strength of less than 8.3 MPa and slightly higher than that of well-compacted soil [1]. It is convenient to deliver and owns a self-leveling capacity. Using this material, therefore, tends to reduce labor of construction, equipment cost, and suitable for narrow space site comparing to compacting-conventional backfills. In addition, CLSM also has a remarkably low strength requirement in comparison with normal concrete. If future re-excavation is desired for maintenance purposes, the long-term strength should be less than 1.4 MPa [2–4]. For this reason, a number of non-standard materials, in which its physical and chemical properties are high variations, have been successfully employed for making flowable fills. From literature reviews, industrial wastes and recycled materials, commonly agreed to be a promising application as cement substitutes, e.g. blast furnace slag, cement kiln dust [4–6] and fly ash [7] have been published. In addition, recycled concrete [8], waste electric arc furnace dust, incineration bottom ash and quarry dust [9,10], scrap tires [2,11], and
reservoir siltation [12] have been reported to be potential sources using as fine aggregates in the past few years. Moreover, on-site surplus soil generated from either pipe trench or deep excavation projects has been also known as an alternatively effective solution in production of CLSM, which is expected to apply trench filling or backfilling constructions [13–16]. CLSM prepared with soil is also called as soil cement slurry or ready-mixed soil material that likely combines the advantages of CLSM and soil cement defined as ACI 230 [17]. Green [18] has studied on soil-based CLSM incorporating with Class C, F fly ash and claimed that a increase in losses content there would be a considerable strength reduction. And Chen and Chang, [13] created a CLSM with fine ingredient, normalized from three primary soils and indicated that later-strength gain after 28 days could be limited and controllable, which is a key benefit for making excavatable CLSM. As regards soil type, ACI 229 [1] recommends that fine clay soil have exhibited problems with incomplete mixing, stickiness of mixtures, and unsuitable for CLSM applications. Historical reviews [18,19], however, have shown that silty sand with fine content (passing No. 200 sieve) being less than 30% and non-plastic soil could be considered for CLSM production. Furthermore, Finney et al. [14] and Wu and Lee [16] revealed that on-site clay soil or reservoir siltation could be acceptable for production of CLSM with careful mix design. The use of residual soil after excavation hopes to provide great benefits in reducing cost of project and overcoming the shortage of natural recourses. On the other hand, slag in this study refers to ground-granulated blast furnace slag (GGBFS), being a byproduct obtained from blast furnace in the production of cast iron. When molten slag is quickly quenched from a high temperature with water in pond or powerful water jets, most of the lime, magnesia, silica and alumina are held in a non-crystalline or glassy state [20,21]. When this slag is finely ground into particle size of less than 45 μm, it will be self-cementing with a slow hydration rate. Blending slag with Portland cement, the rate hydration of slag is accelerated due to presence of calcium hydroxide and gypsum [20]. Consequently, GGBFS is commonly used as a cementitious material and may substitute for Portland cement from 10% to 90% [21,22] to enhance the workability and durability of concrete. The application of blending cement in construction was widely agreed to provide an important benefit of environmental protection. In fact, a large quantity of soil generated after excavated construction needs to be removed, whereas a similar amount of natural granulated materials should be collected and transported for backfills. These works may cause a negative effect on environment and result in cost increase owing to long distance of transportation. In this study, an experimental plan on CLSM using combination of concrete sand and on-site surplus soil as fine aggregate, blast furnace slag was used as a cement substitute, partially replacing to Portland cement with different levels. A series of test procedures was conducted on the proposed CLSM specimens to investigate its engineering properties. The work is significant because several prior studies often focused on using with fly ash, few with slag and lack of reports on soil proportion effects in CLSM mixtures. As mentioned before, the findings derived from the experiment will show a potential solution of waste consumption, which plays a key role in sustainable development.

2. Experimental program

2.1. Materials

Fine aggregate ranging from 4.45 mm to 0.075 mm in particle size is an essential component of CLSM, commonly up to 80–85%. In the present work, it was formed by blending well residual soil and river sand to enhance the particle distribution. The soil, taken from construction site after basement excavation, is a brown in color and sandy–clayey soil with liquid limit (LL) and plastic index (PI) is 22 and 2.3, respectively. And it was classified as a soil of SP–SM (poorly graded sand with silt) in according with the USCS system [23]. Meanwhile, the natural sand was obtained from Laonung River in the South of Taiwan. The results of analysis of the sand and soil are tabulated as in Table 1 with the fineness modulus of 2.57 and 1.24, respectively. The grading curves are graphically illustrated in Fig. 1, and it was obviously seen that the sand meets the ASTM C33 requirement of fine aggregate. Fig. 1. The grading curve for sand, soil, and combinations.

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Table 1

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>River sand:</td>
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<tr>
<td>Specific gravity (g/cm³)</td>
<td>2.66</td>
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<tr>
<td>Water absorption (%)</td>
<td>3.50</td>
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<tr>
<td>Fineness modulus (FM)</td>
<td>2.57</td>
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<tr>
<td>Surplus soil:</td>
<td></td>
</tr>
<tr>
<td>Specific gravity (g/cm³)</td>
<td>2.69</td>
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<tr>
<td>Optimum moisture content (%)</td>
<td>12.0</td>
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<tr>
<td>Liquid limit (LL)</td>
<td>22.0</td>
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<tr>
<td>Plastic limit (PL)</td>
<td>19.7</td>
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<tr>
<td>Plastic index (PI)</td>
<td>2.30</td>
</tr>
<tr>
<td>Fineness modulus (FM)</td>
<td>1.24</td>
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Table 2

<table>
<thead>
<tr>
<th>Results of analysis</th>
<th>Portland cement, Type I (Taiwan Cement Corp.) (%)</th>
<th>Slag (China Steel Corp.) (%)</th>
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<tbody>
<tr>
<td>Chemical constituents</td>
<td></td>
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<tr>
<td>Silicon dioxide, SiO₂</td>
<td>20.87</td>
<td>33.82</td>
</tr>
<tr>
<td>Aluminum oxide, Al₂O₃</td>
<td>4.56</td>
<td>14.11</td>
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<tr>
<td>Ferric oxide, Fe₂O₃</td>
<td>3.44</td>
<td>0.34</td>
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<tr>
<td>Calcium oxide, CaO</td>
<td>63.14</td>
<td>41.04</td>
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<tr>
<td>Magnesium oxide, MgO</td>
<td>2.82</td>
<td>6.96</td>
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<tr>
<td>Sulfur trioxide, SO₃</td>
<td>2.06</td>
<td>0.70</td>
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<tr>
<td>Physical properties</td>
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<td></td>
</tr>
<tr>
<td>Loss of ignition (LOI)</td>
<td>2.30</td>
<td>0.35</td>
</tr>
<tr>
<td>Fineness, Blaine (cm²/g)</td>
<td>3851</td>
<td>4390</td>
</tr>
<tr>
<td>Specific gravity</td>
<td>3.15</td>
<td>2.89</td>
</tr>
</tbody>
</table>
3.6. Module of subgrade reaction – nonrepetitive static plate load (NSPL) test

NSPL test was conducted by applying a static load on a circular bearing plate, which is placed on the tested material surfaces. Deflection (or settlement) after each load increment was measured. The procedure was repetitive until the load capacity or selected total deflection has been reached, whichever occurs first in accordance with ASTM D1196 [33]. As a result, a load–deflection curve was obtained. From the plot, the module of subgrade reaction (K), which is defined as a ratio of stress and the conventional settlement of 1.25 mm (0.5 in.), implies the stiffness of material [38]. A higher K-modulus, a higher bearing capacity will be. Fig. 12 shows the relationship between normal applied stress and deflection for M64 specimens at the age of 28 days. The K-modulus was estimated to be 1200, 1070, 800, and 600 MN/m² for M64-0, M64-10, M64-20, and M64-30 samples, respectively. It is clearly revealed that an increase in slag level would cause a fall of K-value and bearing capacity. The K as above is considered being several times greater than that of dense sand soil.

4. Conclusions

1. The flowability of CLSM could be improved as slag substitution ratio increases because slag probably makes a reduction the size and volume of soil. Without slag, the tube slump values were measured, ranging from 245 mm to 267 mm. When the slag level was 30%, the slump has a noticeable improvement of approximately 46%, in averages. In addition, sand–soil proportion was also on the evidence of remarkable influence on workability. Higher proportion of soil in mixture, an increase slump is likely to happen.

2. Increasing slag ratio was believed to accompany by setting time extension. With 30% slag replacement the setting time was measured to be extended 33–66%. The low activity in nature of slag may be responsible for this behavior. In addition, a large amount of soil in mixture would lead to increase ball drop indentation and delay readiness of load application. When sand to soil proportion changes from 6:4 to 4:6, the ball drop is increased approximately 10%.

3. When the slag partially replaces to OPC, the strength compressive has a significant reduction. The 91-day strength of specimens containing 30% slag replacement reached approximately 70–78% that of references with pure OPC. A large amount of slag dosage a more strength fall would be because slag is widely known to be not as good as OPC in providing the strength. Moreover, a mixture prepared with high soil content tends to reduce the compressive strength.

4. Pulse velocity was also revealed to be affected by slag level and sand–soil proportion with a similar manner that influence on strength. Moreover, testing data indicates the relationship between pulse velocity and compressive strength could be expressed as an exponential function with high value of the coefficient of determination, which is usually true for conventional concrete.

5. Regarding compacting application, the applied stress–deflection curves were obtained and thereby moduli of subgrade reaction (K-modulus) were calculated with different slag substitution ratios. When OPC was substituted by slag up to 30%, a dramatically drop (50%, from 1200 to 600 MN/m²) in K-modulus could be happened.

Acknowledgement

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