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# Evaluating compressive strength of roller compacted concrete (RCC) using steel slag (SS) aggregate

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ABSTRACT: Selection of construction material for a specific application depends on the material's ability to withstand the applied load. Roller Compacted Concrete (RCC) typically used for pavement construction is a stiff and zero slump concrete which is placed and compacted carefully using a vibratory roller. Its prime advantages include high construction speed, low cost and better performance with minimum maintenance. Steel slag (SS) is a byproduct produced during purification of steel from scrap materials. This study incorporated SS in RCC production to reduce stockpiling and also to improve sustainability in construction sector by using a by-product/waste material replacing natural aggregates. Vebe consistency and compressive strength characteristics of RCC incorporating different compositions (viz. 10%, 20%, 30%, 40% and 50%) of SS are evaluated. With soil compaction approach the mix proportion was determined from optimum moisture content and maximum dry density of the mixture. Two different strength class samples were prepared with different cement content (13% and 14%). The results obtained were compared with the strength characteristics of RCC prepared with natural and SS aggregates. The experimental results showed that up to 30% replacement of SS gives results compared to conventional RCC.

## 1 INTRODUCTION

Concrete is a composite material composed of aggregate fragments within the hydraulic-cement binding medium. The binder is formed by mixing hydraulic cement with water (ASTM C125-03, 2003). The Selection of construction material for a specific application depends on the material's ability to withstand the applied load. However, strength should not be the only criteria in this process. The elastic property, durability and dimensional stability of that material also have a significant impact (Mehta & Monteiro, 2006). Recent design and construction of infrastructures have emphasized economically, socially and environmentally appropriate construction material to the achievement of Sustainable Development Goal (SDG). Roller Compacted Concrete (RCC) is a milestone in the concrete pavement technology. Prime advantages of RCC include high construction speed, low cost and better performance with minimum maintenance (Delatte *et al*., 2003; Harrington *et al.*, 2010; Rao *et al.*, 2013).

The first application of RCC for heavy-duty pavement was in the United States during the construction of the railroad intermodal hub for Burlington Northern at Texas (Logie & Oliverson, 1987). Automobiles manufacturers have special attention on RCC. Starting with General Motors Saturn Plant, RCC pavements have been used by Honda, Mercedes, Hyundai, Kia, BMW and Volkswagen (Portland Cement Association, 2018). RCC is a stiff and zero-slump concrete placed and compacted using vibratory rollers (ACI Committee 325, 2001). Fresh mixed RCC is much stiffer than conventional concrete and its consistency should remain same under vibratory roller during compaction (Khayat & Libre, 2014). Typical compressive strength range (28 MPa to 41 MPa) of RCC is comparable with conventional normal weight concrete as per ACI 211.1 91; however, some projects have achieved compressive strength more than 48 MPa (Harrington *et al.*, 2010). The selection of densely graded aggregates and low w/c ratio would require achieving high compressive strength.

Aggregates generally comprised 60-75% volume of concrete and to achieve sustainable development, construction materials need to be engineered by reducing the use of natural aggregate. Steel slag (SS) is a waste produced during steel production from scrap materials. Approximately, 2 - 4 tons of wastes are generated for the production of each ton of steel including solid slags and sludge byproducts (Das *et al*., 2007). Being a solid and hard material, this slag could be used as a substitute for aggregates in the manufacturing of concrete.

This would reduce stockpiling the product as a landfill and at the same time incorporating a waste/byproduct material would help to achieve sustainable construction practice. Slag aggregate's water absorption is significantly less compared to burnt clay aggregate and could provide better workability and compressive strength (Mohammed *et. al*, 2016). Researchers have studied the influence of partial replacement of aggregate by Ground Granulated Blast Furnace Slag (GGBS) in concrete (Siddique, 2014; Khatib & Hibbert, 2005). Since pavement construction requires low abrasive and high strength aggregate, the SS incorporation has a good prospect in the production of RCC.

The performance of RCC could be best achieved when it is reasonably segregation free and it is consistently compacted throughout the complete lift close to its' maximum density (ACI Committee 309, 2000; Harrington *et al*., 2010). RCC is unconventionally graded concrete with stiff consistency, the mixture proportioning and properties differs from normal concrete because (i) it's not air-entrained, (ii) lower water content, (iii) lower paste content (iv) requires a larger fine aggregate content and (v) nominal mixture size aggregate not greater than 19 for minimizing segregation and producing smooth surface texture (ACI Committee 325, 2001). The effective consolidation of RCC is important. Proper proportioning is hence crucial to ensure the availability of sufficient paste in the mix for coating the aggregate constituents and fill the voids of the compacted mixture after careful vibratory roller compaction (Harrington *et al*., 2010). While several methods are used to maintain proportioning the RCC pavement mixtures, the most common methods of proportioning are based on concrete consistency and soil-compaction test.

The proportioning by evaluation of consistency test involves proportioning the RCC mixtures for optimum workability for a certain strength using vebe apparatus (ACI Committee 325, 2001; Jansen 2012; Shafigh *et al.*, 2019). This method usually requires choosing parameters, for instance, water content, cementitious materials and aggregate content. The parameters can be optimized to vary one parameter at a time to achieve the desired level of consistency. The soil-compaction approach develops a relationship between dry or wet unit weight with RCC moisture content by compacting specimens of range of moisture contents (ACI Committee 325, 2001; Shafigh *et al.*, 2019). A comparatively rich amount of cementitious material and aggregates are used in RCC to differentiate it from soil cement and cement-treated base course. Based on the durability requirements such as required compressive and flexural the cementitious material volume is selected (Khayat and Libre, 2014).

Difficulties were encountered in obtaining sawed beams from the actual pavement area. There is also a lack of standardized test methods for constructing beams in the real site also in the laboratory. Therefore, sufficient information on the flexural strength of RCC is not available. Limited test results found in the literature indicate, considering the mix design, its flexural strength is usually high; ranging from 3.5-7 MPa and is principally related to the mixtures' density and compressive strength (Harrington *et al.*, 2010). This research, therefore, aimed to proportion RCC using the soil-compaction approach by replacing natural stone aggregate by SS aggregate. The mix proportions were selected so that RCC behaves as stiff consistency class and their compressive strength was evaluated considering the SS replacement level.

## 2 MATERIALS AND METHODOLOGY

For the experimental works Ordinary Portland Cement (OPC), crushed stone aggregate, SS aggregate and graded river sand were used. OPC of class 52.5N was used binding material. The percentage of clinker and gypsum was 95-100% and 0-5% respectively with a specific gravity of 3.14. The river sand was coarse and salt-free obtained from the north-east region of Bangladesh. Sieve analysis of the coarse and fine aggregates was performed as per ASTM C778 specification. Properties of river sand and crushed stone coarse aggregate are given in Table 1. No chemical admixture was used to experiment.

Table 1. Properties of aggregate.

| Property | Fine aggregate | Stone aggregate |
|---|---|---|
| Bulk specific gravity (OD Basis) | 2.55 | 2.69 |
| Absorption capacity (%) | 1.38 | 0.70 |
| Fineness modulus (FM) | 2.64 | - |
| Dry rodded unit weight (kg/m$^3$) | 1610 | 1570 |

SS aggregate used for this research was obtained from the steel rebar industry during separating the molten steel from impurities in furnaces. The SS comes in chunk form and ground to obtain in required size at the steel industry. The fineness modulus of the material collected from the site was 7.2. Later the collected samples were separated into two different size classes, 4.75mm - 12.5mm and 12.5mm - 25.4mm by standard sieves. Sieve analysis was performed according to ASTM C136. Properties of the SS aggregates are given in Table 2.

Table 2. Properties of steel slag.

| Angularity Number | 12 |
|---|---|
| Elongation index | 28% |
| Los angles abrasion value | 41 |
| Unit weight/bulk density | 1350 kg/m$^3$ |
| Specific gravity | 2.58 |
| Absorption capacity | 1.9 |

## 3 EXPERIMENTAL WORKS

As a relatively recently developed material, there is a scarcity of established methods for mix design of RCC. The experimental program was based on mainly fixing the design mix by trials, specimen preparation, and test of the specimens. The mix design of RCC is different from the conventional mix proportioning method for its relatively stiff consistency of fresh RCC. Mix design of the RCC was established based on the soil compaction method. Modified proctor procedure (ASTM D1557) was followed to obtain the maximum density of the prepared RCC by minimizing internal voids. Laboratory specimen was obtained to test the optimum moisture content which would give the maximum dense or compacted sample.

The nominal aggregate size 25 mm was selected based on the available size of SS aggregate and to incorporate them for comparison with the control sample. For mix proportioning with the available aggregate classes, a well-graded mixture of coarse aggregate was used at the experiment. For that reason, the mix ratio of coarse and fine aggregate was 55% and 45% of the aggregate percentage, respectively. From the original mix, the coarse aggregate (stone chips) was replaced by 10%, 20%, 30%, 40% and 50% SS. The mix proportioning details are given in Table 3.

Table 3. Mix proportion of RCC.

| Sample ID | SS Aggregate (weight % of total CA) | Cement (weight % of total dry mix) | Total Aggregate (weight % of total dry mix) | Fine Aggregate (weight % of total Aggregate) | Coarse Aggregate (weight % of total Aggregate) | 12.5-25mm Aggregate (weight % of total CA) | 4.75-12.5 mm Aggregate (weight % of total CA) | Water (weight % of total dry mixture) |
|---|---|---|---|---|---|---|---|---|
| *13% Cement Content (C-25 concrete)* | | | | | | | | |
| SS1-0 | 0 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| SS1-10 | 10 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| SS1-20 | 20 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| SS1-30 | 30 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| SS1-40 | 40 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| SS1-50 | 50 | 13 | 87 | 55 | 45 | 45 | 55 | 6.5 |
| *14% Cement Content (C-30 concrete)* | | | | | | | | |
| SS2-0 | 0 | 13 | 86 | 55 | 45 | 45 | 55 | 6.0 |
| SS2-10 | 10 | 13 | 86 | 55 | 45 | 45 | 55 | 6.0 |
| SS2-20 | 20 | 13 | 86 | 55 | 45 | 45 | 55 | 6.0 |
| SS2-30 | 30 | 13 | 86 | 55 | 45 | 45 | 55 | 6.0 |
| SS2-40 | 40 | 13 | 86 | 55 | 45 | 45 | 55 | 6.0 |
| SS2-50 | 50 | 13 | 87 | 55 | 45 | 45 | 55 | 6.0 |

With 13% binder content of total dry materials the target compressive strength was 25MPa. It was fixed based on the chart of cementitious content and compressive strength proposed by (Harrington *et al.*, 2010). Similarly, for the target compressive strength of 30 MPa, the cement or binder content used was 14% of the total volume of the dry mixture, where aggregates content was 86%.

Suitable workability is essential to get the compaction of the mixture. The RCC mixture workability was measured by the vebe apparatus using a vibratory table (See Figure 1). The test method followed ASTM C1170. The vibratory table was equipped with an electromechanical vibrator able to produce 3600 ± 100 vibrations per minute. A surcharge of 12.5 kg was used at the vibratory table which is mentioned as procedure B at ASTM C1170 for stiff consistency (ASTM C1170, 2014).

Figure 1. Measuring vebe time of RCC.

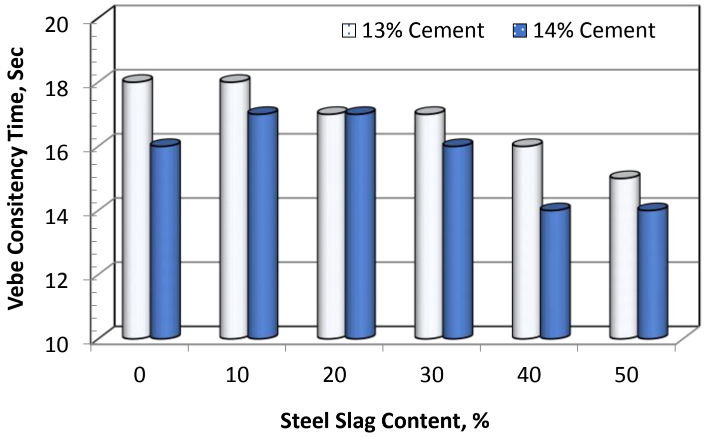


Figure 2. Vebe consistency time variation with the increase in SS content.

On obtaining the required consistency, samples were prepared for the compressive strength test according to ASTM C1435 (ASTM C1435, 2014). Type A cylindrical mold was used according to ASTM C470 (ASTM C470, 2015). The power input of the 11.6 kg vibratory hammer was 1500W. At its full load, the vibrator was capable of providing 2100 impacts per minute. The diameter of the steel plate and shaft was 149 mm while the assembly has a total weight of 4 kg.

## 4 RESULT AND DISCUSSION

As shown in Figure 2, the vebe times for all the prepared mixtures were found in the range of 14-18s. Therefore, according to ASTM C1170 with a 12.5kg surcharge, the RCC can be classified in stiff consistency class. In general, the vebe time decreased with an increase in SS content in RCC. This indicates some added benefits in terms of the workability of the SS added to concrete.

The compressive strength test results of the prepared samples are given in Figures 3 & 4. The average of 3 test samples is reported for individual mix proportion. The maximum and minimum of these three results are given in the Figures as well. For the SS1 series of concrete (13% cement content), a 10% replacement of SS aggregate provides the highest compressive strength for the RCC which is 8% higher than the control concrete without SS aggregate. Similar strength was obtained with 20% SS replacement then reduction of compressive strength was obtained with an increase in SS aggregate replacement level. With a 50% replacement of stone aggregate, the compressive strength obtained is approximately 90% of the control sample. The difference between the maximum and minimum test results are found higher in 50% SS replaced RCC.

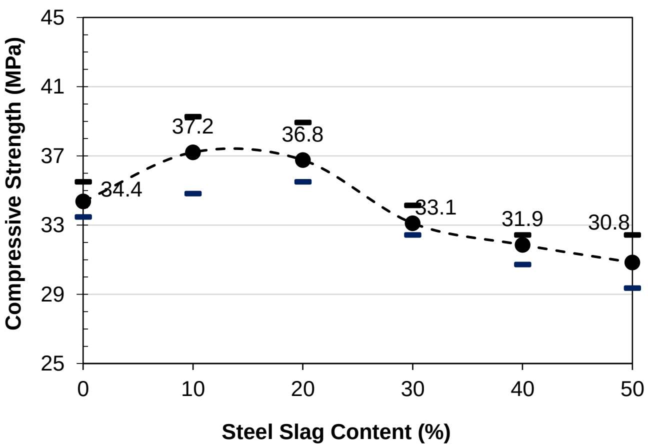


Figure 3. Compressive strength of SS1 series concrete.

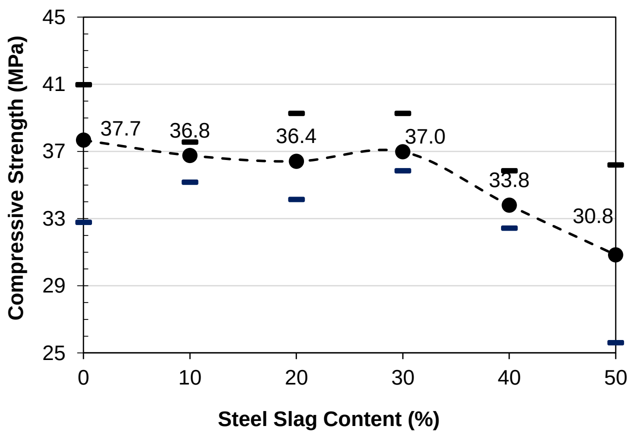


Figure 4. Compressive strength of SS1 series concrete.

As shown in Figure 4, For SS2 series concrete the compressive strength remained similar up to SS replacement level 30% and is comparable with control concrete without SS aggregate. Further increase in SS aggregate content linearly decreased the compressive strength of RCC significantly. However, for both SS1 and

SS2 series RCC the general target strengths (30.8 MPa for both 25MPa and 30 MPa target) were achieved for the highest level (50%) of SS aggregate replacement. This indicates overall similar behavior with both 13% and 14% cement content. For both SS1 and SS2 series, the compressive strength test results were more scattered in two ends (0% and 50% replacement level).

## 5 CONCLUSIONS

This study explored the possibility of producing RCC by replacing natural aggregate with industrial by-product/waste materials. The mix design of RCC is a complex mechanism and requires trials. Initially, the mix design has been established for stiff consistency class. With the same mix proportion, the vebe time and compressive strength were decreased with the increase in SS aggregate content in RCC. In light of the compressive strength test results, it was concluded that with proper mix design up to 30% natural aggregate can be saved by replacing with SS aggregate without compromising the compressive strength. To recommend the use of SS aggregate in pavement technology further study on flexural strength and other durability requirements would be necessary.

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