Properties of Roller Compacted Concrete (RCC) using Steel Slag (SS) Aggregate

By

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Declaration

I hereby declare that the work contained in this Thesis has not been previously submitted to meet requirements for an award at this or any other higher education institution. To the best of my knowledge and belief, the Thesis contains no material previously published or written by another person except where due reference is cited. Furthermore, the Thesis complies with PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Dedication

To my beloved Grand Father, ATM Nazir

The thesis, titled "**Properties of Roller Compacted Concrete (RCC) using Steel Slag (SS) Aggregate**", submitted by **Muhammad Tanveer Raihan**, Student ID No. **15MCE018P**, Session: 2016-2017, has been accepted as satisfactory in partial fulfilment of the requirements for the degree of Master of Engineering in Civil Engineering on the 1st June 2023.

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This is to certify that **Muhammad Tanveer Raihan** has carried out this research work under my/our supervision, and that he has fulfilled the relevant Academic Ordinance of the Chittagong University of Engineering and Technology, so that he is qualified to submit the following Thesis in the application for the degree of MASTER of ENGINEERING in CIVIL ENGINEERING. Furthermore, the Thesis complies with the PLAGIARISM and ACADEMIC INTEGRITY regulation of CUET.

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Abstract

The selection of construction material for a specific application primarily depends on its ability to withstand the applied load. Roller Compacted Concrete (RCC), typically used for pavement construction, is a stiff, zero-slump concrete placed and compacted carefully using a vibratory roller. Its prime advantages include high construction speed, low cost, and better performance with minimum maintenance. The concept of sustainable construction materials always guides us to reduce the pressure on natural resources and optimized the use of construction materials. Steel slag (SS) is a byproduct produced during steel purification from scrap materials. This study incorporated SS in RCC production to reduce stockpiling and improve sustainability in the construction sector by using a byproduct/waste material replacing natural aggregates. The experimental works include the evaluation of the physical, chemical & mechanical properties of steel slag aggregate. Initially, Vebe consistency and then compressive, tensile and flexure strength characteristics of RCC incorporating different compositions (viz. 10%, 20%, 30%, 40%, and 50%) of SS was evaluated. From the soil compaction approach, the mix proportion was determined using the obtained optimum moisture content and maximum dry density of the mixture. Two different strength class samples were prepared with different cement content viz. 13% and 14%. The results were compared with the strength characteristics of RCC prepared with natural (control) and SS aggregates. The experimental results showed that up to 30% replacement of SS gives results compared to conventional RCC with natural aggregate. Furthermore, with this replacement rate, there is no need to trade off strength for economic gains.

বিমূর্ত

নির্মাণ কাজের জন্য নির্মাণ সামগ্রীর নির্বাচন ওই নির্মাণ উপকরণ নিজস্ব বৈশিষ্ট্য ও এর উপর প্রয়োগকৃত ভার সহ্য করার ক্ষমতার উপর নির্ভর করে। রোলার কমপ্যাক্টেড কংক্রিট সাধারণত একটি জমানো এবং শূন্য স্লাম্প কংক্রিট যা একটি কম্পনকারী রোলার ব্যবহার করে সাবধানে স্থাপন করা হয়। এর প্রধান সুবিধাগুলির মধ্যে রয়েছে দ্রুত নির্মাণ কাজ সম্পাদন, কম খরচ এবং সর্বনিম্ন রক্ষণাবেক্ষণের সাথে আরও ভাল কর্মক্ষমতা। টেকসই নির্মাণ সামগ্রী এর ব্যাবহার আমাদের সর্বদা প্রাকৃতিক সম্পদের উপর চাপ কমাতে সাহায্য করে। স্টিল স্ল্যাগ হল ইস্পাত তৈরির সময় উৎপাদিত একটি উপজাত। এই গবেষণায় মূলত উপজাত এর মজুদ কমান এবং প্রাকৃতিক নির্মাণ উপকরণ প্রতিস্থাপন করে উপজাত পণ্য/বর্জ্য পদার্থ ব্যবহার করে নির্মাণ খাতে স্থায়িত্ব উন্নত করতে রোলার কমপ্যাক্টেড কংক্রিট উৎপাদনে স্টিল স্ল্যাগ অন্তর্ভুক্ত করা হয়েছে। পরীক্ষামূলক কাজের মধ্যে স্টিল স্ল্যাগ এর ভৌত, রাসায়নিক ও বিভিন্ন বৈশিষ্ট্যের মূল্যায়ন। বিভিন্ন অনুপাতের স্টিল স্ল্যাগ (যেমন ১০%, ২০%, ৩০%, ৪০% এবং ৫০%) অনযান্ত্রিক করে রোলার কমপ্যাক্টেড কংক্রিট এর ব্যাবহার ক্ষমতা এবং ভার বহন শক্তির বৈশিষ্ট্যগুলি মূল্যায়ন করা হয়। মাটির কম্প্যাকশন পদ্ধতির সাথে মিশ্রণের অনুপাত সর্বোত্তম আর্দ্রতা এবং মিশ্রণের সর্বাধিক শুষ্ক ঘনত্ব থেকে নির্ধারণ করা হয়েছিল। দুটি ভিন্ন শক্তি শ্রেণীর নমুনা বিভিন্ন সিমেন্ট অনুপাত (১৩% এবং ১৪%) সহ প্রস্তুত করা হয়েছে। প্রাপ্ত ফলাফলগুলি প্রাকৃতিক নির্মাণ উপকরণ এবং স্টিল স্ল্যাগ এর মাধ্যমে প্রস্তুত করা রোলার কমপ্যাক্টেড কংক্রিট এর শক্তি বৈশিষ্ট্যের সাথে তুলনা করা হয়েছিল। পরীক্ষামূলক ফলাফলগুলি দেখিয়েছে যে ৩০%% পর্যন্ত স্টিল স্ল্যাগ এর প্রতিস্থাপন প্রাকৃতিক সমষ্টির সাথে প্রচলিত রোলার কমপ্যাক্টেড কংক্রিট এর তুলনায় ভাল ফলাফল দেয়। তদুপরি, এই প্রতিস্থাপন হারের সাথে, অর্থনৈতিক লাভের জন্য শক্তিমাত্রাই কোন প্রকার ছার এর প্রয়োজন হয় না।

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Nomenclature

RCC – Roller Compacted Concrete

SS – Steel Slag

CS – Compressive Strength

TS – Tensile Strength

FS – Flexure Strength

MDD – Maximum Dry Density

Chapter 1: INTRODUCTION

1.1 BACKGROUND

Concrete is a composite material made of aggregate pieces bound together with hydraulic cement. By combining hydraulic cement and water, the binder is created (ASTM, 2003). It is the most often utilised building material for infrastructure construction. In the modern age, concrete is becoming more complicated with the compound interest of performance, economy, ecology and energy conservation (Yaphary et al., 2017).

The ability of the material to sustain the given load determines the choice of construction material for a particular application. However, choosing a construction material should not be based solely on strength. A material's elastic, durability, and dimensional stability properties have an important impact on the lifespan cost of a project (Mehta & Monteiro, 2006). Recent infrastructure design and construction has strongly emphasised that sustainable construction material significantly contributes to achieving sustainable development goals.

1.2 ROLLER COMPACTED CONCRETE

In the history of concrete pavement technology, roller compacted concrete (RCC) represents a turning point. High construction speed, cheap cost, and excellent performance with minimal maintenance are among the critical benefits of RCC. (Adaska, 2006; Delatte et al., 2003; Gao et al., 2006; Mardani-Aghabaglou & Ramyar, 2013; Yerramala & Ganesh Babu, 2011). RCC was used for heavy-duty pavement for the first time in the United States while Burlington Northern was building a railroad intermodal terminal in Texas. (Logie & Oliverson, 1987). In 2012, Georgia Port Authority approved bidders to use RCC for expanding the capacity of its 78,600 sq. yards area Ocean Terminal (Nickelson, 2012). In addition, automakers paid considerable attention to RCC. RCC pavements have been utilised by Honda, Mercedes, Hyundai, Kia, BMW, and Volkswagen since General Motors Saturn Plant introduced them. (Portland Cement Association, 2018).

It is a stiff, zero-slump concrete placed and compacted with vibratory rollers (ACI Committee 325, 2001). Fresh RCC is generally stiffer than conventional concrete, and its consistency must be stiff enough to remain in place under the compaction of a vibratory roller (Khayat & Libre, 2014). According to ACI 211.1-91; the range of compressive strength standards for RCC is comparable to that of traditional normal-weight concrete. This range is from 28 MPa to 41 MPa; however, some projects have attained a strength of more than 48 MPa. Selection of densely graded aggregates and low w/c ratio would require gaining high compressive strength. It was challenging to get sawed beams from the real pavement area.

Additionally, there are no standardised test procedures for building beams on actual construction sites or in laboratories. As a result, there is little knowledge of RCC's flexural strength. According to the few test results published in the literature, the flexural strength of the mixes ranges from 3.5 to 7 MPa and depends mainly on its density and compressive strength (Harrington et al., 2010).

Aggregates generally occupy 60-75% volume of concrete (Kosmatka & Wilson, 2011). Construction materials must be engineered to use less natural aggregate to achieve sustainable development. Steel slag (SS) is a byproduct produced during the production of steel from scrap steel materials. Approximately 2 - 4 tons of waste are generated for the production of 1-ton steel that includes solid wastes, viz. slags and sludge (Das et al., 2007). This slag could be utilised as a replacement or supplementary material in the production of concrete because it is a solid and durable substance. Using slag in concrete construction would reduce product stockpiling and ensure sustainable development by incorporating a waste/byproduct material. Slag aggregate absorbs considerably less water than burnt clay aggregate, providing more workability and compressive strength (Mohammed et al., 2016). The use of ground granulated blast furnace slag (abbreviated as GGBS) as a partial replacement for aggregates in concrete has gained acceptance due to the efforts of researchers. Since low-abrasive and high-strength aggregates are needed for pavement construction, incorporating SS has a promising future in the production of RCC.

1.3 PRESENT STATE OF THE PROBLEM

In this current world, the availability of natural resources is limited. We must consider the efficient use of materials utilizing less energy and resources. Considering sustainable construction, improved and optimized use of materials, and innovation in material processing, recycling and waste management is crucial for any development work. Concrete manufacturing requires a considerable amount of natural aggregate resources. Therefore, it is necessary to explore the way to use recycled materials in concrete construction to achieve sustainability in this sector considering the circular economy.

1.4 OBJECTIVES OF THIS STUDY

The main objective of this research is to study the behavior of RCC incorporating SS aggregate in different compositions and suggest the optimal composition for effective and efficient use of the byproduct. The followings are the objectives of the research:

1. to test physical, chemical, and mechanical properties of SS aggregate;
2. to evaluate strength characteristics (compressive, split tensile, and flexure) of RCC incorporating SS with different compositions;
3. to suggest an optimal composition of materials for practical application of SS-incorporated RCC.

1.5 OUTLINE OF METHODOLOGY

Two types of RCC specimens were prepared for this experimental study. The control sample was with conventional natural aggregate and CEM I as a binder. Others incorporated different level of SS aggregate as a replacement of conventional natural aggregates. The different tests and variables were the following:

RCC Test Specimen:

(a) Control sample with Ordinary Portland Cement (OPC) and natural aggregate (stone chips)

(b) Concrete with SS aggregate

Specimen Size:

(a) ⌀ 150mm × 300mm size cylinders for compressive strength test;

(b) 150mm × 150mm × 150 mm size cube for split tensile strength;

(c) Laboratory Prepared vibrator compacted specified-sized flexure beam

SS Aggregate Amount:

Slag aggregate was replaced with 10%, 20%, 30%, 40%, and 50% conventional natural aggregates.

Curing Periods:

Underwater curing of the prepared sample was conducted for the period of 7 and 28 days.

Laboratory Tests:

(a) Physical, chemical, and mechanical properties of SS;

(b) Compressive Strength of RCC;

(c) Split Tensile Strength of RCC;

(d) Flexural Strength of RCC.

After all the laboratory activities, the result was analyzed and presented in graphical and tabular format. A combined analysis of the outcomes of laboratory results is discussed. Available opportunities for further study is also added.

Chapter 2: LITERATURE REVIEW

2.1 GENERAL

Around the world, large-scale construction projects frequently use concrete. Binder material, fine aggregate, coarse aggregate, and water comprises the material production. The principal filling material in concrete is coarse aggregate. The concrete performance depends on its ingredients, placement method, the environment, etc. The aggregate properties with the quality of binder material and mix proportion directly influence the behaviour of hardened concrete.

2.2 SUSTAINABLE CONCRETE CONSTRUCTION

Concrete, the combination of constituents of different natural resources, significantly contribute to environmental hazards. The energy required for concrete production, water consumption during the preparation and curing works, construction and demolition waste after a specific lifetime also hampers sustainable concrete development (Meyer, 2009). Due to the rapid urbanisation, the construction industry is booming. Therefore, the need for natural resources for concrete construction is also increasing. The tremendous use of these natural resources like mountain rock for gravel production creates serious environmental concerns and needs responsive awareness from the industry for sustainable management and recycling process. Olofinnade et al. (2021) worked on how crushed waste furnace steel slag can replace natural sand in concrete interlocking paving block units for non-traffic applications. Qasrawi (2014) studied on using steel slag aggregate on the properties of normal concrete.

Glavind and Jepsen (2002) investigated some ways to produce sustainable concrete construction, they are following:

- To employ more conventional residual products, like as fly ash, in considerable amounts

- To employ concrete industry leftovers, such as stone dust (from aggregate crushing) and concrete slurry (from washing of mixers and other equipment)

- To incorporate residual products from other industries that aren't typically utilised in concrete, such as biofuel fly ash and sewage sludge incinerator ash (from sewage treatment plants)

- To employ new types of cement that are less harmful to the environment (mineralised cement, limestone addition, waste-derived fuels).

2.3 ROLLER COMPACTED CONCRETE (RCC)

RCC is a special kind of concrete which have the property of conventional concrete with the construction mechanism of asphalt concrete. It is named based on the construction method used for the final output. RCC initiates a significant breakthrough in mass concrete construction through accessible placement technology, superior compaction and consolidation technology (Omran et al., 2017). It is a zero-slump concrete mixture that can be placed with asphalt paver and compacted using the vibratory roller (Debbarma et al., 2019). Compared to conventional concrete pavement construction, typically, RCC pavements are constructed without formworks, dowels or reinforcement (Harrington et al., 2010). RCC that has been freshly mixed and uncompacted resembles damp gravel. However, some wetter combinations resemble traditional no-slump concrete. RCC is a type of zero-slump concrete, although fresh RCC is stiffer than ordinary zero-slump concrete. This makes it possible to remain stiff enough under vibratory rollers, which is necessary for the requisite blending and distribution of paste to prevent segregation (Harrington et al., 2010). RCC behaves at its fresh stage with similar characteristics to soil and later hours as characteristics of hardened concrete. It has widespread application in mass concreting and pavement construction. Dams and pavements are two typical applications for roller-compacted concrete in engineered construction. Large amounts of concrete are generally deposited in roller-compacted concrete dams (RCCD) to construct a monolithic mass-concrete structure (Malkawi et al., 2003).

2.3.1 History of RCC

RCC has its history from the 1930s and 1940s (Harrington et al., 2010). Army Corps of Engineers of United States (USACE) was one of the initial developers who used RCC on a large scale for test roads for tanks and hard-stand for equipment (Delatte et al., 2005). In the 1960s, a large quantity of a concrete mixture with no slump was produced and then spread using bulldozers at Alpe Gere Dam in Italy and Manicougan lake in Canada (ACI Committee 207, 2011). From 1972 to 1974, Cannon (Cannon, 1972) performed experimental works on low cement content concrete which was transported by trucks, placed with bulldozers and compacted with vibratory rollers. The first widespread implementation of RCC pavement was in 1976 in the Canadian province of British Columbia (Tayabji & Okamoto, 1987). In 1983, the world had only one big all-RCC dam named Willow Creek in Colorado (Schrader, 1982a, 1982b). For the construction of military facilities, USACE constructed a road with a thickness of 229-330 mm and an area of 392 sq. meters and also a road for the passage of tanks with a thickness of 330-254 mm and an area of 493 sq. meters using RCC (ACI Committee 325, 2001). Actually, from being primarily linked with North America, RCC technology has spread to other parts of the globe. American Concrete Pavement Association (ACPA) maintains one directory for projects using roller compacted concrete pavements, and till June 2019, it reported more than 600 projects were completed using RCC pavements (American Concrete Pavement Association, 2019). After 2014, this number is more than 200, whereas the construction works contain the construction of industrial/trucking facilities, port/intermodal facilities, storage yards, military bases, arterial streets and even airports. It significantly contributes to applications with low-speed heavily loaded pavements (Delatte et al., 2003). Although the United States built the greatest number of RCC dams, countries like China, Spain, and Brazil currently build more of them, and their use is on the rise in countries like Vietnam, India, and others in Asia and Southeast Asia.

2.3.2 RCC in Pavement

RCC has its history in Columbus, Ohio, roads of the residential project which was counting 30000 Annual Average Daily Traffic (AADT), was constructed using 8-inch RCC overlay with 3-inch asphalt pavement overlay for a smooth surface and to avoid worn-out (Portland Cement Association, 2018). Moreover, it was opened within 24 hours after construction, which helped ensure smooth traffic management. The private sector constructed the first heavy-duty RCC pavement in the USA and was the railroad intermodal hub facility for Burlington Northern in Houston, Texas (Logie & Oliverson, 1987). In Canada, the first RCC pavement was built in 1976 at Caycuse on Vancouver Island, British Columbia, for a log sorting yard (ACI Committee 325, 2001). After successful paving at Caycuse, between 1976 and 1978, another three dry land log sorting yards were built on Queen Charlotte Island in British Columbia, performing well with very little maintenance. The Texas Department of Transportation completed its first mainline, high-speed RCC Federal Highway, US 83 Leakey, in November 2016 which is a heavy truck highway with a speed limit of 90 km/h and serves quarries and oil/gas operations (Jones, 2017). Over the course of three weeks, 42000 sq. meter of 200mm thick RCC was installed at a rate of roughly half lane of one mile at each day. Even the road was available to traffic during the paving works. More than 543,464 sq m of 203 and 254mm thick RCC pavement were constructed at the General Motors' Saturn Automotive manufacturing plant, and 360,000 sq m of 254mm thick RCC pavement was built at Ft. Drum, NY (ACI

Committee 325, 2001). The increasing use of RCC pavements from the early 1980s to 2007 is shown in in Fig. 2.1.

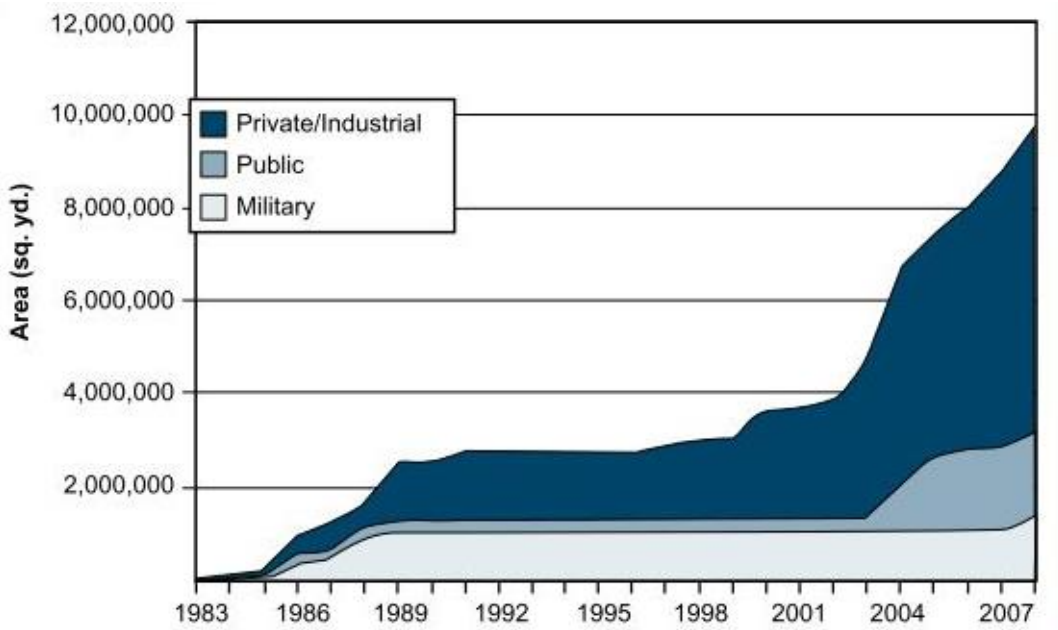

Fig. 2.1 Use of RCC pavement since early 1980s to 2007
(Pittman & Anderton, 2009)

Generally, it is not essential or mandatory to provide a wearing course over the RCC pavements, but if necessary, Hot Mix Asphalt (HMA) overlay can be used for smoothness in time (ACI Committee 325, 2001). Due to its dryness, transit mixers and ready-mix trucks can mix less RCC than traditional concrete.

2.3.3 Advantages of RCC

The main advantages of RCC over conventional concreting and asphalt pavement are mainly the following:

- Low cost

- High efficiency

- Quick construction

- Open to traffic soon after installation

- Resistance to shoving and pushing

- Long-life pavement

- Low maintenance

- No rutting

- No pot holes

- Fuel and hydraulic fluid spill resistance

- Does not soften when exposed to high temperatures etc.

RCC is very convenient in case of preparation, transportation, laying, compacting and curing. The material can save up to 60% compared to conventional pavement construction (Pittman, 1994; Vahedifard et al., 2010). The lower cement content compared to conventional concrete pavements also helps reduce construction costs (Delatte et al., 2003). USACE examined 49 RCC tank hardstands, tank routes, shipping docks, port infrastructure, servicing yards, municipal roads, roadways, parking places, and other applications. They found RCC pavement can save 14-58% cost than Portland Cement Concrete pavements (USACE, 1995). With asphalt and hydraulic cement concrete overlays, RCC pavements can be used on streets and highways with higher traffic speeds (Rao et al., 2013). The lower cement content in RCC also leads to a slower hydration process, which means a lower hydration heat than conventional cement concrete (Cervera et al., 2000). It is less vulnerable to shrinkage due to its low water content (Gaspar, 2014).

2.3.4 Materials of RCC

The designer has some flexibility in developing a composition with the highest density and strength at the minimum cement content for a specific project. Typically, the following elements are taken into account according to The Federal Highway Administration (FHWA) (FHWA, 2016):

- Maximum aggregate size in nominal terms

- Amount of water
- Sand percentage
- Binder content
- Gradation of aggregates, blending, storage, and segregating properties
- Relationship between moisture content and density
- Size and proportion of the aggregate
- Incorporation of admixtures
- The concrete mixture's consistency; it must be firm enough to withstand vibratory rolling

RCC is non-air entrained concrete with lower water content, lower cement paste, high fine aggregate and nominal maximum size aggregates of less than 19 mm (ACI Committee 325, 2001). The ratio of sand/aggregate and water content are the most critical parameters in fixing the mix proportion (Kokubu et al., 1996).

To ensure enough Portland cement for early strength development and to minimize concrete surface scaling, fly ash should be used in conjunction with cement only up to 25% by weight. In addition, fly ash can reduce permeability and increase durability. (ACI Committee 327, 2015).

2.3.5 Mix Proportioning of RCC

The precise proportioning of ingredients and the selection of materials is crucial to manufacturing high-quality RCC compositions. Therefore, the mix design process should not only be based on trial and error but also on a scientific and systematic approach that considers the intended technical characteristics, building requirements, and economics. During the selection of the RCC mixture, the following characteristics should be considered to achieve the required goal (Harrington et al., 2010):

- The mixture must have sufficient paste volume to fill the voids between the aggregates and the coating around them.
- The mixture must show desired elastic properties and produce mechanical strength.
- The mixture must be workable to be paced with the required density.
- The structure must be durable enough to undergo in the specified environment.

According to RCC pavements the guide (Harrington et al., 2010), there are two general approaches for the mix design of RCC. They are:

- Soil-Compaction approach: It is an aggregate cement technique in which the mix proportion is selected based on the aggregates' ideal moisture content and dry density. The pavements are typically constructed using this approach.
- Consistency or workability approach: It is a water-cement ratio-based approach where the consistency is constant and the mix proportion in determined by absolute volume. This method is commonly used for hydraulic structures, i.e. dams, spillways etc.

For the mix design principle, there are two more approaches. They are the solid suspension model and the method of optimum paste volume. (Portland Cement Association, 2006). The solid suspension model's most significant benefit is that it can instantly calculate the proper proportions of an RCC combination. This eliminates the need to produce a large number of laboratory trial groupings. The concept behind the optimal paste volume method is that an ideal mix should only contain enough paste to cover any gaps after the aggregates have reached their maximum density due to compaction. The typical levels of air entrainment for high freeze-thaw resistance is not considered necessary for RCC, a good-quality paste containing just a few percentages of trapped air has shown to be quite beneficial sometimes (Schrader, 2018)

2.3.5.1 Soil Compaction Method

The most widely used mixed proportioning approach for RCC pavements is the soil compaction method. To demonstrate a connection between the density of an RCC mix and the quantity of moisture, it contains, this proportioning technique compacts samples throughout a range of moisture contents. The Guide for Roller Compacted Concrete Pavement outlines the following procedures as part of the soil compaction process. (Harrington et al., 2010):

Selecting well-graded aggregate:

The first step is to ensure that the aggregates are optimised regarding their gradation, resistance to segregation, and compatibility with one another. The gradation of the mixed aggregates ought to be comparable to the grading used for maximum density. Fig. 2.2 depicts a recommended RCC gradation band and a 0.45 Power curve for a nominal size of 3/4 in. (19 mm). The 0.45 Power Curve is one strategy that can be used to define a dense gradation that is getting closer to the maximum density of aggregates of any dimension (NSSGA, 1991). The gradation proposed in Production of Roller-Compacted Concrete (Portland Cement Association, 2006) is used in the figure, except that the maximum percent passing on the No. 4 sieve is significantly raised.

Selection of Mid-range Cementitious material:

Project criteria, cost factors, resource availability, and production concerns will determine the cementitious materials chosen. The formula below can be used to determine how much cementitious material should be included as a percentage of the total dry components:

$$Cementitious\ Material\ (\%) = \frac{Weight\ of\ cementitious\ material}{Weight\ of\ cementious\ material + oven\ dried\ aggregates} \times 100 \qquad \text{(Eq. 2.1)}$$

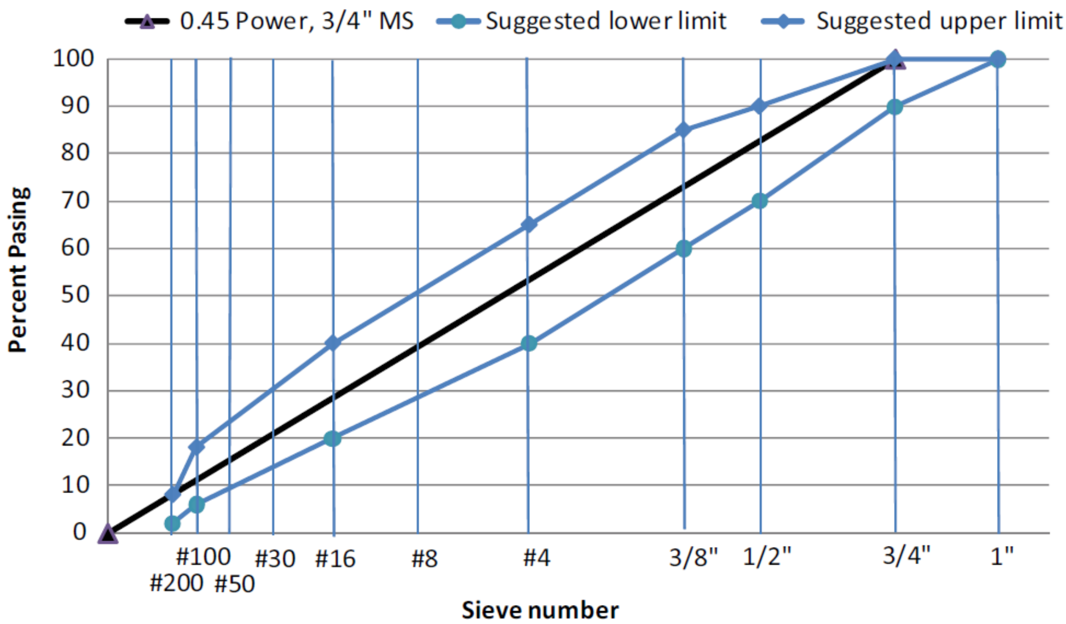

Fig. 2.2 The 0.45 power curve and recommended aggregate gradation band (Harrington et al., 2010)

Development of moisture-density relationship:

The different moisture level is used for a fixed cementitious material content to generate a moisture-density plot similar to that illustrated in Fig. 2.3. The level of moisture should be adjusted so that it falls somewhere in this range, as shown in Fig. 2.3, or throughout a range chosen based on previous experience with the aggregates being evaluated. The following formula is used to calculate the moisture content:

$$MC\ (\%) = \frac{Weight\ of\ water}{Weight\ of\ cementious\ material + oven\ dried\ aggregates} \times 100 \qquad Eq. (2.2)$$

The modified Proctor test method (ASTM, 2012a) can be used to establish the maximum dry density and optimal moisture content for each cementitious composition. The standard Proctor test (ASTM, 2012b) should be considered when utilising weaker aggregates to avoid fracturing the aggregates during testing. Another method for determining the moisture-density relationship of RCC is the Standard test method for determining consistency and density of roller-compacted concrete using a vibrating table (ASTM, 2014b).

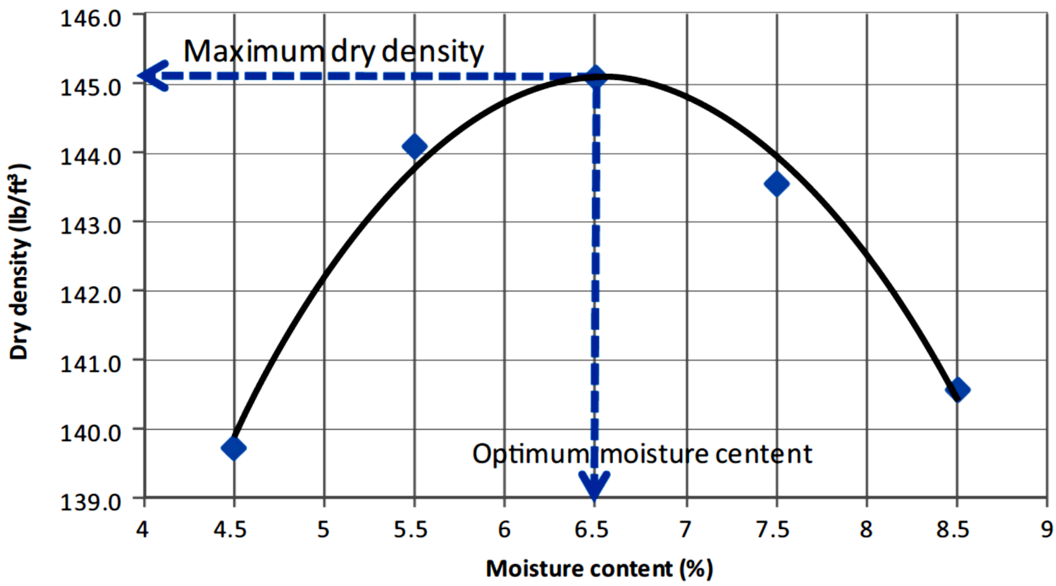

Fig. 2.3 Moisture-density curve (Harrington et al., 2010)

Preparation of samples to determine compressive strength:

Specimens for compressive strength were prepared using the vibrating hammer (ASTM, 2014b) or the vibrating table method for each cementitious component (ASTM, 2008). Molding should take place at the required moisture content for the mix's cementitious component for every specimen.

Test specimens to determine the cementitious content necessary:

The mentioned cementitious contents determine the specimens' compressive strength. As illustrated in Fig. 2.4, the data are plotted, generating a compressive strength vs cementitious content curve. Based on this curve, cementitious content can be chosen to fulfil the requisite strength.

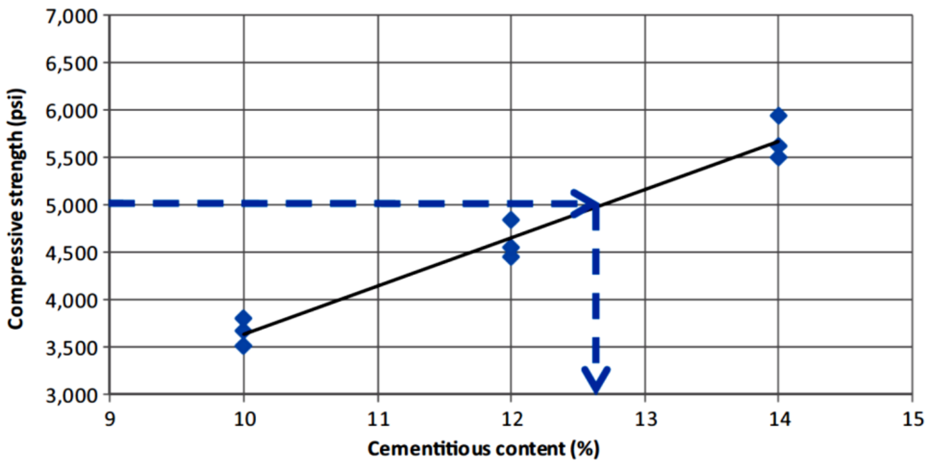

Fig. 2.4 Strength vs Cementitious content (Harrington et al., 2010)

Calculation of the proportions of the mixture:

Suppose the needed cementitious content differs significantly from all other cementitious materials evaluated. In that case, a moisture-density relationship test may be required to identify the ideal moisture content at the cementitious content. However, this required moisture level (%) might also be extrapolated, provided the ideal moisture content did not fluctuate much over the cementitious content range used during testing. The final mix percentages for the project can be predicted once the cementitious and ideal moisture content has been established. The aggregates' saturated surface-dry (SSD) state should be utilised to determine aggregate weight and volume.

2.3.6 Consistency

The consistency of concrete is one of the important characteristics of its plastic form. It has a direct relation to workability and strength. The constructability of RCC is defined by consistency as the most essential feature. Due to the concrete's extreme stiffness, the traditional slump test cannot be performed on the material. The amount of time that an RCC mixture is left in the Vebe test is the measurement that is used to determine how consistent the combination is (ASTM, 2014b). The specimen is placed on a table that vibrates to complete the test. The consistency of the concrete, also known as the Vebe time, can be determined by how long it takes for the table to vibrate until a mortar ring appears in the specimen. The A and B procedures for carrying out this test are predicated on the rigidity of the evaluated concrete. In procedure A, a surcharge weighing 22.7 kilograms is added on top of the material stuffed within the specimen while it is being vibrated. When the Vebe time determined using Method A is less than 5 seconds, Method B is employed, which does not incur an extra expenditure for the surcharge.

On the other hand, the RCCP cannot use the second strategy because it is ineffective. It's possible that a huge aggregate will make it more difficult for the mortar ring to develop. As a consequence of this, the test might need a significant number of replications. It is essential to obtain an RCC mixture that has the appropriate consistency. If the combination is too rigid or damp, the material will disintegrate while it is compacted or placed. In some case, the maximum density may not be obtained if the mixture is too rigid or dry; as a result, additional compacting energy will be required. If the RCC mixture is prepared correctly, achieving the desired consistency and getting a high compacted density should be possible. This, in turn, should result in good interlocking of aggregate and increased strength. The research conducted by Chhorn and Lee (Chhorn & Lee, 2017) looked into the components that affect consistency. When the sand/aggregate ratio is raised, RCC becomes stiffer, and adding further water to the mixture makes it less stiff. It was also revealed that a typical RCC's working time is less than one hour. However, the workable time can be increased by using admixture in RCC. According to ACI 325 (ACI Committee 325, 2001), the Vebe time for RCC used in pavement should be between 30 and 40 seconds. Marchand et al. (Marchand et al., 1997), on the other hand, recommended that a Vebe time of 50 to 75 seconds may be employed on RCC when it was being used for pavement applications. Nevertheless, it is impossible to say which Vebe time range offers the most significant benefits. Consequently, the application of Vebe times spanning from 30 to 75 seconds in the building of RCCPs ought to be investigated. There is not yet a study that demonstrates how the presence of this characteristic influences the performance of a Roller-Compressed Concrete Pavement (RCCP).

2.4 STEEL SLAG AGGREGATE

Slag from the purification of steel is a byproduct. It is created by filtering impurities from molten steel in steel-making furnaces. When slag cools, a mixture of silicates and oxides turns into the solid stone-like phase. Almost all steel is currently produced in integrated steel plants that use a variant of the basic oxygen process or in speciality steel plants (mini-mills) that use an electric arc furnace method. An open-hearth furnace is no longer utilised in production.

Hot liquid blast furnace metal, slag, and fluxes consisting of lime (CaO) and dolomitic lime (CaO.MgO or "dolime") are introduced into a converter during the basic oxygen process (furnace). With the help of a lance, oxygen under high pressure is fed into the exchanger. The contaminants in the charge mix with the oxygen, which removes them. Lime and dolomite combine with carbon in the form of carbon monoxide gas, silicon, manganese, phosphorus, and some iron in the form of liquid oxides to make steel slag. The liquid steel is transferred to a ladle at the final stage of the refining process, while the steel slag is left in the vessel and moved to a separate slag pot.

Different kinds of steel slag are made during the process of making steel. The different categories are furnace or tap slag, raker slag, synthetic or ladle slags, and pit or cleanup slag. Furnace slag, also called tap slag, is the steel slag that forms in the first step of making steel. Most of the time, this is where people get gravel from steel slag. After the molten steel is removed from the furnace, it is put into a ladle and refined more to eliminate any leftover impurities. This method is called "ladle refining" because it is done in the transfer ladle. During ladle refining, more fluxes are melted in the ladle to make more steel slags. These slags are mixed with the rest of the furnace slag to help absorb deoxidation products (called inclusions), keep heat in, and protect the ladle refractories. Raker and ladle slags are steel slags made during this step.

In many countries, steel slag is used as a filler for granular foundations, banks, engineered fill, expressway shoulders, and hot mix asphalt surfaces. Steel slag needs to be processed and filtered before it can be used as a building material. This is so that it meets the gradation requirements for the purpose. The slag processor may be required to meet specific moisture content criteria and to use practices for material handling (processing and stockpiling) that are comparable to those used in the traditional aggregates industry. These requirements and procedures are intended to prevent the possibility of segregation. In addition, as was indicated earlier, it is necessary to control the expansion that results from hydration reactions before using the substance.

2.4.1 Environmental Benefit of Steel Slag

From steel production at the plants, 10–15% of steel production is expected to be produced (U.S Geological Survey, 2020). According to figures from the World Steel Association (World steel), Europe makes 15.7 million tons as a waste product of steel slag, and 11.5 million tons of it are recycled (World Steel Association, 2019). In China, which makes the most steel in the world, about 30% of all steel slag is recycled, making 80 million tons of steel waste yearly (Kang et al., 2018). Durability, mechanical strength, and usability, which are fundamental features of concrete, greatly depend on the quality and attributes of the mixing ingredients employed in its creation. In this sense, aggregate is one of the most important elements of concrete (Qasrawi et al., 2009).

Cement paste binds aggregates generated by crushing big stones sourced from natural resources (Maslehuddin et al., 2003). Using natural resources without limits to make concrete has been bad for the earth for many years. For example, taking gravel and sand from the beds of streams without any rules has harmed the environment.

Recycled products have been used a lot as aggregates in concrete in recent years. For example, finely crushed and sieved gravel stones from construction waste can be used instead of natural aggregate. Slag from different metallurgical businesses can also be used (Pellegrino & Gaddo, 2009). Steel slag has a low amount of amorphous silica and a high amount of iron oxide. Compared to powdered blast furnace slag, it has little or no pozzolanic activity and can not be used in mixed cement. Therefore, the primary use of steel slag is as a replacement for aggregate (Muhmood et al., 2009; Qasrawi et al., 2009). Additionally, steel slag's high-density makes it useful for producing items like bases, retaining walls, bulwark blocks, acoustic barriers, and radiation insulators. (Manso et al., 2006).

Chapter 3: MATERIALS AND METHODOLOGY

3.1 GENERAL

To produce two types of RCC test specimens, all the ingredients of concrete were tested individually. Significant work involves selecting mix proportion for roller compacted concrete and its mixing. A typical flow diagram is shown in Fig. 3.1.

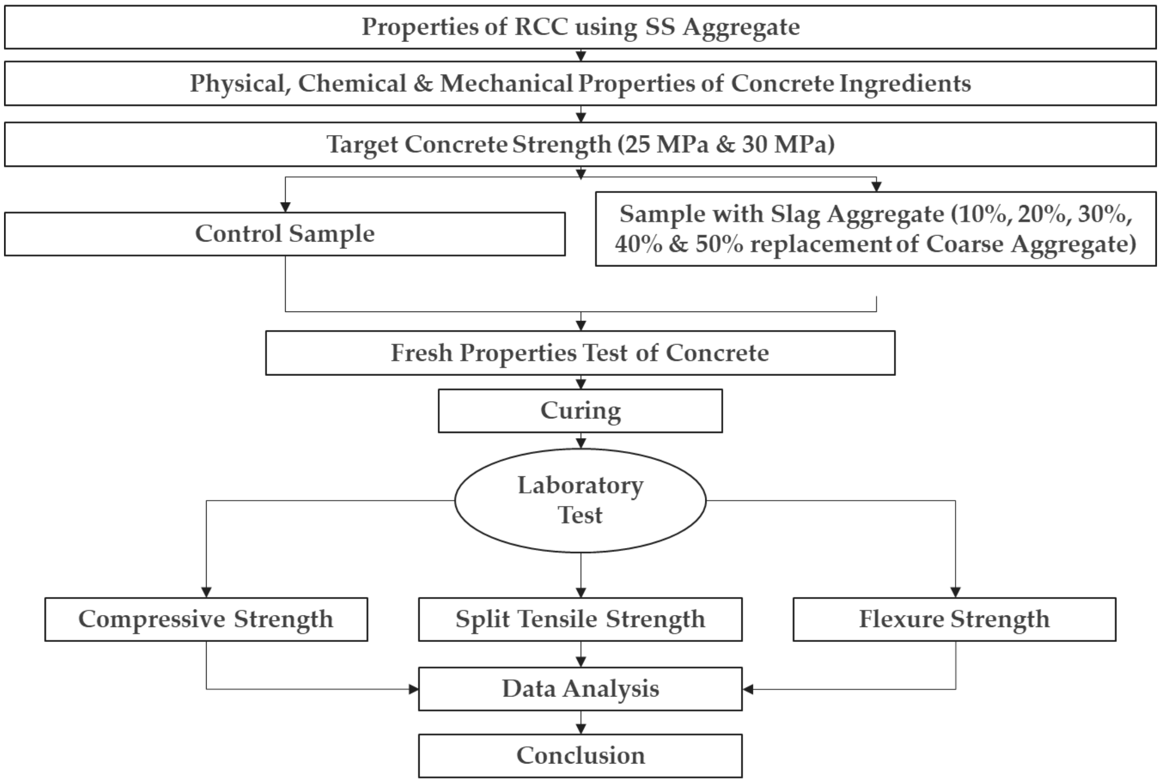

Fig. 3.1 Experimental work plan

The following materials were considered for the experimental works:

- Binder (CEM-I)
- Fine Aggregate (Coarse Sand)
- Coarse Aggregate (Stone chips and steel slag)

3.2 CEMENT

As a binding material, CEM-I was used for all the experimental works which conformed to BS EN 197-1 (BSI, 2011). Gypsum constituted 0-5% and the rest 95-100% was clinker. The related physical properties and chemical composition of CEM-I are given in Table 3.1 and

Table 3.2. A compressive strength test was carried out as per ASTM C109 (ASTM, 2016).

Table 3.1. Physical Propertied of CEM I

Characteristics	Value obtained in the laboratory	Value specified as per ASTM C150
Fineness (#200 Sieve) %	97.8%	> 90%
Normal Consistency (%)	26%	22%-30%
Setting Time (Vicat Test) Initial (min) Final (min)	 96 minutes 195 minutes	 > 45 minutes < 375 minutes
Specific Gravity	3.14	---
Compressive Strength (MPa) 3-days 7-days 28-days	 13.9 MPa 21.0 MPa 31.5 MPa	 > 12 MPa > 19 MPa > 28 MPa

Table 3.2. Chemical Composition of CEM I (Unique Cement Industries, 2019)

Characteristics	Value obtained Experimentally (%)	Standard Limits (%)
CaO	64.5	60-67
SiO_2	21.13	17-25
AL_2O_3	5.3	3-8
FE_2O_3	3.35	0.5-6
MgO	1.8	0.1-4
SO_3	2.46	1-3
K_2O	0.50	0.3-1
Na_2O	0.17	04-1.3
TiO_2	0.48	-
P_2O_5	0.1	-
SrO	0.1	-

MnO	0.07	-
ZnO	0.04	-

3.3 PROPERTIES OF COARSE AGGREGATES

Two different kinds of coarse aggregates were employed: stone chips and steel slag. The properties of both the aggregates are described separately. Stone chips are crushed stone and collected from the North-Eastern part of Bangladesh. Steel slag aggregates are collected from the BSRM steel melting factory at Mirsharai, Chattogram (Fig. 3.2 and Fig. 3.3).

Fig. 3.2 Steel Slag collection from BSRM Steel Plants

Fig. 3.3 Steel Slag crushing at BSRM Steel Plants

3.3.1 Grading of Coarse Aggregates

Natural crushed stone as coarse aggregate with a maximum nominal size of 25 mm was used, and sieve analysis of the aggregates was conducted as per ASTM C136 (ASTM, 2014a). The sieve analysis data were compared with the recommendations of ASTM C33 (ASTM, 2018).

Table 3.3. Grading of stone chips

Sieve No.	Opening (mm)	Weight Retained (gm)	% Retained	Cumulative % Retained	Cumulative % Finer	ASTM C33-18 grading limit
1″	25	0	-	-	100	100
$3/4$″	19	136	2.22	2.22	97.78	90-100
$1/2$″	12.5	2720	44.46	46.68	53.32	--
$3/8$″	9.5	1612	26.35	73.03	26.97	20-55
#4	4.75	1457	23.81	96.85	3.15	0-10
#8	2.36	192	3.14	99.98	0.02	0-5

Initial sieving was performed to remove all the aggregates larger than 25mm. Then with the initially sieved sample, a sieve analysis was performed to obtain the grading of the slag aggregate.

Table 3.4. Grading of steel slag

Sieve No.	Opening (mm)	Weight Retained (gm)	% Retained	Cumulative % Retained	Cumulative % Finer	ASTM C33-18 grading limit
1′′	25	0	-	-	100	100
$3/4$′′	19	2699	28.29	28.29	71.71	90-100
$1/2$′′	12.5	3821	40.05	68.34	31.66	--
$3/8$′′	9.5	996	10.44	78.78	21.22	20-55
#4	4.75	881	9.23	88.02	11.98	0-10
#8	2.36	207	2.17	90.19	9.81	0-5

From the sieve analysis of both stone chips and steel slag aggregate, a combined gradation was chosen to get the maximum availability of the aggregates. A 45% of the total coarse aggregate passed 25mm and retained on a 12.5mm sieve, while 55% of the total coarse aggregate quality was between 12.5mm to 4.75mm in size aggregate. The proportion of steel slag was replaced accordingly.

3.3.2 Dry Rodded Unit Weight of Coarse Aggregates

Dry rodded unit weight of coarse aggregate was determined as per ASTM C29 (ASTM, 1997). After filling one-third of the mould with dry, coarse aggregate, the mould was rodded 25 times with a 16 mm dia tamping rod. This process was repeated when the mould was two-thirds full and again after the aggregate overflowed out of the mould. After levelling the aggregate in the mould weight of the aggregate was measured. From that, dry rodded unit weight of coarse aggregate was calculated.

Table 3.5. Dry rodded unit weight of coarse aggregates

Type of Aggregate	Dry Rodded Unit Weight (kg/m^3)
Stone Chips	1550
Steel Slag	1450

3.3.3 Specific Gravity and Water Absorption Test

ASTM C127 (ASTM, 2015a) was followed to determine specific gravity and water absorption. According to this method, the coarse aggregate was immersed under water at room temperature for 24 hours. The sample was then taken out of the water and dried with a water-absorbent cloth to remove all the surface water film around the particle. The large particles are wiped individually. The SSD weight of the sample was taken in the air. Immediately saturated surface dry sample was placed in a container, and the apparent mass in water was determined. Entrapped air was removed by shaking the container. The sample was then dried in an oven set at 110^0 C. It was then left in the air at room temperature for 1 to 3 hours. After cooling to a comfortable temperature (approximately 50^0 C) mass was measured.

Table 3.6. Specific gravity and absorption of coarse aggregate

Properties	Stone Chips	Steel Slag
Specific Gravity (OD)	2.71	2.53
Specific Gravity (SSD)	2.73	2.63
Apparent Specific Gravity	2.78	2.71
Absorption Capacity (%)	0.77	1.85

3.3.4 Los Angeles Abrasion Value of Coarse Aggregates

Following ASTM C131, the resistance of a small-size coarse aggregate to abrasion and impact was determined using the Los Angeles Machine (ASTM, 2014a). In a spinning steel drum filled with a specific number of steel spheres, the test examines how much mineral aggregates of standard grading are broken down by abrasion, impact, and grinding. The test sample's grade determines how many steel spheres are to be used.

A shelf plate picks up the sample and the steel spheres as the drum rotates. The shelf plate carries the sample and the spheres around until they are placed on the drum's opposite side, creating an impact-crushing effect. After that, the contents roll around inside the drum, acting similar to abrasion and grinding, until the shelf plate takes up the sample together with the steel spheres, and the process begins again. Following the predetermined number of revolutions, which is five hundred, the contents of the drum are emptied, and the aggregate portion is sieved to determine the degree of degradation, expressed as a percentage loss.

Table 3.7. Los Angeles abrasion value test

Material Type	Total Original Mass (gm)	Aggregate passing 1.70 mm Sieve	Los Angeles Abrasion Value (%)
Stone Chips	5000	1428	28.6
Steel Slag	5000	1986	39.7

The Los Angeles abrasion value test results of stone and steel are given inTable 3.7. Due to being more porous (absorption capacity of 1.85%), steel slag aggregate shows a higher Los Angeles Abrasion Value than natural stone aggregate.

3.4 PROPERTIES OF FINE AGGREGATE

Two types of fine aggregates used in this project were natural coarse sand obtained from the local market originating from the North-Eastern part of Bangladesh. There was no replacement of these fine aggregates for the experimental works.

3.4.1 Grading of Fine Aggregate for Concrete

Sand is commonly used as fine aggregate. For concreting work, only Coarse sand was used. Sieve analysis of this aggregate was conducted according to ASTM C136 (ASTM, 2001). Gradation of this, used for experimental work, is compared with the recommendation of ASTM C33 (ASTM, 2018) in Table 3.8. The grain size distrivution with ASTM comparison is given in Fig. 3.4.

According to ASTM C136,

Fineness Modulus = (0.50+8.83+21.33+49.67+84.67+98.67)/100

= 263.67/100 = 2.64

Table 3.8. Grading of Sylhet sand

Sieve No.	Opening (mm)	Weight Retained (gm)	% Retained	Cumulative % Retained	Cumulative % Finer	ASTM C33 grading limit
$^3/_8$	9.5	0	0	0	100	100
#4	4.75	3	0.50	0.50	99.50	95-100
#8	2.36	50	8.33	8.83	91.17	80-100
#16	1.18	75	12.50	21.33	78.67	50-85
#30	0.6	170	28.33	49.67	50.33	25-60
#50	0.3	210	35.00	84.67	15.33	-
#100	0.15	84	14.00	98.67	1.33	0-10
Pan	---	8	-	-	-	-

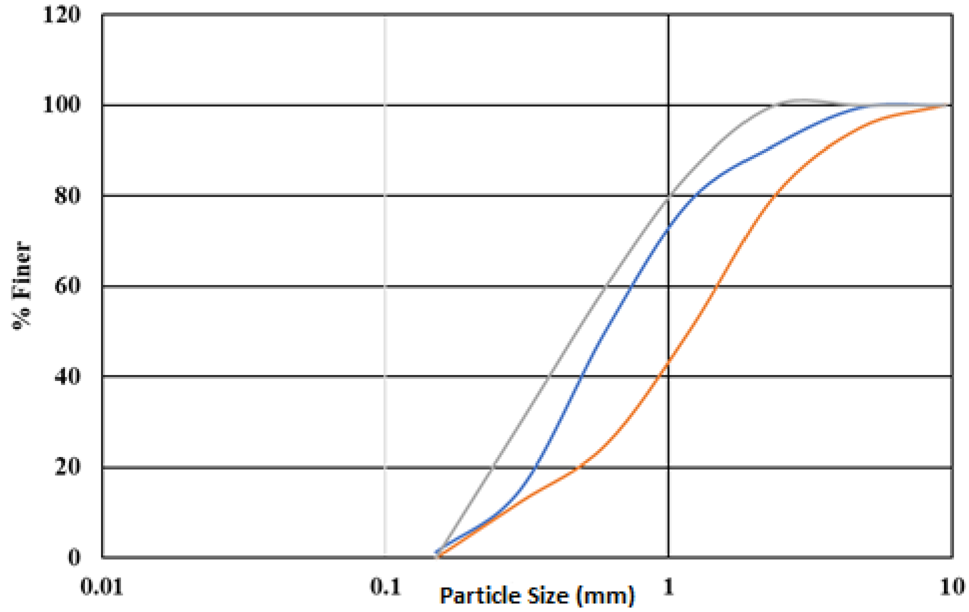

Fig. 3.4 Grain size distribution chart

3.4.2 Specific Gravity and Water Absorption Test

Fine aggregate was tested for specific gravity and absorption according to ASTM C128 (ASTM, 2015b). A sample of aggregate is soaked in water for 24 hours to plug the pores effectively. It is then withdrawn from the water, the water is evaporated off the particles' surfaces, and the mass is calculated. The sample is then placed in a graduated container, and the sample's volume is measured using a gravimetric or volumetric method. Finally, the sample is dried in the oven, and the mass is determined again. Determining density, relative density (specific gravity), and absorption is feasible using the mass data obtained and the formulas given in ASTM C128.

Table 3.9. Specific gravity and absorption test of fine aggregates

Properties	Sylhet Sand
Specific Gravity (OD)	2.37
Specific Gravity (SSD)	2.41
Apparent Specific Gravity	2.55
Absorption Capacity (%)	2.31

3.4.3 Bulk Density

The ASTM C29 (ASTM, 2017) standard was used to determine the bulk density of fine aggregates. One-third of the mould was filled with air dry fine aggregate, which was levelled with fingers before being rodded 25 times with a 16 mm diameter tamping rod. The same thing was repeated with the container until it was two-thirds full, then overflowed. The aggregate was struck off, leveled, and weighed. After that, the bulk density of fine aggregate was calculated. For natural sand, the bulk density was found to be 1590 kg/m^3.

3.5 WATER

Ordinary potable water (tap water) was used for mixing and curing according to ASTM C1602 (ASTM, 2012c).

3.6 MIX DESIGN

The RCC mix design differs from conventional concrete due to its mixture properties, especially the stiff consistency. The literature followed must study the soil compaction method for the mix design of RCC. The steps followed are mentioned below:

STEP 1: Selection of Aggregate

The selection of aggregate for the RCC mix is similar to conventional concrete. The aggregate covers around 75 to 85% of the total mixture content at RCC (ACI Committee 325, 2001). The maximum size of aggregate was less than 25mm. This was similar to steel slag aggregate. This nominal aggregate size is selected based on the available size of Steel Slag from the crushing plant. According to the PCA guideline (Portland Cement Association, 2006), RCC contains larger fine aggregate content than coarse aggregate. The combined gradation of both fine and coarse aggregate was followed to prepare the mixture. From the combined quantity of fine and coarse aggregate, 55% was fine aggregate, and 45% was coarse aggregate by mass.

STEP 2: Selection of Cement Content

The cement content was selected based on the strength requirement. A 13% cement content was chosen for C25 concrete and 14% for C30 concrete. This binder contributes to the total quantity of dry aggregates. It means for the C25 grade concrete mixture, there are 13% cement and 87% fine and coarse aggregates; for the C30 grade concrete mixture, there are 14% cement and 86% fine and coarse aggregates.

STEP 3: Selection of Water Content

The water content for each mixture was determined using a moisture-density relationship following the a modified proctor compaction test (ASTM, 2012a). The water content at which the maximum density was achieved with the aggregate proportion for the control sample was selected for the mix design. It was observed that with 14% cement content, the maximum density was found at 6% moisture content. Therefore, the water content for C30 concrete was selected as 6%. After getting the result of the control sample for C30 concretes, again 6.5% water content was chosen for C25 concrete with 13% cement content.

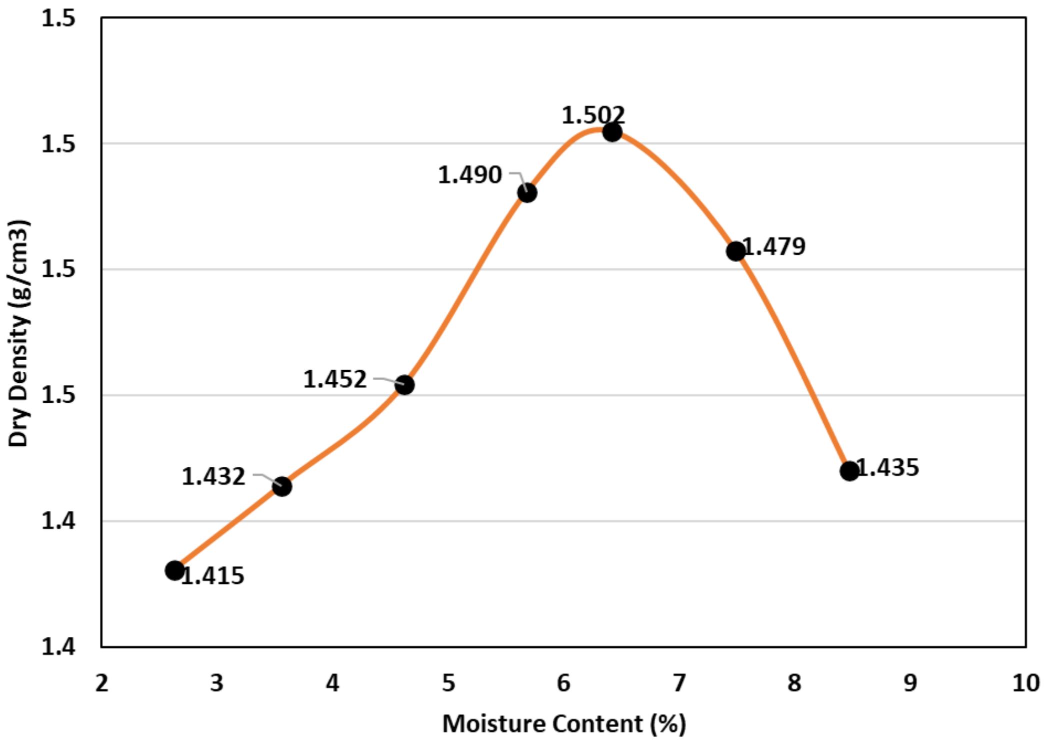

Fig. 3.5 Optimum moisture content for C30 concrete

STEP 4: Test Specimen Preparation

The first batch of waterThe first batch of RCC was mixed for 14% cement content. The estimated compressive strength for this 14% cement content was 30 MPa with 6% water content. The mix proportions for C30 and C25 concrete are given in Table 3.10 & Table 3.11, respectively. Initially, C30 concrete mix was designed and tested. Then the design was modified for C25 concrete.

Table 3.10. Mix proportion for 30 MPa concrete mix (SS1 Concrete)

Parameters	Quantity of Materials						
Sample Description (SS)	-	C (0%)	10%	20%	30%	40%	50%
Concrete batch size	%	100	100	100	100	100	100
	kg	90	90	90	90	90	90
Cement	%	14	14	14	14	14	14
	kg	12.6	12.6	12.6	12.6	12.6	12.6
Total Aggregates	%	86	86	86	86	86	86
	kg	77.4	77.4	77.4	77.4	77.4	77.4
Fine Aggregate	%	55	55	55	55	55	55
	kg	42.57	42.57	42.57	42.57	42.57	42.57
Total Coarse Aggregate (Stone +SS)	%	45	45	45	45	45	45
	kg	34.83	34.83	34.83	34.83	34.83	34.83
Total 12.5-25 mm aggregate (Stone +SS)	%	45	45	45	45	45	45
	kg	15.67	15.67	15.67	15.67	15.67	15.67
4.75-12.5 mm aggregate (Stone +SS)	%	55	55	55	55	55	55
	kg	19.16	19.16	19.16	19.16	19.16	19.16
Total Steel Slag	%	0	10	20	30	40	50
	kg	0.00	3.48	6.97	10.45	13.93	17.42
12.5-25 mm Stone Chips	kg	15.67	14.11	12.54	10.97	9.40	7.84
4.75-12.5 mm Stone Chips	kg	19.16	17.24	15.33	13.41	11.49	9.58
12.5-25 mm Steel Slag	kg	0.00	1.57	3.13	4.70	6.27	7.84
4.75-12.5 mm Steel Slag	kg	0.00	1.92	3.83	5.75	7.66	9.58
Water	%	6	6	6	6	6	6
	kg	5.4	5.4	5.4	5.4	5.4	5.4

Table 3.11. Mix proportion for 25 MPa concrete mix (SS2 Concrete)

Parameters	Quantity of Materials						
Sample Description (SS)	-	C (0%)	10%	20%	30%	40%	50%
Concrete batch size	%	100	100	100	100	100	100
	kg	90	90	90	90	90	90
Cement	%	13	13	13	13	13	13
	kg	11.7	11.7	11.7	11.7	11.7	11.7
Total Aggregates	%	87	87	87	87	87	87
	kg	78.3	78.3	78.3	78.3	78.3	78.3
Fine Aggregate	%	55	55	55	55	55	55
	kg	43.07	43.07	43.07	43.07	43.07	43.07
Total Coarse Aggregate (Stone +SS)	%	45	45	45	45	45	45
	kg	35.24	35.24	35.24	35.24	35.24	35.24
Total 12.5-25 mm aggregate (Stone +SS)	%	45	45	45	45	45	45
	kg	15.86	15.86	15.86	15.86	15.86	15.86
4.75-12.5 mm aggregate (Stone +SS)	%	55	55	55	55	55	55
	kg	19.38	19.38	19.38	19.38	19.38	19.38
Total Steel Slag	%	0	10	20	30	40	50
	kg	0.00	3.52	7.05	10.57	14.09	17.62
12.5-25 mm Stone Chips	kg	15.86	14.27	12.68	11.10	9.51	7.93
4.75-12.5 mm Stone Chips	kg	19.38	17.44	15.50	13.57	11.63	9.69
12.5-25 mm Steel Slag	kg	0	1.59	3.17	4.76	6.34	7.93
4.75-12.5 mm Steel Slag	kg	0	1.94	3.88	5.81	7.75	9.69
Water	%	6.5	6.5	6.5	6.5	6.5	6.5
	kg	5.85	5.85	5.85	5.85	5.85	5.85

Fig. 3.6 Modified proctor test of soil

Fig. 3.7 Dry RCC mixture

Fig. 3.8 RCC mixture compaction in cylinder

Fig. 3.9 Prepared cylinder sample

The RCC was mixed and prepared for casting cylinder and prism samples according to the mix design. Then with the vibrating hammer, the mixture was compacted into three layers. The compaction was continued until the mortar came over the steel plate. Finally, the cylinder samples and the prism moulds were demoulded after 24 hr of concreting.

Chapter 4: RESULTS & DISCUSSION

4.1 GENERAL

At the initial research stage, the properties of OPC, stone chips and steel slag were evaluated. The properties of the cement, such as setting time, consistency were conducted to understand the fundamental properties of the binder material. The compressive and tensile strength of the hydraulic cement was also performed. The physical properties of steel slag aggregate were tested to estimate their behaviour in RCC. Experimental works were performed using cylindrical and cubic specimens, respectively, to evaluate RCC's compressive strength and tensile strength

4.2 STEEL SLAG

Chemical composition and characterisation of steel slag aggregate were conducted in the laboratory using XRF, XRF and SEM analysis. The oxide and mineralogical composition indicate the material's formation. The SEM alongside EPS gives the materials' surface morphology and elemental composition.

4.2.1 Chemical Composition of Steel Slag Aggregate

The quantitative oxide composition of steel slag aggregate was estimated by XRF analysis. The test data are given in

Table 4.1. From the test results, it is observed that a significant part of the steel slag aggregate is composed of silicon dioxide, also known as silica, most commonly found in nature as quartz and has a notable amount of calcium oxide and ferric oxide as the inorganic compound (Yi et al., 2012). The amount of aluminium oxide and magnesium oxide also exists around 5% each in steel slag. Other oxides, such as MnO, TiO_2, Na_2O, and ZnO are in minor quantities.

Table 4.1. Chemical composition of steel slag aggregate by XRF analysis

Oxides	Steel Slag
SiO_2	47.7
CaO	23.4
Fe_2O_3	10.9
Al_2O_3	5.4
MgO	5.1
MnO	3.8
TiO_2	0.9
Na_2O	0.7
ZnO	0.6
K_2O	0.5
SO_3	0.5
Bao	0.2
P_2O_5	0.1
Cl	0.1
CuO	0.0

4.2.2 Mineralogical Composition of Steel Slag

The X-ray Diffraction (XRD) test is a non-destructive way of characterising crystalline materials. It helps to analyse and determine the structure, phase, crystal orientation and other structural parameters (Kohli & Mittal, 2019). The type of the substance is determined using an XRD graph (Intensity vs 2θ). The material can be classified as crystalline with a sharp and high peak. When there is a larger peak, the material is said to be poly crystalline, however, material without a peak but a disorderly pattern is said to be amorphous. Fig. 4.1 shows the X-ray Diffraction (XRD) diagram of the Steel Slag collected from the plant. XRD identified the mineralogical compounds present in the Steel Slag.

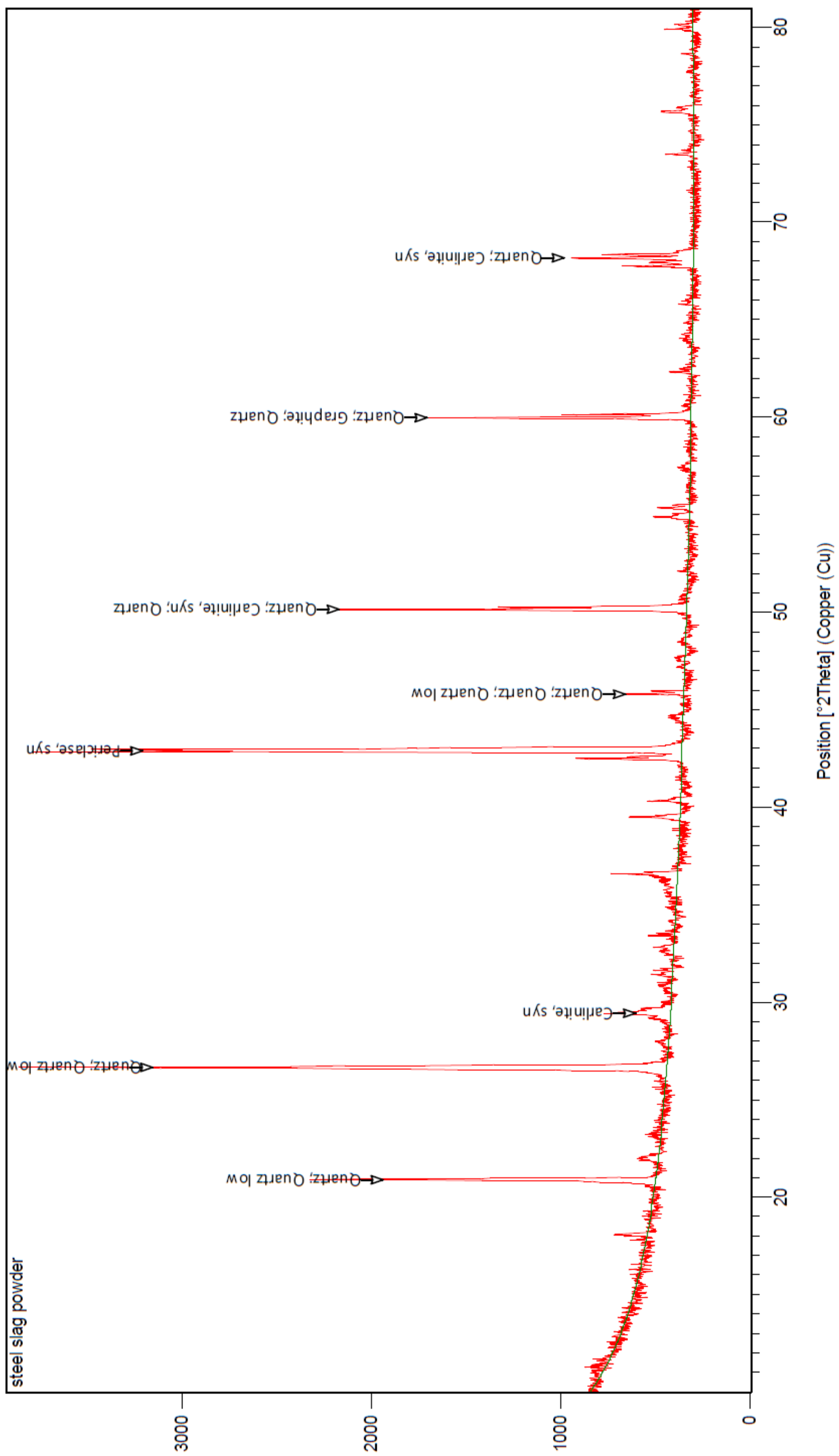

Fig. 4.1 XRD data of steel slag

Steel slag's major identified crystalline phases are carlinite, periclase and quartz. Carlinite is a trigonal-pyramidal mineral containing sulfur and thallium. The magnesium mineral, periclase, is found naturally in contact with metamorphic rocks. It is also a significant part of the majority of basic refractory bricks. Quartz is a silica (silicon dioxide) based hard & crystalline. According to the peak analysis, some Graphite is also observed from the XRD analysis.

4.3 MORPHOLOGY

The morphological properties of the aggregates suggestively influence the workability, durability, and friction properties of cement concrete and asphalt mixes (Al-Rousan et al., 2007; Chowdhury et al., 2001). Furthermore, due to the rapid advancement in imaging techniques with available experimental options, diagnosis of the material helps us to understand its behaviour more significantly.

Energy dispersive X-ray spectroscopy (EDX) is a diagnostic method for the elemental characterisation of materials based on specimen characteristics X-rays (Colpan et al., 2018). The energy dispersive X-ray (EDX) micro-analytical results gave quantitative elemental information of steel slag in Table 4.2 and Table 4.4. The elemental composition indicates the major elements present in the slag sample. EDX is conducted in random spots to get the composition of that spot during SEM analysis. In general, C, O, Ca, Al, Fe, Si, and Mn are the main elements found in this EDX analysis. SEM images are given in Fig. 4.2, Fig. 4.3 and Fig. 4.4. The steel slag particles are found relatively pores in nature. The image was captured with high magnification and indicates air intrusion during the cooling process of the hot slag.

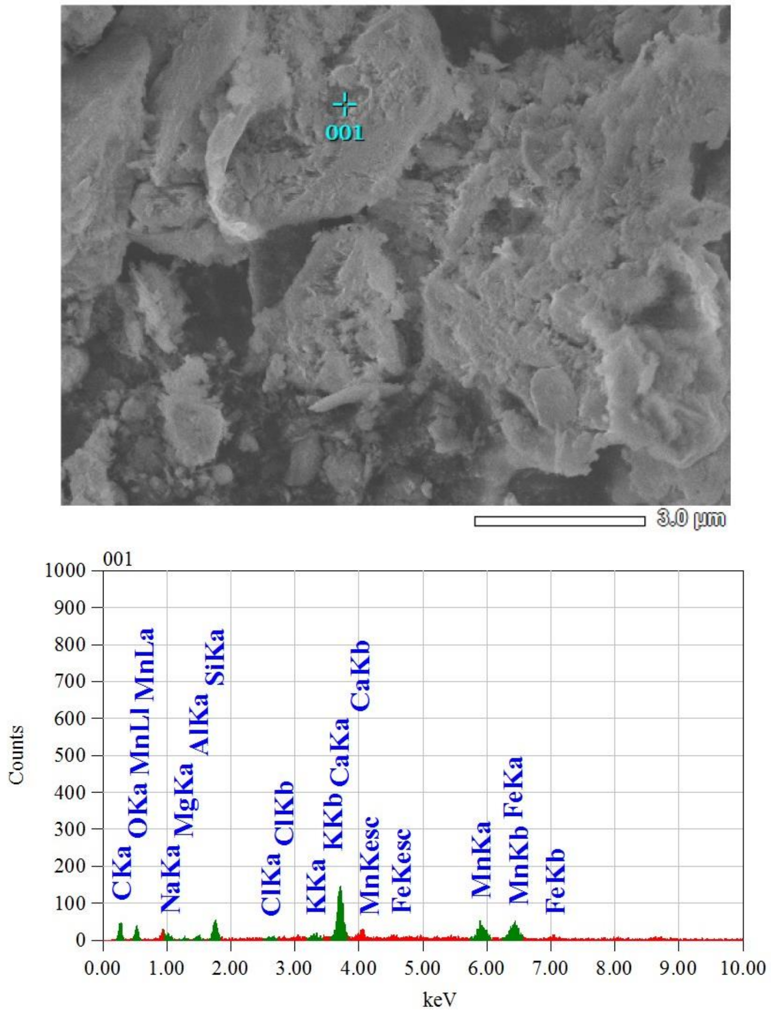

Fig. 4.2 Morphological analysis of steel slag by SEM and EDX

Table 4.2. Quantitative elemental information of Steel Slag by EDX spot

Element	C	O	Na	Mg	Al	Si	Cl	K	Ca	Mn	Fe
Mass (%)	25.48	4.39	0.54	0.31	0.74	4.00	0.36	1.05	22.70	17.78	22.66

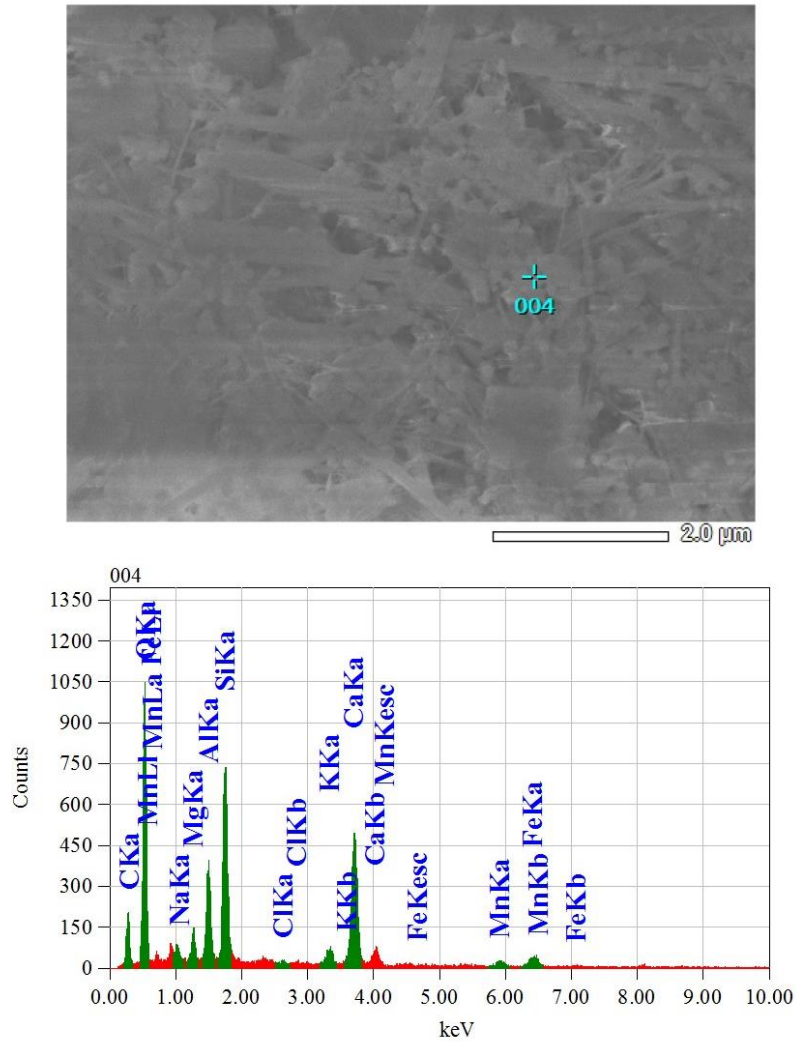

Fig. 4.3 Morphological analysis of Steel Slag by SEM image with EDX

Table 4.3. Quantitative elemental information of Steel Slag by EDX spot

Element	C	O	Na	Mg	Al	Si	Cl	K	Ca	Mn	Fe
Mass (%)	27.81	26.52	0.56	1.73	5.40	12.23	0.31	1.71	17.22	2.25	4.26

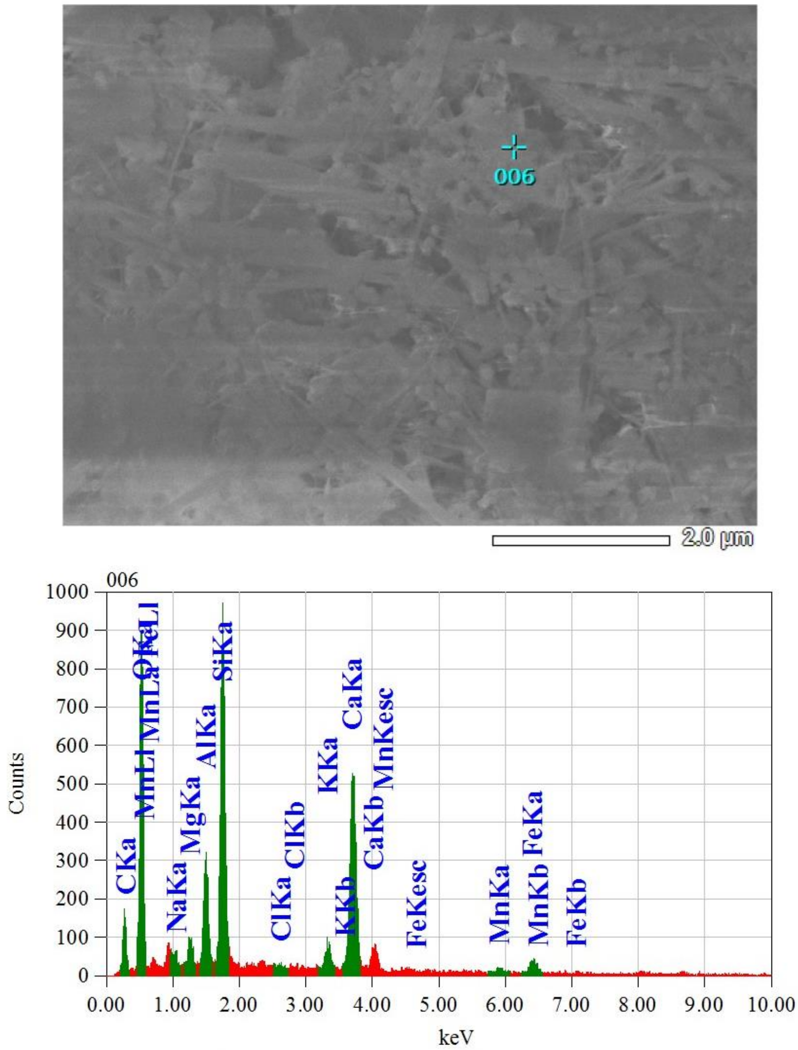

Fig. 4.4 Morphological analysis of Steel Slag by SEM image with EDX

Table 4.4. Quantitative elemental information of Steel Slag by EDX spot

Element	C	O	Na	Mg	Al	Si	Cl	K	Ca	Mn	Fe
Mass (%)	24.52	26.23	0.41	1.29	4.50	15.14	0.17	2.15	20.06	1.33	4.22

4.4 VEBE CONSISTENCY

Adequate workability is crucial to achieve the optimum compaction of the RCC mixture. The vebe consistency test process is given in Fig. 4.5. The result of vebe consistency test of the prepared RCC mixture is given in Fig. 4.6. The vebe consistency value range was between 14-18 sec with the use of 12.5kg surcharge.

Therefore, according to ASTM C1170, the RCC can be classified as stiff consistency class.

Fig. 4.5 Vebe Consistency test

As shown in Fig. 4.6, 14% cement content gives better consistency as the higher cement content lubricates the mixture better. In general, the vebe time decreased with increased steel slag content in the RCC. It indicates some added benefits regarding the workability of the steel slag, added to the concrete. The decreased workability might be observed due to the porous character of slag aggregate particles compared to natural stone aggregates, which consume more cement-sand paste and reduce concrete workability (Qasrawi, 2014). Furthermore, Olofinnade et al. (2021) reported that concerning the ratio of sand replaced with steel increases, the workability of the concrete mixes was improving. As the mixture was prepared following the methodology of maximum dry density, we can encounter different trends, which can guide further research.

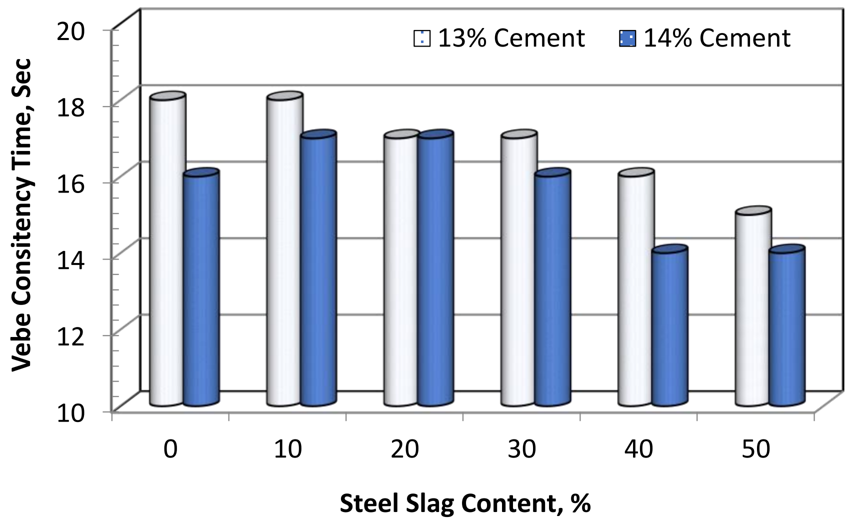

Fig. 4.6 Vebe Consistency time variation with the increase in SS content

4.5 COMPRESSIVE STRENGTH

The compressive strength test of the RCC cylinder is shown in Fig. 4.7. The compressive strength data are shown in Table 4.5 and

Table 4.6. The average of 3 test samples is reported for individual mix proportion. The maximum and minimum of these three results are also given in the Fig. 4.9 and Fig. 4.8. For SS1 series (14% cement content) 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. For the SS2 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 is found to be higher in 50% SS replaced RCC.

Fig. 4.7 Compressive strength test of cylinder

Table 4.5. 14% Cement Content Compressive Strength (SS1 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	37.7	40.97	32.77
10	36.8	37.55	35.16
20	36.4	39.26	34.14
30	37.0	39.26	35.85
40	33.8	35.85	32.43
50	30.8	36.19	25.60

Table 4.6. 13% Cement Content Compressive Strength (SS2 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	34.4	35.50	33.46
10	37.2	39.26	34.82
20	36.8	38.92	35.50
30	33.1	34.14	32.43
40	31.9	32.43	30.72
50	30.8	32.43	29.36

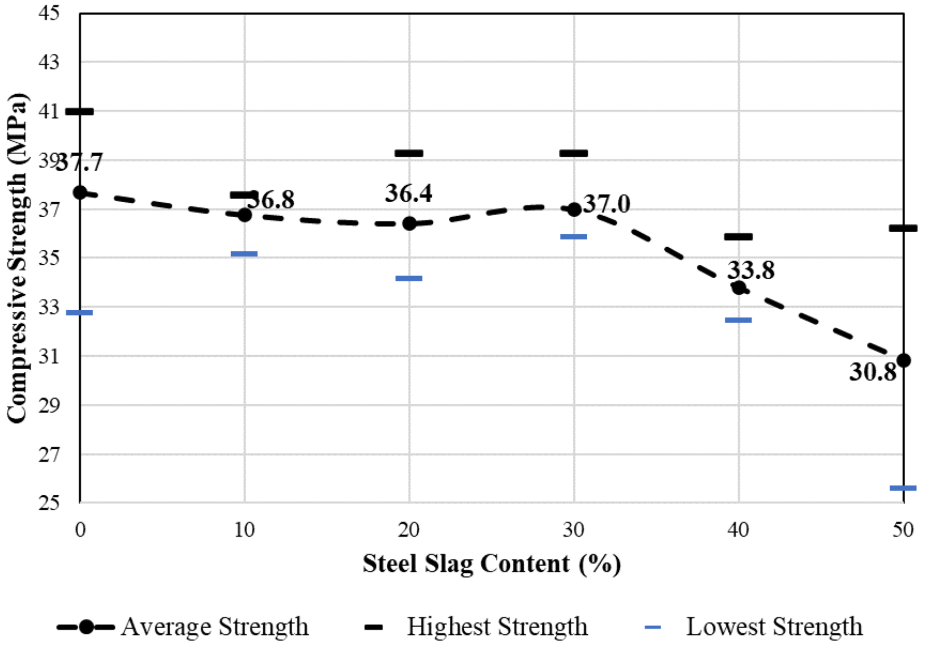

Fig. 4.8 Compressive strength of SS1 series concrete

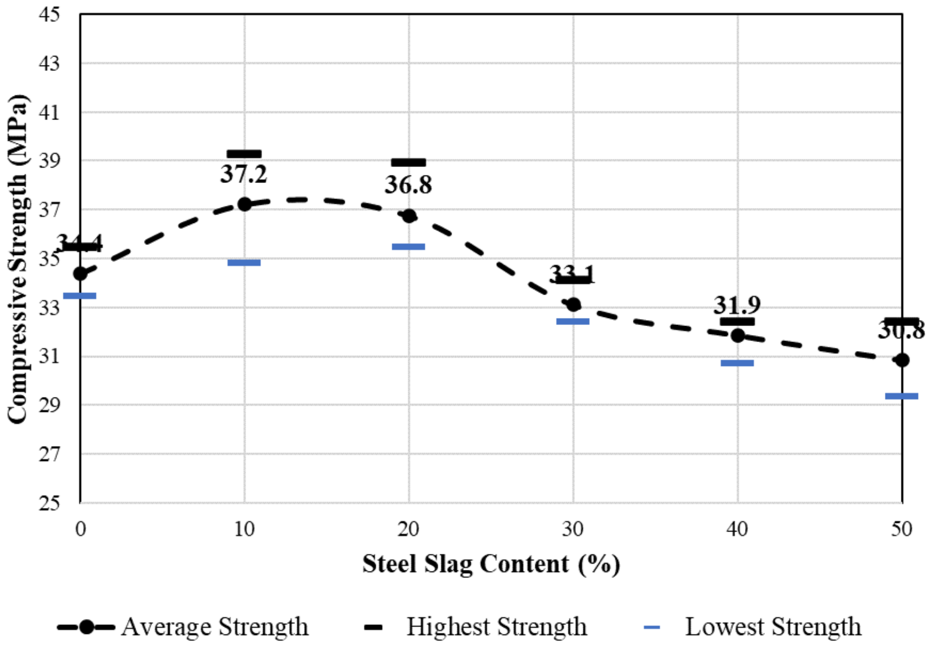

Fig. 4.9 Compressive strength of SS2 series concrete

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 similar behaviour with 14% and 13% cement content overall. For both SS1 and SS2 series, the compressive strength test results were more scattered in two ends (0% and 50% replacement level). Taha et al. (2014) stated that they observed an 11% improvement in compressive strength for 100% replacement of steel slag with comparison to control concrete. Devi & Gnanavel (2014) found that their concrete's compressive strength steadily improves up to 30% replacement of steel slag for coarse aggregate and then falls over time as the replacement level increases.

Increased compressive strength may be due to the strong connection between the cement/mortar matrix and steel slag aggregate particles which might be attributed to the rough and porous surface of the steel slag particles. With respect to the failure plane evaluation, it goes through the steel slag particles, indicating a strong link between the cement/mortar matrix and the steel slag particles.

4.6 TENSILE STRENGTH

The cube sample preparation for the tensile strength test is given in Fig. 4.10. Table 4.7 and Table 4.8 give the results of the split tensile strength test. As shown in Fig. 4.11, SS1 series RCC's tensile strength was highest at 20% replacement, approximately 34.10% higher than the control sample. For SS2 series concrete (Fig. 4.12), the tensile strength remained similar up to the SS replacement level of 30% and is slightly higher than the control concrete without SS aggregate. Further increase in SS aggregate content linearly decreased the tensile strength of RCC. However, the changes in tensile strength results are minimal. Although the compressive strength can be improved by increasing the compaction, the improvement in tensile strength is not significant (Chhorn et al., 2018).

Fig. 4.10 Tensile test sample preparation

Table 4.7. 14% Cement Content Tensile Strength (SS1 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	2.2	2.56	1.88
10	2.7	2.74	2.56
20	2.9	3.08	2.73
30	2.7	2.91	2.56
40	2.5	2.56	2.39
50	2.2	2.56	1.88

Table 4.8. 13% Cement Content Tensile Strength (SS2 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	2.5	2.60	2.46
10	2.7	2.84	2.56
20	2.7	2.80	2.60
30	2.5	2.56	2.39
40	2.3	2.39	2.05
50	2.2	2.26	2.12

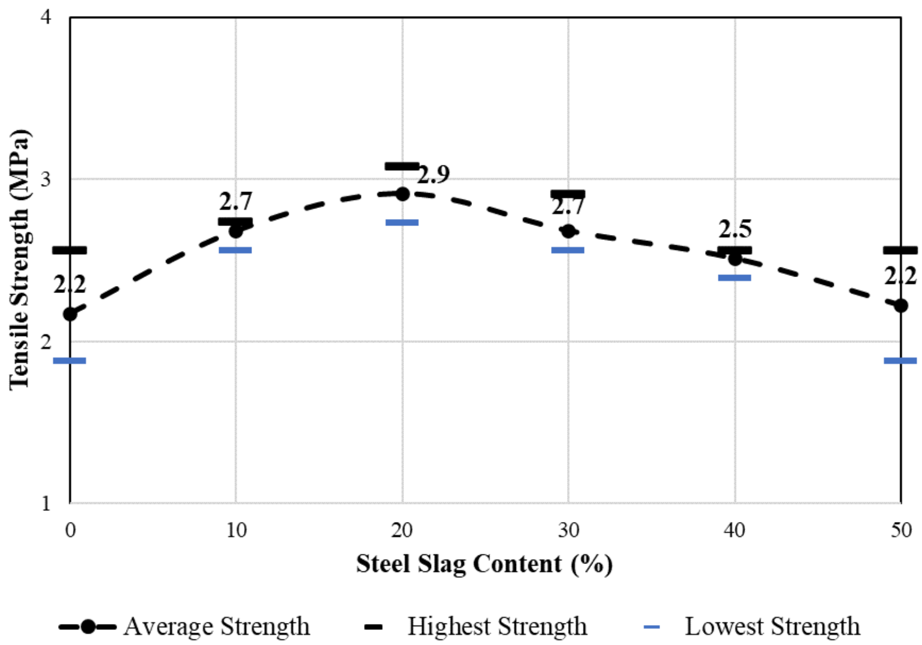

Fig. 4.11 Tensile strength of SS1 (14% cement content) series concrete

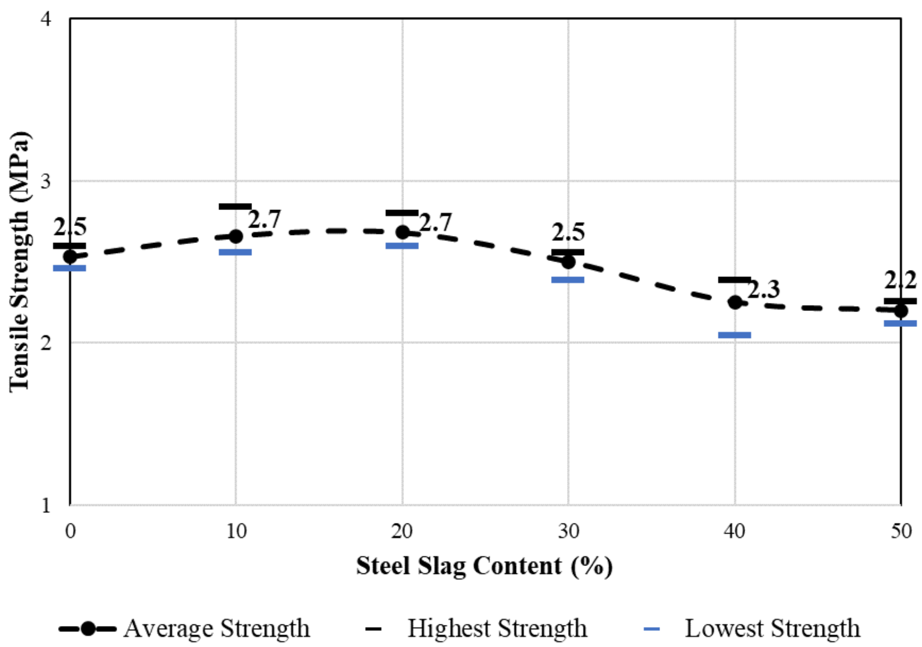

Fig. 4.12 Tensile strength of SS2 (13% cement content) series concrete

4.7 FLEXURAL STRENGTH

Fig. 4.13 shows the prism sample preparation for the flexural strength test of RCC. Fig. 4.14 and Fig. 4.15 describes the flexural strength result from experimental data. The raw, detailed data are given in Table 4.9 and Table 4.10.

A considerable flexural strength of 11.5 MPa was observed for 30% replacement of coarse aggregate with SS. For SS1 (14% cement replacement), after replacing 30% steel slag, the strength increased by approximately 10.5% compared to the control specimen's strength. On the other hand, the strength decreased to 16.7% for the 40% replacement of slag aggregate and was reduced to around 25% after replacing 50% slag aggregate compared to the control sample. For SS2 (13% cement replacement), after replacing 30% steel slag, the strength increased by approximately 3.3% compared to the control specimen's strength. Compared to the control sample, the strength decreased to 30.3% for the 40% replacement of slag aggregate was decreased around 25% after replacing 50%. According to (Harrington et al., 2010) flexural strength is mainly related to the concrete's density & compressive strength, generally ranging from 3.5 to 7 MPa.

Fig. 4.13 Flexure test sample preparation

Table 4.9. 14% Cement Content Flexure Strength (SS1 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	12.2	12.24	12.05
10	12.9	13.56	12.38
20	13.1	13.30	12.80
30	13.4	13.85	13.20
40	10.1	10.92	8.64
50	9.2	9.88	8.44

Table 4.10. 13% Cement Content Flexure Strength (SS2 Concrete)

% of Slag	Average Strength	Highest Strength	Lowest Strength
0	11.1	11.98	10.33
10	10.4	10.90	9.82
20	11.2	12.00	10.30
30	11.5	11.78	11.17
40	7.7	8.88	6.10
50	8.4	9.21	7.63

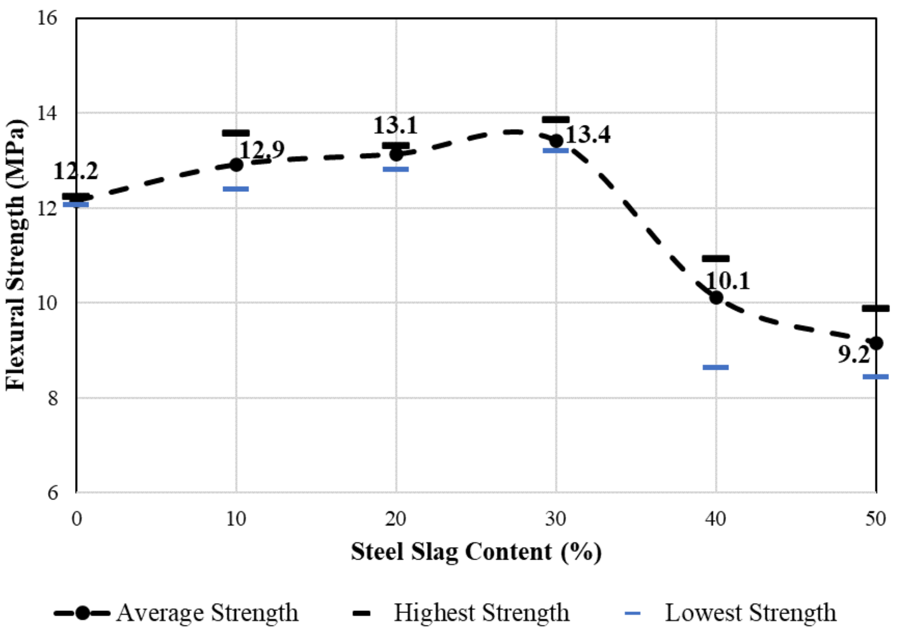

Fig. 4.14 Flexural strength of SS1 (14% cement content) series concrete

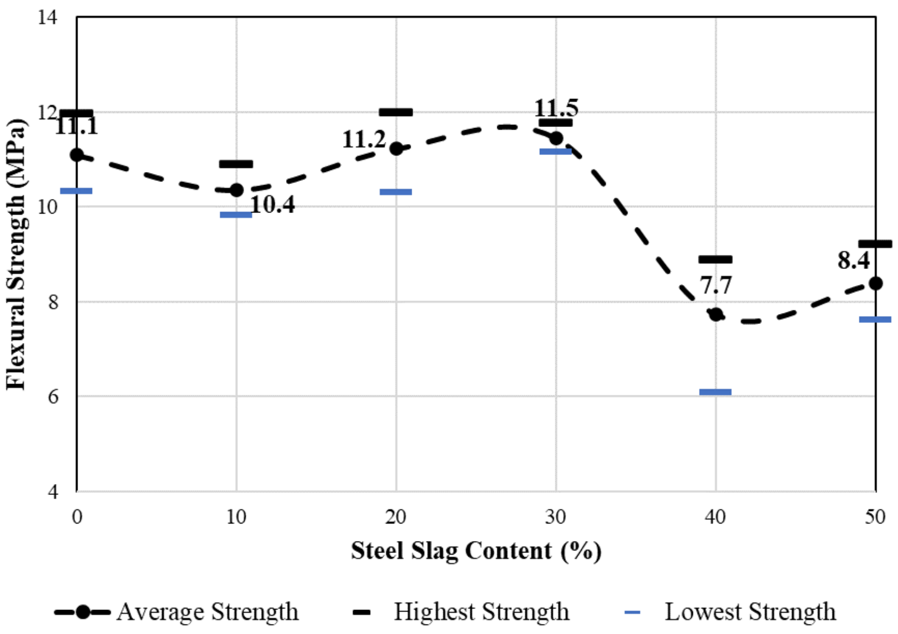

Fig. 4.15 Flexural strength of SS2 (13% cement content) series concrete

From the overall results of compressive, tensile and flexural strength, it was concluded that the 30% replacement of coarse aggregate with steel slag gives us the most reasonable strength with good economic consideration.

4.8 PRACTICAL IMPLICATION

Steel slag from the steel industries has been identified as a viable alternative to natural stone aggregate. Slag utilisation improves the workability, mechanical property, and durability of the produced concrete, lowering costs and increasing greenness. As this is not a low-grade product, roller compacted concrete with steel slag aggregate can be used at the following works:

- parking lots
- power plants
- road shoulders
- storage facilities
- military facilities etc.

This study, therefore, will allow the management of the connected sector to find new ways to use waste and save the environment.

4.8.1 Economic Benefit

Slag recycling saves money and helps the environment by minimising pollution from nonbiodegradable slag deposits. Separating the heavy metals from the deposited slag might be possible. However, this encapsulates in concrete. Materials with improved mechanical properties make them acceptable for road pavement with any traffic load, steel slags have been utilised extensively as pavement aggregates (Santos et al., 2015). Considering the cost of steel slag as US$ 25/ton (including transportation from the steel industry) and other materials costs, an approximate cost-benefit chart is presented in Fig. 4.16 and Fig. 4.17.

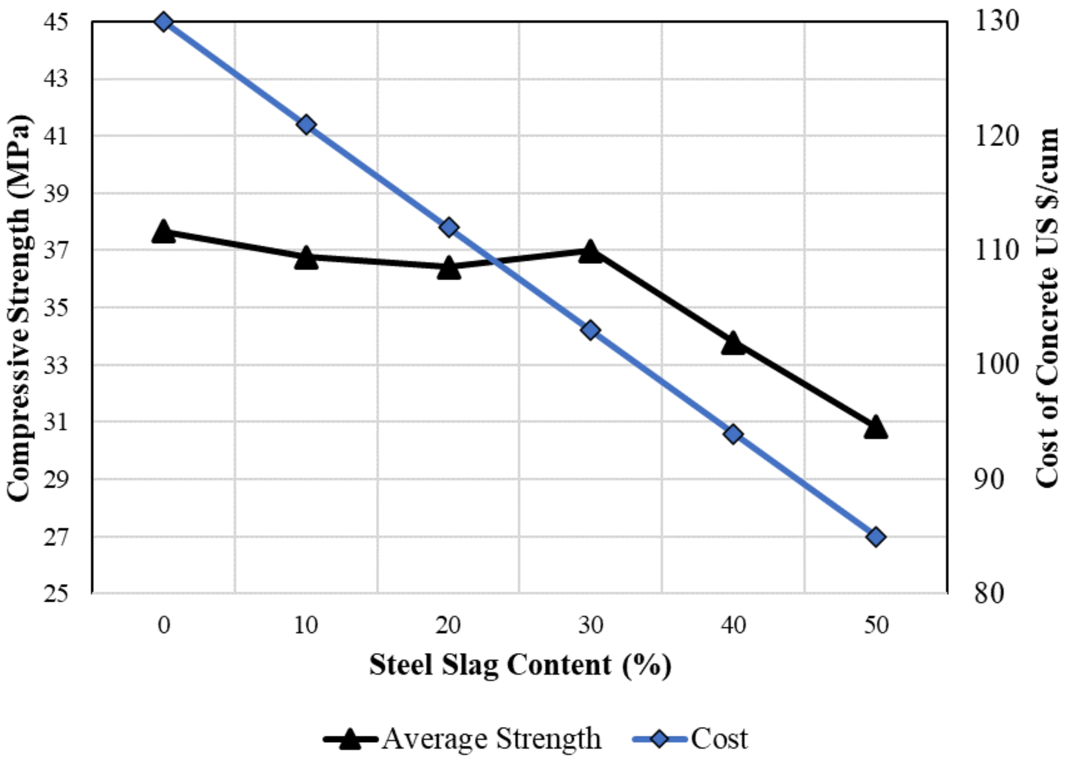

Fig. 4.16 Cost-benefit chart SS1 (14% cement content) series concrete

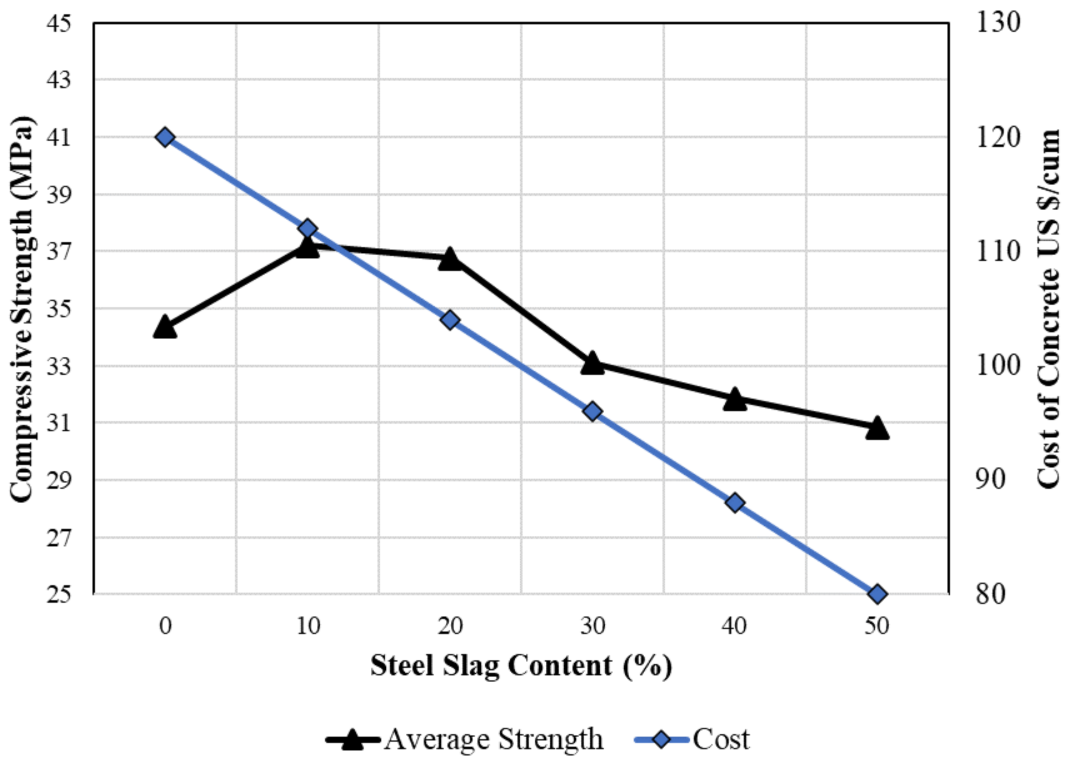

Fig. 4.17 Cost-benefit chart SS2 (13% cement content) series concrete

The charts show that a good economic benefit can be obtained by replacing 30% steel slag aggregates with a better strength characteristic. We don't have to compromise the strengths for up to 30% replacement class and can save approximately 20-25% on materials cost. Currently, the PWD schedule of estimates is applied for this analysis. The currency is then converted to USD.

Recycling slag benefits the economy and the environment since it reduces the amount of pollution caused by the accumulation of nonbiodegradable slag. Around 20% cost of materials can be saved without compromising strengths for up to 30% of the coarse aggregate replacement. As governments around the world revaluate their environmental policies, new possibilities emerge for expanding the use of industrial byproducts. Reducing waste and conserving natural resources are two environmental goals that may be accomplished simultaneously through using steel slags in RCC.

Chapter 5: CONCLUSION

5.1 GENERAL

The study attempted to determine how the characteristics of roller-compacted concrete (RCC) affects by the partial replacement of natural aggregate with induction furnace steel slag. The following specific conclusions are made from the experimental study.

5.2 CONCLUSION

- **Characteristics of steel slag aggregate:** The three most prevalent crystalline phases of steel slag are quartz, periclase, and carlinite. A substantial part of steel slag aggregate is composed of silicon dioxide, also known as silica, found in nature as quartz, and calcium oxide and ferric oxide as inorganic compounds.
- **Strength Characteristics:**
    - **Compressive Strength of RCC:** In terms of compressive strength, steel slag aggregate can reduce the amount of natural aggregate in RCC by approximately 30%.
    - **Tensile Strength of RCC:** Roller-Compressed Concrete has a very low criterion for tensile strength. There were minimal changes in the results with replaced steel slag aggregate.
    - **Flexural Strength of RCC:** A significant increase in flexural strength was noted with replacing 30% steel slag.
- **Optimal Composition:**

  We can suggest an optiman and economical composition of 30% replacement of steel slag which can save the cost of concrete around

20% in comparision to use of natural aggregate. It is also conceivable to replace a greater proportion, which could facilitate the usage of recycled aggregates. However, this will necessitate compromising the strength achieved with standard natural aggregate.

5.3 LIMITATIONS OF THE STUDY

The study also has some limitations based on the experimental workflow. Some of those are given below.

- There is no specific guideline for preparing the flexure specimens. Therefore, the samples were designed based on a process similar to compressive strength sample preparation for ordinary concrete.
- The coarse aggregate class and steel slag characteristics are not the same in every case. Therefore, the properties of the aggregate can influence the experimental results. This might need to verify with a further experimental study.

5.4 RECOMMENDATION FOR FURTHER STUDY

There are options for further study to get more valuable outcomes. For example:

- Study on the durability of Roller Compacted Concrete sample prepared with steel slag aggregate.
- Study the use of steel slag powder as a fine material for preparing Roller Compacted Concrete.

Bibliography

ACI Committee 207. (2011). *Roller-compacted mass concrete: Vol. 207.5R*.

Standard Practice for Selecting Proportions for Normal, Heavyweight, and Mass Concrete (ACI 211.1-91), (2002).

ACI Committee 325. (2001). *Report on Roller-Compacted Concrete Pavements*.

ACI Committee 327. (2015). *Guide to Roller-Compacted Concrete Pavements*.

Adaska, W. (2006). Roller-Compacted Concrete (RCC), PCA Research & Development Information Serial No. 2975. *Skokie, IL: Portland Cement Association*.

American Concrete Pavement Association. (2019). *The National RCC Explorer*. http://rcc.acpa.org/webapps/rccexplorer/index.html

ASTM. (2003). Standard Terminology Relating to Concrete and Concrete Aggregates. *ASTM International, West Conshohocken, PA*, 1–4. https://doi.org/10.1520/C0125-15B.2

ASTM. (2008). Standard Practice for Making Roller-Compacted Concrete in Cylinder Molds Using a Vibrating Table, C1176/C1176M-08. *ASTM International*, *February*, 1–4. https://doi.org/10.1520/C1176

ASTM. (2012a). ASTM, D1557-12, Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort, ASTM International, West Conshohocken, PA, 2012. *ASTM Standard Guide*, *91*(September 2000).

ASTM. (2012b). Standard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete. *ASTM Lnternational*, *i*(c).

ASTM. (2014a). ASTM C136 / C136M - 14 Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. *ASTM International, West Conshohocken*.

ASTM. (2014b). Determining Consistency and Density of Roller-Compacted Concrete Using a Vibrating Table. *Annual Book of ASTM Standards*, *91*(8), 1–5. https://doi.org/10.1520/C1170

ASTM. (2018). ASTM C33/C33M − 18: Standard Specification for Concrete Aggregates. In *ASTM*.

Cannon, R. W. (1972). Concrete Dam Construction Using Earth Compaction Methods, Economical Construction of Concrete Dams. *ASCE*. https://ci.nii.ac.jp/naid/10002952630/

Cervera, M., Oliver, J., & Prato, T. (2000). Simulation of construction of RCC dams. II: Stress and damage. *Journal of Structural Engineering New York, N.Y.* https://doi.org/10.1061/(ASCE)0733-9445(2000)126:9(1062)

Chhorn, C., Hong, S. J., & Lee, S. W. (2018). Relationship between compressive and tensile strengths of roller-compacted concrete. *Journal of Traffic and Transportation Engineering (English Edition)*, *5*(3), 215–223. https://doi.org/10.1016/j.jtte.2017.09.002

Chhorn, C., & Lee, S. W. (2017). Consistency control of roller-compacted concrete for pavement.

KSCE Journal of Civil Engineering, *21*(5), 1757–1763. https://doi.org/10.1007/s12205-016-0820-y

Das, B., Prakash, S., Reddy, P. S. R., & Misra, V. N. (2007). An overview of utilization of slag and sludge from steel industries. *Resources, Conservation and Recycling*, *50*(1), 40–57. https://doi.org/10.1016/j.resconrec.2006.05.008

Debbarma, S., Singh, S., & R.N, G. D. R. (2019). Laboratory Investigation on the Fresh, Mechanical, and Durability Properties of Roller Compacted Concrete Pavement Containing Reclaimed Asphalt Pavement Aggregates. *Transportation Research Record*. https://doi.org/10.1177/0361198119849585

Delatte, N., Amer, N., & Storey, C. (2003). *Improved Management of RCC Pavement Technology*. *January*, 46.

Delatte, N., Amer, N., & Storey, C. (2005). Effect of density on strength and freeze-thaw durability of roller compacted concrete. *Proceedings - 8th International Conference on Concrete Pavements: Innovations for Concrete Pavement: Technology Transfer for the Next Generation*, *1*(2940), 268–282.

FHWA. (2016). *Roller-Compacted Concrete Pavement* (Issue June). https://www.fhwa.dot.gov/pavement/concrete/pubs/hif16003.pdf

Gao, P. wei, Wu, S. xing, Lin, P. hua, Wu, Z. ru, & Tang, M. shu. (2006). The characteristics of air void and frost resistance of RCC with fly ash and expansive agent. *Construction and Building Materials*, *20*(8). https://doi.org/10.1016/j.conbuildmat.2005.01.039

Gaspar, A. P. P. T. (2014). *Contribution to control uncertainties in numerical modelling of dam performances. An application to an RCC dam. September*, 230.

Glavind, M., & Jepsen, M. T. (2002). Evaluation of Green Concrete Types. *Symposium A Quarterly Journal In Modern Foreign Literatures*, *June*, 4–6.

Harrington, D., Abdo, F., Adaska, W., & Hazaree, C. (2010). Guide for Roller-Compacted Concrete Pavements. *Institute for Transportation, Iowa State Univerisity*, *August*, 104. http://trid.trb.org/view.aspx?id=1082276

Jones, M. (2017). *Roller Compacted Concrete - Background to the Development of Highways England ' s Design Guidance and Specification*. *April*.

Kang, L., Du, H. L., Zhang, H., & Ma, W. L. (2018). Systematic research on the application of steel slag resources under the background of big data. *Complexity*, *2018*. https://doi.org/10.1155/2018/6703908

Khayat, K., & Libre, N. (2014). Roller Compacted Concrete : Field Evaluation and Mixture Optimization. *A National University Transportation Center at Missouri University of Science and Technology*, *August*(NUTC R363), 118. https://doi.org/10.13140/2.1.1647.2962

Kokubu, K., Cabrera, J. G., & Ueno, A. (1996). Compaction properties of roller compacted concrete. *Cement and Concrete Composites*, *18*(2), 109–117. https://doi.org/10.1016/0958-9465(95)00007-0

Kosmatka, S. H., & Wilson, M. L. (2011). *Design and Control of Concrete Mixtures – The Guide to Applications, Methods and Materials.* (15th ed.).

Logie, C. V., & Oliverson, J. E. (1987). BURLINGTON NORTHERN RAILROAD INTERMODAL

HUB FACILITY. *Concrete International*.

Malkawi, A. I. H., Mutasher, S. A., & Qiu, T. J. (2003). Thermal-Structural Modeling and Temperature Control of Roller Compacted Concrete Gravity Dam. *Journal of Performance of Constructed Facilities*, *17*(4). https://doi.org/10.1061/(asce)0887-3828(2003)17:4(177)

Manso, J. M., Polanco, J. A., Losañez, M., & González, J. J. (2006). Durability of concrete made with EAF slag as aggregate. *Cement and Concrete Composites*, *28*(6). https://doi.org/10.1016/j.cemconcomp.2006.02.008

Marchand, J., Gagne, R., Ouellet, E., & Lepage, S. (1997). Mixture proportioning of roller compacted concrete - A review. *American Concrete Institute, ACI Special Publication*, *SP-171*.

Mardani-Aghabaglou, A., & Ramyar, K. (2013). Mechanical properties of high-volume fly ash roller compacted concrete designed by maximum density method. *Construction and Building Materials*, *38*. https://doi.org/10.1016/j.conbuildmat.2012.07.109

Maslehuddin, M., Sharif, A. M., Shameem, M., Ibrahim, M., & Barry, M. S. (2003). Comparison of properties of steel slag and crushed limestone aggregate concretes. *Construction and Building Materials*, *17*(2). https://doi.org/10.1016/S0950-0618(02)00095-8

Mehta, P. K., & Monteiro, P. J. M. (2006). *Concrete Microstructure, Properties, and Materials* (Third Edit). McGraw-Hill. https://doi.org/10.1036/0071462899

Meyer, C. (2009). The greening of the concrete industry. *Cement and Concrete Composites*, *31*(8). https://doi.org/10.1016/j.cemconcomp.2008.12.010

Mohammed, T. U., Rahman, M. N., Mahmood, A. H., Hasan, T., & Apurbo, S. M. (2016). Utilization of steel slag in concrete as coarse aggregate. *Sustainable Construction Materials and Technologies*, *2016-Augus*(February), 0–7.

Muhmood, L., Vitta, S., & Venkateswaran, D. (2009). Cementitious and pozzolanic behavior of electric arc furnace steel slags. *Cement and Concrete Research*, *39*(2). https://doi.org/10.1016/j.cemconres.2008.11.002

Nickelson, B. (2012). *Georgia's Port of Savannah Chooses Roller-Compacted Concrete For Its Ocean Terminal Expansion*. http://secement.org/wp-content/uploads/2015/12/PCA-SE-SPOTLIGHT_RCC_GA_1501_1.pdf

NSSGA. (1991). *Aggregate Handbook from National Stone Sand & Gravel Association*.

Olofinnade, O., Morawo, A., Okedairo, O., & Kim, B. (2021). Solid waste management in developing countries: Reusing of steel slag aggregate in eco-friendly interlocking concrete paving blocks production. *Case Studies in Construction Materials*, *14*. https://doi.org/10.1016/j.cscm.2021.e00532

Omran, A., Harbec, D., Tagnit-Hamou, A., & Gagne, R. (2017). Production of roller-compacted concrete using glass powder: Field study. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2016.12.099

Pellegrino, C., & Gaddo, V. (2009). Mechanical and durability characteristics of concrete containing EAF slag as aggregate. *Cement and Concrete Composites*, *31*(9). https://doi.org/10.1016/j.cemconcomp.2009.05.006

Pittman, D. W. (1994). *Development of design procedure for roller compacted concrete (RCC) pavement*. https://elibrary.ru/item.asp?id=5722164

Pittman, D. W., & Anderton, G. L. (2009). The Use of Roller-Compacted Concrete (RCC) Pavements in the United States. *Sixth International Conference on Maintenance and Rehabilitation of Pavements and Technological Control (MAIREPAV6)*.

Portland Cement Association. (2006). *Production of Roller-Compacted Concrete* (Vol. 4, Issue 4). https://www.cement.org/docs/default-source/cement-concrete-applications/is332.pdf

Portland Cement Association. (2018). *Columbus Embraces Roller-Compacted Concrete Pavement*. https://www.cement.org/cement-concrete-applications/paving/roller-compacted-concrete-(rcc)/roller-compacted-concrete-(rcc)-case-histories/columbus-ohio

Qasrawi, H. (2014). The use of steel slag aggregate to enhance the mechanical properties of recycled aggregate concrete and retain the environment. *Construction and Building Materials*, *54*. https://doi.org/10.1016/j.conbuildmat.2013.12.063

Qasrawi, H., Shalabi, F., & Asi, I. (2009). Use of low CaO unprocessed steel slag in concrete as fine aggregate. *Construction and Building Materials*, *23*(2). https://doi.org/10.1016/j.conbuildmat.2008.06.003

Rao, S., Darter, M., Tompkins, D., Vancur, M., Khazanovich, L., Signore, J., Coleri, E., Wu, R., Harvey, J., & Vandenbossche, J. (2013). *Composite Pavement Systems: HMA/PCC composite pavements, Volume 1*. Transportation Research Board. https://books.google.com.bd/books?id=o1zn2oqvQmEC

Schrader, E. K. (1982a). WORLD'S FIRST ALL-ROLLCRETE DAM. *Civil Engineering New York, N.Y.*, *52*(4). https://doi.org/10.1016/0148-9062(82)91048-8

Schrader, E. K. (2018). Appropriate laboratory compaction methods for different types of Roller Compacted Concrete (RCC). In *Roller Compacted Concrete Dams* (pp. 1037–1044). Routledge.

Schrader, E. K. (1982b). FIRST CONCRETE GRAVITY DAM DESIGNED AND BUILT FOR ROLLER COMPACTED CONSTRUCTION METHODS. *Concrete International*, *4*(10).

Tayabji, S. D., & Okamoto, P. A. (1987). Engineering Properties of Roller-Compacted Concrete. *Transportation Research Record*, *1136*, 33–45. http://onlinepubs.trb.org/Onlinepubs/trr/1987/1136/1136-004.pdf

U.S Geological Survey. (2020). Mineral commodity summaries 2020: U.S. Geological Survey. In *U.S Geological Survey*.

Unique Cement Industries. (2019). *Quality Test Certificate of Cement*.

USACE. (1995). Roller Compacted Concrete Pavement Design and Construction. *Engineer Technical Letter 1110-3-475*.

Vahedifard, F., Nili, M., & Meehan, C. L. (2010). Assessing the effects of supplementary cementitious materials on the performance of low-cement roller compacted concrete pavement. *Construction and Building Materials*. https://doi.org/10.1016/j.conbuildmat.2010.06.003

World Steel Association. (2019). Steel Statistical Yearbook 2019 Concise version. *World Steel Association*.

Yaphary, Y. L., Lam, R. H. W., & Lau, D. (2017). Chemical Technologies for Modern Concrete Production. *Procedia Engineering*. https://doi.org/10.1016/j.proeng.2017.02.150

Yerramala, A., & Ganesh Babu, K. (2011). Transport properties of high volume fly ash roller compacted concrete. *Cement and Concrete Composites*, *33*(10). https://doi.org/10.1016/j.cemconcomp.2011.07.010