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Investigation of Performance of Copper Slag and Ore Tailings Novel Trial Self-compacting Concrete Mixtures

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ABSTRACT

A non-conventional concrete with the properties of flow-ability, filling-ability, and passing-ability without any need for mechanical compaction but flow under self-weight is known as self-compacting concrete. This study developed trial mixtures for self-compacting concrete (SCC) using locally available waste products. The copper slag and ore tailings from Bamangwato Concessions Limited Mine in Selebi-Phikwe, Botswana were used as source of fine aggregate, and fines substitute. Eight mix proportions were developed with the quantities of cement, granite, copper slag, ore tailings and water-cement ratio as variables. The mix proportions were developed in accordance with recommendations from American Concrete Institute (ACI 237R-07) and fresh SCC properties (flow ability, passing ability, filling-ability, and segregation) were performed to assess the performance of the mixes. It was observed that the range of slump flow values were between (500 – 750 mm), V-funnel values (1.46 – 7.46 s), passing-ability of (0.76 – 1.0). The hardened properties of SCC (strength and density) were between 8.1 and 33.3 MPa, and 2093 to 2406 kg/m^3) respectively. It could be concluded that SCC produced from mine wastes (copper slag and ore tailings) is found suitable for the use in unreinforced and normal concrete applications.

Keywords: Self-compacting concrete, filling-ability, flow-ability, passing-ability, slump flow, segregation and compressive strength.

INTRODUCTION

Concrete composed of conventional materials but flow without mechanical compaction rather than its own weight and without segregation is referred to self-compacting concrete (SCC) (Habibi and Ghomashi, 2018). However, understanding how to distinguish between a bonafide SCC and a conventional concrete holds significant importance. SCC has exceptional workability and boasts distinct advantages over conventional 'flowing' concrete. Studies such as Benaicha et al. (2019) has indicated that SCC has superior performance over conventional concrete which include rheological and mechanical properties. Unlike conventional concrete, SCC does not need any form of compaction. Other good quality of SCC as reported in Su et al. (2001) included high fluidity, better resistance to segregation and filling ability property. It effectively resists segregation, ensuring that its constituent materials remain uniformly distributed during transportation and placement. Furthermore, SCC keeps a stable composition throughout these processes. It should be noted that SCC comprises the same ingredients with traditional concrete which include fine and coarse aggregates, cement, mineral additive and admixture to positively alter the performance of concrete. However, the ultimate composition of the mixture and its properties in the fresh state exhibit notable differences. The performance of SCC has largely been described to be the function of raw materials and their inherent characteristics (Ashish and Verma, 2019). In material composition, high amount of mineral fillers which include supplementary cementitious materials and finely divided powder, and admixtures such as viscosity modifying admixture, water reducing admixture and high range water reducing admixture for SCC rheological and stability control are normally added in greater proportions. Additionally, SCC is known to employ reduced quantity, and lower maximum size of coarse aggregate. The alterations made to the composition of the mixture have an impact on the properties and performance of the concrete once it has reached its hardened condition. Furthermore, Ashish and Verma (2019) explained performance and application requirements have been identified as major determining factor when developing SCC mixes.

The production of good self-compacting qualities takes precedence over the later toughened features, which receive less initial attention as a result. The mass ratio of mixture composition in one cubic metre volume of concrete is a function of cement and fines content, quantity of paste, dosage of admixture, size and volume of fine and coarse aggregates all together. The mechanical, stability and other durability properties of SCC can then be tested and verified using similar approaches for conventional concrete. Because there are so many ways in

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which the constituent elements of SCC may be combined, there are a significant number of factors that need to be brought into harmony with one another (for example, mineral filler, superplasticizers, and viscosity agents). Usually, the good correlation between paste and concrete is ensured through the high content of mortar. The significant and early work done on SCC by Okamura and Ozawa (1994) led to the establishment of a rather straightforward step-by-step technique to develop mixture designs which restricts the type and sizes of SCC constituents. The American Concrete Institute adopted this technique and created a coherent table (ACI-237R-18) obtaining ranges of the amount of coarse aggregate, powder, mortar and paste required for an SCC. This is the standard selected to develop the mixture designs in this study. The developed SCC mixes were exposed to a series of tests to validate their efficiency and class according to the European Federation of Specialist Construction Chemicals and Concrete Systems, EFNARC.

The volume of conventional concrete is usually being occupied with third-fourth of aggregates sourced from an environment. Despite the harm caused to the environment, concrete is an essential product to the development of economies all over the world, and so it is vital to incorporate strategies that reduce the impact. In an attempt to save the environment and simultaneously improve the engineering performance of the concrete and cut construction cost, use of supplementary cementitious materials such as ground granulated blast furnace slag, fly ash, bottom ash, silica fume have been used Zhao et al. (2021). Sand has become the most popular natural resource being consumed worldwide seconding water. The indiscriminate extraction of this resource, however, is causing major physical and biological damage to our environment.

A growing trend of sand extraction is from marine, coastal and freshwater ecosystems of which some practices did not fully comply with environmental policies and regulations (Gallagher and Peduzzi, 2019). Crushed rock, sand and gravel are essential to the world at large for urbanization and infrastructure, water treatment and glass production to name a few. However, effective policy and good framework should be put in place to meet the ever increasing demand Gallagher and Peduzzi (2019). For this reason, sand consumption and production could benefit from green economy policies and planning.

Bamangwato Concessions Limited (BCL) operated a Nickel-Copper Mine in Selebi Phikwe from the year 1973 until her liquidation and produced both the viable products but also by products which are a challenge to dispose of according to Gabasiane et al. (2019). This caused several environmental problems such as gas emissions into the atmosphere and dump waste in the form of slag and copper tailings in the region. These wastes were sourced and physically and chemically characterized by Oyejobi and reported in Oyejobi et al. (2023).

In the manufacture and extraction of copper, there are different stages, however, copper slag and ore tailings are mine wastes obtained at different stages of flotation and concentration respectively Onuaguluchi and Eren (2012). As known, conventional concrete requires vibration for compaction to take place, and to allow the concrete to fill in the spaces between reinforcement and the corners of formwork. This process consumes a lot of energy which is an economic burden as well as a health hazard to tradesmen. Also, inadequate vibration results in honeycombs and gaps within reinforcement. With these problems, this study is intended to find an appropriate mix proportion for the design of an SCC using ore tailings and copper slag sourced from a local mine. The performance of the SCC is assessed through fresh, plastic and mechanical properties. This is achieved by carrying out a series of tests which include filling ability, passing ability, flow ability and segregation resistance of SCC. The hardened properties tested are compressive strength and density respectively. In this paper, copper slag was used in place of fine aggregate for the SCC and the addition of ore tailings as part replacement of both fine aggregates and fines are studied to determine its efficiency in assisting the flow ability and stability of the concrete.

MATERIALS AND METHODS

The materials used for the SCC mixtures are cement (CEM II 42.5N), crushed angular granite as coarse aggregates (maximum size 19 mm), copper slag as fine aggregates, water, and copper ore tailings. Particle distribution test was carried out to determine the gradation of the aggregates used as well as specific gravity tests as presented in Figure 1. The mix design in Table 1 is developed in accordance with ACI 237R-07 with a few modification.

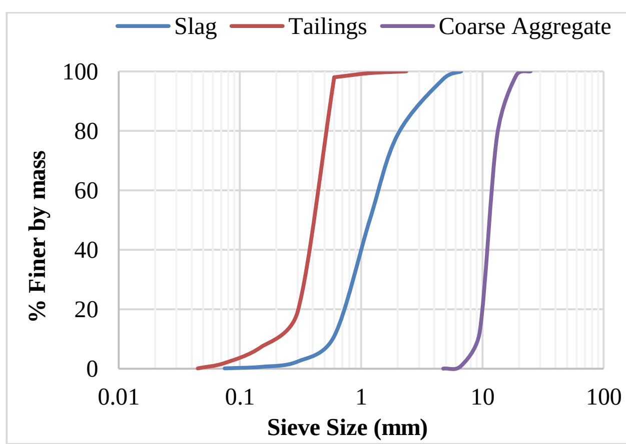

Figure 1. Particle size distributions of copper slag, tailings and coarse aggregate

Flow- ability property of SCC

The procedure for this test followed ASTM C143/C143 M (2015) modified with the intention of determining free flow of the concrete when there is no obstruction. The concrete was poured into the slump cone at once without either manual or mechanical vibration. This was followed with lifting of the cone within approximately 30 seconds of filling and the concrete subsided under its own weight. The typical flow is shown in Figure 2 and the mean of the values taken from different directions is reported as the slump flow value of the SCC.

Figure 2. Slump flow of developed SCC

Filling-ability property of SCC

The SCC ability to fill the container is measured using the fabricated V-shaped funnel shown in Figure 3 similar to the recommendations given in European guidelines EN12350-1 as per the dimensions. The equipment was set up on a firm ground with a receiving container below it. The V-shaped funnel in Figure 3 was dampened with no trace of water. With the bottom of the funnel kept shut, the funnel is filled with concrete without any agitation when filled and levelled. Subsequently, the funnel gate is opened and the interval between when the gate was opened and when we could see vertically through the funnel was taken as the flow time measured in seconds.

Figure 3. V-Funnel apparatus filled with fresh concrete.

Table 1. Mix Proportions for trial mixture

TM	Cement (kg)	Fine Aggregates (kg)	Coarse Aggregates (kg)	Water (kg)	Tailings (kg)	Slump flow (mm)	V- funnel (seconds)	Passing-ability	Segregation	28-day Strength (N/mm^2)
1	7.45	11.76	10.29	5.55	7.32	500	7.50	0.80	9	33.50
2	7.45	11.76	10.29	6.55	7.32	590	6.20	0.81	10	28.10
3	7.14	9.96	8.71	6.32	6.93	610	4.20	0.84	10	24.60
4	7.55	9.96	8.71	6.68	7.33	640	2.10	0.93	11	36.10
5	7.96	9.96	8.71	7.05	7.73	750	1.50	1.00	12	23.70
6	14.10	9.96	8.71	6.32	0	615	2.50	0.89	16	34.70
7	13.36	9.96	8.71	6.68	0.70	630	2.10	0.92	16	39.90
8	12.66	9.96	8.71	7.05	1.41	642	1.50	0.96	16	31.10

Passing- ability characteristic of SCC

The fabricated L-box shown in Figure 4 is conformable to the specification given in European standard and is used to measure passing ratio between the depth of concrete in the L-box (H2) and the concrete depth behind the gate (H1). Fresh concrete sampled in line with EN 12350- 1 was poured into the L box vertical compartment and allowed it to stand for one minute. This is followed by the gentle opening of the gate for concrete to pass between the two smooth bars of twelve millimeters diameter with gap interval of 59 mm. At the end of the movement, vertical distances between the top of concrete and top of the horizontal portion of the L box were measured and the mean height of the concrete was calculated. The ratio of H2/H1 gives the passing ability result of the L-box test.

Sieve segregation resistance property of SCC

A PVC cylinder was divided into three equal parts which were stacked together. Sampled concrete was poured into the stack of cylinders, ensuring they do not shift and allowed to settle for approximately 15 minutes. Once the time elapsed the cylinders were separated and placed on separate 4.75 mm sieves. After a waiting period of 120 seconds, the weight of the passed material is measured. This is followed with the calculation of segregation ratio which was taken as the fraction of the material that passed the sieve. The resistance of SCC to segregation was inspected visually and measured with sieve test.

Figure 4 - L- box apparatus with SCC

Compressive strength of SCC

ASTM C39/C39 M (2021) standard was used for the determination of compressive strength of SCC. After the cast, the cubes are allowed to undergo a day rest and later transferred to the water tank for water curing until the testing date, which was carried out on 7, 14, and 28 days.

RESULTS AND DISCUSSIONS

Slump flow values of SCC

The spread of SCC fresh concrete is measured from different directions with the values of average diameter reported in Table 1. All the mixes apart from TM1 met the specification for slump flow class range of (550 – 650 mm) according to European guidelines. TM 5 falls into slump flow 2 (660 – 750 mm). For mixes 1 and 2 in Figure 5, the slight increase in the slump flow was because of additional water, Table 1, however, slight reduction in cement content, copper slag and coarse aggregate with light increase in water resulted in increase in slump flow with optimal slump value of 750 mm. With drastic reduction in tailings and increase in cement content (mixes 6 – 8) and at constant fine and coarse aggregates respectively, there was also increase in slump flow values. Mix numbers 2, 3, 4 and 5 yielded good slump values and this could be attributed to a well-balanced mix proportions.

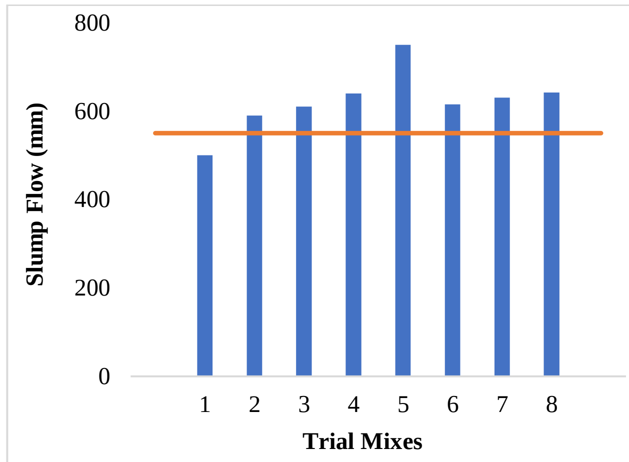

Figure 5. Slump Flows values for mixes

Filling-ability result of SCC

TM1 to TM 8 conformed to criteria of less than 10 seconds stipulated for funnel class VF 1, Table 1 and Figure 6 respectively. It was observed that flow time of concrete at constant fine and coarse aggregates was dependent on both tailings and cement. Also, it could be deduced that an increase in slump flow values is accomplished by reduction in the time taken, with the least time being 1.5 seconds for slump flow value of 750 mm.

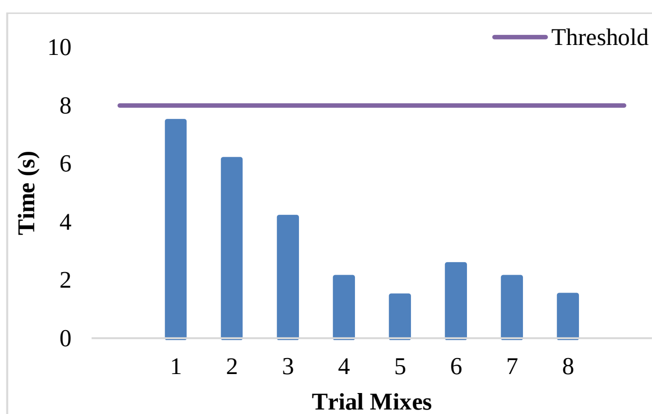

Figure 6. V-Funnel results for SCC mixes

Passing-ability values of SCC

All the mixes met the specification for the passing ability requirement for PA1 class with 2 reinforcement bars according to EN 206-1: 2013, the highest value of 1 is recorded for TM5, Table 1 and Figure 7. Previously, TM5 had been reported to have 750 mm slump flow and 1.5 seconds for flow time. The amount of powder (tailings) in the mix and good spherical shape, and well graded copper slag play significant role in this.

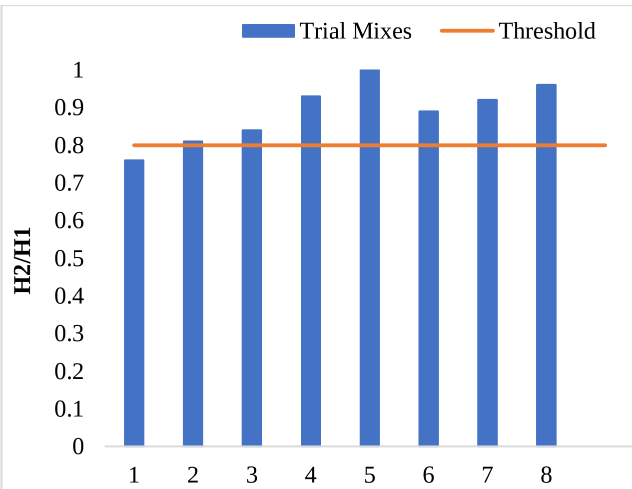

Figure 7. L-Box result for SCC

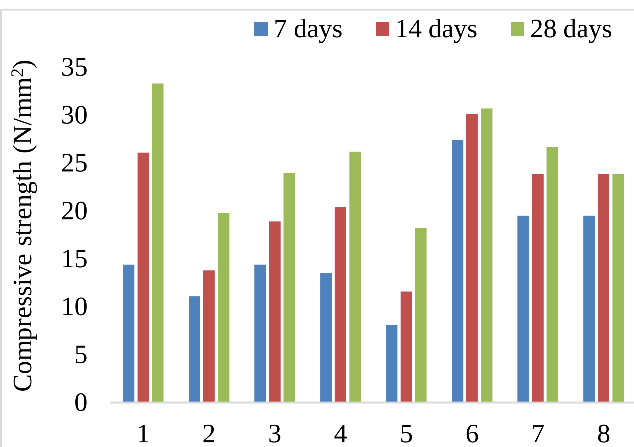

Figure 8. Compressive strength of SCC

Sieve segregation resistance values of SCC

From the physical observation, there was limited or no bleed water from the mix. When calculated in percentage, mixes 1 and 2 had the least segregation value, Table 1, the highest segregation values of 12, 13 and 14 could be because of increase in cement content. In all, all the mixes have values that are below 20 according to European specifications.

Compressive strength of SCC

The trend of strength development is illustrated in Figure 8 across the curing age. The mixes with good SCC characteristics are marked with lower compressive strengths and this could be because of moderate high water-cement ratio in the mixes, tailings in the mixes only served as filler and not as binder.

CONCLUSIONS

This study has found that copper slag could be an excellent choice for making self-compacting concrete due to its rounded particles which aid in workability when fresh and its moderate strength when hardened. Ore tailings increase the flow ability however high quantity makes the concrete prone to segregation when fresh and weakens its strength when hardened. The mixes with slump flow values between 550 and 650 mm fall in SF1 and can find their use in lightly reinforced or unreinforced concrete structures, structures with small sections and casting that involves pump injections. For other mixes above this limit (> 660 and ≤ 750 mm), they can be used for normal applications. In addition, the filling ability results indicated that SCC has inherent property to flow and fill the available space without any need for special vibration. The minimum passing achieved by all mixes indicated that the developed mixes could pass through obstructions without any blocking. From the visual inspection shows that the developed mixes were cohesive and homogeneous with limited amount of segregation. Lastly, the compressive strength reveals that the developed mixes could be used for varying project applications such as lightly reinforced or unreinforced concrete structures.

DECLARATIONS

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Data availability

The datasets used and/or analysed during the current study available from the corresponding author on reasonable request.

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Authors' contribution

First Author performed the experiments, analysed the data obtained and wrote the manuscript. Second Author designed the experimental process and revised the manuscript. Both authors read and approved the final manuscript.

Competing interests

The authors declare no competing interests in this research and publication.

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