Ferrochrome Slag as a Partial Replacement of Fine Aggregate in Concrete

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Abstract

Ferrochrome slag (FCS) is investigated as a partial replacement for fine aggregate (sand) in concrete production. The study aims at reducing environmental pollution that arises from the dumping of the slag. Both physical and mechanical properties of the FCS were studied. For the concrete mix, fine aggregates were replaced with FCS aggregates in proportions of 25, 50, 75, and 100%, while 0% replacement was used as the control (reference) sample. Aggregate properties investigated are grading, fineness modulus, compacted bulk density uncompacted bulk density, relative density, and water absorption. The investigated properties of fresh and hardened concrete are slump, compressive strength, tensile splitting strength, and flexural strength. The physical characterization results of FCS obtained indicate that it complies with the national standard specifications for natural aggregates. The performance of the hardened concrete improved as the rate of FCS substitution increased. The optimum percentage replacement of FCS based on this study is 100% as it gives increments of 19.76%, 5.4% and 20.68% for compressive strength, split tensile strength and flexural strength respectively when compared with the control sample at 28 days curing period. FCS shows positive indication of inclusion in concrete.

Keywords: Aggregates, Ferrochrome slag, Natural sand, Properties.

1. INTRODUCTION

Social and economic advances have resulted in intense use of natural resources, such as fossil fuels and aggregates, resulting in a significant decline in non-renewable resources. According to Bribián et al. (2011), approximately 60% of the world's raw natural resources are consumed by the construction industry. Natural resources and landfills for disposing of industrial wastes are under tremendous strain worldwide, so it's imperative to explore alternative options for concrete constituents. One of the alternative options that has received attention in recent times is the incorporation of industrial wastes in concrete. Ferrochrome slag (FCS) is one of the industrial wastes that has been identified as one of the potential alternatives to natural aggregate, which could reduce the demand for natural raw materials. FCS results from the manufacture of high carbon ferrochrome alloys. The main component of this slag is silicon dioxide (SiO_2), magnesium oxide (MgO), and aluminium oxide (Al_2O_3). In addition, it contains chrome, ferrous/ferric oxides, and calcium oxide (CaO). Globally, 12-16 million tons of FCS are produced annually, while Oman produces approximately 355 000 tons of FCS each year from two ferrochrome industries (Islam, et al., 2021). The construction industry can be one of the end users of FCS and help to promote green building practices and to develop the construction industry in a sustainable manner. FCS was found to possess good engineering properties and thus its potential for use in concrete was considered. However, the source of the slag may have effect in its final effect on concrete. Hence, it is necessary to characterize a local slag that is intended to be used in concrete. This research worked towards the promotion and optimization of the beneficial reuse of local FCS as an aggregate in concrete. It is becoming increasingly important for the construction industry and regulatory bodies in South Africa to improve waste management techniques and reduce FCS waste deposits at landfills.

According to JMA (2013) the common disposal methods for ferrochrome slag are on landfill sites in the amount of 62 million tonnes of slag. Kambole, et al. (2021) evaluated the chemical and mineralogical properties of FCS using X-ray fluorescence and X-ray diffraction techniques, respectively. Their study showed that the toxic element present in ferrochromium slag is locked in the chromite ((Fe,Mg,Al)CrO4) mineralogical phase, which is considered stable. This implies that FeCr slag used under normal environmental conditions has negligible to no Chromium (Cr) release. Kambole, et al. (2021) also concluded that FCS aggregates is considered as non-hazardous solid waste as it contains no toxic elements based on South African COLTO specifications for aggregates in granular road bases. Their findings support the research by Emery (1982) and Khalifa (2018), which confirmed that FCS is an excellent alternative to the large amounts of natural aggregate used in rigid and flexible pavements, hot-mix asphalt as granular layers, capping and sub-base layers in road construction, benefiting both society and the environment. The slump loss when using FCS was notable in studies conducted by Islam, et al. (2021) and Sathwik, et al. (2016). It was concluded in their studies that FCS reduces the workability of concrete mixes with increase in replacement percentage. The slag particles absorbed more water than natural sand because of their rough surface texture and high-water absorption rate.

In terms of mechanical properties, a study on developing the normal strength concrete using FCS aggregate in place of coarse aggregates was conducted by Susheel, et al. (2016). Their research found a gradual increase in compressive strength and split tensile strength with increasing FCS aggregate replacement percentage up to 75%. However, at 100% replacement, the traits of increased strength decreased slightly. There is a need to ascertain the optimum replacement percentage of FCS for use in concrete. A substantial percentage of FCS has been found to have positive benefits when used as a partial substitute in concrete, and increasing FCS in concrete could have a significant impact on alleviating some of the problems affecting our environment. However, optimization of FCS quantities in concrete and holistic characterization of the physical properties of new FCS source are important for documentation and standardization. Hence, this study aims to optimize the use of South Africa FCS from a local Ferrochrome company in concrete production and to promote its reuse.

2. MATERIALS AND METHODS

2.1. Materials

Crusher sand of maximum size of 4.75 mm was used as fine aggregate, and 22.5mm stone conforming to SANS 1083 as coarse aggregate. All concrete mixes contained CEM II A-M (V-L) 42.5R as the main binder, supplied by AfriSam Cement, South Africa and no admixtures were used. The cement used had a relative density of 2.96 g/ml. It is common practice in South Africa to use these materials in construction. FCS was collected from a local Ferrochrome company in South Africa and was used as partial replacement of fine aggregate in proportions of 0, 25, 50, 75, and 100%. Potable water from the laboratory was used for the mixing.

2.2. Methods

FCS materials were examined in this research for their effect on fresh and hardened concrete properties. The study began by characterizing the crusher sand and FCS, followed by a concrete mix design for control concrete, using the Cement and Concrete Institute (C&CI) mix design method. The properties evaluated included grading, compacted bulk density, uncompacted bulk density, relative density, water absorption, compressive, splitting tensile and flexural strength.

2.2.1 Aggregate tests

2.2.1.1 Grading

A sieve analysis was conducted as described in SANS 3001-AG1 to determine the particle size distribution of both fine and coarse aggregates. The test samples were dried at 110°C in a well-ventilated oven and cooled to room temperature. For the purposes of calculating the fineness modulus, the dried material was successively sieved through sieves of the following apertures: 7.1 mm 5 mm, 2 mm, 1 mm, 0.6 mm, 0.3 mm, 0.15 mm, 0.075 mm and pan, in the order of the largest aperture sieve to the smallest aperture sieve. The following apertures were used to sieve coarse aggregates: 28 mm, 20 mm, 14 mm, 10 mm, 7.1mm and 5 mm. The Flakiness Index of the coarse aggregate was achieved by conducting a particle shape test according to SANS 5847:2008 and SANS 3001-AG4:2015. The shape of aggregate particles and variations can influence the concrete's strength and workability as well as water demand. The gradation analysis of the aggregates used, and the FCS were done and reported in section 3.

2.2.1.2 Density Tests

Using SANS 5845:2006 as a guide, the compacted and uncompacted bulk densities of crusher sand and blended fine aggregate were determined. For each aggregate sample, the uncompacted bulk density (UBD) and compacted bulk density (CBD) tests were repeated three times. UBD and CBD were calculated based on the average of the results. The bulk density of a material is affected by properties such as particle shape and grading. The relative densities of crusher sand blended fine aggregates and coarse aggregates were tested according to SANS 3001-AG20:2011. A higher relative density of an aggregate indicates a higher quality and greater strength.

2.2.1.3 Water Absorption

The water absorption of the aggregate's samples was calculated based on SANS 5843:2008. A high-water absorption rate will result in unworkable concrete, thereby increasing the water demand in the mix. The water absorption for the test sample was calculated as the loss in mass between the saturated surface-dry and the oven-dry conditions of the oven-dried mass of the test sample.

2.2.2 Concrete tests

2.2.2.1 Workability

The workability of each freshly mixed concrete was checked by measuring its slump in accordance with SANS 5862-1:2006. Concrete workability refers to its ability to be transported, placed, compacted, and finished without its individual materials separating (Kutegeza and Alexander, 2004).
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2.2.2.2 Compressive, Split and Flexural Strength tests

In the control mix, no FCS was added as this served as the reference sample. The South Africa Cement and concrete institute (C&CI) mix design method was used for the trial mix. Mix design for samples with FCS was calculated taking into consideration the densities of fine aggregate and FCS. Hence varied quantities of coarse aggregate were achieved. The concrete samples were cured in potable water that was maintained at a temperature of 22 to 25°C until testing ages. Compressive strength and split tensile strength tests were done according to SANS 5863:2006 and SANS 6253:2006 respectively using 100 mm x 100 mm cube mould. A total of 90 cubes were prepared for Compressive strength and split tensile strength tests and they were tested at 7, 14 and 28 curing days. The Flexural strength test was done according to SANS 5864:2006 using a 150 x 150 x 750 mm beam mould. A total of 30 beams were prepared for the flexural strength test and tested at 7 and 28 curing days. The average of three results were recorded for each test.

3. RESULTS AND DISCUSSION

3.1 Grading Analysis

Aggregate size distribution has a considerable effect on the properties of concrete, as smaller aggregates provide a larger surface area for bonding. Figure 1 shows the grading curves for the crusher sand, FCS and coarse aggregate used. The particle size of both crusher sand and FCS are fairly well distributed across the range. The grading analysis results show that crusher sand is the coarser of the two fine aggregates, with a fineness modulus (FM) of 3.19 and 2.56 for crusher sand and FCS respectively. As can be seen in Table 1, the crusher sand used in this study belongs to the coarse sand fineness, while FCS belongs to the medium sand fineness group. A high FM in a fine material reduces the water demand in the concrete, hence having direct effect on concrete strength.

3.2 Compacted Bulk and Uncompacted Bulk Density

The uncompacted and uncompacted bulk densities of the crusher sand and blended fine aggregate were calculated to the nearest 10 kg/m^3 and reported on Table 2. The results showed that both the compacted bulk and uncompacted bulk densities (CBD and UBD, respectively) increase as the FCS content increases. Crusher sand has the lowest CBD and UBD as its particles are loosely packed compared to that of FCS.

Table 1: Classification of sands based on fineness modulus (Alexander & Mindess, 2005)

Fineness Modulus	Sand Fineness
< 1.0	Very Fine
1.0 – 2.0	Fine
2.0 – 2.9	Medium
2.9 – 3.5	Coarse
> 3.5	Very Coarse

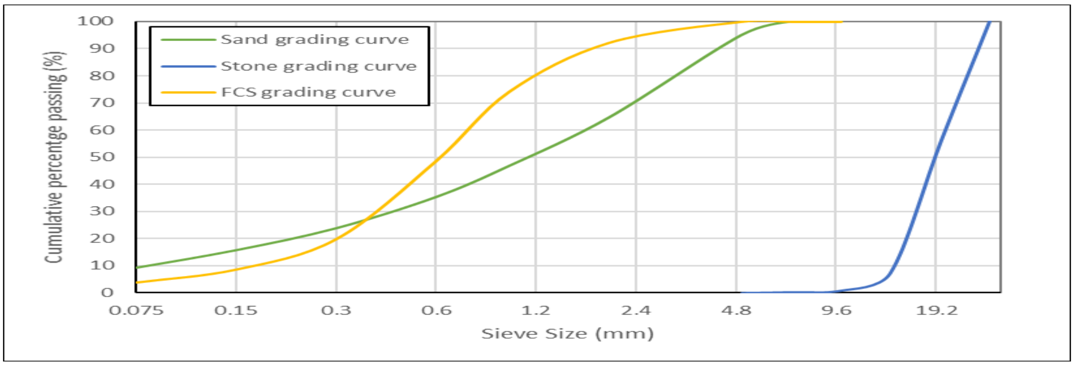


Figure 1: FCS gradation curve

Table 2: Compacted and uncompacted bulk densities

% Replacement	Bulk Density (kg/m^3)	
	Uncompacted	Compacted
0% FCS	1622	1910
25% FCS	1641	1947
50% FCS	1664	1948
75% FCS	1662	1959
100% FCS	1688	1969

3.3 Compacted Bulk and Uncompacted Bulk Density

The relative densities of the aggregates are shown in Table 3. The results indicate that increasing FCS content leads to an increase in relative density. In general, relative densities for aggregates range between 2.5 and 3.0 (Wickins, 2013). However, Owens (2013) argues that the relative density of natural sands and stones lies between 2.6 and 2.95. Nevertheless, aggregates that fall below these ranges are assumed to contain a large degree of lower density materials, resulting in their rejection before even being considered for testing (Immelman, 2013). If the relative density of an aggregate reaches beyond these limits, it means that pores of aggregates are filled with too much moisture. The minimum (2.62) and maximum (2.87) calculated relative densities are within acceptable limits.

Table 3: Relative densities of the aggregates

% Replacement	Specific gravity
25% FCS	2.73
50% FCS	2.78
75% FCS	2.82
100% FCS	2.87
Natural aggregates	**Specific gravity**
Crusher sand	2.68
Greywacke stone (22.5mm)	2.62

3.4 Water Absorption

Water absorption is a significant and useful quality of an aggregate, a high-water absorption rate affects the required water content in concrete mix proportions by reducing the water required for hydration of the cement. Table 4 indicates the measured water absorption for FCS, crusher sand and coarse aggregate. It can be observed that FCS has a water absorption rate 20.9% less than that of crusher sand. The natural coarse aggregate had the lowest water absorption value equating to 0.51%. The water absorption results obtained in this study subscribe to the requirements of SANS 5843, which specifies a maximum absorption value of 1%.

Table 4: Water absorption of aggregates

Aggregate	Water absorption (%)
Ferrochrome slag	0.53
Crusher sand	0.67
Coarse aggregate (22.5mm)	0.51

3.5 Concrete Mix Design

The mix design was calculated independently for each mix using the South Africa concrete and cement institute (C&CI) method. The mix proportions were selected on a basis of finding balance between requirement of workability, consistency, density, strength, and durability of the concrete. The specified target strength of the concrete was 40 MPa. The proportions obtained from the trial mix design are presented in Table 5. An approximate water/cement ratio of 0.58 for the target strength of 40 MPa was determined as specified by Owens, 2013.

Table 5: Trial mix proportions

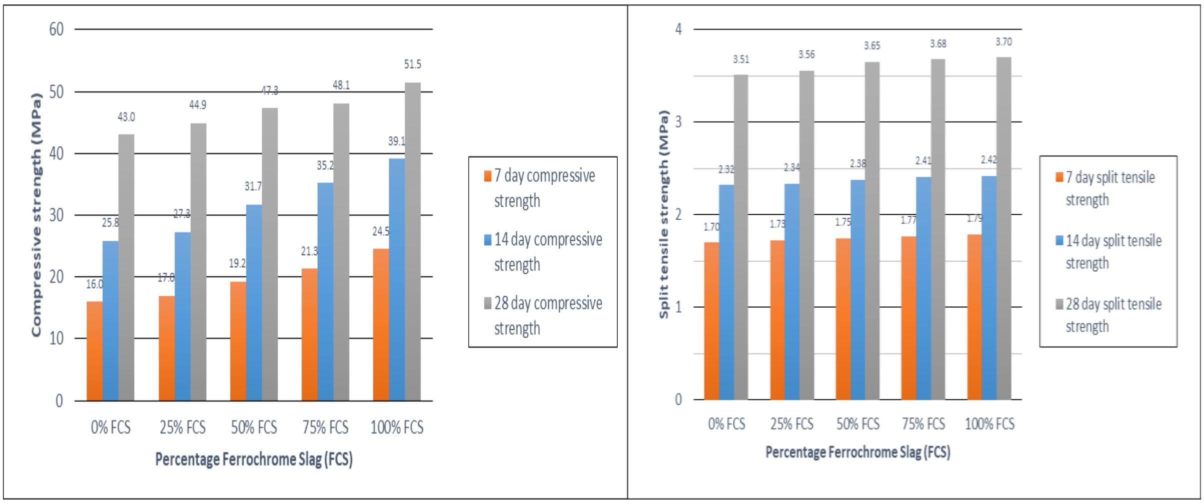
% Replacement	W/C ratio	Cement (kg/m^3)	Fine aggregate (kg/m^3)		Coarse aggregate (kg/m^3)	Water (l/m^3)	Slump (mm)
			Sand	FCS			
0 % FCS	0.58	344.8	656.8	0	1096	200	54
25 % FCS	0.58	344.8	492.6	164.2	1121	200	50
50 % FCS	0.58	344.8	328.4	328.4	1145	200	45
75 % FCS	0.58	344.8	164.2	492.6	1170	200	43
100 % FCS	0.58	344.8	0	656.8	1194	200	41

3.6 Workability

The slump results (Table 5) show that as FCS concentrations increase in the mixture, the workability decreases. The trend of the results could be attributed to the increased content of coarse aggregate in the blended mix. However, lower workability would have been expected for samples with higher content of crusher sand based on its higher water absorption rate compared to FCS. All mixes fell within the slump range of 40 mm - 60 mm which indicates low to medium workability concrete.

3.7 Compressive Strength

As shown in Figure 8 (a), an increasing strength trend can be observed for the compressive test results as the percentage replacement of FCS to sand increases. FCS effectively replaced crusher sand in concrete specimens, resulting in a higher strength development than control sample (0% FCS). The high strength of FCS blended samples may be attributed to the greater density of the blended aggregates. Samples with 100% FCS was observed to have 20 % higher strength at 28 days curing when compared with the control sample with 0 % FCS. All the samples met the characteristic strength of 40 MPa with the minimum 28-day compressive strength of 43 MPa recorded for the control sample.



(a) (b)

Figure 8: (a) Compressive strength of concrete samples at different ages (b) Splitting tensile strength test results at different ages.

3.8 Split Tensile Strength

Figure 8 (b) shows the splitting tensile strengths of all concrete mixes at 7, 14 and 28 days. By partially substituting FCS aggregate for crusher sand, the concrete's splitting tensile strength was slightly increased at 28 days of curing by 1.4%, 4%, 4.8% and 5.4% more than the control mix (0% FCS), at 25%, 50%, 75% and 100% replacement percentages, respectively. Similar trend observed for compressive strength was also observed for the split tensile strength, however, the increased in strength of blended fine aggregate concrete over the control sample are negligible.

3.9 Flexural Strength

The flexural strength was increased with increased FCS content. The concrete mix containing 100% FCS concrete has 20.7% strength increment at 28 days curing period in relation to the control sample as presented in Table 6.

Table 6: Flexural strength test results at different ages

% Replacement	Mean flexural strength (MPa)	
	7 days	**28 days**
0 % FCS	2.88	5.56
25 % FCS	3.14	5.89
50 % FCS	3.21	5.96
75 % FCS	3.29	6.46
100 % FCS	2.58	6.71

4. CONCLUSION

The local FCS studied showed an indication of positive use in concrete making. Blended fine aggregate concrete improved the overall performance of the hardened concrete as the percentage of FCS substitution increased. The investigated properties of FCS examined in this study complied with the specifications for natural aggregates. As a result, FCS used exhibited similar characteristics to natural aggregates. The FCS decreases concrete's workability as the proportion increases; hence, appropriate admixture can be considered for FCS concrete if improved workability is required. Blended concrete with FCS exhibited higher compressive, split tensile, and flexural strengths than control sample at all curing ages, making it a suitable aggregate replacement material. Optimum percentage as recorded in this study is 100% FCS replacement. In addition, further test on durability will be conducted as the second phase of this study.

5. REFERENCES

Alexander, M. & Mindess, S., 2005. Aggregates for concrete. Published by Taylor and Francis Group, London and New York. ISBN 0-415-25839-1.

Bribián, I. G., Capilla, A. V. & Usón, A. A., 2011. Life cycle assessment of building materials: Comparative analysis of energy and environmental impacts and evaluation of the eco-efficiency, s.l.: Building and Environment. Vol. 46 (5), pp 1133-1140.

Emery, J., 1982. Slag Utilization in Pavement Construction. Extending Aggregate Resources, pp. 95-118.

Immelman, D. W., 2013. The influence of percentage replacement on the aggregate and concrete properties from commercially produced coarse recycled concrete aggregate. Thesis (MScEng)--Stellenbosch University, Stellenbosch University. http://hdl.handle.net/10019.1/80388.

Islam, M. Z., Sohel, K. M., Al-Jabri, K. & Harthy, A. A., 2021. Properties of concrete with ferrochrome slag as a fine aggregate at elevated temperatures. Case Studies in Construction MateriJMA Consulting (Pty) Ltd, 2013. Beneficial Use of Ferrochrome Slag as Aggregate Material, Johannesburg: Ferro Alloy Producers Association.

Kambole, C., Paige-Green, P., Kupolati, W. K. & Ndambuki, J. M., 2021. Ferrochrome slag aggregate: physical-chemical characteristics and potential use in lightly cemented road bases. World Journal of Engineering, Vol. 20 No. 1, pp. 93-102. https://doi.org/10.1108/WJE-12-2020-0666.

Khalifa, S. A.-J., 2018. Research on the use of Ferro-Chrome slag in civil engineering applications MATEC Web Conference, 2nd International Congress on Materials & Structural Stability (CMSS-2017), Volume 149, https://doi.org/10.1051/matecconf/201814901017.

Kutegeza, B. & Alexander, Mark. (2004). The performance of concrete made with commercially produced recycled coarse and fine aggregates in the Western Cape. Proceedings of the International Conference on Sustainable Waste Management and Recycling: Construction Demolition Waste. 235-244.

Owens, G., 2013. Fundamentals of Concrete. 3 Edition. Publisher: Cement and Concrete Institute, Midrand, South Africa.

Paul, S. C., 2011. Mechanical behaviour and durability performance of concrete containing recycled concrete aggregate, Thesis (MScEng)--Stellenbosch University, Stellenbosch University. http://hdl.handle.net/10019.1/17962.

Sathwik, S. R., Sanjith, J. & Sudhakar, G. N., 2016. Development of High Strength Concrete Using Ferrochrome Slag Aggregate As Replacement to Coarse Aggregate. American Journal of Engineering Research (AJER), Vol. 5 (9), pp. 83-87.

SANS 3001-AG1, 2014. Civil engineering test methods Part AG1: Particle size analysis of aggregates by sieving, Pretoria, South Africa: South African Bureau of Standards.

SANS 5843, 2008. Water absorption of aggregates, Pretoria, South Africa: South African Bureau of Standards.

SANS 5845:2006. Bulk Densities and voids Content of Aggregates: South African Bureau of Standards.

SANS 5862-1, 2006. Concrete tests Part 1: Consistence of freshly mixed concrete - Slump test, Pretoria, South Africa: South African Bureau of Standards.

SANS 5863, 2006. Concrete tests - Compressive strength of hardened concrete, Pretoria, South Africa: South African Bureau of Standards.

SANS 6253, 2006. Concrete tests - Tensile splitting strength of concrete, Pretoria, South Africa: South African Bureau of Standards.

Susheel, S. M. et al., 2016. Development of Normal Strength Concrete using Ferrochrome Slag Aggregate as Replacement to Coarse Aggregate. International Journal of Innovative Science, Engineering & Technology, III(6), pp. 250-253.

Wickins, K. (2013). The use of construction and demolition waste in concrete in Cape Town. (Thesis). University of Cape Town, Faculty of Engineering & the Built Environment, Department of Civil Engineering. http://hdl.handle.net/11427/14047.