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Suitability of Basic Oxygen Furnace Slag as a Coarse Aggregate in Concrete Made with Supplementary Cementitious Materials

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Abstract. Basic Oxygen Furnace Slag (BOFS), a by-product of steelmaking, offers an environmentally friendly alternative to natural coarse aggregates (NCA) in concrete. In South Africa alone, over a million tons of BOFS is produced annually, however, the low utilisation rate of the by-product often leads to growing landfills of the material. The low utilisation rate is primarily due to the free lime content of BOFS, which causes volume instability of the BOFS due to the larger calcium hydroxide crystal which forms during the hydration process and thus limits the potential applications for use. This study explores whether the incorporation of supplementary cementitious materials (SCMs), namely ground granulated blast furnace slag (GGBS) and Metakaolin (MK), may improve the volume stability of concrete made with BOFS as an aggregate but reacting with the BOFS hydration products. Concrete mixes were prepared with 0%, 50%, and 100% volumetric replacement of NCA by BOFS. Furthermore, ordinary portland cement was partially replaced with 60% GGBS in some mixes and 15% MK in others. The compressive strength test was used to assess potential reactivity between BOFS and SCMs, while prism expansion tests evaluated the impact on volume stability and the concrete microstructure was assessed by microcrack analysis method. Results show that BOFS aggregates react with SCMs, due to the difference in the rate of compressive strength gain of the BOFS mixes, relative to those with NCA. Furthermore, including SCMs improved the overall volume stability of concrete made with BOFS, though microcracks were more prevalent. This suggests that while macro-scale stability improved, microstructural issues remain.

Introduction and Background

The world produced 1.8 million tonnes of steel in 2022, and experts expect this figure to grow further due to anticipated global economic growth [1]. South Africa produces between 80 to 100 kilograms of steel per capita, which is the same as India, the second largest steel producer in the world [2]. The steel production processes mainly uses two steel converters, namely, the electric arc furnace or the basic oxygen furnace (BOF) to produce over 3,500 different grades of steel [3]. The EAF route uses scrap steel as feedstock, whereas the BOF process uses a mixture of scrap steel and molten pig iron in the furnace. Research reports that 70% of global steel producers use the BOF, whereas in South Africa, about 60% of steel producers utilise the BOF route [4]. The BOF steel production route results in a solid BOF slag (BOFS) by-product, which accounts for 100 to 200 kg of slag production per ton of steel produced [2]. This translates to approximately 131 to 262 million tons of BOFS produced around the world, every year. Globally, utilisation rates of BOFS remain low, and waste slag landfill sites continue to exist and grow, as the steel production rate increases around the world [5]. Several current uses of BOFS include agriculture, as a soil pH neutraliser, in the cement production kiln to generate tricalcium aluminoferrite, and in the construction sector as backfill, sub-grade, and pavement material [5]. Low utilisation rates of

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BOFS result in both an economical and environmental challenge to the steel producer. The economic challenge of landfilling BOFS is the opportunity cost of not considering the by-product as a commercial product. Additionally, the environmental challenge lies in the large land space occupied by these landfills, which exacerbates the environmental footprint of steel plants due to the potential leaching of soluble elements into both surface and underground water resources [6, 7].

Past studies show that the construction sector could use steel slag as an aggregate. However, a mandatory natural aging process of 3 to 18 months limits its immediate use. The aging process helps to hydrate or carbonate the reactive uncombined CaO in the BOFS, which improves its volume stability [8]. Yet researchers such as Mahiex *et al.* [9] found that the BOFS stored in stockpiles during aging continues to remain reactive due to heterogeneous exposure to the environment throughout the stockpile. This unreliability further limits the use of BOFS. Despite these negative aspects, researchers have considered using the BOFS as an aggregate to compare it structural performance, relative to natural aggregates. The use of the by-product exhibits enhanced performance benefits when used as an aggregate in concrete where researchers such as Sharma *et al.* and Zago *et al*. [10, 11], have found that as the replacement percentages of natural aggregates with BOFS in concrete increase, the mechanical strength and abrasion resistance of the concrete improves. This positive aspect makes explorations of novel knowledge related to use of the by-product as an aggregate in concrete a significant research path.

The current study aims to enhance the understanding of using pozzolana and latent cement replacement in concrete made with BOFS. It investigates whether the expansion caused by the hydration of free CaO to form $Ca(OH)_2$ on the surface of the BOFS aggregate can be reduced through pozzolanic reactions. These reactions may consume the $Ca(OH)_2$ crystals as they form, producing calcium silicate hydrates, which could improve the mechanical performance of concrete. An understanding of such a mechanism, will unlock more applications of the BOFS, which is otherwise landfilled.

Material Characterisation;

Physical characterisation of the BOFS: Table 1 provides a comparative overview of the specific density, 24-hour water absorption, and Aggregate Crushing Value (ACV) of the aggregates evaluated. The specific densities were determined using a helium gas pycnometer, the water absorption values were determined using ASTM C127-15 and the ACV was determined using SANS 3001-AG10:2012 as a guideline. As shown in the table, the BOFS exhibits a slightly higher specific density relative to the natural aggregate (NA). This difference was considered during the concrete mix design phase, where volumetric replacements of NA with BOFS and it was also ensured that the particle size distribution (PSD) curve of the BOFS aggregates matched that of the 22 mm Andesite PSD, which conformed to the grading limits specified by BS 822:1992.

Table 1: Physical properties of the coarse aggregates

	22mm Andesite Stone	*BOFS*
Water Absorption (%)	0.38	1.45
Mean Specific Denisty (kg/m^3)	2893.1	3274.5
ACV (%)	5.64	11.17

Similarly, the ACV of BOFS is higher than that of NA, indicating that BOFS aggregates are more susceptible to crushing under compressive loads compared to NA, which suggests that NA possesses greater mechanical strength in this regard. The NA has a lower water absorption value (0.38%) relative to BOFS (1.45%). This difference could affect the effective w:b value of concrete

and have an impact on the mechanical performance of concrete [12]. Figure 1 illustrates that the shape of the NA and BOFS coarse aggregates is largely consistent



Figure 1: Visual comparison of the particle shape and roughness of the aggregates

Experimental Procedure

Concrete Mix design: Three binder systems were used, each with a unique blend of binders used. The PC replacement percentages of both MK and GGBS blends were strategically selected to have replacement percentages, which are both 1.5 times higher than the known replacement percentages for optimal strength development i.e. 10% PC replacement with MK and 40% PC replacement with GGBS. This was to ensure that sufficient unreacted SCM particles were present in the paste, thereby ensuring that the limiting reagent would be the BOFS hydration products. Therefore, the first binder blend, as a control, was 100% PC, the second binder blend was a 15% replacement of PC with MK, and the third was a 60% replacement of PC with GGBS. The high percentage replacements are selected to ensure that there are unreacted SCM particles in the concrete paste, which could react with the BOFS hydration products.

In addition to the various binder blends, two different coarse aggregates were used in the current study: NA and BOFS. For each binder blend, a concrete mix with 100% NA, and a 100% BOFS mix existed, with a unique nomenclature as per Table 2 below. The mixes are uniquely identified with the binder system used (PC = 100% PC, MK=15% PC replacement with MK, GGBS= 60% PC replacement with GGBS) and their coarse aggregate content/blend (NA = 100% NA, and BOFS -100 = 100% BOFS).

Table 2: Mix Designs used in the current study

MIXES	*Mix Proportions [kg/m^3]*							Total Density *[kg/m^3]*
	PC	MK	GGBS	WATER	FINE AGGREGATE	NATURAL COARSE AGGREGATE	BOFS	
NA / PC	388.9	-	-	175	950.5	1073.3	0	2587.7
NA / MK	330.6	58.3	-	175	950.5	1073.3	0	2587.7
NA / GGBS	155.6	-	233.3	175	950.5	1073.3	0	2587.7
BOFS - 100 / PC	388.9	-	-	175	950.5	0	1370.3	2884.7
BOFS - 100 / MK	330.6	58.3	-	175	950.5	0	1370.3	2884.7
BOFS - 100 / GGBS	155.6	-	233.3	175	950.5	0	1370.3	2884.7

Testing Regime: The current study used concrete compressive strength as an indicative testing regime to determine whether a reaction exists between the hydration products of BOFS and the SCM's used in the study. Testing was conducted at 3, 7 and 28-days of curing in a water (22 ± 2 ºC), where SANS 5863 was used as a guideline for this. To assess whether the potential reaction

affected the overall stability of the concrete, the concrete prism expansion test was conducted, as per the guidance of ASTM C157.

Results and Discussions

Compressive strength test: The results from the compressive strength tests are presented in Figure 2, 3 and 4. For the PC-binder mixes (Figure 2), the strength of the BOFS mix is higher than that of the NA mix at 3- and 7-days, where at 28-days the strength is only around 1% higher than the NA mix.

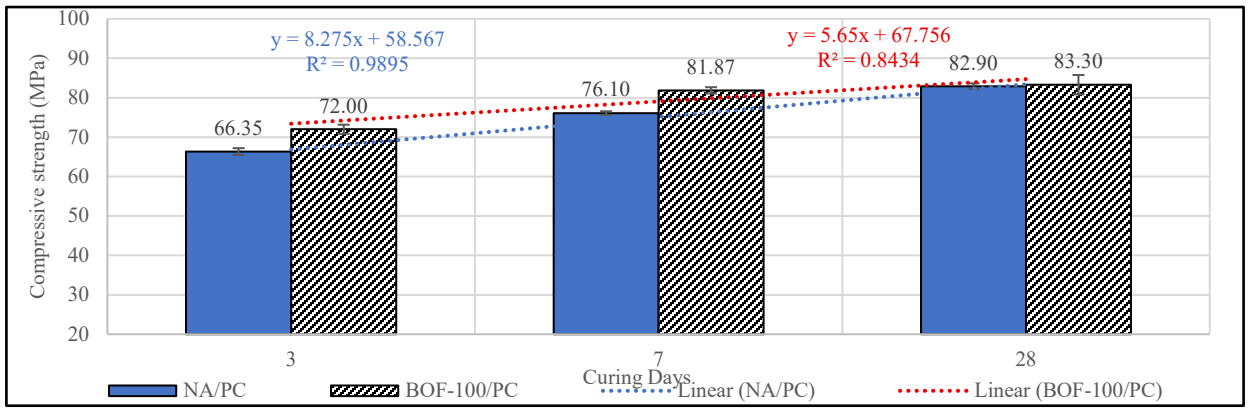


Figure 2: Average compressive strength results of PC-binder concrete

The compressive strength of the concrete made with BOFS and NA mixes in the GGBS-binder system is both 30 MPa at 3-days, but the strength of the BOFS mix is 7% higher, with a 95% confidence interval, than the NA mix at 7-days and 17% higher at 28-days. This is indicative of a faster strength gain of the BOFS mixes relative to the NA mixes, which is indicated by the steeper strength trendline of the BOFS mix, with a GGBS-binder system, shown in Figure 3.

As GGBS is a latent cement replacement, an alkaline environment is required to activate of the amorphous siliceous and aluminous content of the GGBS, resulting in the formation of the expected C-A-S-H formations. This could explain why the enhanced strength benefits of BOFS are not immediately prevalent (3-days), but as the relatively slow BOFS hydration occurs and produces additional CH in the system and thus a more alkaline environment, the GGBS is activated at a faster rate than that in the NA mixes.

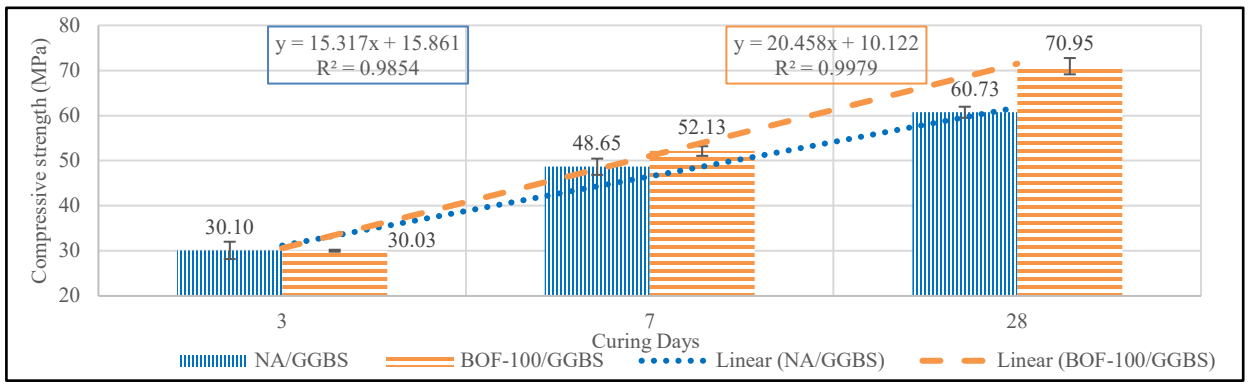


Figure 3: Average compressive strength results of GGBS-binder concrete

Similarly, in the MK-binder system (Figure 4) the early day strength (3- and 7-day) of the BOFS mix is lower than that of the NA mix, however from 28-days the strength of the BOFS mix is about 3% higher than the NA mix. MK is a pozzolan which reacts with the formed CH to produce additional C-S-H and C-A-S-H amorphous gels in the concrete. The difference is that once the

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BOFS hydrates, the additional CH introduced into the system would then need to react with the unreacted MK in the paste to form additional amorphous gels, which improve the strength of the concrete. This delayed reaction and subsequent late increase in strength is observed by the steeper gradient (14.667 > 9.8667) of the compressive strength trendline of the BOFS mix, relative to the NA mix.

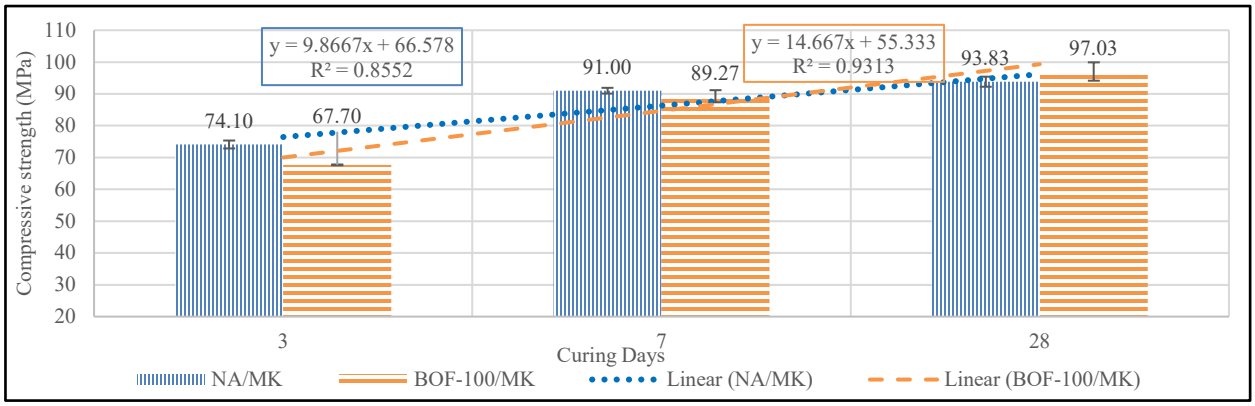


Figure 4: Average compressive strength results of MK-binder concrete

Prism expansion test: The results from the 28-day cured concrete prism expansion test are presented in Figure 5. The difference in the relative length expansion of the concrete prisms at 28-days between the mixes with NA and those with BOFS, is indicative of increased volume instability across all the respective binder systems used when BOFS is used. The difference between the relative length expansion of the BOFS and NA concrete mixes is 0.05 for the PC-binder mixes, 0.04 for the MK-binder mixes and 0.06 for the GGBS-binder mixes. This implies the following regarding the volume stability (VS) of the various binder systems:

$$VS_{\text{BOFS in MK-Binder system}} > VS_{\text{BOFS in PC-Binder system}} > VS_{\text{BOFS in GGBS-Binder system}}$$

The above indicates that the use of an MK-binder system improves the volume stability of concrete made with BOFS, relative to a conventional PC-binder system. This observation is indicative of a potential pozzolanic reaction, which occurs between the CH crystal as it forms during BOFS hydration and the unreacted MK particles in the paste, which limits further expansion.

Additionally, these results suggest that the use of a GGBS-binder system does not improve the volume stability of concrete made with BOFS. This is potentially due to the lower compressive strength of the GGBS-binder system concrete at 28 days, relative to the PC-binder system (shown in Figure 3). The lower compressive strength means that the hardened concrete paste around the BOFS aggregate can counteract less of the internal forces from BOFS expansion than the PC and MK-binder systems. This is believed to result in less restrictive actions by the hardened concrete paste, and thus easier movement of the surrounding concrete, leading to more concrete expansion relative to the PC-binder system.

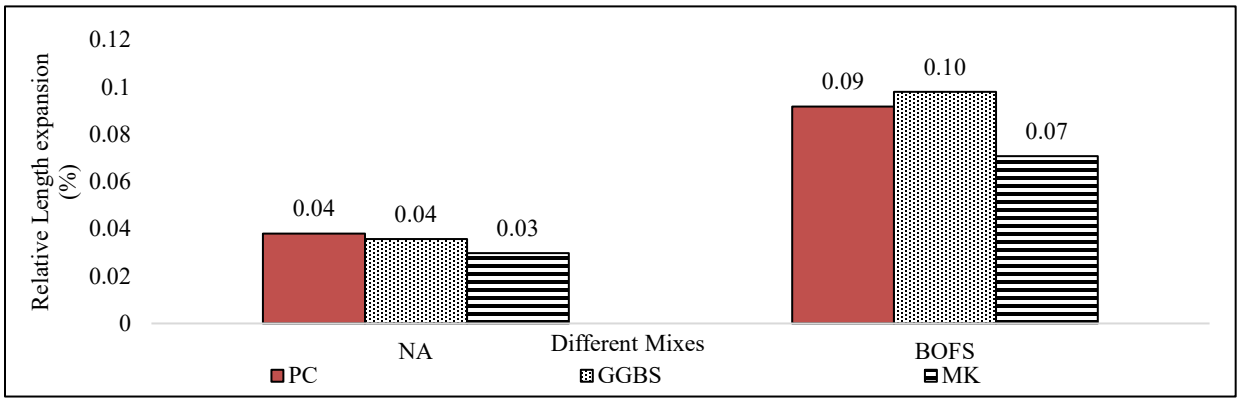


Figure 5: 28- day concrete prism length expansion results

Conclusions

This study demonstrates that BOFS can be effectively used as a coarse aggregate in concrete, particularly when combined with SCMs. The results confirm that pozzolanic and latent hydraulic reactions occur between BOFS hydration products and SCMs, enhancing compressive strength over time. While all mixes with BOFS showed higher volume expansion relative to natural aggregate mixes, the use of MK improved volume stability, indicating potential mitigation of expansion through pozzolanic reactions. These findings support the broader utilisation of BOFS in concrete applications, advancing sustainability in steel by-product management and concrete technology.

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