STRENGTH PROPERTIES OF CONCRETE WITH PARTIAL UTILIZATION OF SOUTH AFRICAN WASTE FOUNDRY SAND

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Abstract
The foundry industries incur a considerable cost in discarding Waste Foundry Sand (WFS) to landfill sites. In addition, the lifespan of landfill sites is decreasing due to increasing waste. Recycling the greater part of these wastes is the best environmental solution for resolving the waste disposal problem at landfill sites in South Africa. This paper presents a study on the properties of concrete with partial substitution of sand with WFS. The sand for the different concretes was substituted at either 30%, 70%, or 100% by masswith WFS at water/ cement ratios (w/c) of 0.4 and 0.6. The concrete properties with the various partial replacements of WFS, which were evaluated at the ages of 7 and 28days, were compared with the relevant reference (control) mixes (containing 0% WFS). This research indicated that generally 30% was the optimum replacement of sand with WFS. However, for all the properties considered upto 70% WFS can effectively replace sand in concrete without significantly reducing the concrete's strength properties (compared to the control samples). The incorporation of WFS in concrete can be used as an alternate building technology material in construction, hence contributing to sustainable development and circular economy.

Key Words–**Concrete technology, Comprehensive strength, Waste Foundry Sand, Recycled materials, Sustainable development, Circular economy.**

1. Introduction

Concrete is the most extensively utilized building material. More than 30 billion tons of concrete are used every year [1]. The overall consumed concrete capacity is intensifying speedily and annually, especially as a result of an exponential upsurge in population growth, urbanization, and economic development in developing countries [2]. To decrease the usage of sand in concrete, the Department of Environmental Affairs (DEA), under the South African Waste Management Act, encourages the usage of alternative concrete materials, such as reprocessed aggregates [3]. The partial substitution of normal sand with Waste Foundry Sand (WFS), where it remains technically feasible, will assist in protecting the environment, by saving in both the CO_2 emissions associated with the quarrying of normal aggregate and in the disposal costs of waste materials and consequently reduce pressure on landfills [4]. Other waste materials such as coal bottom ash, sewage sludge ash, recycled demolition materials, stone dust and as well as WFS, to mention but a few, might potentially be utilized as a substitution of fine aggregate in the manufacturing of concrete. These waste materials exhibit the potential to be utilized for area development, street infrastructure upgrading, and housing/living conditions improvement along various informal settlement masses in South Africa.

The American Foundrymen's Society (AFS) reported up to 33% of WFS might be utilized as a sand replacement in ready-mix concrete, concrete pavers, asphalt paving mixes, and precast concrete blocks [5]. In the Republic of South Africa, one of the principal industries in the engineering sector is the foundry industry and more than 80% of manufactured products contain castings. In accordance with the South African Institute of Foundrymen (SAIF), there are a total of 170 foundry manufacturing plants, which includeferrous (steel and iron), and non-foundry (Brass, Zinc, and aluminum). Geographically, 114 (66%) of these foundries are situated in the Province of Gauteng in South Africa [6]. Approximately 3000 tonnes of foundry sand are disposed of per annum by particular foundries from Gauteng, totaling 342,000 tonnes being disposed of per annum by all the foundries situated in Gauteng [6]. Many potential uses have been identified for the discarded foundry sand, such as concrete production, flowable fill, embankments, hot mix asphalt, and highway sub-bases [7].

2. Materials and Methods

2.1 Materials

2.1.1 Cement

In this research, 42.5R, CEM II / A-M(V-L) Portland Cement solely from the Afrisam Roodepoort plant, was used, all obtained from the same batch. The physical and chemical characterization satisfied the criteria of SANS 50197-1:2013 [20].

2.1.2 Fine Aggregate

Crusher sand from the Eikenhof quarry, complying with SANS 1083: 2008 [21], was utilized as fine aggregate. The physical properties of the sand are shown in Table 1.

Table 1
Physical characteristics of crusher sand

Characteristics	Experimental values
Fineness modulus	4.31
Bulk Density (Loose), kg/m3	1996
Specific Gravity	2.91

2.1.3 Coarse Aggregate

Crushed stone with a nominal size of 22 mm from the Afrisam Eikenhof quarry, complying with SANS 1083: 2008 [21], was used as coarse aggregate. Table 2 shows the physical properties and the coarse aggregates.

Table 2Physical properties of coarse aggregates

Properties	Unit	Observed values
Maximum size	(mm)	22
Specific Gravity	-	2.93
Bulk Density	(kg/m3)	1620

2.1.4 Water

Potable water without the content of alkalis, acids, salts and other detrimental materials was utilized for mixing and curing, as it conformed to the requirement of SANS 51008:2006 [22].

2.1.5 Waste Foundry Sand

Chemically bonded sand from the Forbes Bros. Founders Foundry in Gauteng was used in this study as shown in Figure 1. It was examined to determine its conventionality with relevant engineering standards when utilized to a certain degree as a substitute for the fine aggregate. Table 3 illustrates the physical characterization of the WFS, while the gradation curve of the chemically bonded sand is presented in Figure 2.

Table 3,Physical characteristics of chemically bonded WFS

Properties	Observed Values
Colour	Grey (Blackish)
Moisture Content (%)	8.3
Specific Gravity	2.6
Loose Bulk Density (kg/m^3)	1387
Fineness Modulus	1.4
Clay content	0,0
pH	9.3
Material Finer than 75µ (%)	3

Figure 1. Chemically bonded sand

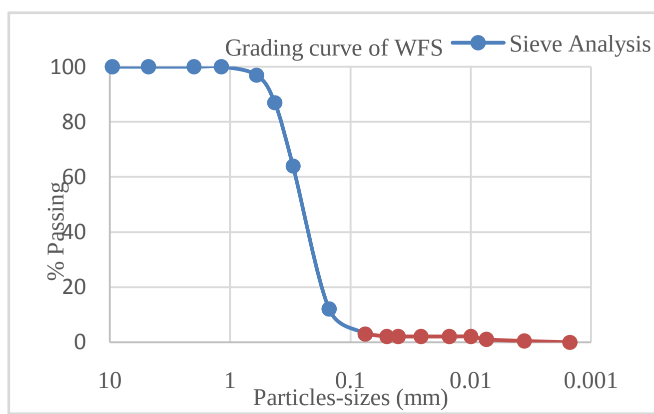


Figure 2. Particle size analysis of WFS

A detailed analysis and discussion of the physical and chemical properties of this WFS sand is included in [23] Iloh et al., (2019). The physical properties investigated were particle gradation, moisture content, loose bulk density, specific gravity, loss on ignition, clay content, and fineness modulus. The chemical properties included X-ray fluorescence (XRF), X-ray diffraction (XRD), scanning electron microscopy/energy-dispersive X-ray spectroscopy (SEM/EDS), and pH. This sand essentially met the standards pertaining to grading requirements. Furthermore, the chemical test results showed the composition of these sands to be comparable with results from other investigations and suitable for use as a natural sand replacement in concrete [23].

2.1.6 Admixtures

No superplasticizers were used in the concrete, for both the chemically bonded sand and the control mix.

2.2 Methods

2.2.1 Concrete Mix Design

Suitable materials for concrete were selected, and their proportion was determined to produce economical concrete that satisfied the requirements for concreting. Three different concrete mix proportions, with different percentages of WFS replacement, and the control concrete mix were designed. Two different control concrete mixes with w/c's of 0.40 and 0.60 were prepared in accordance with the Cement & Concrete Institute (C&CI) design method to achieve desired design strength [24].

2.2.2 Mix Proportions

Principally, two control mixes, a M50 (60 MPa) and a M30 (40 Mpa) were aimed for in terms of 28 day target mean strength. The fine aggregates were substituted with WFS by weight and in percentage variations of 30, 70, and 100 %, to evaluate the replacement effect of sand (by WFS) on the properties of concrete workability and strength. The outcomes of the mixes were compared to the relevant control mixes (containing 0% WFS), designated as M0 and M4. The concrete mixes with a w/c of 0.4 incorporating 30%, 70%, and 100% fine aggregate (sand) replacement with WFS were designated as M1, M2, and M3, respectively. The concrete mixes with a w/c of 0.6 incorporating 30%, 70%, and 100% sand replacement with WFS were designated as M5, M6 and M7, respectively. The mix design for Mixtures A and B at w/c's of 0.4 and 0.6, respectively, is presented in Tables 4 and 5.

Table 4.Mix Proportion A – M50 (60 Mpa)

Mixture No.	Unit	M0	M1	M2	M3
Cement	Kg/m3	525	525	525	525
Coarse aggregate (22mm)	Kg/m3	988	988	988	988
Crusher sand	Kg/m3	832	582	250	0
WFS %	%	0	30	70	100
WFS	Kg/m3	0	250	582	832
W/C ratios	-	0.40	0.40	0.40	0.40
Water	Kg/m3	210	210	210	210

Table 5, Mix Proportions B - M30 (40 MPa)

Mixture No.	Unit	M4	M5	M6	M7
Cement	Kg/m3	410	410	410	410
Coarse aggregate (22mm)	Kg/m3	988	988	988	988
Crusher sand	Kg/m3	832	582	250	0
WFS	%	0	30	70	100
WFS	Kg/m3	0	250	582	832
Water	Kg/m3	246	246	246	246
W/C ratios		0.60	0.60	0.60	0.60

2.2.3 Consistency Test

The consistency of the fresh concrete mixes was determined by means of the slump test, which was conducted in accordance with SANS 5861-1: 2006 [25].

2.2.4 Hardened Concrete Properties

Casting of all concrete samples was achieved through a mechanical mixing technique and then filled into 100 mm cubes, 750 x 150 x 150 mm prisms, and 150 mm diameter x 300 mm high cylinders, as presented in Figure 3 (a), (b) and (c). The specimens were demoulded and submerged into the curing basin according to the requirements of SANS 5861-3: 2006 [26] and SANS 5862-1: 2006 [27].

b

Figure 3: Concrete test samples

2.2.5 Strength Properties

2.2.5.1. Compressive Strength

The compressive strength test was performed according to SANS 5863: 2006 [28], using the (Denision T.I.B / M.C model number 28896 with a capacity of 200 tons) compression machine for testing. For the compressive strength determination, 12 (100 mm cube) specimens were cast for each mix and cured for 7 or 28-days. In the case of each mix, the averages of the 3 cubes tested at 7-days and 28-days were taken as the 7-day and 28-day strength, respectively. Figure 4 shows a sample failing during loading.

Figure 4. Failed compressive strength sample

2.2.5.2. Tensile Splitting Strength

The cylindrical specimens were cast in accordance with the requirements specified in SANS 5860: 2006 [29]. Three specimens were cast for each mix and tested in accordance with SANS 6253: 2006 [30]. Figure 5 (a and b) shows the loading of samples (to failure). The average of three results of each mix (at each testing age) was taken as the strength.

Figure 5. Testing of tensile strength samples (a) Sample of loaded specimen; (b) Sample of failed specimen

2.2.5.3 Flexural Strength

The concrete beams (150 mm x 150 mm x 750 mm) complied with SANS 5860: 2006 [29]. The flexural strength of the specimens was conducted in accordance with (SANS 5864: 2006) [31]. Figure 6 (a and b) shows the loading to failure of samples during testing. The average of three results of each mix (at each testing age) was taken as the strength.

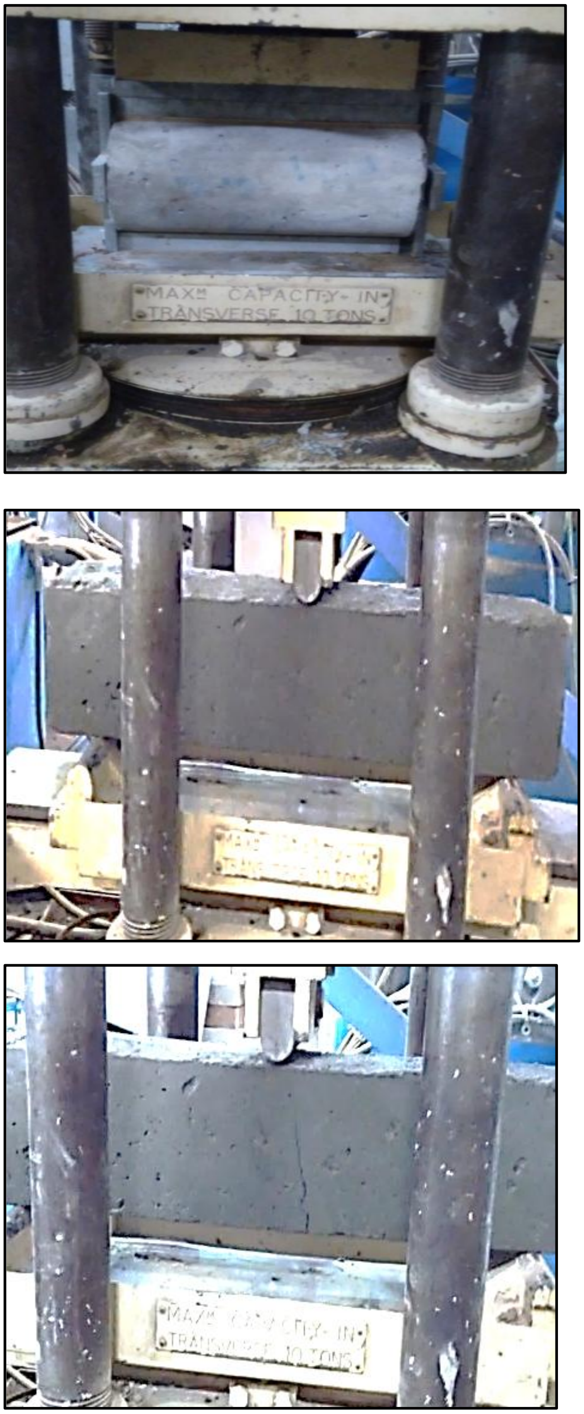


Figure 6.Testing of flexural strength samples
(a) Loaded sample; (b) Failed sample

Figure 7: Slump versus Percentage of WFS Replacement for both grades

3. Results and Discussion

The results of the concrete (consistence) workability and strength are discussed below.

3.1. Consistency Test

The results generally revealed that the replacement of sand with WFS to a certain degree (30%) increased the slump of the concrete, compared to the control samples. Further increases in the WFS content resulted in decreased slump values, as indicated in Figure 7. This trend was also evident in the research of [32].

As observed from Figure 7, excluding the control samples, for each percentage replacement, the slump of the concretes with the lower w/c (0.4) was lower than those with the higher w/c (0.6). This was expected, as the higher the water content the higher the slump, all other factors being equal [10], [33]. A 30% replacement of sand with WFS resulted in increased slump values of 100% and 136%, compared to the control mixes, in the case of the w/c of 0.4 and 0.6, respectively. A 70% sand replacement with WFS resulted in a decrease in slump values by 55% and 96%, compared to the 30% replacement slumps in the case of the w/c of 0.4 and 0.6, respectively. At 70% replacement the slump of the concrete with w/c of 0.6 was higher than the relevant control mix. In the case of both w/c's the slump of the 100% sand replacement (with WFS) mixes was the lowest of all the mixes (including the control mix). The decrease in the slump of the concrete with the increased replacement of WFS may be most likely because of the high water absorption due to the fine nature of WFS, resulting in an increased water demand [34], [35], [36], [37], [38], [39] and [40]. This trend was also in agreement with [41]. Interestingly, [42] found that 100% replacement increased the workability by 33%. On the basis of these slump results, although 30% replacement was the optimum replacement, up to 70% replacement of the sand with WFS would not significantly (negatively) affect the slump of the concrete (when compared to the control samples).

3.2 Strength Properties

3.2.1. Compressive Strength

Figure 8 shows the compressive strength results of Mix A (with a w/c of 0.4) and Figure 9 shows the results of Mix B (with a w/c of 0.6), at 7 and 28-days.

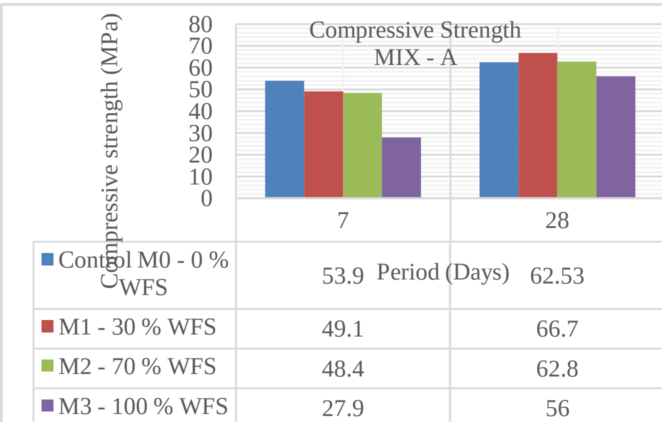


Figure 8. Compressive Strength of Mix A with 0.40 w/c

In the case of the mix with a w/c of 0.4 (Figure 8), in the case of the control mix and the various percentages of sand replacement, all the concretes achieved a higher strength at 28 days (compared to the 7 day strength). In the case of the 7 day strengths, the strengths for 30% and 70% replacements decreased slightly (on average by 10%) compared to the control sample. The strength of the 100% replacement decreased by 48%, compared to the control sample. This confirms that, in this case, an increase in the substitution percentage of normal sand by WFS, brought about the concrete strength decrease. Regarding the 28 day strengths, the highest increase in strength (7%) relative to the control sample, was achieved in the 30% replacement. This compares very favorably with [43] who reported a 7.6% increase at the same 30% replacement relative to the control sample. [44], [45], and [46] also found the highest strength was achieved at 30% replacement and then reduced with increased WFS substitution. The strength of the 70% replacement increased insignificantly compared to the control sample. Finally, the 100% replacement was only 10% lower than the control sample. Hence, at 28 days, although 30% replacement was the optimum replacement, up to 70% replacement of the sand with WFS would not negatively affect the strength (compared to the control samples). Depending on the project type, 100% replacement could also be considered.

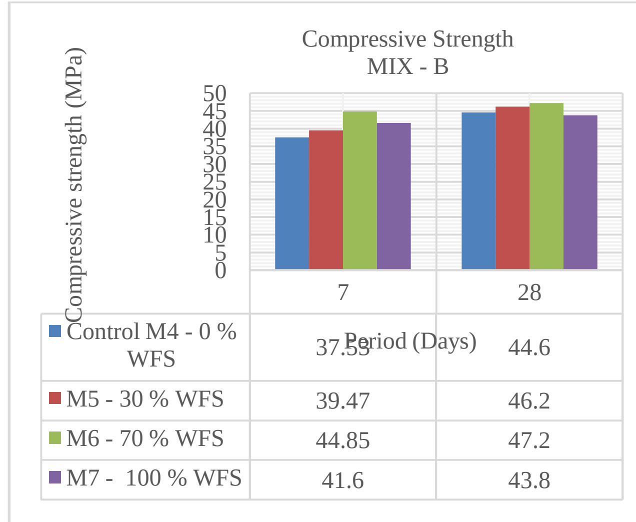


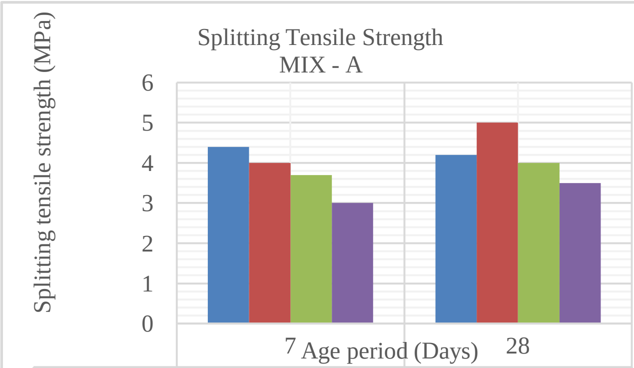
Figure 9. Compressive strength of Mix B with 0.6 w/c

In the case of the mix with a w/c of 0.6 (Figure 9), in the case of the control mix and the various percentages of sand replacement, all the concretes achieved a higher strength at 28 days (compared to the 7-day strength). This implies that the concrete at the age of 7-days had a lower rate of cement hydration when compared to 28-day of age of the concrete, which had a greater proportion of cement hydration and a lesser capillary permeability [47].

These results indicated that for both the 7-day and 28-day strengths, all the mixes with WFS achieved a higher strength than the control mix, except the 100% replacement for the 28 days (which was 2% lower than the control). Furthermore, at both ages, the 70% replacement yielded the highest strength relative to the control, being 19.5% and 5.8% higher than the control of the 7-day and 28-day strengths, respectively. According to [36], the increase in strength with an increase in WFS replacement may be due to a denser concrete due to the WFS fine grains acting as a void filler. In addition, at 28-days, up to 70% replacement would not negatively affect the strength. Depending on the project, 100% replacement could also be considered. The upsurge in the compressive strength showed that WFS might be utilized effectively in producing concrete as a partial substitution for fine aggregate [34].

3.2.2. Tensile Splitting Strength

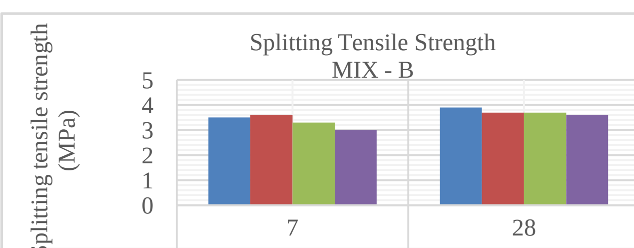
Figure 10 shows the Tensile Splitting strength results of Mix A (with a w/c of 0.4), and Figure 11 shows the results of Mix B (with a w/c of 0.6), at 7 and 28-days.



	7	28
0% WFS	4.4	4.2
30% WFS	4	5
70% WFS	3.7	4
100% WFS	3	3.5

Figure 10. Splitting Tensile strength of Mix A with 0.4 w/c

In the case of the mix with a w/c of 0.4 (Figure 10), the flexural strength results generally showed the same trends as the compressive strength results (as in Figure 8). In the case of the various percentages of sand replacement, all the concretes achieved a higher strength at 28 days (compared to the 7-day strength). However, the 28-day strength of the control concrete was slightly lower than the 7-day strength. Furthermore, when considering the 7-day strengths, the strengths for 30%, 70%, and 100% replacements decreased by approximately 9% (0.4 MPa), 16 % (0.7 MPa), and 32 % (1.4 MPa), respectively, compared to the control sample. This confirms that an increase in WFS replacement resulted in a decrease in concrete strength [47]. In the case of the 28-day strengths, the strength of the 30% replacement increased by 19% compared to the control sample. The strength of the 70 % replacement decreased slightly (5%) compared to the control sample. Finally, the 100% replacement was only approximately 17% lower than the control sample. Hence, at 28-days, up to 30% replacement would not negatively affect the strength. Depending on the project type, 70% replacement could also be considered.



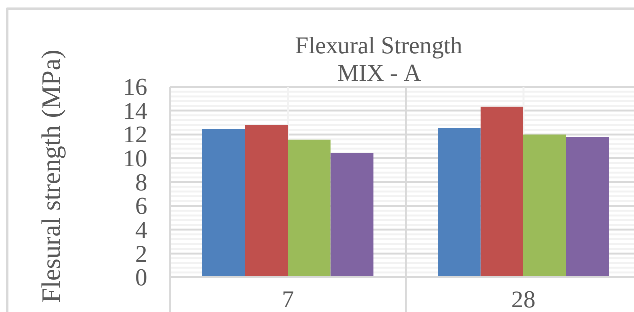
	7	28
0% WFS	3.5	3.9
30% WFS	3.6	3.7
70% WFS	3.3	3.7
100% WFS	3	3.6

Figure 11: Splitting Tensile strength of Mix B with 0.6 w/c

In the case of the mix with a w/c of 0.6 (Figure 11), in the case of the control mix and the various percentages of sand replacement, all the concretes achieved a higher strength at 28-days (compared to the 7-day strength). Regarding the 7-day strengths, the 30% replacement achieved a splitting tensile strength approximately 3 % higher than the control. At 70% and 100% replacements, the strengths decreased by approximately 6% and 14%, respectively. However, the results of the 28-day strengths indicated that the 30% and 70% replacements achieved a 5% lower strength (0.2 MPa) compared to the control. The 100% replacement achieved an 8% lower strength (0.3 MPa) compared to the control. These results indicate that at 28-days, up to 100% replacement would not significantly negatively affect the strength.

3.2.3. Flexural Strength

Figure 12 shows the Flexural strength results of Mix A (with a w/c of 0.4) and Figure 13 shows the results of Mix B (with a w/c of 0.6), at 7 and 28-days.



	7	28
0% WFS	12.44	12.56
30% WFS	12.78	14.33
70% WFS	11.56	12
100 WFS	10.44	11.78

Figure 12. Flexural strength of Mix A with 0.4 w/c

In the case of the mix with a w/c of 0.4 (Figure 12), as expected, due to the extent of cement hydration, the flexural strength at 28days, was higher than that at 7 days for the control concrete as well as all the percentages of replacement. When considering the results of both ages, the 30 % replacement concretes exhibited the highest flexural strength, being 2.7 % (0.3 MPa) and 14.1 % (1.8 MPa) higher than the control mixes at 7 and 28 days, respectively. Furthermore, in both 7 and 28 days, the 70% and 100% replacement mixes yielded lower strengths than the control mix for those ages. The decrease in strength for these replacements was less in the case of the 28-day samples (5% and 0.7 MPa, on average). Depending on the project type and built environment applications, up to 100% could be considered.

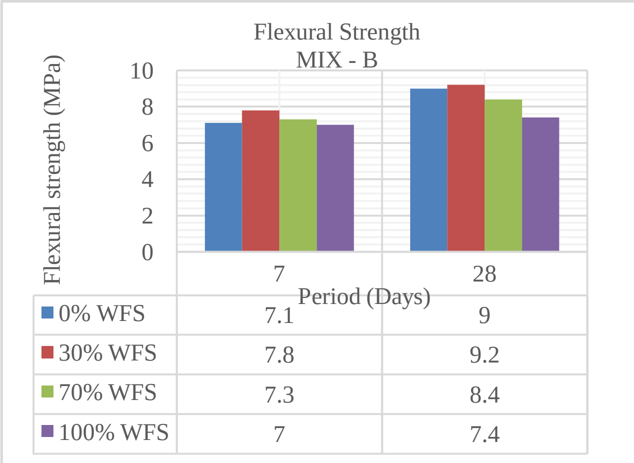


Figure 13. Flexural strength of Mix B with 0.6 w/c

In the case of the mix with a w/c of 0.6 (Figure 13), as expected, due to the degree of hydration, the flexural strength at 28 days, was higher than that at 7 days for the control concrete as well as all the percentages of replacement. When considering the results of both ages, as was the case with Mix A (Figure 12), the 30% replacement concretes exhibited the highest flexural strength being 10% (0.7 MPa) and 2% (0.2 MPa) higher than the control mixes at 7 and 28 days, respectively. In the case of the 70% replacement concretes, the flexural strength at 7 days was a mere 3% higher than the control strength whereas at 28 days, the flexural strength was 7% (0.6 MPa) lower than the control concrete. The 100% replacement concretes yielded flexural strengths of approximately 1% and 18% lower than the control strengths at 7 and 28 days, respectively. On the basis of the flexural strength tests, although 30% replacement was the optimum, 70% replacement could be considered.

4. Conclusions

The utilization of South African WFS sand as a replacement for sand in concrete manufacture was assessed based on the consistency and strength properties of the concrete. With regards to the slump of the concretes, at 70% replacement the slumps of the concrete of Mix A (w/c of 0.4) and Mix B (w/c of 0.6) were 9% lower and 18% higher than their relevant control samples, respectively. Hence, up to 70% WFS inclusion would not significantly negatively affect the concrete slump. The current study on WFS consistence (slump) indicates that in addition to water having a direct influence on the workability of concrete, the chemically bonded sand also had a direct influence on the workability of concrete. When considering the compressive strength of the concretes, for both w/c's (0.4 and 0.6), at both 7 and 28 days, the strength generally increased with the replacement of sand with up to 70% of WFS. The average increase in strength at 28 days, considering both w/c's for up to 70% WFS inclusion was 4%. Hence, up to 70% WFS inclusion would not significantly negatively affect the concrete compressive strength. In the case of the tensile splitting strength, the 28-day strength of the concretes with a w/c of 0.4 was 19% higher than the relevant control sample.

However, the decreases in strength, relative to the control samples, in the case of the 70% WFS for 0.4 w/c and 30% and 70% for the 0.6 w/c were approximately 5% (0.2 MPa). Hence, although 30% was the optimum replacement, up to 70% WFS inclusion would not significantly negatively affect the concrete split tensile strength. The flexural strength test results indicated that all the mixes with 30% WFS exhibited an increase in strength, ranging from 2% to 14%, relative to the control samples. Although the mixes with 70% and 100% WFS had a lower strength than their control samples, at 28 days, the 70% WFS samples had an average strength of 6% (0.6 MPa) lower than their control samples. Hence, depending on the intended use of the concrete, 30% sand replacement with WFS was the optimum replacement, however 70% replacement may be acceptable. [40] summarized the results of a number of researchers and also concluded that 30% was the optimum replacement percentage.

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Declaration of Competing Interest
The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Conflict of interest
The authors declare that they have no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Data Availability Statement
All graphs and data obtained or generated during the investigation appear in the published article.

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Author's Contributions

All of the authors have contributed equally to the article. Further, all of the authors have validated and approved the final manuscript.

Ethics
There are no ethical issues with the publication of this manuscript.

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