Capillarity of Concrete Incorporating Waste Foundry Sand

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Abstract:

Currently, most of the waste foundry sand (WFS) generated in the UK and many parts of the world are sent to landfill. The rising cost of land-filling and the associated environmental problems have prompted the metal casting industry into reusing the WFS. Concrete is a potential material where WFS can be utilised to partially replace the natural fine aggregate. This paper presents the results of an experimental investigation into concrete produced by replacing the fine aggregates (natural sand) with various amounts of WFS. The natural fine aggregate was replaced with 0%, 30%, 60% and 100% WFS. The water content, coarse aggregate, cement and the water to cement ratio remained constant. Concretes were cured at 1, 7, 28 and 90 days. The properties investigated at the various curing times were; water absorption by capillary action, compressive strength and ultrasonic pulse velocity (UPV). The results indicate that there is systematic increase in water absorption by capillary action, a decrease in compressive strength and UPV with increasing amounts of WFS in concrete. There seems to be a linear relationship between strength and capillary water absorption. Also an exponential relationship exists between strength and UPV.

Keywords: Capillary water absorption, strength, sustainability, ultrasonic pulse velocity, waste foundry sand

Introduction

Due to the rising cost of raw materials and the continuous depletion of natural resources, the use of waste materials and industrial by-products is a potential alternative in the construction industry [1]. Various types of industrial by-products and waste materials are generated. These include coal fly ash, slag, demolished concrete and bricks. If incorporated, each of these waste products has specific effects on the properties of construction materials produced such as concrete. The utilisation of such waste materials in concrete or low-strength construction materials not only makes it economical, but also do help in alleviating the problems associated with their disposal and environmental impact [2]; thus contributing towards sustainable development.

Approximately 100 million tons of sand is used annually by foundry industry in USA alone, of that 9 million tons are discarded and are available to be recycled into other products. Also Indian foundry units generate 1.71 million tons of waste foundry sand per year approximately (Siddique 2011).

In the metal casting industry, sand is used for making the moulds when casting. After a certain number of times of usage, this sand is replenished and the result is waste foundry sand which is normally disposed off in landfill. In recent years, there have been attempts to use waste foundry sand in construction applications [1,3]. Javed and Lovell [4] conducted an experimental investigation on the effect of WFS on the mechanical properties and environmental impact of concrete. They found that the rate of strength gain was lower for foundry sand mixes than for conventional materials. This slightly lower strength gain with increasing the amounts of WF is in agreement with results obtained elsewhere [5]. Also the leaching of WFS was comparable to natural soils indicating that if WFS is incorporated in concrete or flowable fill its environmental impact would be minimal [6]. Replacing up to 55% of natural fine aggregate with WFS in flowable fill is an economical alternative to conventional compacted fill [4]. Naik et al [7] concluded that in flowable fill up to 85% of the fly ash used in the reference mixes can be replaced with WFS.

Siddique et al [8] and Singh and Siddique [9], evaluated various mechanical and durability properties of concrete containing WFS. These properties included compressive strength, split-tensile strength, chloride penetration resistance and carbonation. Test results indicated that industrial by-products can produce concrete with sufficient strength and durability to replace normal concrete, thus enabling the use of foundry sand as construction material for structural applications. The strength difference between WFS concretes and normal concrete is less distinct after 28 days of curing. In addition, the maximum carbonation depth and the resistance to chloride for concretes with WFS were comparable to those of ordinary concretes. This indicates that the use of WFS can be a viable substitute of natural fine aggregates in concrete. While the shrinkage is increased with increasing the amount of WFS in concrete [5], this should not inhibit its usage in concrete materials.

Naik et al [10] and Alonso-Santurde et al [11] investigated the use of WFS in the production of clay bricks or masonry units and found that up to 35% of natural sand can be replaced with WFS. Also in the manufacturing of clay brick, WFS can be used not only to produce blocks with adequate properties but also to reduce the plasticity during preparation and before calcining.

There is not much information in the literature on the capillary water absorption of concrete containing WFS. Therefore, this paper reports the results of an experimental investigation on water absorption by capillary action at various ages of curing of concrete incorporating different contents of WFS. Also strength and ultrasonic pulse velocity results were also reported in addition to correlations between the various properties.

Experimental

The cement used was Portland cement (PC). The chemical characteristics of cement are given in Table 1. The natural sand (fine aggregate) used complied with BS EN 12620:2002+A1:2008.

The coarse aggregate was 10 mm nominal size. The waste foundry sand (WFS) was obtained from a foundry in the West Midlands-UK. The particle size distributions (sieving) of natural sand, coarse aggregate and WFS are ilustrated in Table 2.

Tipical chemical composition of waste foundry sand

Constituent	Value (%)
Fe2O3	84.8
CaO	0.81
MgO	5.39
SO3	1.42
Na2O	0.86
K2O	0.21
TiO2	0.87
Mn2O3	1.14
SrO	0.22
	0.047
	0.03

Table 1: Chemical compositions of the cement

Constituent	Values
Loss on ignition	1.5 (%)
Insoluble residue	0.5 (%)
Brightness	43 (%)
SiO_2	22.8 (%)
Al_2O_3	3.8 (%)
Fe_2O_3	1.4 (%)
CaO	66.5 (%)
MgO	0.8 (%)
SO_3	3.3 (%)
K_2O	0.7 (%)
Na_2O	0.1 (%)
Cl	<0.1 (%)

Flexural tensile strengths (28Days)	9.9 (Mpa)
Compressive strengths (28 Days)	75.5 (Mpa)

Table 2: Particle size distribution of aggregates

Sieve (mm)	Cumulative Passing (%)		
	WFS*	Natural Sand	10mm
12.5	-	-	100
10	-	-	82.0
8	100	100	40.2
4	100	97.4	2.3
2	100	88.9	1.2
1	100	81.4	1.1
0.5	99.6	63.3	1.1
0.250	99.3	16.2	0.9
0.125	5.6	1.8	0.5
0.063	0.3	0.1	0.2
Filler	0.0	0.0	0.0

* Waste foundry sand

Four different mixtures were used for this investigation. The control mixture (M1) had a proportion of 1 (cement): 2 (sand): 4 (coarse aggregate). In mixtures M2-M4, the natural sand was replaced with 30, 60 and 100% (by weight) of WFS. The water to cement ratio (W/C) for all mixes was of 0.5. Further details about the mixes are presented in Table 3.

Table 3: Details of mixtures

Mix No.	Mix Code	WFS* (%)	Mixture constituents (kg/m³)				
			Cement	Water	Coarse Aggregate	Natural Sand	WFS*
1	0 WFS	0	320	160	1280	640	0
2	30 WFS	30	320	160	1280	448	192
3	60 WFS	60	320	160	1280	256	384
4	100 WFS	100	320	160	1280	0	640

* WFS (% by mass of natural sand)

Specimens were cast in steel moulds. Cubes of 100mm in size were used for the determination of compressive strength and ultrasonic pulse velocity (UPV). For capillary water absorption (CWA) specimens of 100mm x 100mm x 50mm in size were used. After casting, specimens were covered and left in the laboratory at 20±2ºC for 24 hours. After that, demoulding took place and specimens were placed in water tank at 20±2ºC for different wet curing periods. Testing was conducted at 1, 7, 28 and 90 days. For the capillary water absorption test, samples were dried in an oven at 80ºC until a constant dry mass was achieved and were then cooled in an airtight container at 20ºC before testing. In this test, the mass resulting from absorption of water as a function of time is monitored when only one surface (100mmx100mm) of the specimen is exposed to water. The weight gain per unit area is plotted against the square root of time and the slope of the initial part of the curve was termed as the water absorption coefficient (WAC). The WAC is a measure of the rate of water absorption by capillary action. Further details about the test are reported elsewhere [12, 13].

Results and Discussion

The amount of water absorbed per unit area for concrete containing different amounts of waste foundry sand (WFS) versus square root of time at the ages of 1, 7, 28 and 90 days of curing, is shown in Figures 1 to 4 respectively. Generally, there is higher amount of water uptake with the increase in foundry sand content at the end of the test period. There is small difference in water uptake between the various mixes after 1 day of curing (Figure 1) and this difference becomes noticeable at 7 days curing and beyond (Figures 2-4). Mixtures containing 60 and 100% waste foundry sand as replacement of natural sand show substantially higher water uptake at the end of the testing period compared with mixtures containing 0 and 30% WFS. For example at 90 days of curing, the water uptake at the end of the test period by the mix containing 100% WFS is nearly 3 times more than that of the reference mix (i.e. 0% WFS). Also after 1 day of curing nearly all mixtures did not appear to absorb more water towards the end of the test period (i.e. the last part of the curve is horizontal), whereas at the other curing ages the samples were still absorbing water. The ongoing hydration of concretes beyond 1 day of curing may cause blockage of pores and water would take longer time to be absorbed.

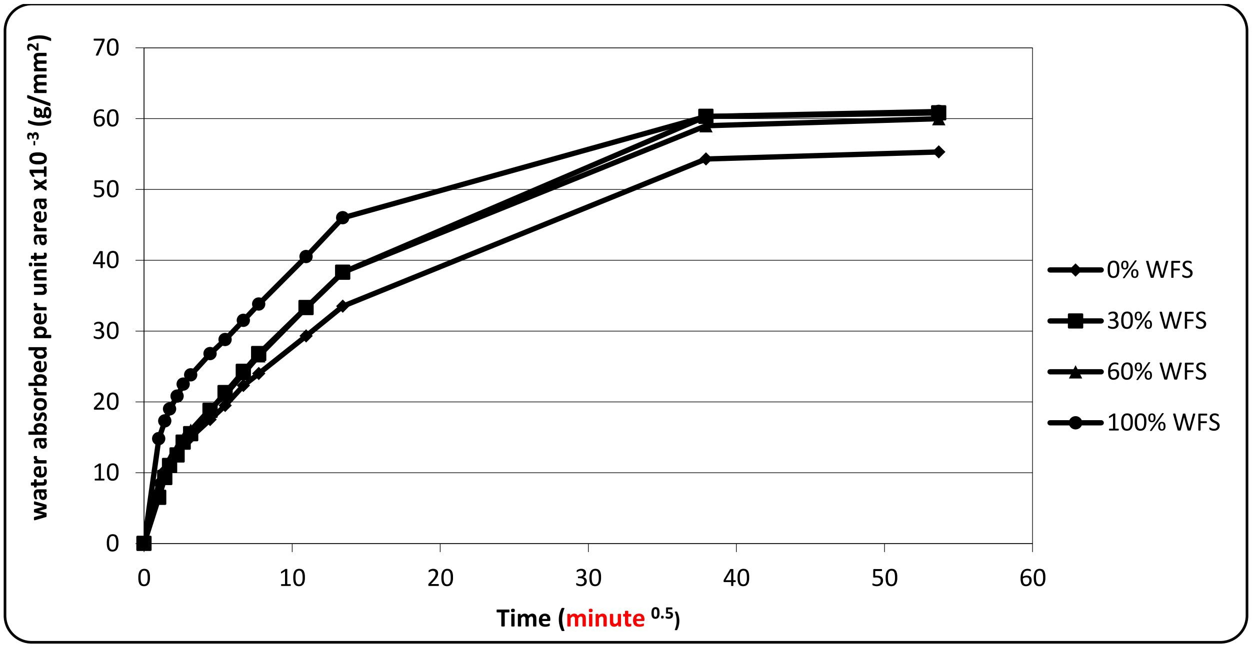

Figure 1: Water absorbed by capillary action for concretes containing varying amounts of WFS after 1 day of curing.

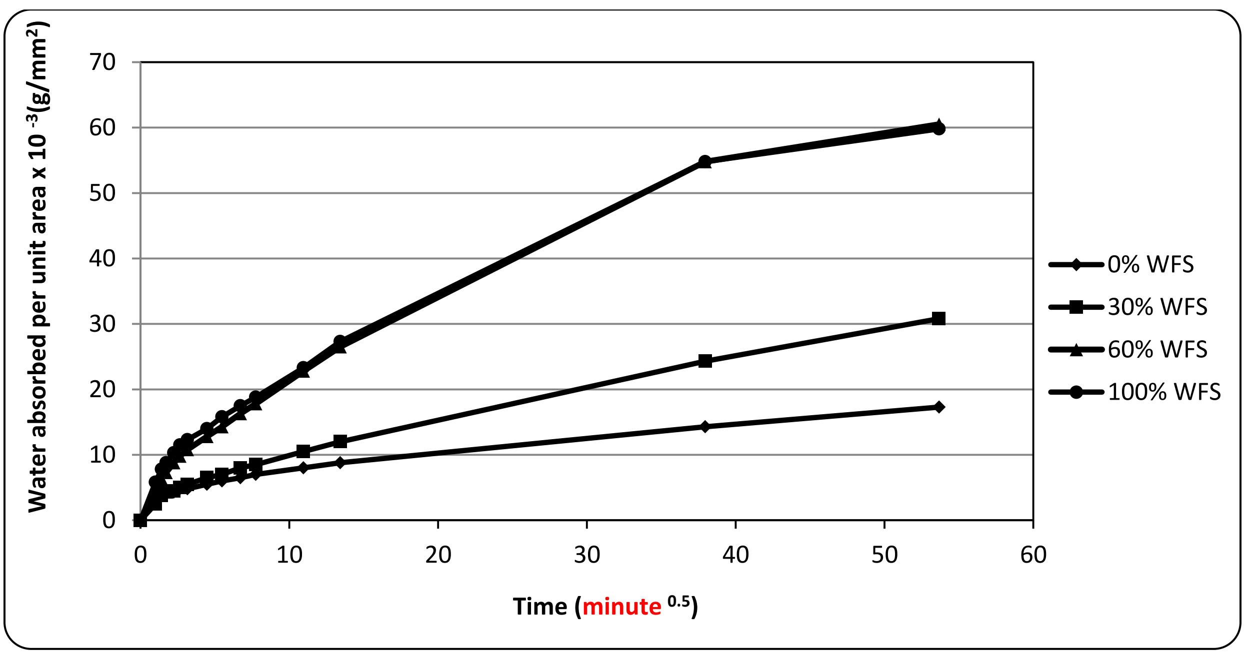

Figure 2: Water absorbed by capillary action for concretes containing varying amounts of WFS after 7 days of curing.

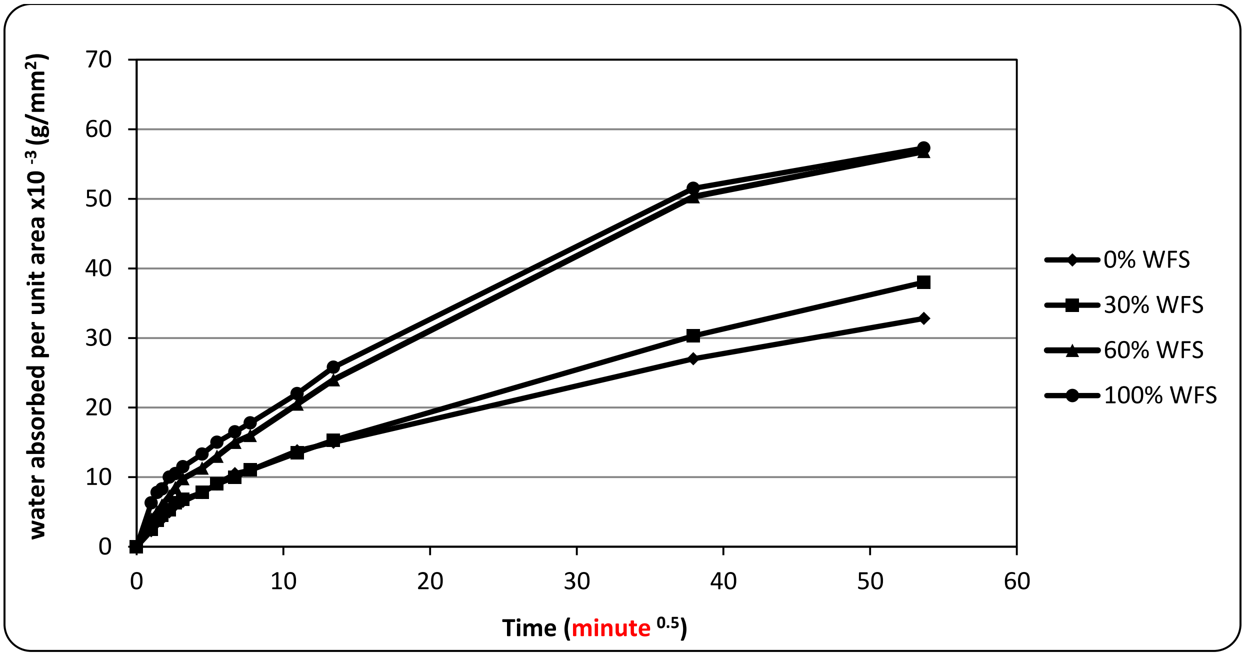

Figure 3: Water absorbed by capillary action for concretes containing varying amounts of WFS after 28 days of curing.

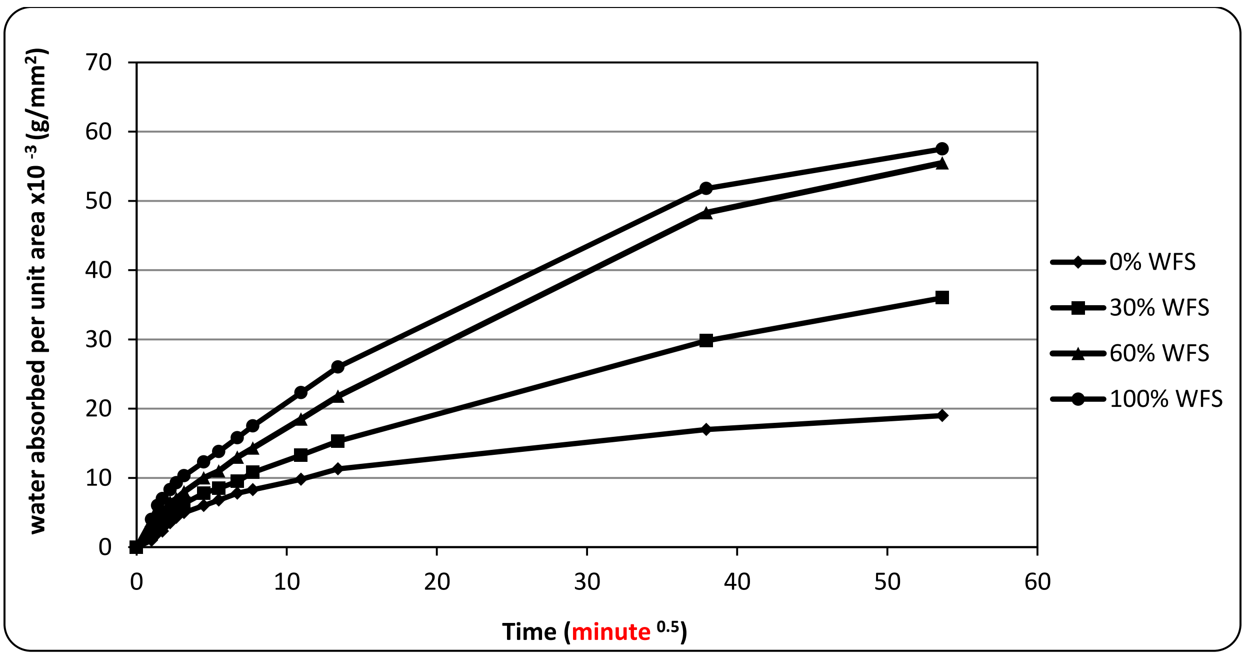

Figure 4: Water absorbed by capillary action for concretes containing varying amounts of WFS after 90 days of curing.

The rate of initial water absorption, which is referred to as the water absorption coefficient (WAC) and expressed as the slope of the initial part of the curve is shown in Figure 5 for all mixtures (with and without WFS) at all curing times. The WAC is generally higher when the WFS content in the mixture increases. Also and as can be expected after 1 day of curing, the WAC is noticeably larger than that at the other curing periods. Beyond 7 days of curing, the WAC reduces for all mixtures. Figure 5 also indicates that there is a linear relationship between the WAC and the percentage of WFS in the mixtures at the different curing periods. If a linear equation is fitted to the experimental data, the following equations are obtained at the various curing periods:

$$Y(1Day) = 0.012X + 3.2817 \qquad R^2 = 0.8805$$

$$Y(7Days) = 0.0152X + 2.0027 \qquad R^2 = 0.9536$$

$$Y(28Days) = 0.0147X + 1.7288 \qquad R^2 = 0.9583$$

$$Y(90Days) = 0.0137X + 1.3721 \qquad R^2 = 0.9874$$

For curing ages beyond 7 days, the R^2 is higher than 0.95 indicating a strong linear relationship. Even at 1 day of curing the R^2 is 0.88.

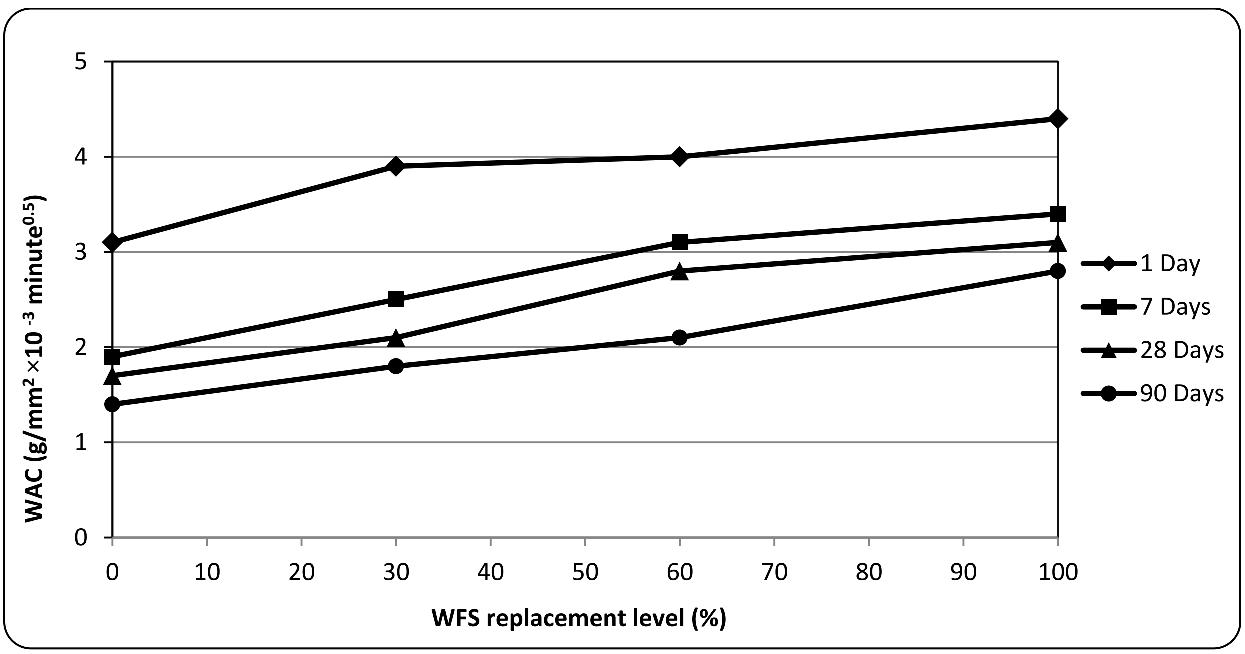

Figure 5: WAC for concretes containing varying amounts of WFS at different curing periods

The compressive strength at the ages of 1, 7, 28 and 90 days of curing for concretes containing varying amounts of waste foundry sand are shown in Figure 6. Although there is an acceptable strength for all concrete with and without waste foundry sand, there is a systematic decrease in compressive strength as the amount of WFS in concrete is increased. For example, at the age of 90 days curing the strength for the control mix (i.e. 0% WFS) is 48 N/mm^2 and this drops down to 24 N/mm^2 (i.e. 50% drop) for the mix containing 100% WFS as replacement of natural sand. For mixtures containing 30% and 60% WFS, the percentage decrease in strength is 26% and 45% respectively at 90 days of curing and the trend is similar at other curing times. The decrease in compressive strength of the concrete may be due to the increase in the surface area of fine particles, which can lead to weakening of interfacial zone between the WFS and the cement paste. Similar results have been reported elsewhere [5,9,14].

Figure 7 plots the ultrasonic pulse velocity (UPV) versus curing time for the various concrete mixtures. The trend is similar to that of strength, in that an increase in WFS leads to a decrease in UPV and there is sharp increase in UPV between the ages of 1 day and 7 days of curing for all mixtures.

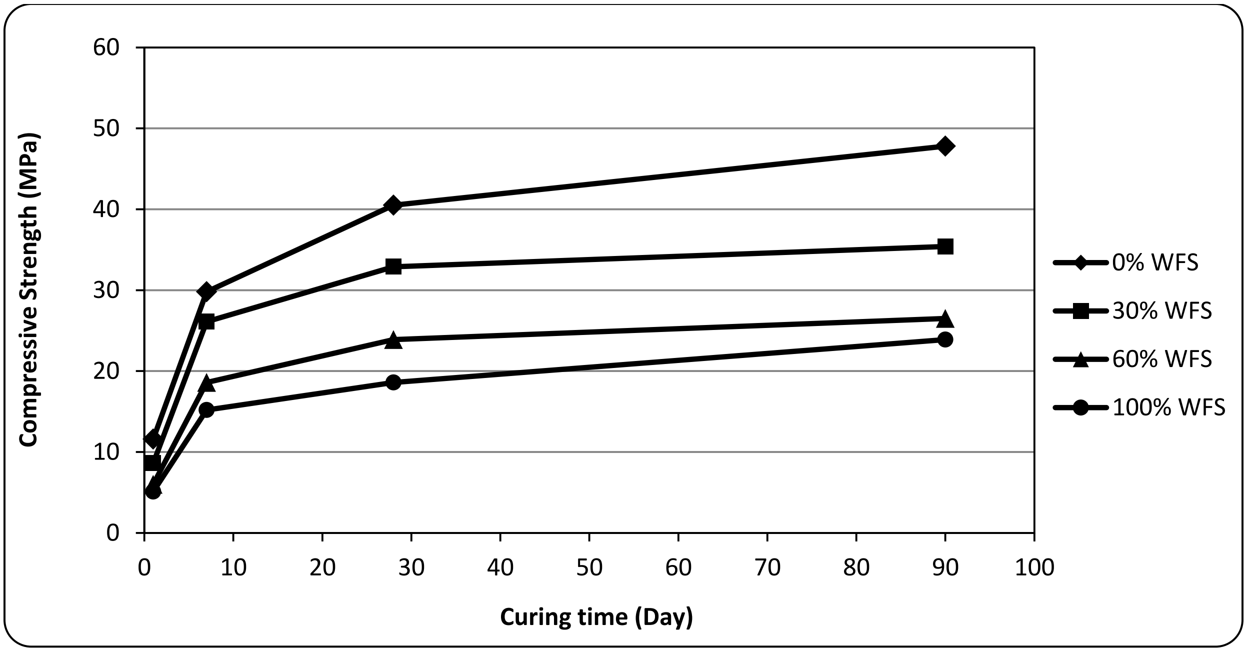

Figure 6: Compressive strength of concretes containing varying amounts of WFS at different curing times

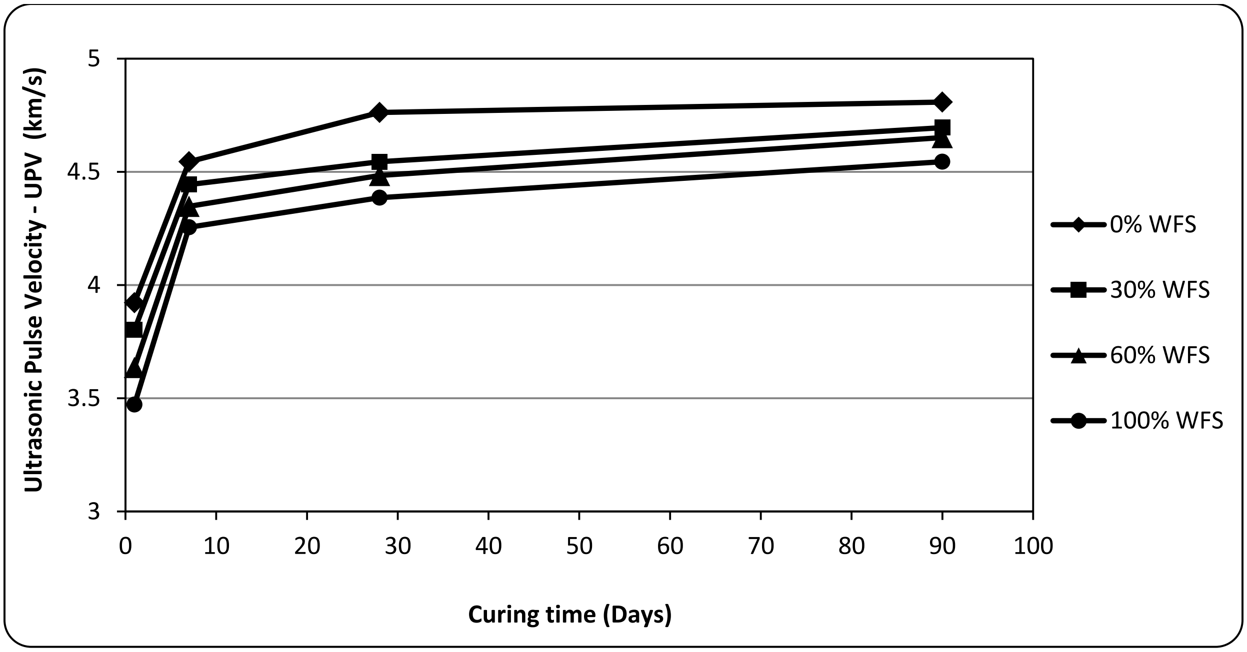

Figure 7: Ultrasonic Pulse Velocity (UPV) of concretes containing varying amounts of WFS at different curing times

The correlation between compressive strength and WAC in plotted in Figure 8. An increase in WAC leads to a decrease in compressive strength. A linear function seems to describe the correlation between strength and WAC, that is:

$Y = -13.349X + 59.949$, with an $R^2 = 0.9234$ indicating a good correlation, where X is the WAC and Y is the compressive strength. The relationship seems to be independent of the curing age or WFS content.

Figure 9 shows the correlation between compressive strength and UPV. An increase in UPV leads to an increase in compressive strength. This is in agreement with results obtained elsewhere [15,16]. An exponential function seems to better describe the correlation between strength and UPV for all mixtures and for all curing ages:

$Y = 0.019e^{1.6009x}$, with $R^2 = 0.9699$ indicating strong correlation, where X is the UPV and Y is the compressive strength. The relationship seems to be independent of the curing time or the WFS content.

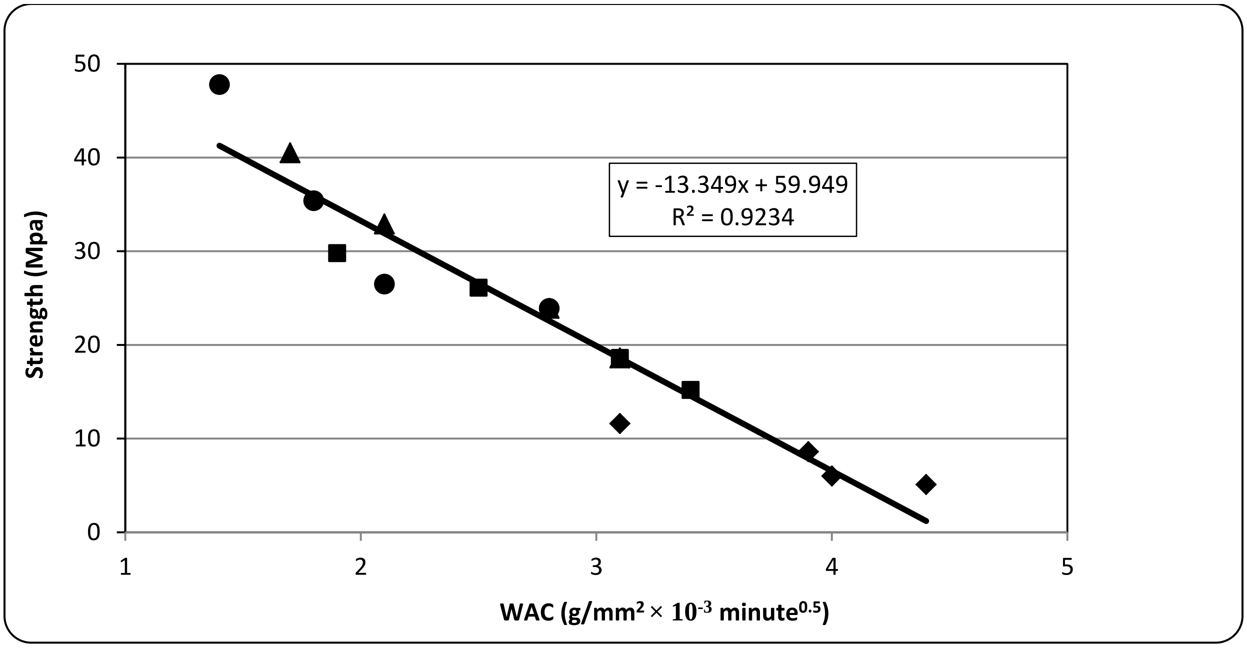

Figure 8: Relationship between compressive strength and WAC

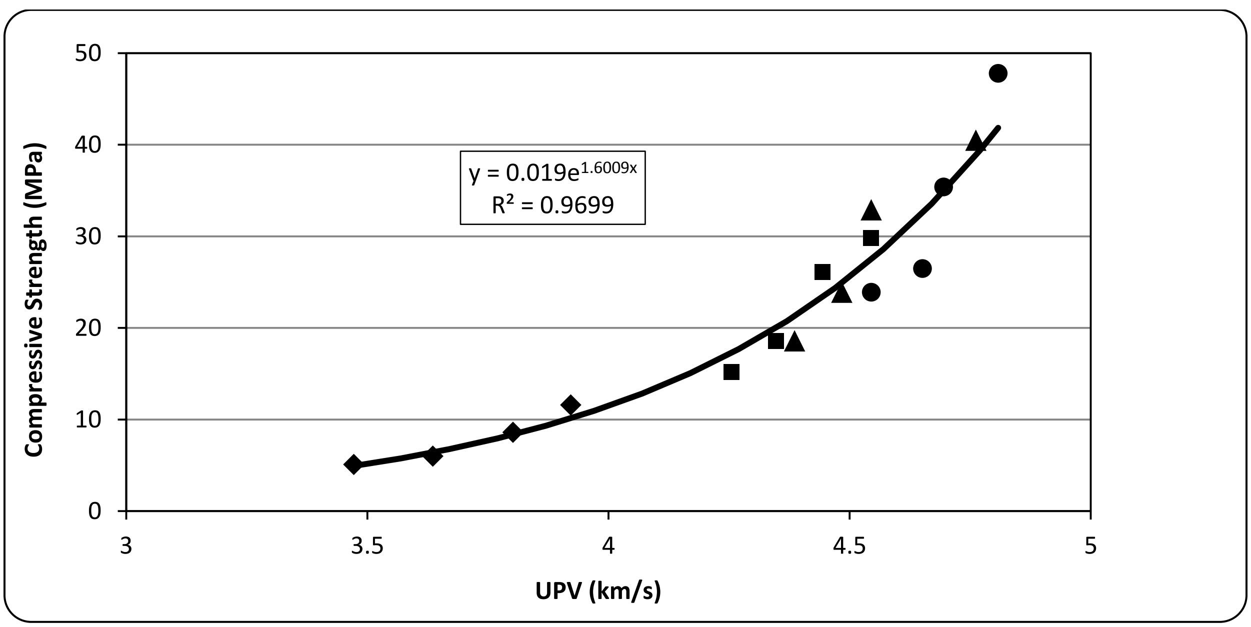

Figure 9: Relationship between compressive strength and UPV

Conclusions

The capillary water absorption, as indicated by rate of water absorbed per unit area, increases when normal sand is replaced with increasing amounts of waste foundry sand. This is accompanied by a decrease in strength and ultrasonic pulse velocity. The level of decrease depends upon the replacement level of foundry sand. However, adequate strength can be achieved using an appropriate replacement level of foundry sand. With appropriate mix design, the utilisation of waste foundry sand in concrete production is possible.

Acknowledgments

The assistance from Soran University (Kurdistan-Iraq) is gratefully acknowledged.

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