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Effect of Iron Powder (Fe_2O_3) on Strength, Workability, and Porosity of the Binary Blended Concrete

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Abstract

In this study, the effect of iron powder (Fe_2O_3) on the compressive strength, tensile strength, workability, and porosity of the binary blended concrete were experimentally investigated. For this purpose, Portland cement was partially replaced by 1.5%, 2.5%, 3.5%, and 5% by weighing of iron powder. The amount of water-binder-ratio was considered constant. The workability of the fresh composite concrete was determined using cone Abrams method; mechanical properties were determined included compressive and tensile strengths at 7, 14, and 28 days and durability evaluated by water absorption and permeable porosity. It was observed that the compressive and tensile strengths change with the replacement of iron powder by up to 5%. However, the maximum improvement was gained at 2.5 wt% for compressive strength and 1.5 wt% for tensile strength. The workability of the fresh mixtures decreased when iron powder amount increased. It was observed that the porosity decreased respectively by 21.88% and 26.77% at 1.5 wt% and 2.5 wt% replacement. Moreover, this present study shows the importance and benefits to improve concrete properties by using micro-particles materials.

Keywords

Iron Powder, The Porosity of Concrete, Workability, Mechanical Properties, Compressive Strength, Tensile Strength

1. Introduction

The concrete is a very important building material used in construction. Even though it gives the impression to be well known and its behavior is usually understood, there is still a large amount of research project carrying out in order to investigate it on the microstructural level. Most research has been done by adding nanoparticles to improve the mechanical and physical properties. Apart from the use of OPC in concrete, there are several others cementitious materials such as fly ash, nano-Fe_2O_3, nano-TiO_2, nano-Al_2O_3 used as cement replacement or admixture to improve the properties of cement-based materials for specific applications.

However, there are few reports on the incorporation of nanoparticles in cement-based concrete. Hui *et al.* (2003) [1] investigated the properties of cement mortars blended with nanoparticles to study their smart mechanical and highest (temperature and strain sensing) potentials. Many researches have been directed toward the utilization of nanoparticles to improve the mechanical properties of mortar and concrete. Recently, Ali Nazeri, *et al.* (2010) [2] investigated the influence of Al_2O_3 nanoparticles on the compressive strength and workability of blended concrete. It showed that the cement could be advantageously replaced with nano-Al_2O_3 particles up to maximum limit of 2.0% with average particle sizes of 15 nm. Furthermore, until now research has been carried out in order to improve the mechanical performance with cement replacement by materials at the microscale level. Previous research on the effect of nano-TiO_2 particles as an admixture to cement paste has been reviewed by Ali Nazeri, *et al.* (2010) [3] and has demonstrated that the finer of nano-TiO_2 higher is the mechanical characteristic.

According to the author's knowledge, there are several studies on incorporating nanoparticles in mortar or concrete. Most of them have been reported on nano-SiO_2 [4] [5] [6] carbon nanotube and nano-Al_2O_3 [6] in cement-based materials. However, the influence of others nanoparticles, such as nano-CuO, nano-ZnO_2, nano-Fe_3O_4, and nano-Fe_2O_3 on the physical and mechanical properties of cement-based materials was also investigated in a few researches [7] [8] [9].

Previous studies [9] revealed and consistently showed a significant improvement in the mechanical properties and durability performance using the nanoparticles as an admixture. The study showed that 3 wt% of nano-Fe_3O_4 in the cementitious materials was the optimal amount to improve both its mechanical and microstructural properties.

The present study aims to give a contribution to the concrete production area. In this scope, the pozzolanic reaction of iron powder in the concrete mixture with a constant water binder ratio was studied. In this paper as mentioned above, the effect of iron powder (Fe_2O_3) on strength, workability, and porosity of binary blended concrete has been studied by the authors to investigate the mechanical and physical properties (compressive, tensile strengths, workability, water absorption, and porosity). However different studies using nanoparticles in concrete reported the microscopy investigation in recent literature. In the current literature, to the best of authors' knowledge, there is no experimental work investigated on the microstructures of concrete incorporating iron powder.

This paper reports only the parameters mentioned above of the concrete mixed with iron powder (Fe_2O_3). The result showed that with the increase of iron powder (1.5% and 2.5%), the compressive strength improved. The iron powder has not more impact on tensile splitting strength when the replacement is beyond 1.5% of replacement. The workability decreased with the increasing of the amount of the iron oxide and the porosity decreased up to 2.5% of replacement and start increasing by 5% of iron powder added. Therefore, the admixtures of nanoparticles in concrete can significantly improve the performance of cement-based materials. Thus, utilizing iron powder for concrete production can contribute to engineering characteristic benefit and a good durability performance since it improves the porosity.

2. Materials and Methods

2.1. Materials and Mixtures

2.1.1. Cement and Iron Powder (Fe_2O_3)

The cement used for this study is the ordinary Portland cement (CEM I 42.5) manufactured by Bamburi Cement Company of Kenya in conformity of EN 197-1 [10]. Iron powder with a predominant particles size of 200 nm was used as provided. The chemical composition of cement and iron powder is given in **Table 1**. The physical properties of cement are given in **Table 2** and **Table 3** the technical data of iron powder as received.

Table 1. Chemical composition of the ordinary portland cement and iron powder.

Parameters	Cement	Iron powder
SiO_2	20.62	4.21
Al_2O_3	5.04	2.67
Fe_2O_3	3.23	88.31
CaO	63.36	0.36
MgO	0.82	2.22
SO_3	2.73	
Na_2O	0.16	0.04
K_2O	0.53	0.02
TiO_2	-	0.01
MnO	-	0.21
Free CaO	0.63	-
Na Eq	0.48	-
Cl^-	< 0.01	-
LOI	2.9	1.01
I.R	1	-
C3A	7.91	-

2.1.2. Aggregates

The aggregates used mainly for this study was the natural sand with particles size less than 5 mm, fineness modulus of 2.62, the specific gravity of 2.45 g/cm^3 and water absorption of 5.23%. The crushed stones with a maximum size of 20 mm, specific gravity of 2.76 g/cm^3 and water absorption of 2.58% were used as coarse aggregate. Figure 1 and Figure 2 give the particles size distribution of the aggregates in conformance of ASTM C33 [11].

2.1.3. The Mix Design and Mixture Proportioning

The mix design of the Portland cement concrete grade M25 in this study was

Table 2. Physical properties of portland cement.

Specific gravity	Loose bulk density (kg/m^3)	Compacted bulk density (kg/m^3)
3.185	1162.3	1398

Table 3. Physical properties of the iron powder.

TECHNICAL DATA			
Designation	Min	Max	Test Method
Water-Soluble Content [%]		1	ASTM D 1208
Oil Absorption [g/100g]	15	25	ASTM D 281
Sieve Residue (0.045 mm) [%]		0.5	ASTM D 185
Predominant Particle size [μM]	0.2		Electron Micrographs
Fe_2O_3 [%]	95		ASTM D 50
$SiO_2 + Al_2O_3$ Content [%]		0.6	DIN 55913
Moisture (After Production) [%]		1	ASTM D 280
Loss on Heating 1000˚C 1/2 h [%]		5	ASTM D 1208
Particle Shape	Spherical		Electron Micrographs
Density [g/ml]	~5.0		ASTM D 153

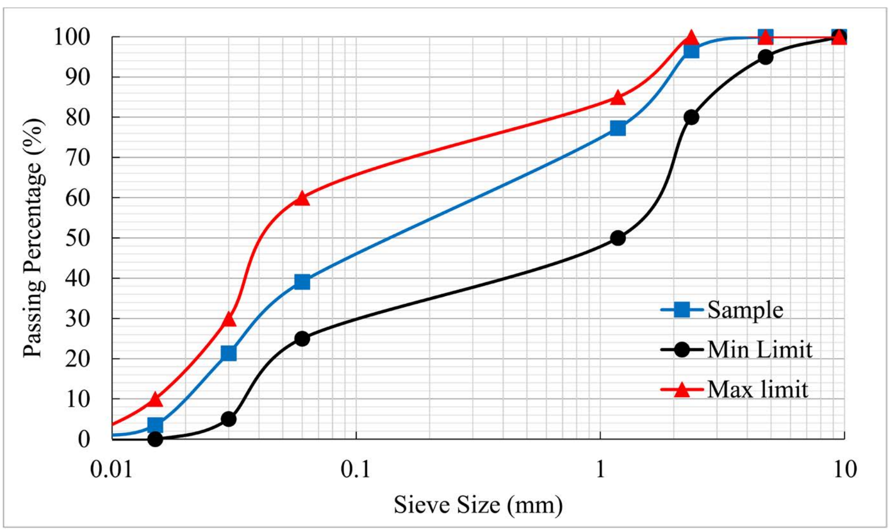

Figure 1. Sieve analysis of fine aggregates graph.

done in accordance with BS EN 206 (2014) [12] and BS EN 8500-2 (2015) [13]. A total of five mixes were prepared in the laboratory. The first mixture M0 was prepared for the control specimens and the mixtures M1 to M4 were prepared with the addition of iron powder, the cement was partially replacement by 1.5%, 2.5%, 3.5% and 5% by weighing with iron powder. The water-binder ratio (w/b) amount for all mixtures was fixed to 0.5. The aggregates used were combined of crushed gravel and fine sand, with the fine percentage of 32% by weighing. The blended cementitious content of all mixtures was 360 kg/m^3. Hand mixing was performed in accordance with BS EN 1881-125 (2013) [14] with a control mechanism to avoid the loss of cementitious materials and water quantified during mixture proportioning. The mix design proportion is given as shown in **Table 4**.

2.2. Preparation of Test Samples

All the mixtures were produced by blending the fine aggregates, coarse aggregates and cementitious materials (cement and iron powder) in the laboratory using hand mixing. They were mixed in a dry condition before adding fresh water. For the control mixture, only cement was used. Slump test and compaction factor test of the fresh concrete were performed promptly to evaluate the consistency of the mixture in accordance with the mixing procedure. The concrete was

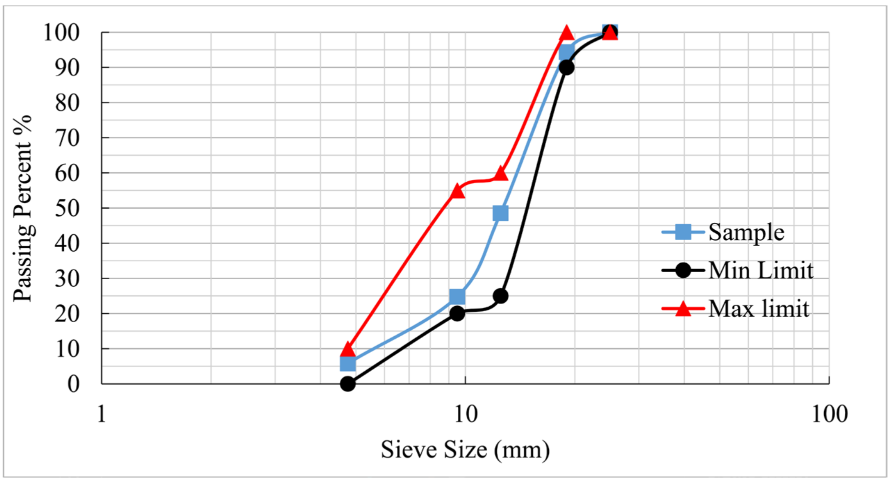

Figure 2. Sieve analysis of coarse aggregates graph.

Table 4. Mix design proportions of concrete mix (kg/m^3).

Designation	Percent of iron powder (%)	Quantities kg/m^3					
		Cement	Water	Fines	Coarses	w/b	Iron powder (Fe_2O_3)
M0	0	360	180	585	1245	0.50	0
M1	1.5	354.6	180	585	1245	0.50	5.4
M2	2.5	351	180	585	1245	0.50	9
M3	3.5	347.4	180	585	1245	0.50	12.6
M4	5	342	180	585	1245	0.50	18

poured in three different types of mold, cubes of 100 mm and 150 mm sides with a cylinder of 100 mm diameter and 200 mm long. The test specimens were stored in moist air for 24 hours after casting. After this period the specimens were demoulded, marked and cured in clear fresh water until taken out to test. The compressive and tensile strengths tests were performed on the concrete samples at 7, 14 and 28 days. The porosity of the hardened concrete was also determined. The results shown are the mean of three samples test. **Figure 3** is showing the preparation of samples.

2.3. Compressive Strength Measurement

The cubes specimens of 100 mm × 100 mm × 100 mm dimensions were casted to determine compressive strength. A total of 33 cubes were casted and cured at 7, 14, 28 days of moisture curing condition in accordance with the prescribed methods BSI 1881-115 (1983) [15]. The test equipment used was the universal testing machine (UTM) and the compressive strength was performed at 7, 14, and 28 days.

2.4. Tensile Splitting Strength Measurement

The tensile strength test was conducted on the cylinder of 100 mm diameter and 200 mm height in accordance with the standard test method BSI 1881-117 (1983) [16]. The samples were tested after 7, 14, and 28 days of curing.

2.5. Workability

The slump test and compactor factor of the mixtures were conducted in conformance with the test method as specified in BSI 1881-102 (1983) [17] and BS 1881-103 (1983) [18] in order to determine the workability of the concrete.

2.6. Water Absorption and Porosity

Water absorption and permeable porosity in concrete were determined by using the formula from Equations (1)-(3) in accordance with the standard test method ASTM C642 (2013).

By using the values for masses determined in accordance with the procedures described in ASTM C642-97 Section 5, the following calculations have been done:

Figure 3. Preparation of samples (a) mixing (b) casting and (c) demolding.

$$\text{Absorption after immerson}\left(\%\right)=\left[\left(B-A\right)/A\right]\times 100 \quad (1)$$

$$\text{Absorption after immersion and boiling}\left(\%\right)=\left[\left(C-A\right)/A\right]\times 100 \quad (2)$$

$$\text{Volume of permeable pore space, \%}=\left[\left(g_2-g_1\right)/g_2\right]\times 100 \quad (3)$$

where A is mass of oven-dried sample in air (g), B is mass of surface-dry sample in the air after immersion (g), C is mass of surface-dry sample in the air after immersion and boiling (g), D is apparent mass of sample in water after immersion and boiling (g), g_1 is bulk density, dry (Mg/m^3), g_2 is apparent density (Mg/m^3) and ρ is density of water (1 Mg/m^3 = 1 g/cm^3).

3. Experiment Results and Discussions

3.1. Compressive Strength

The results for the compressive strength of iron powder blended Portland cement obtained at seven, fourteen, and 28 days and their standard deviation are shown in Figure 4. The results showed that when 1.5% and 2.5% of cement replaced by iron-red powder the compressive strength increased by 11.17% and 27.03% at 28 days respectively. The introduction of iron powder at the levels of 3.5% and 5% shows decreasing of compressive strength by 7.14%, 16.68% at 28 days respectively. The experiment results from previous research showed that the use of nano-Fe_2O_3 particles up to a maximum replacement level of 2.0% produces concrete with improved strength. However, the ultimate strength of concrete was gained at 1.0% of cement replacement [19]. In this study, the highest improvement of compressive strength was gained at 2.5% iron powder content, at 28 days the strength reached 33.64 MPa for a concrete grade of M25. This phenomenon can be explained as when the iron powders are uniformly distributed in concrete each particle has a cubic pattern and distance between the nanoparticles is adjustable [8]. The particles due to their micro fine size, they

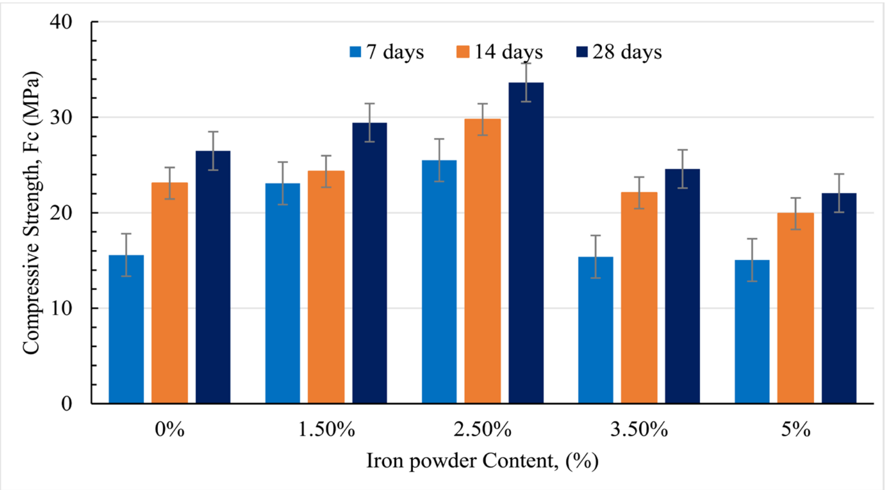

Figure 4. Compressive strength at 7, 14, and 28 days versus the content of the iron red powder.

fill the pores (the nano-filler effect), leading to the further compacting of the microstructure. These main phenomena lead to the improvement of the microstructure by reducing the amount of pores, improving the bond between the aggregate and the cement matrix and increasing the density of the cementitious composite [9]. The high improvement of compressive strength in the blended concrete is due to the rapid consumption of $Ca(OH)_2$ which was formed during hydration of Portland cement especially early ages related to the high reactivity of nano-Fe_2O_3 particles [19].

3.2. Tensile Splitting Strength

The results obtained from tensile splitting strength test at 7, 14, and 28 days are depicted in **Figure 5**. The experiment showed that when 1.5% of cement replaced by iron-red powder, the split tensile strength increased by 4.63% at 28 days. It showed also that when the replacement level at 2.5%, 3.5%, and 5%, the tensile strength decreased by 3.24%, 6.48% and 13.43% at 28 days. From previous research, results showed from the sample containing 1% and 3% Fe_2O_3 nanoparticles, the mechanical properties have improved than the ordinary cement mortar. The results show that the addition of Fe_2O_3 Nanoparticles, increasing amount of compressive strength is more than tensile strength [8]. It was also observed from the previous study, that 1.0% replacement caused a decrease in the split tensile strength of the experimental cement [20]. In this study, split tensile strength started decreasing when the replacement higher than 1.5%.

This may be due to the fact that the quantity of Fe_2O_3 particles present in the mixture was higher than the amount required to combine with the liberated lime during the hydration process, thus leading to excess silica leaching out and causing a deficiency in strength as it replaced a part of the cementing material but did not contribute to its strength [2].

3.3. Slump and Compaction Factor

Slump test conducted in accordance with the standard prescribed in BS 1881-102

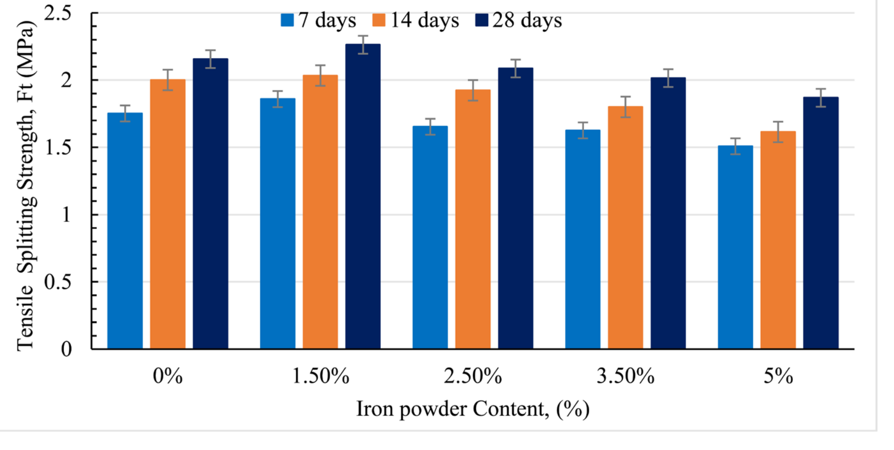

Figure 5. Tensile splitting strength at 7, 14, and 28 days versus iron red powder content.

(1983) [17] in order to determine the consistency of the different concrete mix. For the concrete mix design considered, the specified slump was from 25 - 75 mm. As a procedure, "Abrams cone" was filled in three layers, each layer compacted 25 times using a tamping rod with a diameter of 16 mm. The compaction factor test conducted as specified by the standard BS 1881-103 (1983) [18] performed in order to determine the workability of the different concrete mixes.

The maximum strength of concrete is related to the workability and can only be obtained if the concrete has an adequate degree of workability because of self-compacting ability [2]. From **Figure 6**, the results showed that when iron red powder was added as partial replacement of cement, the slump starts decreasing. It is showing also that there is a strong correlation between the quantity of iron red oxide and the workability of concrete mixes ($R^2 = 0.9439$). The slump flow of the control sample was 40 mm, which consequently decreases to 16 mm when about 5% of cement replaced by iron red oxide. From regression analysis, Equation (4) was found from as linear form relationship:

$$S = 47.9 - 5.9P \tag{4}$$

where S is the slump flow (mm) and P is the content of iron powder (%).

From **Table 5**, the value of the compaction factor varies from 0.97 to 0.89. The result showed that the compaction factor decreased when the iron powder is added. The regression analysis was run to define the relationship between the slump and compaction factor as shown in **Figure 7**, it was found that there is a strong correlation between them as the coefficient of determination R^2 is 0.9709.

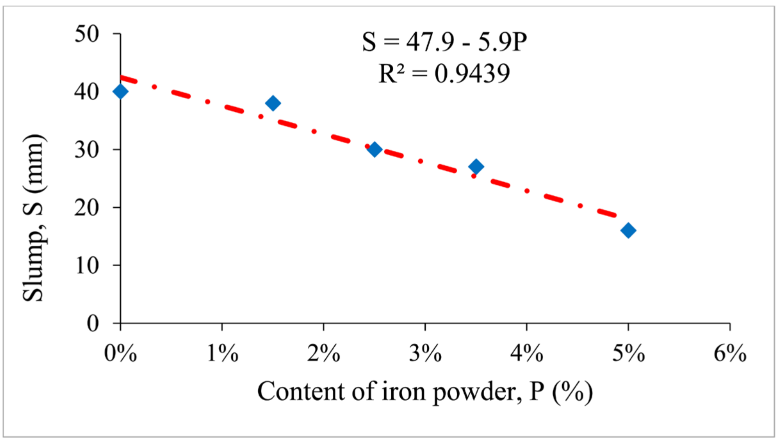

Figure 6. Slump variation for different mixtures with iron red powder.

Table 5. Fresh properties of different concrete mixtures.

Fresh properties	Concrete mixtures				
	M0 (0%)	M1 (1.5%)	M2 (2.5%)	M3 (3.5%)	M4 (5%)
Slump (mm)	40	38	30	27	16
Compaction factor	0.97	0.95	0.93	0.91	0.89
Fresh density (g/cm^3)	2311	2297	2378	2340	2380

This result can be justified by the fineness of iron powder (0.2 μm) and its high water absorption. However, almost all the mixes felt in the expected range of a slump (between 25 - 75 mm) except when 5% of iron powder was added and the compaction factor felt with the ranges specified by the standard BS 1881-103 (1983) [21].

3.4. Water Absorption

Two different types of water absorption were determined using the standard test methods ASTM C-642-97, water absorption after immersion (W_{ai}), and water absorption after immersion and boiling (W_{aib}). The result obtained in Figure 8, showed that W_{ai}, and W_{aib} decreased up to 20.8% and 20.92% respectively when 2.5% of Portland cement is replaced by iron powder. W_{ai} and W_{aib} started

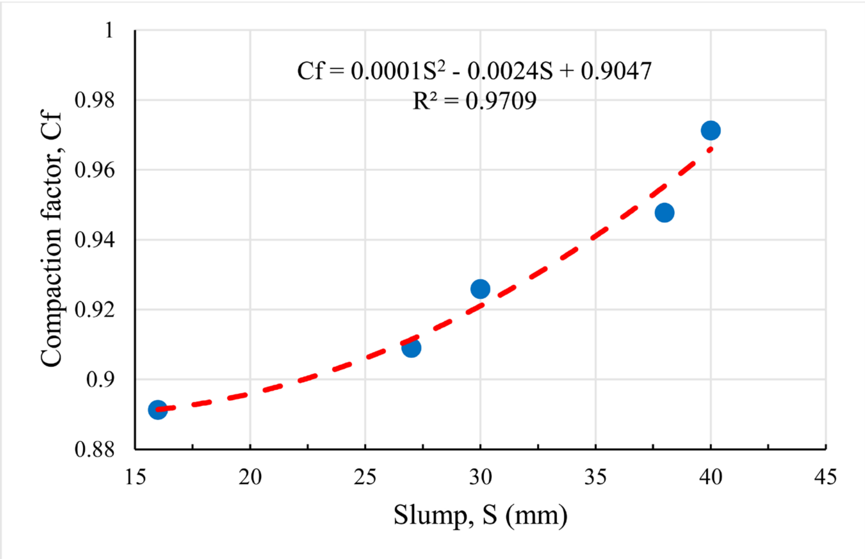

Figure 7. Relation between compaction factor and slump

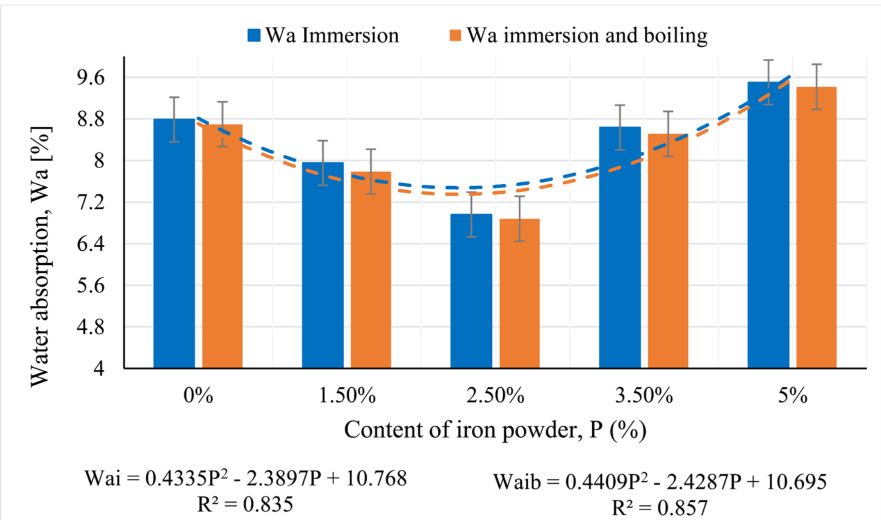

Figure 8. W_{ai} & W_{aib} variation versus the content of iron red powder.

increasing respectively up to 8.02% and 8.28% when 5% of the iron powder is added. The values of W_{ai} are somewhat higher than W_{aib} values. In the mixtures where 0.5% and 1.25% nano-Fe_2O_3 was added, capillarity dropped by 5% and 1%, respectively. On the other hand, the addition of this powder at a proportion of 2.5% increased the capillarity by 3%. Indeed as indicated in the previous study [17]. In this study, the water absorption decreased up to a minimum value of 2.5% of replacement and increased to a maximum value of 5% of cement replacement. The water absorption was correlated to iron powder content in a polynomial function as shown in Equations (5) and (6).

$$W_{ai} = 0.4335 \times P^2 - 2.3897 \times P + 10.768 \quad (5)$$

$$W_{aib} = 0.4409 \times P^2 - 2.4287 \times P + 10.695 \quad (6)$$

where W_{ai} is water absorption after immersion (%), W_{aib}, water absorption after immersion and boiling (%), and P the iron powder content in percentage (%).

The relation between water absorption and compressive strength at 28 days, were analyzed using linear regression as shown in Figure 9. The result showed from this scatter that a better correlation obtained between the compressive strength and water absorption. As can be expected, higher water absorption levels at a higher porosity, and thus lower concrete strength. However, the correlation between those two parameters is high (R^2 = 0.8521) and defined as a linear function as shown Equation (7). This is meant a variation of compressive strength is due to water absorption.

$$F_c = 66.375 - 4.7323 \times W_a \quad (7)$$

where F_c is compressive strength in MPa and W_a the water absorption (%).

3.5. Porosity

The results of the porosity in hardened concrete at 28 days are shown in Table 6. The porosity of the control specimen (M0) is 19.94%, it starts reducing when the iron powder is added as a concrete component. We noticed that when 1.5% and

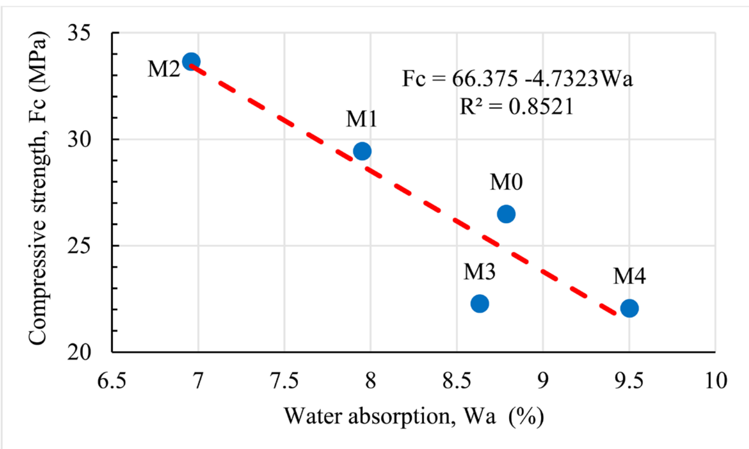

Figure 9. Relation between compressive strength and water absorption.

2.5% of cement is replaced by iron powder, the porosity decreases by 9.38% and 19.16% respectively. It started increasing when 3.5% and 5% of iron powder is added to the concrete. It is shown that the iron powder is slightly more effective in modifying the pore structures and reducing the porosity of the concrete.

The relationship between the porosity and the amount of iron powder in the concrete is shown in Figure 10. This result showed that a certain level of the amount of iron powder, the porosity decreases. This phenomenon is due to the fineness particles of iron powder (200 nm) that fill the pore space of the concrete. The coefficient of determination (R^2 = 0.7869) found in the regression analysis shows that the correlation between the two parameters is significant.

Figure 11 is showing the relationship between compressive strength and the porosity. We can notice from the regression curve that higher is the porosity

Table 6. Porosity of binary blended concrete.

Designation	M0	M1	M2	M3	M4
Porosity (%) at 28 days	19.94	18.07	16.12	19.60	21.51

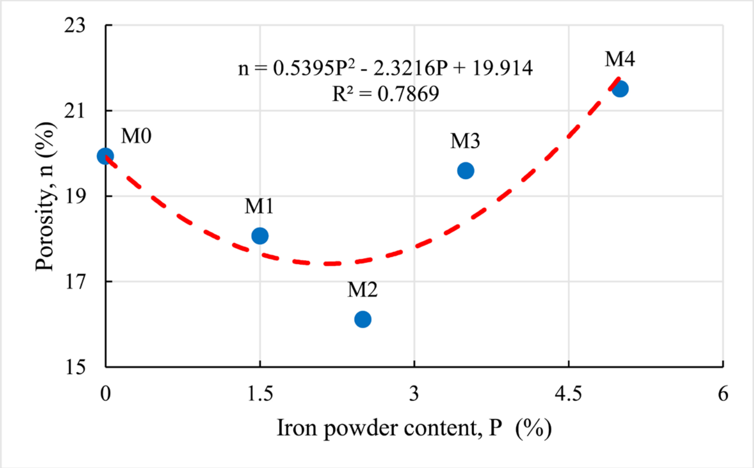

Figure 10. Relationship between porosity and the amount of iron powder.

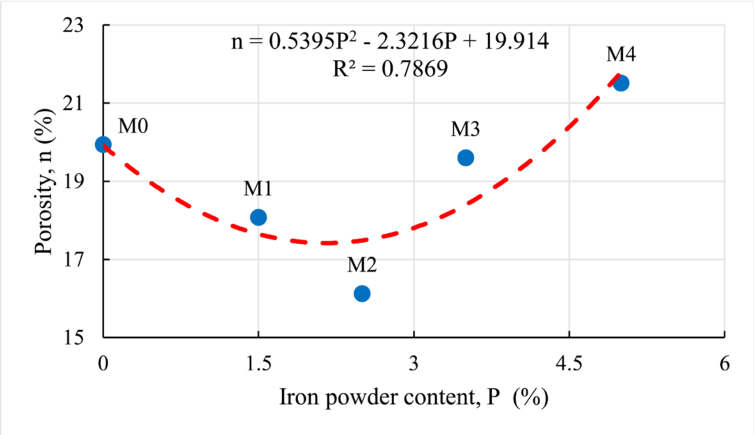

Figure 11. Relationship between compressive strength and porosity.

lesser is a compressive strength. The highest value of the compressive which is 33.64 MPa at 2.5% replacement has the lesser percentage of the porosity of 16.12%. As can be seen, from Equation (8), a linear function was found from regression analysis to correlate the compression strength and the porosity (R^2 = 0.8498).

$$F_c = 69.074 - 2.2207 \times n \tag{8}$$

where F_c is compressive strength in MPa and n the porosity (%).

The relationship between water absorption and porosity of the iron powder concrete was obtained as shown in Equations (9) and (10). From the regression analysis, it was found that the water absorption increased linearly as the porosity increased.

$$W_{ai} = 0.4696 \times n - 0.5774 \tag{9}$$

$$W_{aib} = 0.4723 \times n - 0.7371 \tag{10}$$

where W_{ai} is water absorption after immersion (%), W_{aib} is water absorption after immersion and boiling (%), and n the porosity (%).

4. Conclusions

Based on the findings of this paper, the following points were concluded:

1) The partial replacement of the cement by iron powder improved significantly the compressive strength in comparison of the concrete without iron powder (Fe_2O_3) particles. It is found that it is advantageous if cement is replaced by iron powder up to a maximum limit of 2.5% with predominant particles of 200 nm.

2) The slump of the fresh concrete decreased with the increase of the amount of the iron powder particles.

3) The water absorption of the hardened concrete increased when the percent content of iron powder increased.

4) The porosity decreased from 1.5% and 2.5% of replacement of cement, and then started increased but remained less than the control specimen.

5) It concluded that, the replacement of cement by iron powder improved the compressive strength and porosity but decreased the slump flow.

Conflicts of Interest

This study was funded by Pan African University Institute of Basic Science Technology and Innovation under the program of African Union Commission. The authors declare that they have no conflict of interest. The authors would like to thank the African Union for the scholarship awarded to support this research.

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Notation List

A	Mass of the oven-dried sample in air (g)
B	Mass of the surface-dry sample in the air after immersion (g)
C	Mass of the surface-dry sample in the air after immersion and boiling (g)
D	Apparent mass of sample in water after immersion and boiling (g)
g_1	Bulk density, dry (g/cm^3)
g_2	Apparent density (g/cm^3)
ρ	Density of water (g/cm^3)
S	Slump (mm)
P	Content of iron powder (%)
C_f	Compaction factor
W_{ai}	Water after immersion
W_{aib}	Water after immersion and boiling
W_a	Water absorption
F_c	Compressive strength (MPa)
n	The porosity (%)
F_t	Tensile splitting strength (MPa)