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Effect of the Hematite Powder (Nano-Particles) on High-Strength RC Deep Beam Shear Behavior

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ABSTRACT

As a result of the development of concrete structures, supplementary cementitious materials have become very important, particularly in structural engineering. Hematite powder, a common iron oxide (Fe_2O_3) found in rocks and soils, exhibits black, brown, and red colors. After treatment, it enhances the mechanical properties of concrete. This paper aims to highlight the influence of hematite powder on the behavior of high-strength RC deep beams. The experimental program consists of testing twelve deep beams under two symmetrical concentrated loads with different shear span-to-depth ratios of 1, 0.67, and 0.33. The deep beams are divided into three groups according to the shear span-to-depth ratio. Each group has four deep beams that differ in the proportion of hematite powder. Four replacement ratios of hematite powder were used in this study (0%, 1%, 1.5%, and 2%) based on the weight of cement. The experimental results showed that adding hematite powder by 1%, 1.5%, and 2% to the weight of cement increased concrete strength by 5.5%, 18.3%, and 4.16% respectively; splitting tensile strength by 37.8%, 63.4%, and 25.3% respectively; and increased concrete density by 1.86%, 3.4%, and 3.47% respectively. In addition, the experimental test results demonstrated that the ultimate load increases with a decrease in the (a/h) ratio and increases with increased concrete compressive strength. Diagonal crack width and mid-span deflection increase with an increase in the (a/h) ratio and decrease with an increase in concrete compressive strength.

1. INTRODUCTION

Reinforced concrete deep beams are structural entities with a small span-depth ratio, such as less than 4 [1]. They are designed with strut-and-tie action rather than flexural action like shallow beams [2]. High shear forces associated with similar applications of the beams in bridges, transfer girders, foundations, and shear walls demand specific detailing considerations for reinforcement [3]. As a result of the importance of deep beams and used widely, supplementary cementation materials such as hematite powder can be used in deep beams. Iron oxide powder (Fe_2O_3) is added to increase concrete's density, strength, and durability. This makes it applicable for radiation shielding in nuclear facilities as it increases the density of concrete from the normal 2400 kg/m^3 to more than 3000 kg/m^3. Hematite improves compressive strength, enhances durability by reducing permeability, and provides improved thermal stability. Its high atomic weight enables effective attenuation of gamma and neutron radiation and thus represents a material of interest for medical, nuclear and military applications [4, 5].

Nazari et al. [6] studied the impact of hematite powder (Fe_2O_3) on the compressive strength and workability of concrete by partially replacing cement with hematite powder (particle diameter: 15 nm). The replacement percentages were 0.5%, 1%, 1.5%, and 2% by weight of cement. The results of this study showed that replacing cement with hematite powder increases the compressive strength of concrete up to 2% replacement, with the highest strength observed at 1% replacement. Beyond this point, the strength gradually decreases. Additionally, the results indicated that workability decreases as the hematite content in the concrete mix increases.

Aziz and Yaseen [7] studied the impact of the type and position of shear reinforcement on high-strength deep beams. Their findings concluded that the ultimate load capacity increases with increased web reinforcement. Moreover, inclined shear reinforcement is more effective than vertical reinforcement, and vertical reinforcement is better than horizontal reinforcement. However, using both vertical and horizontal reinforcement together yields better results compared to inclined shear reinforcement alone.

Panjehpour et al. [8] examined the effect of the shear span-to-depth ratio (a/d) on reinforced concrete deep beams. They found that crack width increases with an increase in the shear span-to-depth ratio. Additionally, the results compared with the Strut-and-Tie Model (STM) method recommended by AASHTO LRFD (2012) showed that STM provides more realistic results within the range 0.75 ≤ a/d ≤ 2, compared to ACI 318-11.

Yaseen [9] studied the shear strength of high-performance reinforced concrete deep beams without shear reinforcement (horizontal or vertical). The results showed that mid-span deflection decreases as the concrete strength increases, transitioning from normal-strength concrete to high-strength concrete and further to high-performance concrete. Additionally, diagonal shear cracking load and ultimate load capacity increase as the compressive strength of the concrete increases.

Largeau et al. [10] studied the influence of hematite powder (Fe_2O_3) with a density of 5 g/ml on the compressive strength, tensile strength, and workability of concrete. Four replacement ratios of hematite by weight of cement (1.5%, 2.5%, 3.5%, and 5%) were considered in this study. The experimental results showed that the workability of concrete decreases as the hematite powder content increases. The replacement percentages of 1.5% and 2.5% resulted in an increase in compressive strength by 11.17% and 27.03% at 28 days, respectively. However, 3.5% and 5% replacement led to a decrease in compressive strength by 7.14% and 16.68%, respectively. Additionally, 1.5% hematite replacement increased splitting tensile strength, whereas 2.5%, 3.5%, and 5% replacement reduced splitting tensile strength by 3.24%, 6.48%, and 13.43%, respectively.

Kongsat et al. [11] similarly found that the inclusion of hematite nanoparticles improved the formation of calcium silicate hydrate (C–S–H) gel, leading to better interfacial bonding and increased tensile and flexural strengths.

Albidah et al. [12] studied the effect of coarse aggregate characteristics (toughness and maximum nominal size) and shear (web) reinforcement on reinforced concrete deep beams. The results showed that shear reinforcement and larger aggregate nominal size increase shear strength.

Ghannam et al. [13] tested the impact of granite and iron powders on the compressive and flexural strength of concrete deep beams. The results showed that replacing 10% of sand with granite powder (GP) increased compressive and flexural strength by 30% compared to concrete without granite powder. Additionally, replacing 20% or more of sand with iron powder (IP) also led to increased compressive and flexural strength.

2. MATERIALS AND METHODS

2.1 Portland cement

Table 1. Physical properties of cement

S. NO.	Characteristics	Value	ASTMC150 [14]
1	Area of specified surface m^2 /kg	240	Minimum 230
	Setting Time (min)		
2	Initial	98	Minimum 45
	Final	309	Maximum600
3	Fineness (Blaine) m^2/kg	368	Minimum 250
	Compressive Strength (MPa)		
4	3 days	17.5	Maximum 15
	7 days	28	Maximum 23

The Portland cement used in this research was manufactured by LAFARGE Company. Its physical and chemical properties comply with the European Standard EN 197-1:2011 and the Iraqi Laboratory Specification No. 5/1984 as shown in Table 1.

2.2 Fine aggregate

Clean and washed sand from natural sources, passing through a 4.75 mm sieve, is used. The sieve analysis and sulfate content are also examined. Table 2 shows the results of testing.

Table 2. Sieve analysis of fine aggregate

NO.	Sieve Size (mm)	Passing %	
		Fine Aggregate%	ASTM C33 [15]
1	10	100	100
2	4.75	100	95100
3	2.36	78	80-100
4	1.18	65	50-85
5	0.6	41	25-60
6	0.3	16	5-30
7	0.15	6	0-10
Passing 0.075 mm^0		0.2	0-3
		Sulfate test	
Sulfate content % of S03		0.35	Max. 0.5

2.3 Course aggregate

Crushed and cleaned gravel from natural sources in Basra (Jabal Sanam), retained on a 4.75 mm sieve, is used in the concrete mix. The sulfate content and sieve analysis are conducted in accordance with ASTM C33. Table 3 shows the results of course aggregate testing.

Table 3. Sieve analysis and sulfate test for coarse aggregate

No.	Sieve Size (mm)	Passing %	
		Coarse Aggregate	ASTM C33 [15]
1	19	91	90-100
2	14	24	20-55
3	10	0.7	0-10
4	4.75	0.4	0-5
5	Clay %	1	≤2
		Sulfate Test	
	% of S03	0.06	≤1

2.4 Silica fume

The silica fume used in this study is supplied by Sika and conforms to ASTM C1240 (2004). The chemical properties of silica fume are shown in Table 4.

Table 4. Chemical properties of silica fume

Content	Value	(ASTM C1240) [16]
SiO_2(Silicon Dioxide) (%)	95.87	Not less than 85.0
$A1_2O_3$(Aluminum Oxide) (%)	1.17	
Fe_2O_3 (Iron Oxide) (^{0}/0)	0.09	
CaO (Calcium Oxide) (%)	0.23	
MgO (Magnesium Oxide) (%)	0.02	
So_3(Su1fate) (^{0}/0)	0.25	
Loss on Ignition (L.O.I) @ 975c(%)	2.92	Not more than 4.0
Moisture Content (H_2O) (%)	0.48	Not more than 3.0

2.5 Superplasticizer

Its chemical properties comply with ASTM C494 [17]. It is used to increase concrete workability and reduce water content in the concrete mix. Table 5 shows the chemicals properties of superplasticizer.

Table 5. Chemicals properties of superplasticizer

Technical Items	Description Propertied
Color	Yellow liquid
Packaging	1000 Kg (IBC) 250 KG 20 Kg 4 Kg Jeny cans Bulk Tanks packing available upon request
Density	1.061 +/- 0 01 kg/l at liquid
Chemical base	Modified poly carboxylates-based polymer
pH value	4.5-6
Effect of over dosage	•Delay of initial setting (Related positively with an increased quantity of admixture). •Higher workability •Higher early and final strength

2.6 Hematite powder (Nano Fe_2O_3)

Hematite is an iron oxide particle (Fe_2O_3) used in concrete to increase compressive strength and density. Table 6 shows the physical properties of hematite powder.

2.7 Steel rebar

Grade 60 Ukranian steel bars with grooved (deformed bars) were used in the specimens Φ12 bars are used in the top(compression zone) and bottom(tension zone) as longitudinal reinforcement as well as used in vertical shear reinforcement (stirrups). Table 7 shows the rebar characteristics.

3. CONCRETE MIX

3.1 High-strength concrete mix without hematite powder

Three deep beam specimens were made from a high-strength concrete mix, which consists of cement, sand, gravel, and low water content, so they used superplasticizers to increase workability. Table 8 shows the mix proportion of high-strength concrete.

3.2 High-strength, high-density concrete mix with hematite powder

Nine deep beam specimens were made from a high-strength concrete mix with different ratios of hematite powder. Three hematite powder replacement ratios from cement weight are 1%, 1.5%, and 2% were used in this study, and the W/binder ratio and superplasticizer kept constant in all mixes. Table 9 shows mix proportion of high-strength concrete with hematite powder.

Table 6. Chemicals properties of superplasticizer [17]

Diameter (nm)	surface Volume Ratio (m^2/g)	Bulk Density (g/cm^3)	Real Density (g/cm^3)	Purity %
15±3	155±12	<0.13	5.7	>99

Table 7. Rebar characteristics [18-25]

Diameter Bar (mm)	Actual Diameter Bar (mm)	Yield Strength (N/mm^2)	Tensile Strength (N/mm^2)	Elongation %	Bend
12	11.91	460	636.2	706.8	NO crack

Table 8. Mix proportion of high-strength concrete

Ingredient	Water	Cement	Silica Fume	Sand	Gravel	Superplasticizer	(W/C+S)
Quantities (Kg/m^3)	140	450	50	670	1090	10	0.28

Table 9. Mix proportion of high-strength concrete with hematite powder

Materials	Units	Specimens		
		HSDB-1(1%)	HSDB-2(1.5%)	HSDB-3(2%)
Weight of Hematite (replacing percent)	$\frac{kg}{m^3}$	4.5	6.75	9
Water	$\frac{kg}{m^3}$	138.6	137.9	137.2
Cement	$\frac{kg}{m^3}$	445.5	443.25	441
Sand	$\frac{kg}{m^3}$	670	670	670
Gravel	$\frac{kg}{m^3}$	1090	1090	1090
Silica	$\frac{kg}{m^3}$	49.5	49.25	49
Superplasticizer	Kg/L	10	10	10
Water/(cement+silica)		0.28	0.28	0.28

Table 10. Parameters of deep beam specimens

Type of test Designation Name	Compression Strengtgh Cubic Fcu (N/mm^2)	Compression Strengtgh Cylinder f'c (N/mm^2)	Tensile Spliting Strength Load (N)	Tensile Spliting Strength Fsp	Modulus of Elasticity Ec (N/mm^2)
CONTROL(0%)	60	40.12	97968	3.12	27928.9
HSDB_1(1%)	63.3	50.2	135020	4.3	30422.8
HSDB_2(1.5)	71	57.3	160140	5.1	32031.3
HSDB_3 (2%)	62.5	48.5	122774	3.91	30021

4. DEEP BEAM DETAILS

The dimensions and reinforcement of the deep beam specimen are Chosen according to ACI318M-18 (strut and tie method). The dimensions and rebar of the deep beam are shown in Figure 1. All deep beams are simply supported and tested under two symmetrical concentrated point loads. Table 10 shows parameters of deep beam specimens.

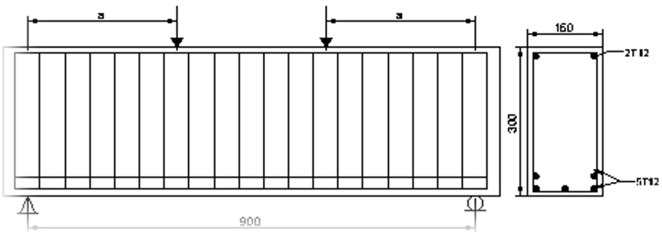

Figure 1. Deep beam details

5. EXPERIMENTAL PROGRAMS

The experimental program of this study is divided into two parts. The first part tested the mechanical properties of mortar, and the second part included a deep beam test.

5.1 Mechanical properties of mortar

For each mix: Six cubes with dimensions of 150 × 150 × 150 mm and six cylinders with dimensions of 100 × 200 mm are used to test the concrete compressive strength at 7 days and 28 days, according to ASTMC109. Three cylinders are used to test the splitting tensile strength of concrete at 28 days, according to ASTM 307, and three cubes are used to measure dry density. All cube specimens are cast in steel molds, while cylinder specimens are cast in plastic molds for 24 hours. Afterward, all specimens are cured underwater until the test time.

5.2 Deep beam test

The testing program included twelve simply supported RC deep beam specimens designed to test the effects of hematite powder and shear span-to-depth ratio (a/h) on concrete shear strength. The dimensions of each beam were standardized to a total span of 1000 mm, an overall depth of 300 mm, and a width of 150 mm. The shear span to effective depth ratio (a/d) was 1, 0.67, and 0.33, and the hematite replacement percentages were 0%, 1%, 1.5%, and 2%. A beam with an (a/h) ratio of 1 was considered a control specimen to study the effect of decreasing the (a/h) ratio on the shear behavior of RC deep beams with a constant hematite ratio. Additionally, 0% hematite powder was considered a control specimen to study the effect of replacing cement with hematite on shear behavior in RC deep beams with a constant (a/h) ratio. Twelve simply supported deep beams were tested under two symmetrical point loads, divided into three groups according to the a/h ratio (1, 0.67, and 0.33).

Figure 2. Deep beam test under a symmetrical point load

Two LVDT devices were used to measure the diagonal shear crack width, and a mechanical dial gauge in the middle of the beam was used to calculate mid-span deflection. Figure 2 illustrates the deep beam test under a symmetrical point load. Figures 3, 4, and 5 show the crack propagation and mod of failure in deep beam specimens at groups A, B and C respectively.

Figure 3. Deep beam specimens at group one (a/h=1)

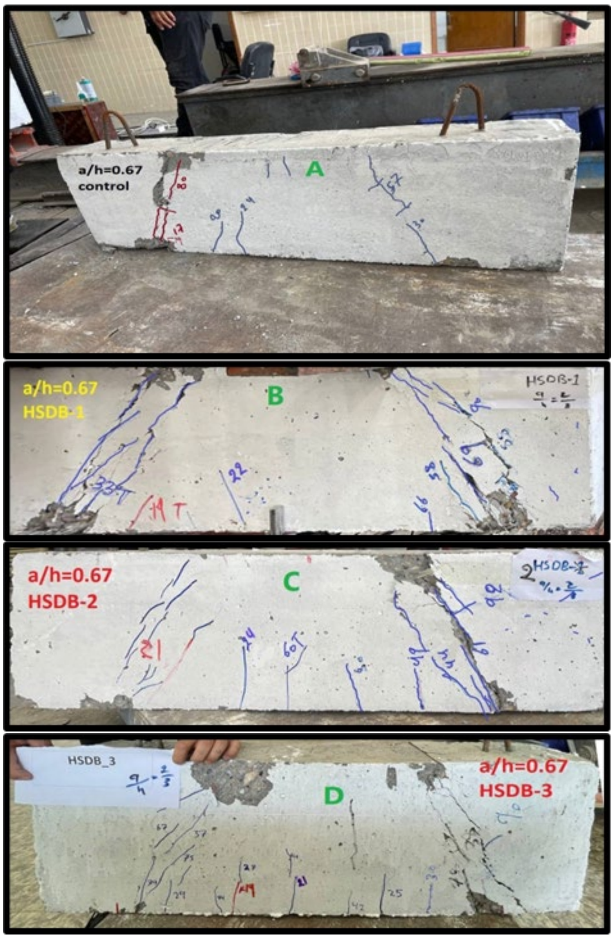

Figure 4. Deep beam specimens at group two (a/h=0.67)

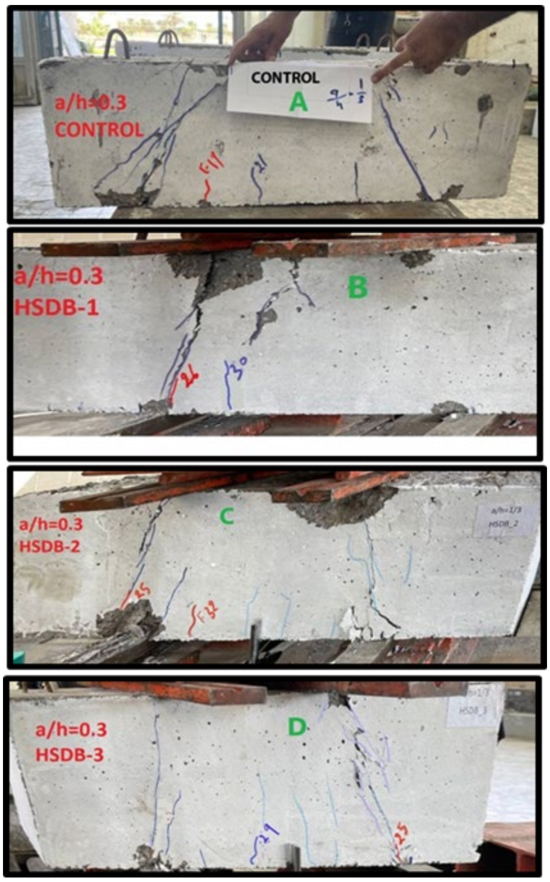

Figure 5. Deep beam specimens at group three (a/h=0.33)

6. RESULTS

6.1 Cubs and cylinders samples

6.1.1 Slump test

Slump tests were conducted on four types of concrete mixes, differing in the percentage of cement replaced by hematite powder. Four replacement ratios of cement weight (0%, 1%, 1.5%, and 2%) by hematite powder were tested for slump and temperature. The results show that the slump decreases as the amount of hematite powder in the concrete mix increases, as illustrated in Table 11.

Table 11. Slump test and corresponding temperature for each mix

Batching Description	Temperature	Slump (mm)
CONTROL	24	220
HSDB_1	23	200
HSDB_2	22.5	193
HSDB_3	25	182

6.1.2 Dry density

Three cubes for each concrete mix were used to measure the dry density of the concrete. The average dry density values for each mix after 28 days of casting are shown in Figure 6. The results show that dry density increases with the increase in hematite percentage in the mix. The average value of dry density for each mix with 0%, 1%, 1.5%, and 2% hematite powder was 2594, 2641.8, 2681.9, and 2683.67 kg/m^3, respectively. The 2% replacement of cement with hematite yielded the highest dry density, with an increase of 3.5% compared to concrete without hematite.

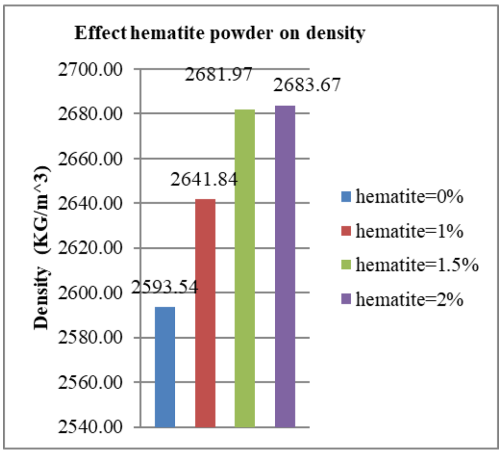

Figure 6. Density for each concrete mix

6.1.3 Compressive strength

After 7 days and 28 days of curing, the cubes and cylinders representing the concrete mixes were tested under compression load. The testing results showed that replacing 1%, 1.5%, and 2% of the cement's weight with hematite powder increased the concrete compressive strength. The rate of increment varied according to the hematite ratio in the concrete. For instance, the average cube compressive strength for concrete containing hematite powder at 1%, 1.5%, and 2% measured at 28 days increased by 5.5%, 18.3%, and 4.16%, respectively, compared to concrete without hematite powder. The 1.5% ratio yielded the highest compressive strength value. Figures 7 and 8 display the compressive strength results for cubes and cylinders. Figures 7 and 8 show the compressive strength results for cubes and cylinders.

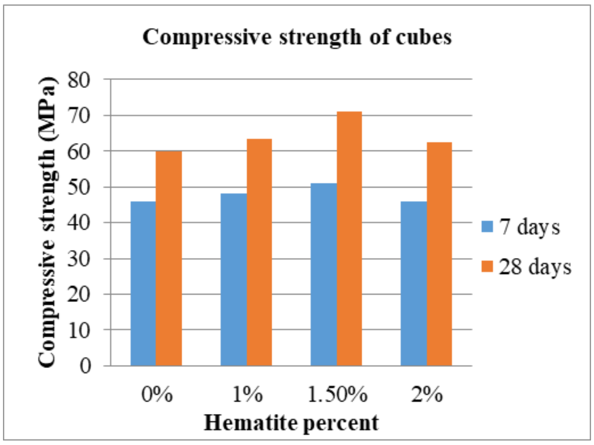

Figure 7. Compressive strength for cubes

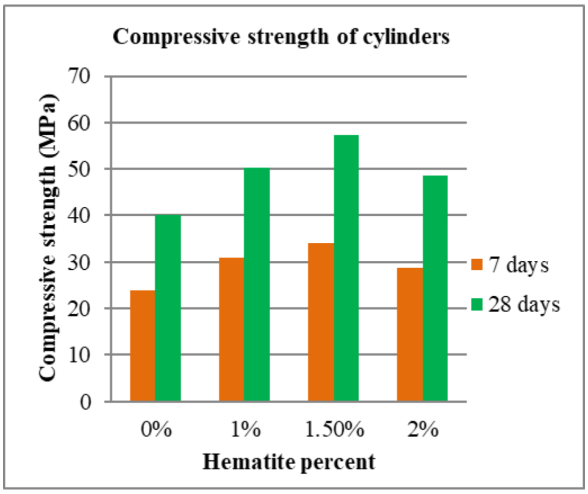

Figure 8. Compressive strength for cylinders

6.1.4 Splitting tensile strength

Figure 9 presents the average tensile strength for each concrete mix. The results showed that the splitting tensile strength increases in concrete with hematite powder compared to concrete without hematite. The average splitting tensile strength at 28 days for 0%, 1%, 1.5%, and 2% hematite powder was 3.12, 4.3, 5.1, and 3.9 MPa, respectively. The 1.5% replacement ratio provided the greatest increment compared to other ratios, with an increase of 63% compared to concrete without hematite.

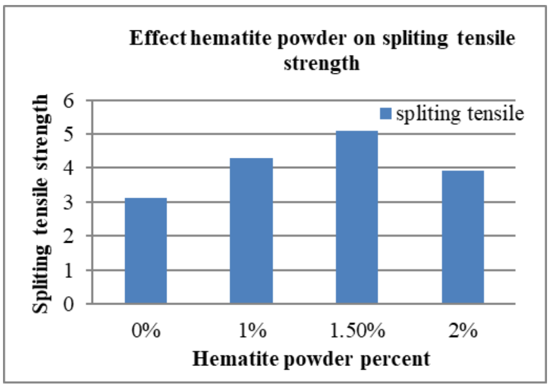

Figure 9. Spliting tensile strength for each concrete mix

6.2 Deep beam specimens

6.2.1 Ultimate load

1) Effect shear span to depth ratio on ultimate load

Practical experiments have shown that the ultimate failure load is significantly affected by the shear span-to-depth ratio, where the ultimate failure load of the deep beam increases as the shear span-to-depth ratio (a/h) decreases. Figure 10 shows the effect of the (a/h) ratio on the ultimate failure load.

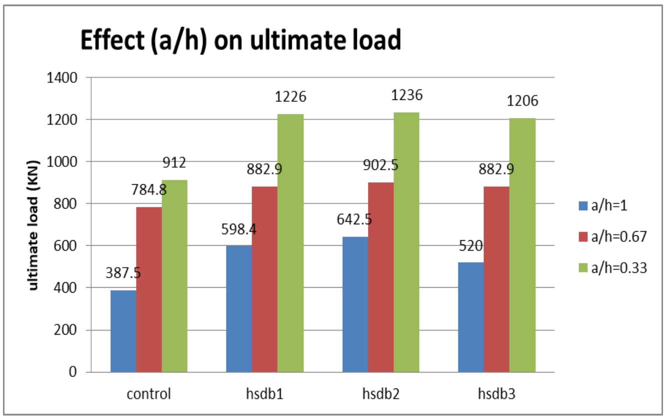

Figure 10. Effect (a/h) ratio on the ultimate failure load

2) Effect compressive strength on ultimate load

For a/h=1, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 54.4%, 65.8%, and 34.17%, respectively. For a/h=0.67, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 12.5%, 15%, and 12.5%, respectively. Additionally, for a/h=0.33, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 32.2%, 35.5%, and 32.2%, respectively. Figure 11 shows the effect of compressive strength on the ultimate load.

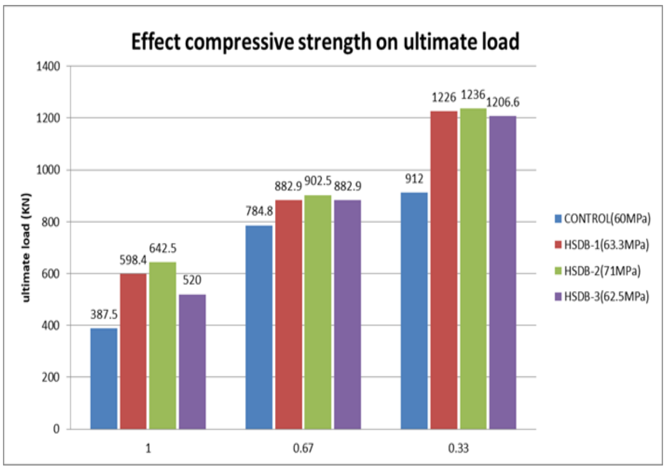

Figure 11. Effect compressive strength on the ultimate failure load

6.2.2 Mid-span deflection

1) Effect shear span to depth ratio on mid-span deflection

The results of the practical tests showed that the mid-span deflection decreases as the a/h ratio decreases. Figures 12-15 show the effect of a/h on mid-span deflection for each specimen.

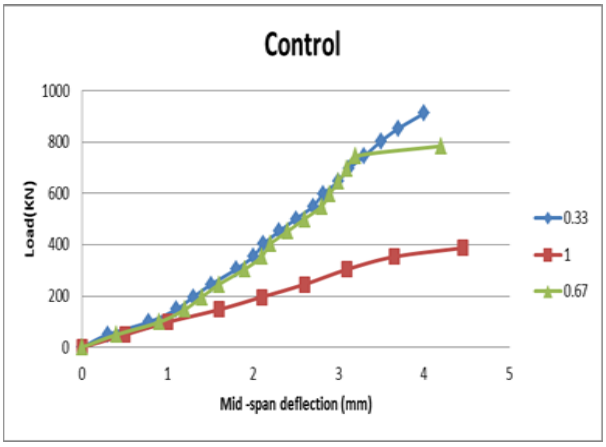

Figure 12. Control specimens

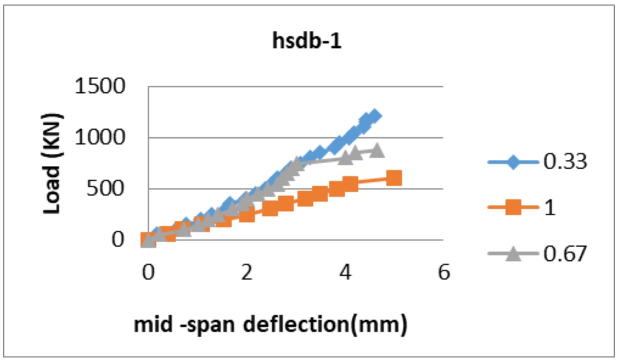

Figure 13. HSDB-1 specimens

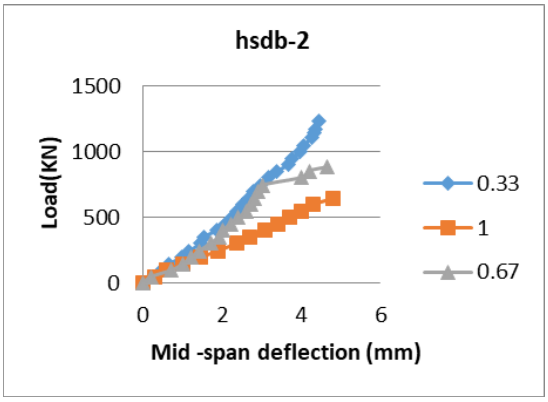

Figure 14. HSDB-2 specimens

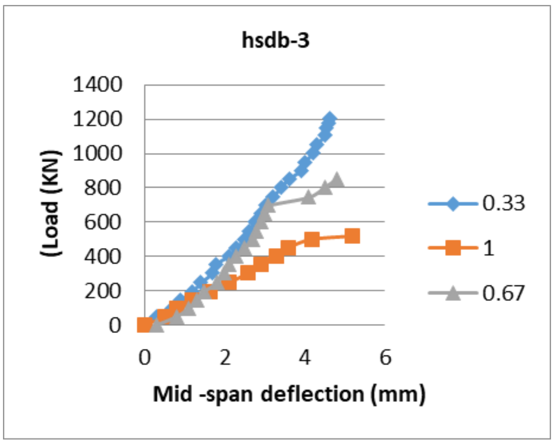

Figure 15. HSDB-3 specimens

2) Effect compressive strength on mid-span deflection

Figures 16-18 show the effect of compressive strength on the deflection at mid-span. It can be observed that the deflection decreases as the compressive strength increases with a constant a/h ratio. For a/h=1, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 12.3%, 7.8%, and 16.8%, respectively. For a/h=0.67, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 10.7%, 9.5%, and 14.3%, respectively. Additionally, for a/h=0.33, when the compressive strength (60 MPa) increases to 63.3, 71, and 62.5 MPa, the ultimate load increases by 15%, 11.3%, and 15.5%, respectively.

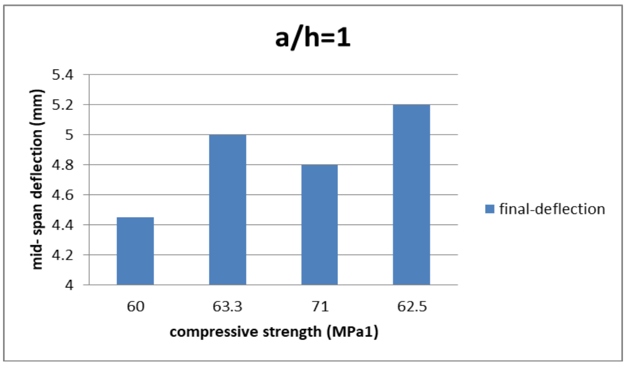

Figure 16. Effect compressive strength on mid-span deflection (a/h=1)

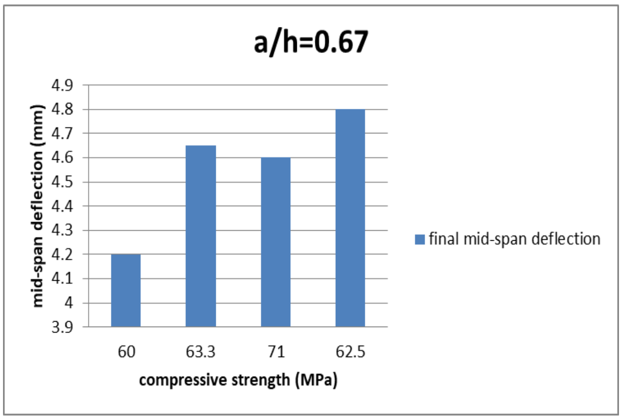

Figure 17. Effect compressive strength on mid-span deflection (a/h=0.67)

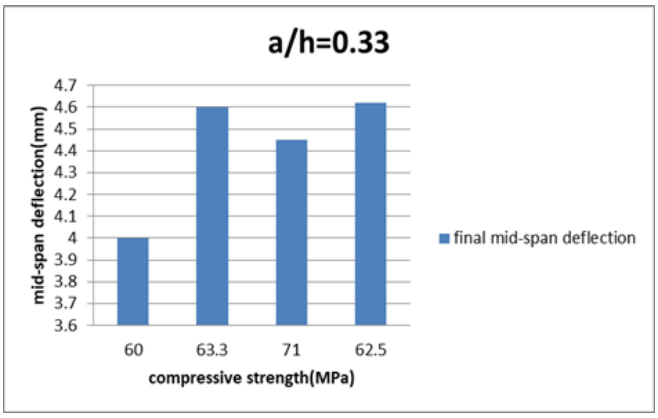

Figure 18. Effect compressive strength on mid-span deflection (a/h=0.33)

7. CRACK WIDTH

7.1 Effect shear span to depth ratio(a/h) on diagonal crack width

The shear span-to-depth ratio is an important factor in determining the width of a diagonal crack. Figures 19-22 show the effect of the a/h ratio on diagonal crack width. It can be observed that the width of the diagonal crack increases with an increase in the shear span-to-depth ratio, with different proportions depending on the compressive strength.

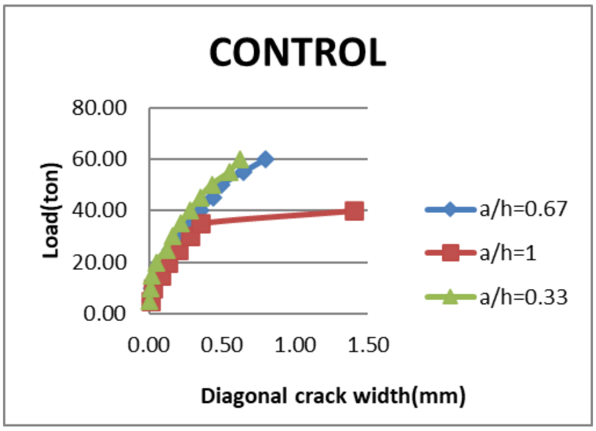

Figure 19. Effect (a/h) on diagonal crack width (CONTROL)

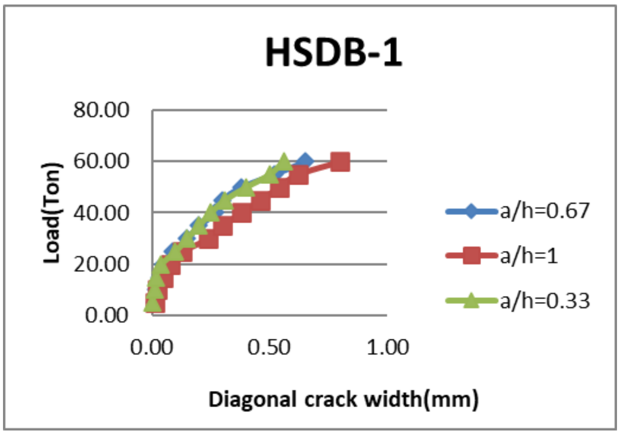

Figure 20. Effect (a/h) on diagonal crack width (HSDB-1)

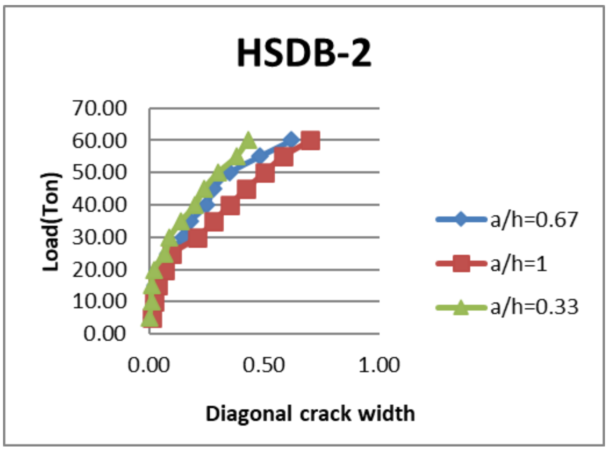

Figure 21. Effect (a/h) on diagonal crack width (HSDB-2)

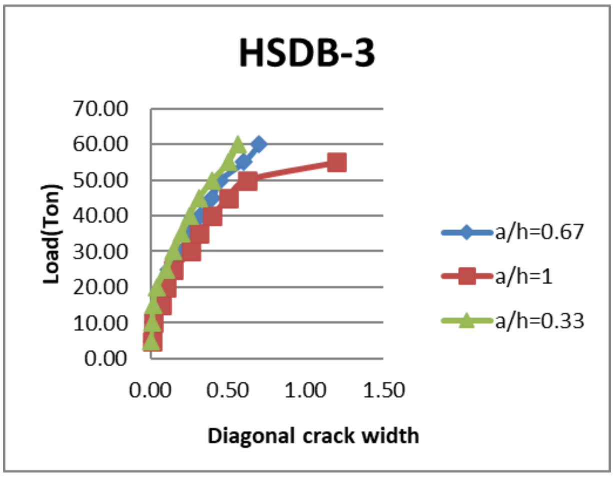

Figure 22. Effect (a/h) on diagonal crack width (HSDB-3)

7.2 Effect compressive strength on diagonal crack width

The diagonal crack width decreases with an increase in concrete compressive strength, and the rate of decrease varies with the a/h ratio. Figures 23-25 show the effect of compressive strength on diagonal crack width.

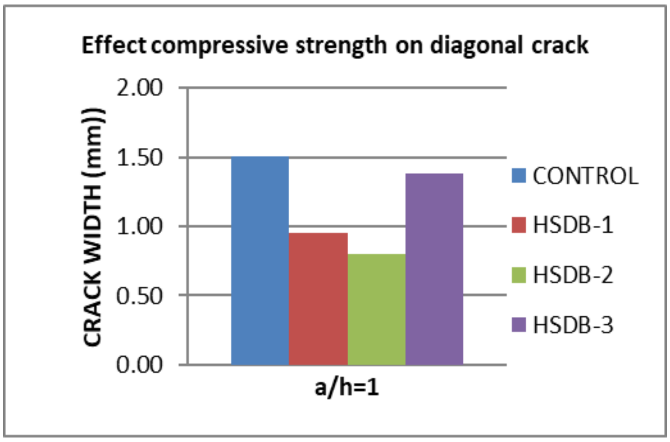

Figure 23. Effect compressive strength on the ultimate failure load

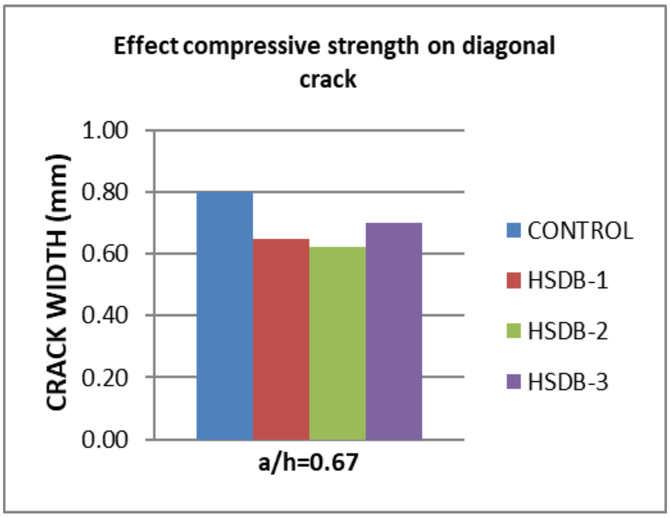

Figure 24. Effect compressive strength on the ultimate failure load (a/h=0.67)

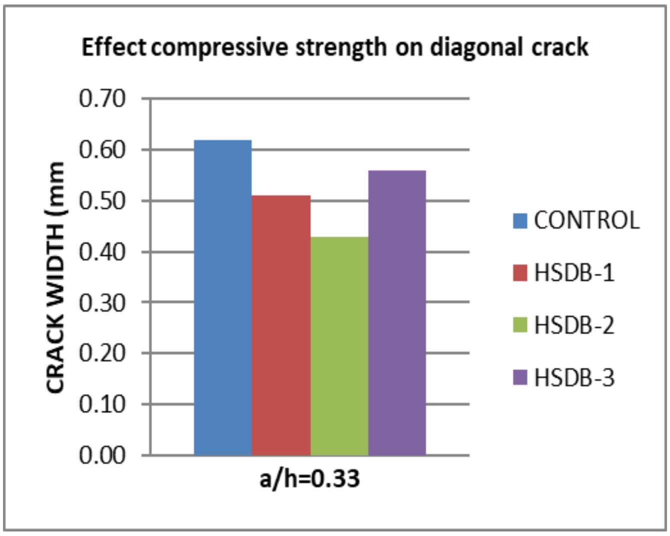

Figure 25. Effect compressive strength on the ultimate failure load (a/h=0.33)

8. RESULTS AND DISCUSSION

8.1 Effect of hematite powder on concrete properties

Hematite powder (Fe_2O_3) fills micro-voids in concrete. When used in a well-balanced ratio, it disperses evenly without causing clumping or reducing strength. This optimal dispersion occurs at a 1.5% replacement ratio.

Hematite strengthens the bond between cement and aggregates. The maximum tensile strength is achieved at 1.5% due to optimal bonding. However, adding more, such as 2%, disrupts this balance.

Hematite increases concrete density, but this effect plateaus beyond 2% due to particle saturation.

8.2 Influence of shear span-to-depth ratio on beam behavior

The shear span-to-depth ratio significantly affects the behavior of deep beams. Lower ratios enhance load-carrying capacity, while higher ratios increase mid-span deflection, leading to large diagonal cracks due to flexural behavior.

Stronger concrete better resists internal stresses, improving load capacity and reducing the likelihood of cracking and deflection.

8.3 Impact of hematite powder on workability and density

Studies show that hematite powder affects concrete workability. As a cementitious material, it absorbs water during mixing, leaving less water available for cement hydration. Consequently, workability decreases with increasing hematite content.

Concrete density, defined as mass per unit volume, is highest when 2% hematite powder is used. However, further increases beyond this percentage do not significantly improve density.

The addition of hematite enhances the mechanical strength of concrete. By optimizing hematite content and adjusting the shear span-to-depth ratio, a structurally efficient beam can be engineered to withstand loads while minimizing cracking.

9. CONCLUSION

1) Replacing cement with hematite powder at weight ratios of 1%, 1.5%, and 2% increases concrete compressive strength by 5.5%, 18.3%, and 4.16%, respectively. It also enhances splitting tensile strength by 37.8%, 63.4%, and 25.3%, respectively, and increases concrete density by 1.86%, 3.4%, and 3.47%, respectively. The optimal replacement ratio is 1.5%.

2) The ultimate load increases as the shear span-to-depth ratio (a/h) decreases, while diagonal crack width and mid-span deflection decrease.

3) Higher concrete compressive strength leads to an increased ultimate load and a reduction in both diagonal crack width and mid-span deflection. The addition of hematite powder in the concrete mix reduces workability, as slump decreases with increasing hematite content.

4) Concrete mixes with 2% hematite powder achieve the highest density, while those with 1.5% exhibit the best mechanical properties.

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