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The Evaluation of Bond Strength of Heavyweight Concrete Containing Iron Pellets

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ABSTRACT

Heavyweight concrete incorporating iron aggregates is widely utilized as a radiation-shielding material in environments with harmful radiation due to its high density. Although this material is also employed as a structural component, certain mechanical properties, such as the bond strength between concrete and reinforcing steel bars, remain insufficiently studied. This paper investigates the bond strength of concrete containing varying percentages of iron pellets and its interaction with steel reinforcement. For this study, 25%, 75%, and 100% of the concrete aggregate was replaced with iron pellets, ensuring an appropriate grain size distribution. After curing under standard conditions, the specimens were subjected to direct pull-out tests. The results indicate that, except for the sample with 25% iron pellets, the inclusion of iron pellets slightly reduces compressive strength but enhances bond strength across all samples. Notably, adding 25% iron pellets combined with 5% micro silica in heavyweight concrete significantly improves compressive strength by 20% and bond strength by 43%.

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1. Introduction

Concrete, a durable, economical, and highly functional material with excellent mechanical properties, is one of the most widely used materials in the construction industry. A key reason for its increasing utilization is its adaptability; concrete can be modified in numerous ways to suit specific environmental conditions or desired performance requirements. One of the high-risk environments where the use of concrete is indispensable is in areas exposed to harmful nuclear radiation. In such settings, concrete is expected not only to fulfill its structural functions and meet durability requirements but also to provide effective shielding against harmful radiation. In these environments, heavyweight concrete, which has a higher density than conventional concrete, is typically employed. Concrete with a density exceeding 2600 kg/m³ is typically classified as heavyweight concrete. This type of concrete reduces the

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transmission of radiation due to the inclusion of elements with high atomic numbers and elevated density. High-density aggregates, often containing iron, are commonly used in the production of heavyweight concrete.

The bond strength between concrete and rebar is a critical mechanical parameter that ensures the composite performance of reinforced concrete components. It enables the effective transfer of forces between the concrete and the rebar, which is essential for structural integrity. This bond strength is primarily achieved through adhesion, friction, and the mechanical interlocking of aggregates with the rebar ribs. Research indicates that the bond strength primarily occurs through the interlocking mechanism of aggregates and reinforcement [1, 2]. Several factors influence bond strength, with the most significant being the concrete's compressive strength, the geometry of the rebar ribs, the rebar diameter, and the presence of transverse reinforcement [3]. Research has demonstrated that ribbed bars exhibit bond strengths up to 30% higher than plain bars, irrespective of the concrete's compressive strength [3]. While increasing the compressive strength enhances bond strength, larger bar diameters typically reduce it [4, 5]. Xuan proposed a predictive relationship for bond strength based on compressive strength [6]. The thickness of the concrete cover over the bars also significantly influences bond strength. This effect is often evaluated using the c/D ratio, where c denotes the concrete cover thickness and D represents the bar diameter [7]. Ahmed et al. highlighted that increasing the c/D ratio enhances bond strength and reduces slip for bars of varying diameters [8]. Additionally, the presence of transverse reinforcement further improves bond strength [4].

Dragomirová and Palou demonstrated that the adhesion between iron-containing aggregates and cement paste is weaker in the transition zone compared to ordinary concrete, potentially compromising the structural integrity of the concrete [9]. Wang et al. investigated the influence of rebar length, diameter, and concrete cover on bond strength in heavyweight concrete, concluding that rebar length is a highly significant parameter affecting bond strength [10]. Additionally, Rosyidah et al. examined the impact of rebar rib geometry on the failure mechanisms associated with bond deterioration [11].

Several methods are available for quantitatively evaluating the bond strength between concrete and rebar, with the most widely used being the direct pull-out test and the beam end test, as outlined in the ASTM C944 standard. In the direct pull-out method, a rebar of specified length is embedded within a cubic or cylindrical concrete specimen. A tensile force is then applied to the rebar, and the maximum force required to pull out the rebar is measured based on the potential failure mechanisms. Although the results obtained from these methods are not directly applicable for design purposes, they serve as valuable comparative criteria. Numerous theoretical and empirical models have been developed to evaluate bond strength, with theoretical models typically yielding more conservative estimates [12]. Empirical models, however, can vary depending on the type of test conducted (reference). Hou et al. proposed a model based on key influential parameters, incorporating results from both direct tensile tests and beam tests [13]. Zhou et al. developed a predictive model for bond strength by analyzing data from a large number of tests conducted by other researchers. Through regression analysis, they found that both beam and pull-out test specimens were influenced by the same coefficients related to the development length-to-diameter ratio and restraint conditions, with the exception of concrete strength [1]. Despite the development of numerous models, no specific model has been proposed for concrete containing iron pellets. Furthermore, although extensive research has been conducted on bond strength, studies on heavyweight concrete, particularly concrete incorporating iron pellets, remain limited. Addressing this gap and responding to the growing interest in the mechanical properties of such concrete, this study investigates the bond strength of concrete with varying percentages of iron aggregate. The effects of different iron aggregate proportions on compressive strength and bond strength are examined, and the results are compared with existing empirical models.

2. Materials and methods

2.1. Materials

The materials used to fabricate the studied samples consisted of Type 2 Portland cement sourced from the Behbahan Cement Factory, potable water from Behbahan city, fine and coarse aggregates obtained from local Behbahan mines, iron aggregate from the Gol Gohar mines in Sirjan, Ahvaz iron shell, Azna micro silica, and a polycarboxylate-based superplasticizer. The properties of the Type 2 cement utilized in this study, including its initial and final setting times, as well as the compressive strength of samples at various curing ages for quality control purposes, are presented in Table 2. Micro silica in powder form, with the properties detailed in Table 3, was incorporated into the mixtures. To maintain consistent workability and reduce the water-to-cement ratio, a polycarboxylate-based superplasticizer, whose properties are outlined in Table 4, was employed. The aggregates, with a modified gradation curve as illustrated in Figure 1, exhibited saturated surface-dry densities of 2528 kg/m³ for coarse aggregates and 2597 kg/m³ for fine aggregates. The water absorption percentages were 1.6% for coarse aggregates and 1.56% for fine aggregates. Iron pellets, with a bulk density of 4540 kg/m³ and chemical composition detailed in Table 1, along with iron shells having a bulk density of 4230 kg/m³, were used as partial replacements for conventional aggregates in this study. The visual appearance and gradation of the iron aggregates are presented in Figure 2.

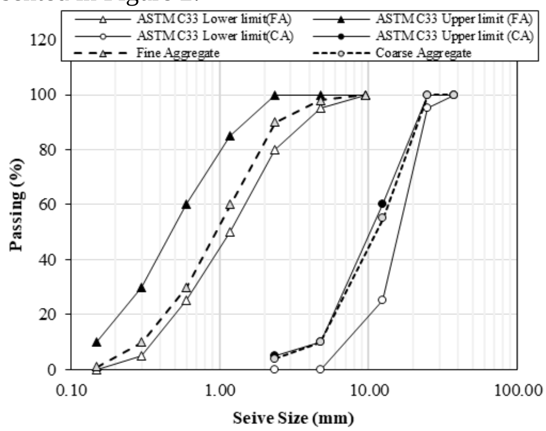

Fig. 1. Aggregate size distributions

Table 1
Chemical composition of iron pelts.

Composition	Fe (T)	SiO_2	Al_2O_3	CaO	MgO	FeO	P	S
Amount (%)	68	3.5	0.7	1.5	1.6	1.2	0.07	0.01

Table 2
Properties of Portland cement type II.

Initial set time (minutes)	Final set time (minutes)	Compressive strength (kg/cm^2)		
		3 days	7 days	28 days
185	220	245	405	546

Table 3
Properties of micro silca powder.

Silica (%)	Moisture (%)	Density (kg/m^3)	Blaine (m^2/gr)
93	0.25		22

Table 4
Properties of Polycarboxylate superplasticizers.

Name	pH	Solid content (kg/m^3)	Specific gravity
HF5000M	7.2	34	1.02

2.2. Sample preparation

To evaluate the influence of iron pellets on bond strength, 25%, 75%, and 100% of the coarse aggregate in the control mix design was replaced with iron pellets. The quantities of materials used in the examined mix designs are detailed in Table 5. Additionally, micro silica was incorporated into the mix design to enhance the permeability properties of the concrete. Two sets of samples were prepared for testing: one for compressive strength testing, consisting of 15 cm cube specimens, and the other for direct pull-out testing, which involved embedding a 14 mm diameter rebar at the center of a cube specimen during casting. As illustrated in Figure 3, a 5 cm length of PVC pipe was used to cover the upper portion of the rebar to prevent concrete-rebar bonding in that region, thereby eliminating stress and pressure effects at the top of the sample. Bond strength was thus developed only along the lower 10 cm of the rebar. The tests were conducted at 28 and 90 days, with three replicates tested for each mix design.

The direct pull-out test is the most widely used method for evaluating bond strength. This test employs a metal box, the dimensions of which are illustrated in Figure 6. As depicted in the figure, one side of the box is secured to the lower jaw of the tensile testing machine, while the upper jaw pulls the rebar after the concrete sample is positioned inside the box. As the tensile force on the rebar increases, different failure modes may occur: (1) if the tensile strength of the rebar is lower than the bond strength, the rebar ruptures at the top of the sample; (2) the rebar is pulled out of the sample without splitting the concrete; or (3) failure occurs due to concrete splitting.

Fig. 2. Iron mill scale and Iron pelts shapes and sizes.

Table 5

Mixes design and material compositions in one cubic meter of concrete samples.

Mixes	water (kg)	cement (kg)	Iron powder (%)	Iron pelts (%)	Iron powder (kg)	Iron pelts (kg)	Fine aggregates (kg)	Coarse aggregates (kg)	Micro-silica(kg)
C	180	370	-	-	-	-	960	860	-
CM	180	350	-	-	-	-	960	860	20
H25M	180	350	25	25	356	336	720	645	20
H75M	180	350	75	75	1068	1010	240	215	20
H100M	180	350	75	100	1068	1350	240	-	20

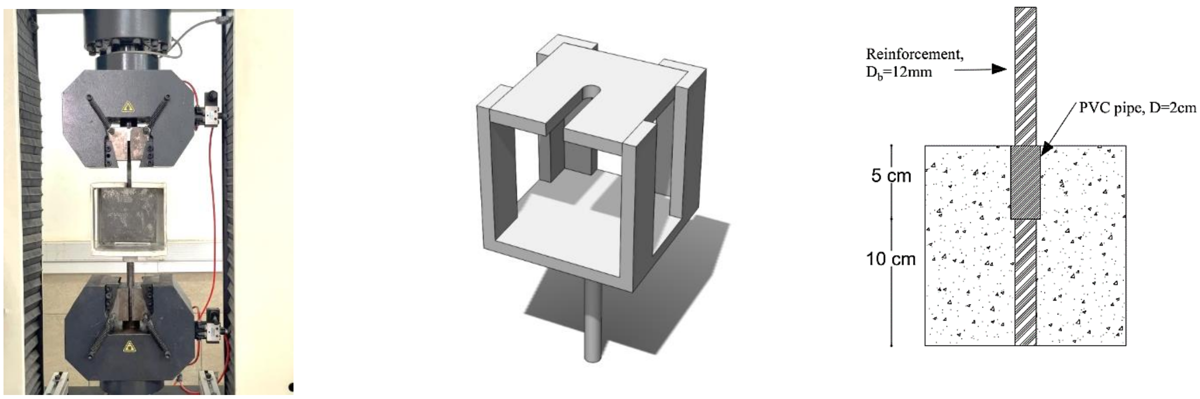

Fig. 3. Test setup and specimen for direct pull out test.

Table 6
Compressive strength of Mixes at 28 days and 90 days.

Mixes	28 days (MPa)	90 days (MPa)	Density(kg/m^3)
C	35	37	2403
CM	31	42	2407
H25M	37	45	2653
H75M	30	37	3169
H100M	28	35	3589

3. Results and discussion

3.1. Compressive strength

The compressive strength results of the samples are presented in Table 2. Figure 2 illustrates the ratio of the compressive strength of each sample to that of the control sample. At 28 days, all samples except the one containing 25% iron pellets exhibited lower compressive strength than the control. The compressive strength ratios for samples H75M and H100M were 0.86 and 0.8, respectively, indicating a maximum strength reduction of 20% when all aggregate was replaced. In contrast, sample H25M showed a 6% increase in compressive strength, suggesting an effective synergy between iron and conventional aggregates in load-bearing capacity.

At 90 days, similar to the 28-day results, the compressive strength of the H25M sample exceeded that of the control sample, showing a significant 22% increase compared to the control. This represents a notable improvement over its 28-day performance. The compressive strength of the H75M sample matched that of the control, while the H100M sample exhibited only a 5% reduction. Overall, the negative effects of using iron aggregate diminished over time, with the samples achieving acceptable strength levels by 90 days. The inclusion of micro silica further enhanced strength development, as evidenced by the results at 90 days. For instance, the control sample without micro silica showed a strength increase from 35 MPa to 37 MPa, whereas the CM sample (with micro silica) demonstrated a more substantial increase from 31 MPa to 42 MPa, highlighting the activation of micro silica's pozzolanic properties. This trend was also observed in samples containing iron aggregate.

Consistent with findings from other studies (references), increasing the proportion of iron aggregate generally reduces compressive strength. However, the strength reduction observed in this study was less pronounced than values reported elsewhere, likely due to the beneficial effects of micro silica (references). For example, Karami et al. reported that the use of naphthalene-based superplasticizers in samples containing iron pellets contributed to increased strength.

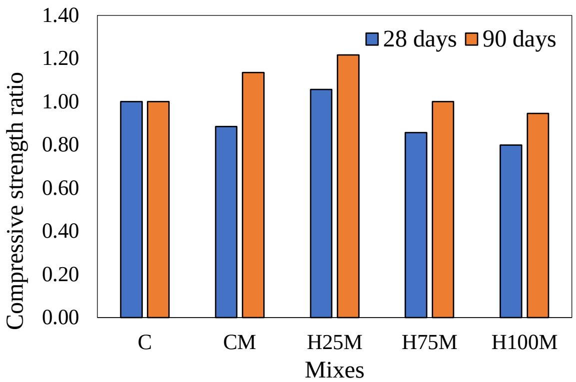

Fig. 4. Compressive strength ratio of specimens to reference specimen

3.2. Bond strength

Based on the experimental setup illustrated in Figure 3, the maximum force sustained by the rebar prior to failure was recorded. The ultimate bond strength, τ_u (in MPa), was calculated using the following equation:

$$t_u = F/(\pi L_d D_b) \tag{1}$$

where F is the maximum force sustained by the specimen (in N), D_b is the rebar diameter (in mm), and L_d is the embedment length of the rebar in contact with the concrete (in mm). For the specimens in this study, L_d was set to 100 mm, and D_b was 14 mm.

Table 3 presents the bond strength values calculated using the maximum force obtained from the direct pull-out test and Equation (1) at 28 and 90 days. The results indicate that, at 28 days, the bond strength of all samples exceeded that of the control sample, with the highest bond strength of 10.25 MPa observed for the H25M sample. As the proportion of iron pellets increased, the bond strength decreased, reaching 8.25 MPa and 8.10 MPa for the H75M and H100M samples, respectively. The inclusion of micro silica also enhanced bond strength at this age, the control sample showing an approximately 9% improvement.

By 90 days, bond strength increased further, likely due to the activation of pozzolanic reactions and the greater contribution of micro silica. The bond strength increased by 24% for samples containing 75% and 100% iron aggregate and by 43% for the sample with 25% iron aggregate. At this age, only the sample containing 25% iron aggregate exhibited higher bond strength than the micro silica-containing control sample. Compared to normal concrete (sample C), the bond strength values demonstrate the effective improvement achieved through the combined use of iron pellets and micro silica.

Table 7
Bond strength of Mixes at 28 days and 90 days, τu.

Mixes	28 days (MPa)	90 days (MPa)
C	7.52	7.92
CM	8.16	13.34
H25M	10.25	14.70
H75M	8.52	10.57
H100M	8.10	10.02

To compare the results of this study with existing empirical models, Table 4 summarizes several widely used models for calculating bond strength. As evident from the table, the most influential parameters in these models are concrete cover, rebar diameter, and concrete compressive strength. In this study, the observed failure mechanism was concrete splitting, which occurs when the maximum tensile stress around the rebar exceeds the concrete's tensile strength. Since the relationship between concrete's ultimate tensile stress and compressive strength is often expressed as a factor of fc0.5fc0.5 in the literature (references), empirical bond strength models typically incorporate this factor along with other influencing parameters. Based on the specimen configurations used in this study, Figure 7 compares the experimental bond strength values with those predicted by the empirical models.

Based on the geometry and compressive strength of specimens, Figures 4 and 5 present the bond strength values predicted by empirical models at 28 and 90 days, respectively. At 28 days, the experimental bond strength values were lower than those predicted by most models, except the model proposed by Hadi, which provided more conservative estimates.

Table 8
Bond strength models.

References	Bond strength, τ_u
Orangun et al. [14]	$0.083045\sqrt{f_c'}\left[1.2+3\left(\frac{c}{d_b}\right)+50\left(\frac{d_b}{L_d}\right)\right]$
Darwin et al. [15]	$0.083045\sqrt{f_c'}\left[\left(1.06+2.12\left(\frac{c}{d_b}\right)\right)+\left(0.92+.08\left(\frac{C^*_{max}}{C_{min}}+75\left(\frac{d_b}{L_d}\right)\right)\right)\right]$
Hadi [16]	$0.083045\sqrt{f_c'}\left[22.8-0.208\left(\frac{c}{d_b}\right)-38.212\left(\frac{d_b}{L_d}\right)\right]$
Esfahani, & Rangan [17]	$8.6\left(\frac{\frac{c}{d_b}+.5}{\frac{c}{d_b}+5.5}\right)f_{ct}$
Diab et al. [18]	$\sqrt{f_c'}\left[0.1377+0.1539\left(\frac{c}{d_b}\right)+2.673\left(\frac{d_b}{L_d}\right)+1.053\left(\frac{h_r}{s_r}\right)\right]$

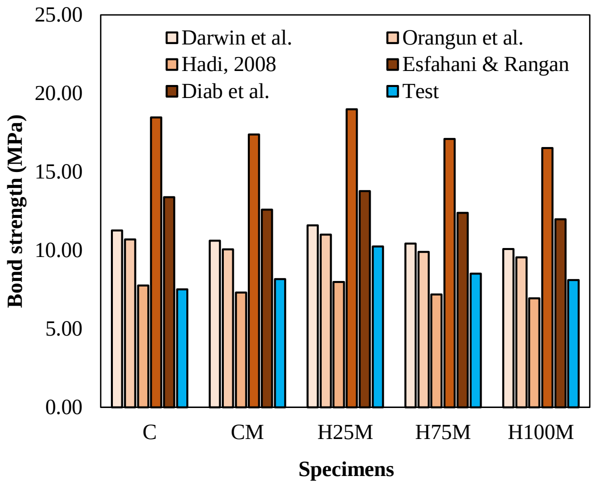

Fig. 5. Bond strength based on some available models and test result at 28 days.

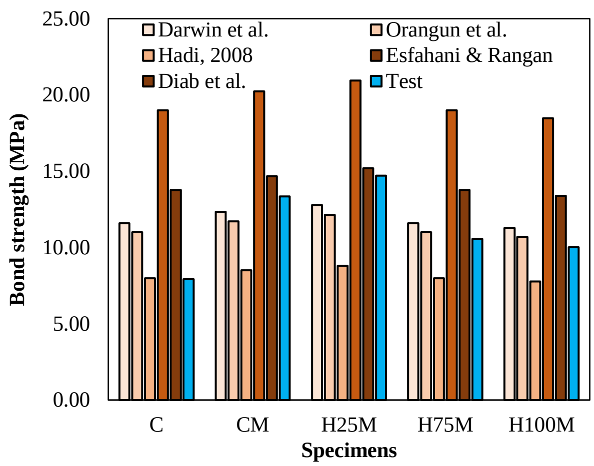

Fig. 6. Bond strength based on some available models and test result at 90 days.

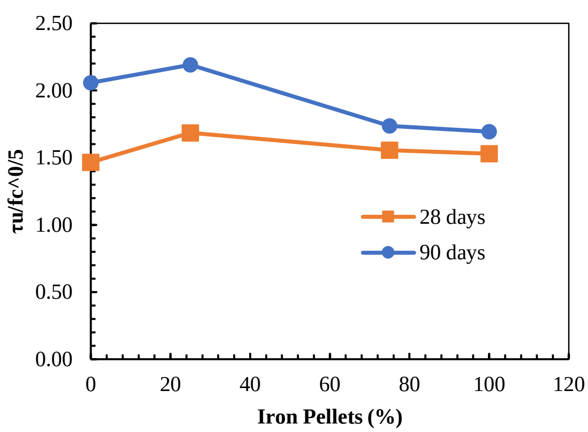

Fig. 7. Bond strength based on percentage of Iron Pelts.

Given the minor discrepancy between Hadi's model and the experimental results, this model can be reasonably applied to other aggregate percentages. By 90 days, the bond strength for the H25M sample exceeded the predictions of most models. However, for samples containing higher proportions of iron aggregate, the experimental values remained consistent with or slightly below the model predictions.

Conclusions

In this study, the compressive strength and bond strength of heavyweight concrete incorporating varying amounts of iron pellets were evaluated at 28 and 90 days using direct pull-out tests. The following general findings were obtained:

- Replacing all aggregate with iron pellets resulted in a 20% reduction in compressive strength, whereas replacing 25% of the aggregate with iron pellets led to a 6% increase in compressive strength at 28 days.
- Increasing the concrete age to 90 days, combined with the addition of micro silica, enhanced the compressive strength of the samples, mitigating the strength reduction caused by iron pellets. In the sample containing 25% iron pellets, the compressive strength exceeded that of the control sample by 20%.
- The inclusion of iron pellets improved bond strength at all ages, with the highest bond strength observed in the sample containing 25% iron pellets. Although bond strength decreased as the percentage of iron pellets increased, it remained higher than that of the control sample without micro silica.
- The combination of micro silica and iron pellets further increased bond strength.

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