Magazine of Civil Engineering. 2021. 108(8). Article No. 10810

Magazine of Civil Engineering

journal homepage: http://engstroy.spbstu.ru/

ISSN 2712-8172

DOI: 10.34910/MCE.108.10

Waste iron powder as aggregate and binder in mortar production

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Keywords: waste iron powder, fine aggregate, mortar, compressive strength, tensile strength, flexural strength

Abstract. This paper study the feasibility of reusing waste iron powder (WIP) in mortar as both natural fine aggregate (NFA) and cement replacement material. Within this context, the physical and mechanical properties of mortar made with five percentage replacements of 0 %, 25 %, 50 %, 75 %, and 100 % for NFA by WIP and 0 %, 2.5 %, 5 %, 7.5 %, and 10 % for cement by fine waste iron powder (FWIP) are studied at 7, 14 and 28 days. Cube, briquette, and prism specimens for compression, tension, and flexural strength, respectively, tests were used. It is found that the workability decreases, and the density of mortar increase with the increased replacement percentage of NFA by WIP. The compressive, tensile, and flexural strength of mortar made with WIP are significantly higher than NFA. The maximum increase in strength of mortar is observed for 75 % WIP, which is 30 % for compressive, 35 % for tensile, and 37 % for flexural strength, respectively, relative to the control at 28 days. Conversely, when FWIP is used as a cement replacement material, all strength decreases with an increase in FWIP. The maximum decrease in strength is observed for 10 % FWIP, which is 40 % for compressive and tensile, and 16 % for flexural strength, accordingly, relative to the control at 28 days. The results presented in this study demonstrate that, to some extent, WIP and FWIP can be used in concrete/mortar production. Successful application of these waste materials may add economical benefit in the production of sustainable building material as well as conserve the natural aggregates.

1. Introduction

The demand for natural fine aggregate (NFA) is increasing as the activities of the construction industry in building infrastructures keep booming. Nevertheless, the demand for other construction materials such as steel, iron, and cement are also increasing, thereby leading to significant waste generation. The use of waste materials generated from the steel industry in concrete can serve to resolve the disposal problem being encountered [1], reduce the demand for NFA, and produce a sustainable building material. In Bangladesh, natural river sand is mainly used as fine aggregate, which is limited and mostly extracted from the riverbed by dredging, resulting in a threat to the environment. In a developing country like Bangladesh, numerous megaprojects are ongoing, which are made with concrete. Therefore, it is expected that there will be a significant amount of depletion of NFA. Hence, it is necessary to find

Miah, M.J., Miah, M.S., Paul, S.C., Kong, S.Y., Babafemi, A.J., Ali, M.K., Patoary, M.M.H. Waste iron powder as aggregate and binder in mortar production. Magazine of Civil Engineering. 2021. 108(8). Article No. 10810. DOI: 10.34910/MCE.108.10

possible alternative raw construction materials that could be used as fine aggregates in the concrete industry. Moreover, it is recorded that the amounts of aggregates used in concrete production the world yearly (estimated at more than 10-11 billion tons 20 years ago), there is great potential for reuse of wastes as aggregate replacement [2–4]. Besides, cement as a binder is an essential material for concrete, and the production of this material produces a lot of carbon dioxide gas in the air, resulting in negative environmental impacts and risks to human life. Therefore, this study investigates the utilization of waste iron powder (WIP) in mortar as both fine aggregate and cement replacement material.

The WIP is the industrial byproduct generated from the workshops, steel mills, and factories in powder form [5], which is not commonly used and is hazardous material to human health since it can be easily inhaled [6]. WIP can be used as a partial or full replacement of NFA in concrete/mortar. The literature shows that using WIP has better mechanical properties, cost-effective, and environment-friendly. Ghannam *et al.* [6] investigated the mechanical properties of concrete made with five percentage replacements (0 %, 5 %, 10 %, 15 %, and 20 %) of sand by iron powder. An increase in compressive and flexural strength was observed for the concrete replacing up to 20 % of sand with iron powder. It was found that iron powder had increased the compressive as well as the split tensile strength of concrete, which is about 25 % higher when fine aggregate was replaced entirely by iron powder [7]. Tayeh and Saffar [8] found that the incorporation of iron powder decreased the compressive strength of mortar, which is inconsistent with the results found in Satyaprakash et al. [7]. The authors explained that the reduction in strength could be due to the small voids appearing on the internal texture of the mortar specimen, which may affect the strength of the mortar.

Furthermore, the replacement of NFA with iron fillings resulted in significantly higher abrasion resistance of concrete. Enhancement of mechanical properties compared to normal concrete was also observed for concrete made with recycled scale and steel chips [9–10]. Similarly, Ismail and Al-Hashmi [11] observed an increase in compressive and flexural strength when 20 % of sand was replaced with waste iron, which is 17 % and 28 % for compressive and flexural strength, respectively, higher than the reference concrete. Other researchers found that the compressive strength of concrete containing iron filings was higher than plain concrete. Besides, the presence of iron filings enhances the ductility of the concrete [12]. Kumar *et al.* [13] investigated the effect of partial/full replacement of sand by iron ore tailing as fine aggregate on the compressive and flexural strength of reinforced concrete. The compressive strength was increased up to 40 % replacement of sand by iron ore tailing, while there was an enhancement of flexural strength for all percentages of sand replacement (10, 20, 30, 40, 60, 80, and 100 %). Similarly, the compressive strength of concrete was increased up to 20 % replacement of sand by iron powder, which is 7.4 % higher than the reference concrete [14]. The increase in compressive strength was also observed up to 45% replacement of sand by iron slag as fine aggregate, which is about 23.3 % higher than the reference concrete [15]. Olutoge *et al.* [16] investigated compressive, splitting tensile, and flexural strength of concrete made with iron as a replacement for sand. The authors found that the mechanical strength was increased up to 20 % replacement of sand by iron fillings, which is 13.5 % for compression, 1 % for splitting tensile, and 4.8 % for flexural strength, respectively, higher than the reference concrete. While above that replacement, the mechanical strength was decreased. Conversely, a decreasing trend of compressive strength was observed with the increasing addition of steel scale waste by Furlani and Maschio [17].

Yunhong et al. [18] investigated the effect of iron tailings on the compressive strength of concrete as supplementary cementing material as four different replacements of cement (10 %, 20 %, 30 %, and 40 %). It was found that as the replacement of cement was increased, the compressive strength was decreased. Similarly, it was found that the increasing content of iron tailing powder has a negative effect on the mechanical strength of autoclaved aerated concrete, and the finer iron tailings can effectively enhance the strength of concrete blocks [19]. The enhancement of mechanical strength could be increased by incorporating mineral admixtures such as fly ash, blast furnace slag, and silica fume in cement with WIP [20–22].

Though several studies have been carried out to investigate the mechanical performance of concrete/mortar made with WIP, some researchers found that WIP enhances the mechanical properties, while other researchers found opposite behavior. To the authors' knowledge, more research is needed to clarify the real effect of WIP as a replacement of NFA and fine waste iron powder (FWIP) as a replacement of cement on the mechanical properties of concrete/mortar. In Bangladesh, this WIP is not commonly used due to the lack of research data. Therefore, the lack of research data, limited information, and knowledge on the mechanical performance of concrete/mortar made with WIP as a replacement for NFA and FWIP as a replacement for cement motivate this research work. Within this context, comprehensive experimental studies are conducted on the possibility of using WIP as fine aggregate and cement replacement. The physical and mechanical (i.e., compressive, tensile, and flexural strength) performances of mortar made with five percentage replacements of 0 %, 25 %, 50 %, 75 % and 100 % for NFA by WIP and 0 %, 2.5 %, 5 %, 7.5 % and 10 % for cement by FWIP are studied here. Additionally, the experimental results are compared with the existing results available in the literature.

2. Materials and Methods

2.1. Materials

Natural river sand passing through a sieve size of 4.75 mm (ASTM standard No. 4 sieve) was used as fine aggregate. The waste iron powder (WIP) is an industrial byproduct generated from the workshops, steel mills, and factories in powder form was used as a replacement for natural fine aggregate (NFA). This byproduct is left largely unused and is hazardous to human health. The WIP image as a fine aggregate and fine waste iron powder (FWIP) as supplementary cementitious material (SCM) is shown in Fig. 1 a & b, respectively. The microscopic morphology of the WIP through the Scanning Electron Microscopy (SEM) was performed. The SEM test was carried out on the surface of WIP, which was dried at 100 °C for 24 h, and the test was performed using JEOL JSM-7600F Schottky Field Emission Scanning Electron Microscope. The SEM image of WIP is presented in Fig. 1c. Both fine aggregates (NFA and WIP) were sieved in the laboratory using the ASTM standard sieves [23]. The grading curves of both NFA and WIP are compared with the upper and lower limits recommended in the ASTM C33 standard [24] are shown in Fig. 2.

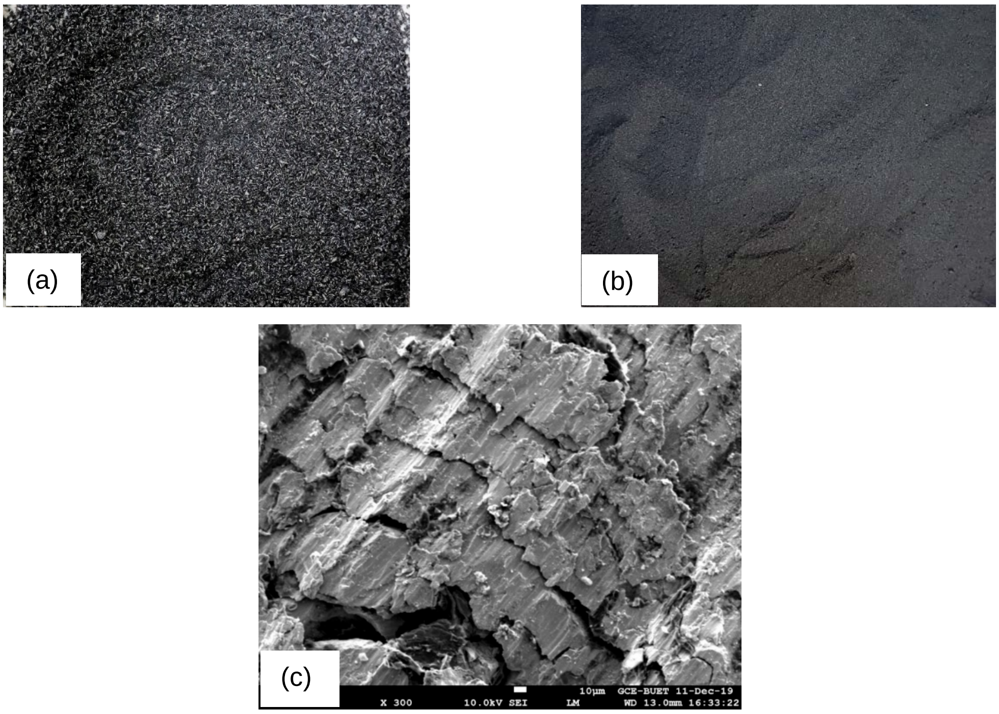


Figure 1. The WIP as fine aggregate (a) and FWIP as supplementary cementitious material (b), and SEM image of WIP (c).

It is observed that both fine aggregates are within the limits of the ASTM C33 [24] standard that ensures a lower void in the mortar mix. It is also interesting to see that the particle distribution of both WIP and NFA are almost the same. Moreover, the specific gravity and absorption capacity of both fine aggregates (NFA and WIP) were tested as per ASTM C128-15 [25]. The specific gravity, fineness modulus, and absorption capacity of the NFA and WIP are 2.56, 3.10 and 5.9, respectively, for NFA and 4.31, 3.15 and 2.6 for WIP, accordingly.

The chemical composition of WIP and cement was determined by X-ray fluorescence (XRF) analysis. The results of the XRF analyses are presented in Table 1. The chemical composition of the WIP has an agreement, as reported by Ghannam et al. [6]. As expected, the Fe_2O_3 content of WIP is significantly higher, resulting in higher specific gravity than natural sand (4.31 for WIP and 2.56 for NFA).

Table 1. Chemical compositions of cement and waste iron powder.

Chemical composition	Cement [%]	WIP [%]
SiO_2	24.90	8.46
Fe_2O_3	3.96	87.46
Al_2O_3	7.52	0.87
K_2O	1.00	0.28
CaO	53.43	1.08
TiO_2	1.18	0.08
MgO	2.52	0.32
Na_2O	0.27	0.27
SO_3	4.77	0.88
P_2O_5	0.21	0.17
Cr_2O_3	0.08	0.13

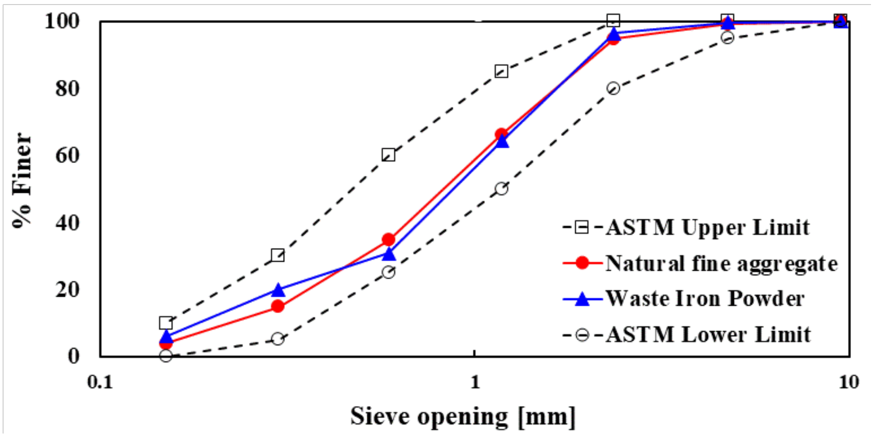


Figure 2. Grading curve of natural fine aggregate and waste iron powder, and comparison with the upper and lower limits recommended in the ASTM C33 standard [24].

2.2. Experimental programs and test procedures

The weight basis mix design with water to cement ratio of 0.45 is used for all mortar mixes, and superplasticizer (SikaPlast®-204 TH) as chemical admixture was used (0.5 % by mass of total cement) to ensure the workability of fresh mortar. In order to investigate the effect of NFA replacement by WIP, five different percentage replacements (0, 25 %, 50 %, 75 %, and 100 %) of NFA are replaced by WIP. Concerning the cement replacement, the FWIP was passed through a sieve size of 75 µm (#200 sieve) and used to replace cement at five different replacement levels (0 %, 2.5 %, 5 %, 7.5 %, and 10 %). The mixture proportions of the mortar mixes for the replacement of NFA and cement are summarized in Tables 2 and 3. The workability of the fresh mortar mixes was studied by measuring the slump values of fresh mortar, and the temperature of the fresh mortar mixes was monitored by using a digital thermometer before pouring the steel molds.

Cube specimens (50 mm) for compression, briquette specimens for tension, and prism specimens (40 mm × 40 mm × 160 mm) for flexural strength tests were made and tested as per ASTM C109 [26], ASTM 307 [27], and ASTM 348 [28], accordingly. The evolution of compressive, tensile, and flexural strength as a function of the mortar age is investigated at 7, 14 and 28 days. A total of 270 specimens (135 for NFA and 135 for cement replacement) were made and tested to attain the goal of the study. 24 h after casting, all the mortar specimens were demoulded and cured underwater (20 ± 2 °C) until the day of the tests. Moreover, the dry density of mortar specimens was measured on the same specimens used for mechanical tests.

Table 2. Mixture proportion of mortar mixes for replacement of NFA by WIP.

Mix ID	Cement [kg/m^3]	Fine Aggregate [Kg/m^3]		Water [kg/m^3]
		NFA [kg/m^3]	WIP [Kg/m^3]	
WIP 0 %	504	1512	0	227
WIP 25 %	504	1134	642	227
WIP 50 %	504	756	1283	227
WIP 75 %	504	378	1925	227
WIP 100 %	504	0	2567	227

Table 3. Mixture proportion of mortar mixes for replacement of cement by FWIP.

Mix ID	Binder [Kg/m^3]		NFA [kg/m^3]	Water [kg/m^3]
	Cement [kg/m^3]	FWIP [Kg/m^3]		
FWIP 0 %	504	0	1512	227
FWIP 2.5 %	491	13	1512	227
FWIP 5 %	479	25	1512	227
FWIP 7.5 %	466	38	1512	227
FWIP 10 %	454	50	1512	227

3. Results and Discussion

3.1. Performance of mortar made with WIP as replacement for NFA

3.1.1. Fresh properties of mortar

The workability of different mortar mixes is evaluated by measuring the slump value of fresh mortar at the time of placing and presented in Table 4. It is observed that the workability of mortar decreased with the increasing replacement percentage of natural fine aggregate (NFA) by waste iron powder (WIP). This behavior could be linked to the highly angular and rough surface texture of WIP (see Fig. 1c). In contrast, the NFA is round in shape (rolling effect), resulting in the reduction of the flowability of the mortar made with WIP due to better interlocking in the mix. The reduction in the flowability could also be linked to the temperature of the mortar at the time of placing. As shown in Table 4, as the temperature of the fresh mortar increases, the workability of the mortar decreases due to the higher heat of hydration of cement paste.

Table 4. Slump and temperature of fresh mortar made with five mortar mixes.

WIP	0 %	25 %	50 %	75 %	100 %
Slump [cm]	24	22	19	17	16
Temperature [^{o}C]	23	26	28	29	31

3.1.2. Mechanical properties

The compressive strength of mortar made with five different percentage replacements (0 %, 25 %, 50 %, 75 %, and 100 %) of NFA by WIP was recorded at 7, 14, and 28 days and presented in Fig. 3a. Three cubic mortar blocks were tested for every data set, and then the average value was calculated. It is clearly seen that mortar made with WIP as fine aggregate has significantly improved the compressive strength at all curing ages compared to the control mortar (100 % NFA). None of the specimens show lower compressive strength as compared to the control specimen. For example, the average compressive strength of mortar measured at 28 days of 0 %, 25 %, 50 %, 75 %, and 100 % are, respectively, 38.5 MPa, 41.9 MPa, 47.9 MPa, 49.9 MPa, and 48.2 MPa. This behavior could be linked to the higher rough surface (see Fig. 1c), higher density, and higher strength of WAP than NFA. By the visual inspection, it has been observed that the WIP is highly sharp in shape and has a rough surface texture than NFA. Probably, this sharp and rough surface provides a better bond between cement and WIP that provides higher strength. While NFA is round in shape, thus provides a weak bond, i.e., a weak interfacial transition zone between sand particle and cement paste, resulting in lower compressive strength.

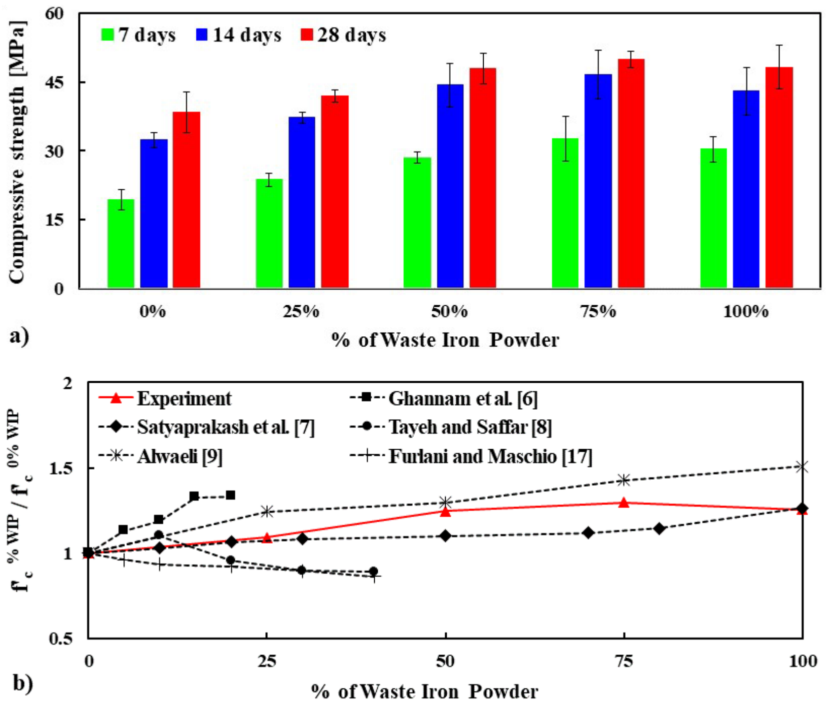


Figure 3. Compressive strength (f'_c) of mortar tested at 7, 14, and 28 days (a), and normalized f'_c of mortar measured at 28 days is compared with results found in the literature (b), respectively.

To gain a deeper understanding the role of different percentage replacement of NFA by WIP on the compressive strength of mortar, normalized compressive strength at 28 days is calculated by dividing the strength of mortar made with 100 % NFA (i.e., f'_c $^{\text{WIP \%}}$ / f'_c $^{\text{WIP = 0\%}}$) and compared with the results found in the literature [6–9, 17], see Fig. 3b. The maximum increase in compressive strength is observed for 75 % WIP mortar, which is about 70 %, 40 %, and 30 % at 7, 14, and 28 days, respectively, higher than 100 % NFA mortar. It is observed that the experimental results are in good agreement with the results found in the literature [7–9].

The tensile and flexural strength of mortar mixes made with different percentage replacement of NFA by WIP is presented in Fig. 4a and 5a, respectively. The normalized tensile and flexural strength at 28 days are compared with the results found in the literature and presented in Fig. 4b and 5b, respectively. It is seen that the tensile and flexural strength increases with the increasing percentage of WIP for all curing ages, which is in good agreement with the results of the compressive strength. The maximum increase in tensile and flexural strength is observed for the mortar made with 100 % WIP and 75 % WIP, respectively. The increase in tensile and flexural strength of mortar for all curing ages are on average 20 % and 38 %, respectively, higher than the mortar made with 100 % NFA. These results are consistent with the results available in the existing studies [6–8]. As described previously, these higher tensile and flexural strengths of mortar made with WIP could be linked to higher strength, higher angularity, and excellent surface roughness (see Fig. 1c), which ensured better bonding between cement paste and WIP than NFA. It is also noted that the WIP provides additional tensile strength to the mortar that prevents the formation of cracking, resulting in higher tensile and flexural strength. These experimental results demonstrate that the NFA could be replaced by up to 75 % with WIP since above that replacement, the flexural and compressive strength decreases, but not below the strength of the control mortar (mortar made with 100 % NFA). The reduction in strength of mortar made with 100 % WIP could be attributed to the small voids appearing on the internal texture of the WIP (see Fig. 1c) and lower workability (see Table 4) that could increase the porosity of mortar and consequently reduce the strength.

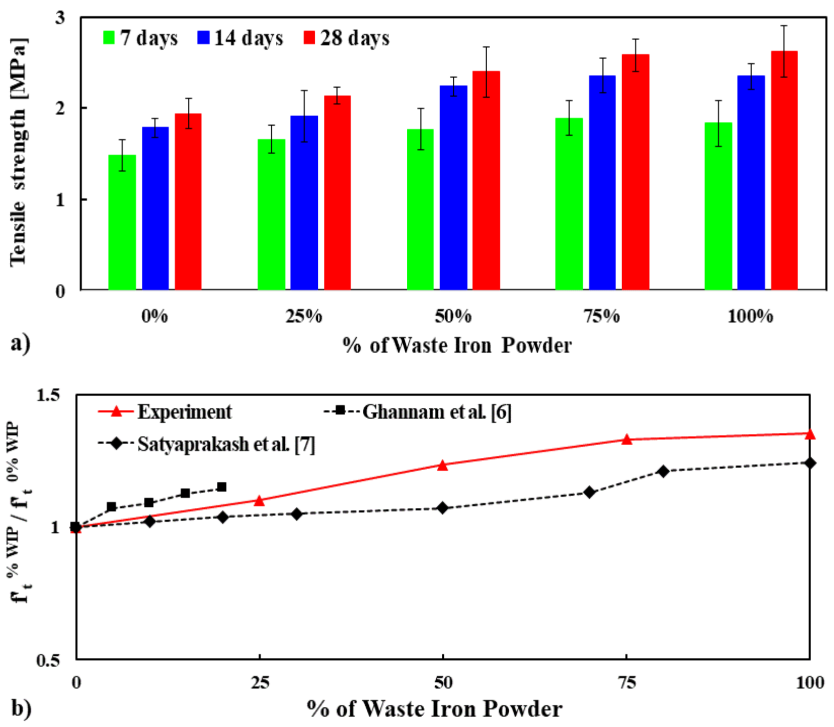


Figure 4. Tensile strength $\left(f_t'\right)$ of mortar tested at 7, 14, and 28 days, and normalized f_t' of mortar mixes measured at 28 days is compared with other results found in the literature (b), respectively.

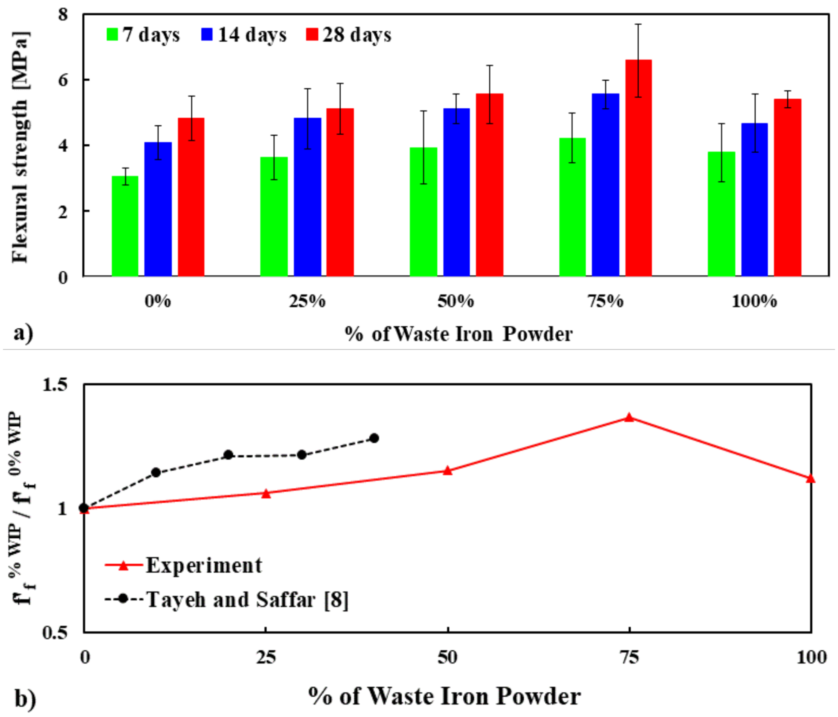


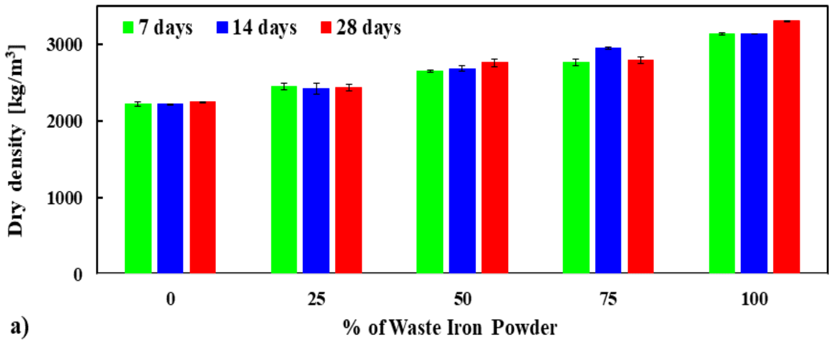
Figure 5. Flexural strength $\left(f_f'\right)$ of mortar performed at 7, 14, and 28 days, and normalized f_f' of mortar mixes performed at 28 days is compared with other results found in the literature (b), respectively.

This high strength (compressive, tensile, and flexural) of mortar made with WIP provides a better future direction for sustainable construction building materials. For example, in Bangladesh, the ferrocement technique is commonly used to retrofit the structure due to the availability of materials and cost-effectiveness [29–30], where the strength of mortar and bond between mortar and parent concrete play an important role. Based on the results presented in this paper, this high strength mortar (≈ 50 MPa or

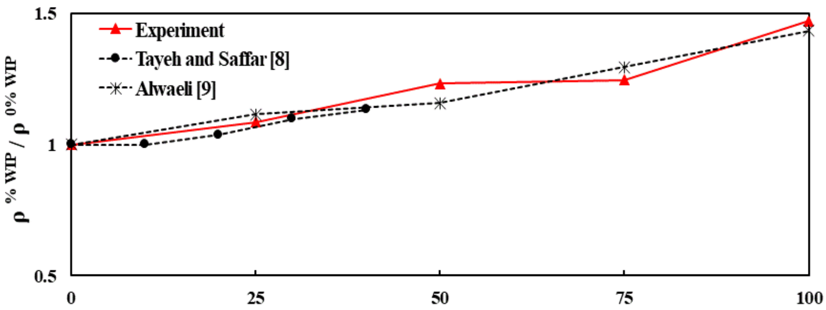
7250 psi) could be used in the ferrocement technique/repair work, which will not only provide higher strength as well as a better bond among mortar, ferrocement steel wire mesh, and parent concrete. It also demonstrates that this mortar will provide higher ductility due to its higher tensile and flexural strength of iron that will prevent the brittle collapse of the structures and save the people inside the structure during extreme external loads, such as earthquake, wind, blast, and fire. Furthermore, the durability performance of ferrocement is also depended on mortar properties due to its lower net cover of mortar, higher surface area of the steel wire mesh (i.e., higher risk of corrosion), the higher porosity and permeability of mortar due to lower strength (i.e., higher penetration of water, higher corrosion) [29].

3.1.3. Dry density

The evolution of the dry density of mortar made with WIP as a function of time is presented in Fig. 6a, and the normalized dry density measured at 28 days are compared with the results found in the literature and presented in Fig. 6b, respectively. As expected, with an increase in the percentage replacement of NFA by WIP, the dry density of mortar increases. The average density of mortar made with 0 %, 25 %, 50 %, 75 % and 100 % WIP are 2240 kg/m^3, 2434 kg/m^3, 2759 kg/m^3, 2791 kg/m^3 and 3298 kg/m^3, respectively, at 28 days. The highest density is observed for the mortar made with 100 % WIP, which is about 10–40 % higher for all curing ages than the mortar made with 100 % NFA. This higher density of mortar made with WIP is directly linked with the higher specific gravity (4.31 for WIP and 2.56 for NFA) and better interlocking between WIP and cement paste than NFA. The higher density of mortar made with WIP is in agreement with other researchers [8, 9]. It is noted that the compressive, tensile, and flexural strength of mortar made with WIP is significantly higher as compared to the mortar made with NFA, which could be another reason for the higher density of mortar made with WIP than NFA.



a)



b)

Figure 6. Dry density (ρ) of mortar tested at 7, 14, and 28 days, and normalized ρ of mortar mixes performed at 28 days is compared with other results found in the literature (b), accordingly.

3.2. Performance of mortar made with FWIP as replacement for cement

The compressive, tensile, and flexural strengths of mortar were investigated using different percentage replacements (0 %, 2.5 %, 5 %, 7.5 %, and 10 %) of cement by fine waste iron powder (FWIP). To fall into the size range of the cement, the FWIP was passed through a sieve opening of 75 µm (#200 sieve). The compressive, tensile, and flexural strength of mortar made with partial replacements of cement by FWIP were performed at 7, 14 and 28 days and are presented in Fig. 7. For every data set, three specimens were tested, and then the average value was calculated.

It is found that the replacement of cement by FWIP decreases the strength of mortar for all curing ages. For example, the average compressive strength of mortar measured at 28 days of 0 %, 2.5 %, 5 %, 7.5 % and 10 % of FWIP are, respectively, 38.5 MPa, 34.2 MPa, 29.4 MPa, 27.4 MPa and 22.4 MPa. Almost similar behavior is observed for tensile and flexural strength of mortar made with FWIP. The decrease in strength of mortar at 28 days as partial replacement of cement by FWIP is 10–40 % lower for compressive and tensile strength, and 4–16 % lower for flexural strength than the mortar made with 100 % cement. This reduction of mechanical strength is in agreement with the literature [19–22]. It is noted that a lower reduction in flexural strength is observed as compared to tensile and compressive strength when cement is replaced by FWIP. Probably, FWIP does not have cementitious as well as pozzolanic behavior (i.e., lower amount of calcium silicate hydrate, CSH), which could explain the lower strength of this mortar. However, incorporating mineral admixtures such as fly ash, blast furnace slag, and silica fume in cement with FWIP could enhance the mechanical strength of mortar. In the literature, it was found that the concrete made with iron tailing powder, cement, and mineral admixture such as slag and fly ash enhances the mechanical properties as well as microstructure of concrete [20–22, 31–33].

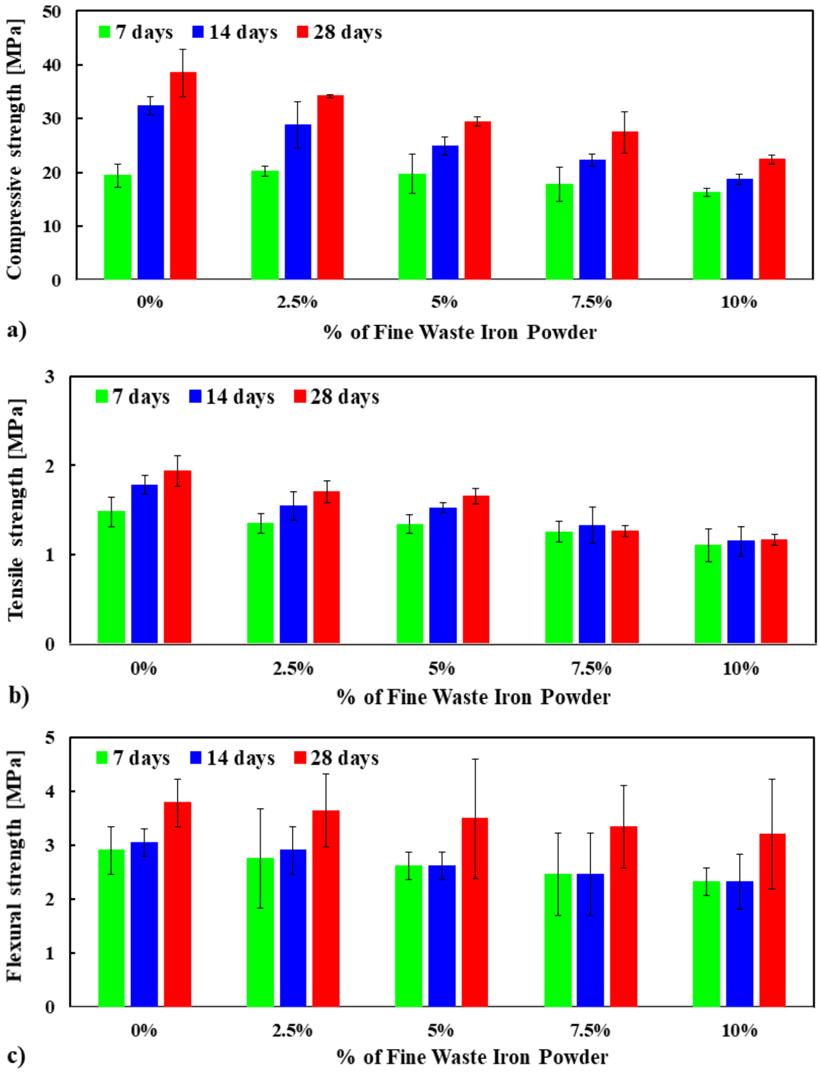


Figure 7. Compressive (a), tensile (b), and flexural (c) strength of mortar made with FWIP as replacement of cement tested at 7, 14, and 28 days, respectively.

4. Conclusions

This paper dealt with the compressive, tensile, and flexural strength as well as dry density of mortar made with five different percentage replacements of 0 %, 25 %, 50 %, 75 %, and 100 % for natural fine aggregate (NFA), and 0 %, 2.5 %, 5 %, 7.5 % and 10 % for cement by fine waste iron powder (FWIP). The cube, briquette, and prism specimens were made to perform compression, tension, and flexural strength of mortar at 7, 14, and 28 days. Based on the results presented herein, the following conclusions can be drawn:

I. The use of WIP as a replacement for NFA in mortar shows significantly higher compressive, tensile, and flexural strength, which is 30 % for compression, 35 % for tensile, and 37 % for flexural strength, respectively, higher when NFA is replaced by 75 % WIP. By contrast, adding FWIP (passed through sieve opening of 75 µm) as partial replacement of cement decreases the compressive, tensile, and flexural strength of mortar.

II. Lower workability is noticed for the mortar made with WIP than NFA, which could be attributed to the highly angular and rough surface texture of WIP than NFA as well as better interlocking, which reduces the mobility of fresh mortar.

III. An increased dry density is observed with the increasing replacement percentage of NFA by WIP. This higher density of mortar made with WIP is directly linked with the higher specific gravity (4.31 for WIP and 2.56 for NFA) and better interlocking between WIP and cement paste than NFA.

IV. From the experimental results of the five mixes, this study implies that WIP can be used up to 75 % replacement of NFA as fine aggregate since WIP is stronger, higher angular, and has an excellent sharp surface texture, which provides better mechanical performances. In contrast, to produce low strength and ultra-low strength mortar, FWIP could be used as partial replacement of cement since the reduction of strength is about 40 % for compression and tension, and 16 % for flexural strength lower compared to 100 % cement mortar at 28 days.

V. The outcome of this research will encourage iron waste producers to continue collecting and storing these hazardous materials, which are cost-effective, enviro-friendly, and sustainable construction building materials.

5. Acknowledgments

The authors acknowledge funding and facilities provided by the Department of Civil Engineering, University of Asia Pacific (UAP) to undertake this research.

6. Conflicts of Interest

The authors declare no conflict of interest.

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