Jordan Journal of Civil Engineering, Volume **19**, No. **3**, **2025**
DOI: https://doi.org/10.14525/JJCE.v19i3.06

Jordan Journal of Civil Engineering

Journal homepage: https://jjce.just.edu.jo

Strength Characterization of Ferrock Incorporated As a Potential Substitute of Cement

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ARTICLE INFO

Article History:
Received: 16/1/2025
Accepted: 22/4/2025

ABSTRACT

The global construction sector is contributing to global warming through cement manufacturing, necessitating the search for eco-friendly, low-carbon materials as alternatives. Iron dust waste generated by steel industries is often disposed of through landfilling, which contributes to soil pollution. Ferrock is made up of iron dust which is produced in steel industries along with other supplementary cementitious materials to improve the performance of concrete. It is a carbon negative material which absorbs carbon during its reactions. Concrete mixes were prepared with ferrock at 0%, 5%, 10%, 15% and 20% replacement of cement. The compressive, split tensile and flexural strength tests were evaluated and their findings revealed that 10% is the optimum ratio which enhanced the aforementioned strengths by 37.4%, 37.5% and 19.4%, respectively, at 28 days of curing as compared with the control mix. Carbonation tests showed that concrete with ferrock had a higher carbonated area than the control mix without ferrock. Ferrock enhances concrete strength, reduces cement usage, and absorbs carbon dioxide from the environment, promoting sustainable development by recycling steel waste dust and reducing carbon emissions.

Keywords: Ferrock, Sustainable construction, Mechanical strength, Carbonation test, Industrial waste, Phenolphthalein.

INTRODUCTION

The growth of the building sector significantly contributes to increasing the level of carbon emissions and the demand for raw materials (Barcelo et al., 2014). This sector currently accounts for around 39% of carbon emissions worldwide, highlighting its significant influence on climate change. A substantial fraction of these emissions emits from cement manufacturing, wherein the transformation of limestone (LS) into lime—a process that intrinsically emits Carbon Dioxide (CO_2) as a by-product—substantially adds to world CO_2 concentrations (Kadawo et al., 2023; Alani et al., 2025). Cement is one of the main ingredients and acts as a binder in concrete (Liu et al., 2023). It also leaves large carbon footprints behind that can be smaller by limiting the use of cement with the help of abundant quantities of available materials (Chen et al., 2023). Incorporation of waste is increasingly being included in concrete composites by recent research studies. These wastes greatly reduce the environmental impact caused by cement manufacturing, along with conserving resources and reducing waste.

The Ministry of Steel reports that India has risen to the position of the world's second-biggest steel manufacturer, generating 99.56 tons of steel in 2020-

2021 (Ministry of Steel: Strategy and target to meet growing steel demand, 2024). The Ministry of Steel has developed standard rules and recommendations for managing hazardous landfilled materials, in addition to encouraging the use of slag waste from the iron and steel industry in building to counter this issue (Government of India, Ministry of Steel, 2024). Steel dust waste is not economical to recycle; so, millions of tons of metallic dust waste are often disposed of *via* landfilling which negatively impacts the morphology of the soil (Abdalqadir et al., 2024).

An innovative material called ferrock was prepared by David Stone (Das et al., 2014). It is not cement and forms when iron dust encounters Oxalic Acid (OA) and carbonates. In the reaction between iron dust and CO_2, complex iron carbonates are made. These are solid, crystalline structures that help ferrock concrete become stronger (Jeffy Pravitha et al., 2023). This new material is made up of Iron Oxide (IO), Fly Ash (FA), Metakaolin (MK), LS, and OA. The main ingredient is IO, which comes from steel industry waste. Iron dust consists of particles which are angular in shape, fill in the gaps in composites and make them stronger (Shinde et al., 2023). When OA is present, iron dust particles react with CO_2 to make a thick layer of iron carbonates. When carbonation happens, the silica present in FA changes into calcium silicate and aluminate, which are very important for filling gaps in the concrete's Interfacial Transition Zone (ITZ). When iron and FA slowly mix, they make certain types of iron silicate crystals that make ferrock stronger and cause it to last longer (Lothenbach et al., 2011). MK is a pozzolanic material made up of clay which can hold water and makes the ferrock paste thicker, stickier, and easier to spread and press to a smooth surface. MK reacts with lime to form a stronger and more durable control mix (Alani et al., 2025). There are a lot of aluminates in MK and FA, which combine hydration products to add more alumina to CSH (Lothenbach et al., 2011); one of the raw materials used is LS, which breaks down in OA to release CO_2, which gives the formation of more carbonate. LS is chemically calcium carbonate. Its natural structure is the same as iron carbonate, and it helps iron carbonate form by acting as a mold for crystal growth. By filling in the holes, LS makes the structure thick (Elgalhud et al., 2016). When it mixes with FA, it creates calcium mono-hemicarboaluminate, which is stronger and lasts longer. One idea is to use scrap and pozzolanic materials to make cement composites easier to work with and to help the rock and cement paste stick better together (Bellum et al., 2023).

The study of ferrock in concrete has predominantly been limited to use in self-compacting concrete. The novelty of the present research is the use of ferrock in M25 grade concrete and provide its impact on hardened properties and carbonation tests. This study aims to employ ferrock as a potential substitute for cement with various ratios in concrete. The Compressive Strength (CS), split Tensile Strength (TS), and Flexural Strength (FS) of five different concrete mixes were tested, compared, and reported. The results indicate that using ferrock as a substitute for cement in concrete enhances strength over the control mix, and a carbonation test indicates that cubes constructed of ferrock absorb CO_2. ferrock functions as a carbon negative material, promoting sustainable growth by lowering CO_2 emissions and reusing waste created by the steel industry.

EXPERIMENTAL SETUP

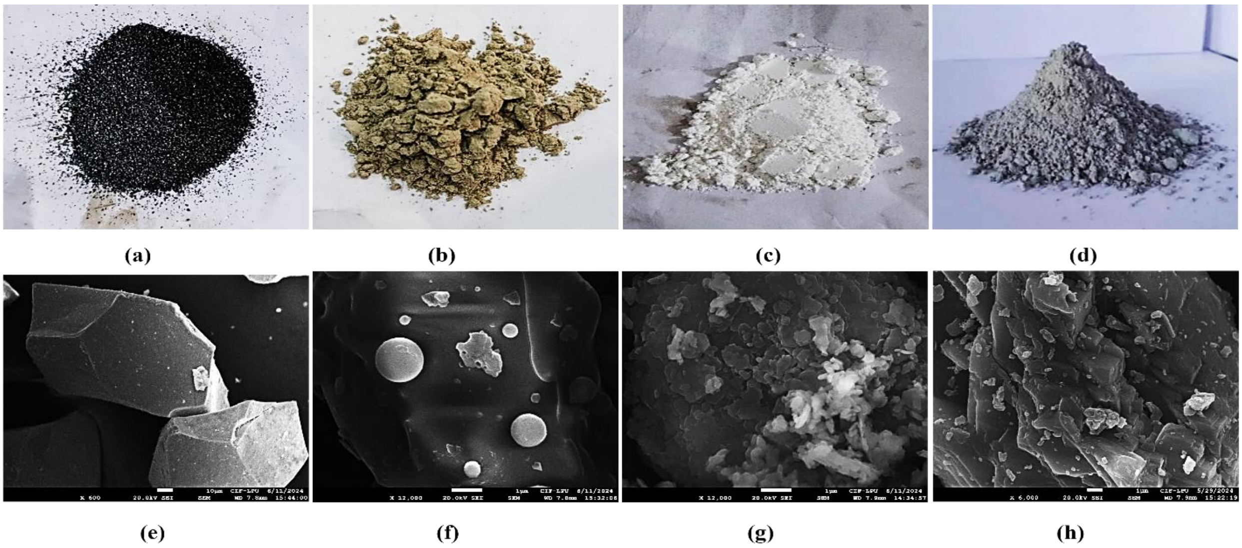
Materials Used

This study used Ordinary Portland Cement (OPC) of grade 43, sand, coarse aggregates for the control mix. Ferrock is used as a substitute of cement in different ratios. River sand is used as fine aggregate which is locally available and coarse aggregate of a maximum size of 20 mm was used as per IS 383: 2016 (“IS 383 (2016)”, 2021). The physical properties of fine and coarse aggregates are fineness modulus, specific gravity and bulk modulus, which are 2.748 and 7.549, 2.678 and 2.649, 1674.8 kg/m^3 and 1689.9 kg/m^3, respectively, as specified in IS 2386-2021 (“Methods of Test for Aggregates for Concrete-Part I : Particle Size and Shape”, 2021). Physical properties of OPC are specific gravity 3.15 and standard consistency 31.8 adopted as specified in BIS: 4031-Part 1 (of Indian Standards, n.d.) and Part 4 (“IS 4031 (Part 4)”, 2024), respectively. The initial and final setting time of OPC are 86 min and 276 min, respectively, adopted in accordance with BIS: 40311-Part 5 (Indian Standards, 2005). Energy dispersive X-ray spectroscopy was used to determine the elemental composition of OPC, as shown in Table 1.

Table 1. Elemental composition of OPC

Elements (wt%)	O	Ca	Si	Al	Fe	K	Na	Mg
OPC	36.32	40.12	8.27	5.24	4.34	0.2	0.24	5.27

Ferrock is a material that exhibits a carbon-negative characteristic, as it sequesters CO_2 throughout its hardening process by converting IO into complex carbon carbonates when reacting with CO_2. The ferrock contains IO, FA, MK, and LS as raw materials (Niveditha et al., 2020). The ferrock used in this study was prepared as a dry mix of all raw materials; after preparing the uniform mix, water was added to prepare slurry. As soon as water is mixed, it reacts with LS to generate CO_2, which provides extra carbonation to IO to react. After 20 minutes, the ferrock mix was ready to mix in concrete. Iron dust was used as the main binder in this study with a maximum particle size of 19 microns. The IO was bought from Herenba Instruments & Engineers, Chennai, India. Figure 1(a) and the SEM image in Figure 1(e) revealed that the particles are angular in shape and have a rough texture. This IO was a waste produced in steel industries, being black in color, with rod-like particles and shiny in texture. FA of class F, MK and LS have a particle size of 0.8 micron which is <75 microns as described in ASTM C 568 ("Designation: C568/C568M-22 Standard Specification for Limestone Dimension Stone 1", n.d.), as shown in Figure 1(b), (c), (d) and the SEM images in Figure 1(f), 1(g), and 1(h). Energy dispersive X-ray spectroscopy (EDS) analysis was performed to study the elemental compositions of the materials used, as shown in Table 2. MK provides thickness, stickiness and workability by retaining water. Scanning Electronic Microscopy (SEM) analysis reveals texture and particle shape of the materials used, as shown in Figure 1. IO particles have an angular shape with a smooth surface, perhaps indicating a crystalline structure. FA particles are spherical and seem to possess a rough surface. MK consists of small particles, whereas LS has a uniform particle shape with a smooth surface.

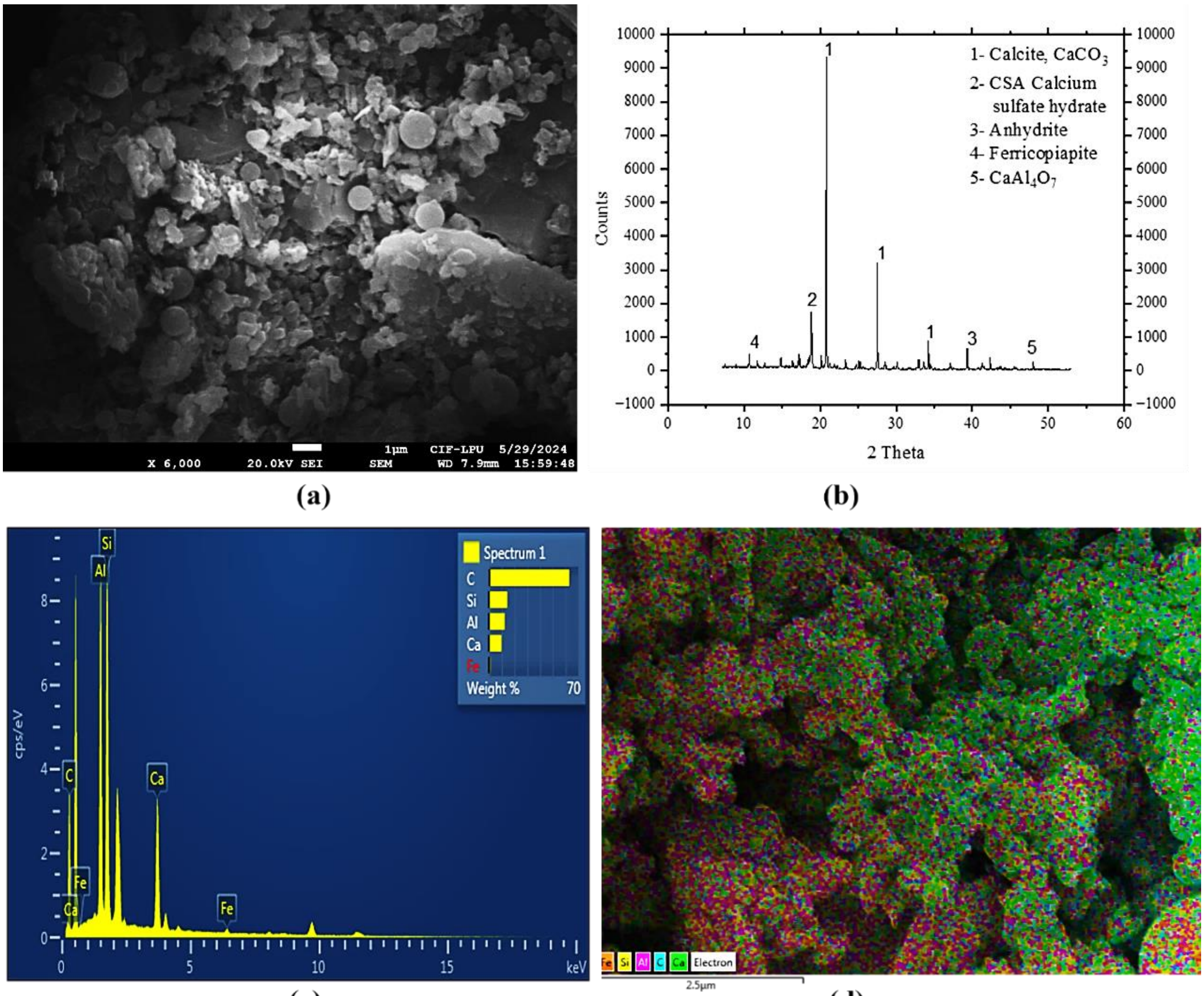

(a) (b) (c) (d)

(e) (f) (g) (h)

Figure (1): Materials used in the study (a) Iron oxide (b) Fly ash (c) Metakaolin (d) Limestone; and SEM images of the materials used (e) Iron oxide (f) Fly ash (g) Metakaolin (h) Limestone

Table 2. Elemental compositions of the materials used

Elements (wt%)	O	Ca	Si	Al	Fe	K	Na	Mg
MK	49.31	0.22	25.74	24.32	0.22	0.04	0.08	0.06
LS	46.76	51.97	0.27	0.14	0.32	0.08	0.05	0.22
FA	49.16	1.42	25.15	20.35	1.87	1.27	0.06	0.72



(a) (b)

(c) (d)

Figure (2): (a) SEM, (b) XRD, (c) EDS and (d) elemental mapping of ferrock

When IO reacts with CO_2 in the presence of OA, IO starts dissolving and forming complex iron carbonates, and this reaction absorbs CO_2. Also, angular particles of IO increase bonding of materials, leading to an improvement in a denser and more compacted matrix. FA was used to form some iron silicates that lead to greater strength when reacting with IO. LS in the presence of water leaves CO_2 to provide more carbonates for mineralization (Das et al., 2014). The micro-structural analysis conducted for specimens showed a highest strength by SEM, XRD, and EDS to study the morphology and elemental composition with its peaks. SEM showed a zoomed image of surface texture of ferrock, as shown in Figure 2(a). XRD found major peaks of quartz, along with peaks of calcite, CSA, Anhydrite, Ferrihydrite $CaAl_4O_7$ and minor peaks of CaP_2O_6, Illite, Ganophyllite, Ferricopiapite, Albite, $MgCl_6H_2O$, Hydrohalite, Epsomite, SiC, Quartz, Montmorillonite, Dolomite, and Struvite, as illustrated in Figure 2(b). This diverse mineral assemblage indicates the presence of both common and specialized phases, which could play a role in the sample's mechanical and chemical behavior. Previous research used ferrock in self-compacting concrete and revealed the presence of Fe_2O_3, SiO_2, Al_2O_3 and MgO in significant amounts, which can be the reason for the improvement in strength (Jeffy Pravitha et al., 2023).

EDS analysis revealed the elemental composition of ferrock, as mentioned in Table 3 and the peaks shown in Figure 2(c), while elemental mapping visualized the distribution of elements in composites, as illustrated in Figure 2(d).

Table 3. Elemental composition of ferrock

Elements (wt%)	C	Al	Si	Ca	Fe
Ferrock	62.83	12.24	14.27	9.67	0.99

Mix Proportions, Casting and Curing of Samples

Five concrete mixes were freshly prepared, specimens were cast and tests were conducted on hardened concrete at 4 days of CO_2 curing followed by 3 days, 7 days, 28 days, 56 days and 90 days of water curing. The mix proportions, notations and quantities of materials used for samples cast are according to Table 4. The study used ferrock as a replacement of OPC with fine and coarse as constant with 707.6 kg and 1066.75 kg, respectively, in each mix. A homogenous mix prepared consists of OPC, sand, coarse aggregate, water and different ratios of ferrock. The fresh concrete mix prepared according to mix proportions was poured into proper oiled molds of the required size as per standards of experiments and left for 24 hours. Then, the samples were unmolded and kept in an airtight container filled with CO_2 for 4 days, which was refilled after the required time to maintain the level of CO_2 (Vijayan et al., 2020) and then transferred to the water tank for curing for 3, 7, 28, 56 and 90 days.

Table 4. Mix proportions along with mix notations

Mix notation	Mix details	OPC (kg)	Water (kg)	Ferrock (kg)
C100F0	100%OPC+ 0% Ferrock+ FA+CA	383.10	191.6	0
C95F5	95%OPC+ 5% Ferrock+FA+CA	363.945	191.6	19.155
C90F10	90%OPC+ 10% Ferrock+FA+CA	344.79	191.6	38.31
C85F15	85%OPC+ 15% Ferrock+FA+CA	325.635	191.6	57.465
C80F20	80%OPC+ 20% Ferrock+FA+CA	306.48	191.6	76.62

Mechanical Strength Test

The fresh mix was prepared as per the mix proportions mentioned in Table 4 and poured in properly oiled molds and unmolded after 24 hours. Then, it was kept in an airtight container for CO_2 curing for 4 days and then again kept in a water tank for water curing. The strength has been tested at 3, 7, 28, 56 and 90 days of water curing and compared. The CS test was performed on cubes of size 150mm x 150mm x 150mm conforming to 10086: 2021 (IS: 10086: 2021) standard. The TS test was performed on cylinders of size 150*300 mm conforming to IS 5816: 1999 (IS: 5816: 1999) under horizontal loading by a universal testing machine. The FS test was performed on a universal testing machine with a three-point loading system on beams of size 100*100*500 mm in accordance with ASTM C78 2016 (“Standard Test Method for Flexural Strength of Concrete (Using Simple Beam with Three-point Loading)”, n.d.). The results of testing have been compared and reported.

Carbonation Test

Concrete cubes of size 50mm x 50mm x 50mm for mixes C100F5, C95F10, C90F15, C85F20 and C80F20 were cast to test carbonation in concrete. Samples were kept in an airtight poly bag filled with a maximum CO_2, refilled after the required time to maintain concentration. After cleaning, a phenolphthalein pH indicator was sprayed over the recently split surface. A pink tint indicates the non-carbonated part of the sample, where the alkalinity of concrete was high (Chinchón-Payá et al., 2016; Jones et al., 1997). The carbonated section of the samples exhibited no coloration, indicating reduced alkalinity in the concrete.

RESULTS AND DISCUSSION

Results of Mechanical Strength Test

The CS test was conducted on cubes, and the findings are presented in Figure 3(a), along with mix notations and curing days. The results found improved strength as compared to C100F0 for each mix with ferrock as a substitute for cement. The findings suggest that concrete mixes with ferrock exhibited an early strength development may be because of the interactions of calcium silicates (C_3S and C_2S) with CO_2 which enhance early strength. The formation of C-S-H can further promote the carbonation of calcium hydroxide

($Ca(OH)_2$), which can result in a precipitation process in the pores of the cement mortar paste, leading to pore confinement (Jeffy Pravitha et al., 2023). The mix C100F5 had an improved strength by 27.74%, 10.16%, 11.68% and 5.08% at 7, 28, 56 and 90 days of curing, respectively. Further increasing the ratio of ferrock replacement in mix C90F10 demonstrated a 63.17%, 36.51%, 36.23% and 28.36% increment in strength at 7, 28, 56 and 90 days of curing respectively. Mix C85F15 with a replacement level of 15% showed an increment of 38.64%, 24.18%, 32.88% and 27.66% in strength at 7, 28, 56 and 90 days of curing, respectively. With 20% replacement in mix C80F20, the improvement was 19.33%, 20.77%, 24.96% and 17.33% in strength at 7, 28, 56 and 90 days of curing, respectively. Findings suggest that the mix with 10% replacement showed the highest improvement in strength. This is because ferrock forms complex iron carbonates to give strength in composites (Karthika et al., 2021). Ferrock includes FA, MK and LS as raw materials which improve the strength of concrete by accelerating pozzolanic reactions (Snellings et al., 2023). In the composition of ferrock, FA, MT and LS are included, which may be the reason for the improvement in strength because of enhancement in pozzolanic reactions with hydration (Hoang-Anh et al., 2018). The pozzolanic reactions in concrete reduce the amount of $Ca(OH)_2$ crystallites due to the hydration effects of iron fines. Calcium silicates (C_3S and C_2S) react with CO_2 to increase the strength in CO_2 -cured samples. This accelerates the carbonation of calcium hydroxide, which confines pores in cement mortar paste. $Ca(OH)_2$ from the hydration process boosts pozzolanic reactions at later ages. Also, the presence of IO improves the crushing value of forming a dense and compact concrete composite (Singh & Siddique, 2016). The study found that the development of C-S-H subsequently promotes the carbonation of calcium hydroxide, resulting in a precipitation process inside the pores of the cement mortar paste, leading to pore confinement (M. Harshitha, 2025).

The TS test was conducted on cylinders, and the findings are presented in Figure 3(b), along with mix notations and curing days. The results found improved strength as compared to C100F0 for each mix with ferrock as a substitute for cement. Mix C95F5 showed 58.33%, 24.43%, 21.68% and 24.71% enhancement in strength at 7, 28, 56 and 90 days of curing, respectively. Further increasing the ratio of ferrock to 10% replacement in mix C90F10 reported a 75%, 37.55%, 41.05% and 35.58% increments in strength at 7, 28, 56 and 90 days of curing, respectively. The C85F15 mixture showed 69.44%, 33.71%, 34.73% and 28.46% increments in strength at 7, 28, 56 and 90 days of curing, respectively. With a 20% substitution in mix C80F20, there were 62.5%, 28.05%, 30.94% and 24.71% enhancements in strength reported at 7, 28, 56 and 90 days of curing, respectively. The results indicate that the mixture with a 10% substitution exhibited the highest enhancement in TS. This is because of the dilution and nucleation effects of ferrock, which provides good resistance to tensile stress (Vijayan et al., 2020). The dilution effect occurs when cement is replaced with a reactivity-rich material, reducing clinker content and causing slower hydration. This increases the water-to-cement ratio, resulting in early age strength development due to less cement to hydrate for available water. Ferrock's finer particles cause a nucleation effect, allowing for the growth of hydration products, like CSH gel, forming a primary strength-giving phase in cement. This increased surface area enhances early age strength by building-up CSH and forming denser products.

Ferrock enhances the concrete's strength by the angular shape of particles of IO. The iron particles with a coarse surface roughness provide a robust ITZ, forming a firm link strengthening the bond between the particles and the cement matrix (Jeffy Pravitha et al., 2023). The incorporation of ferrock enhances absorption and reactivity, resulting in the formation of a stable ferrous complex ($FeCO_3$) that generates rust, therefore reinforcing the concrete matrix. The observed reduction in strength may be attributed to the excessive silica content present in ferrock, which appears to have resulted in the dilution of the C_2S and C_3S phases, subsequently inhibiting the pozzolanic reaction (Choudhary et al., 2020).

The FS test was performed on the beams and the findings are presented in Figure 3(c), along with mix notations and curing days. The results found improved strength as compared to C100F0 for each mix with ferrock as a substitute for cement. Mix C90F5 showed 4.23%, 13.75%, 2.63% and 4.63% enhancement in strength at 7, 28, 56 and 90 days of curing, respectively. Further increasing the ratio of ferrock replacement to 10% in mix C90F10 caused the strength to be improved by 11.54%, 19.38%, 12.11% and 5.85% at 7, 28, 56 and 90 days of curing, respectively. Mix C85F15, with 15%

replacement, showed an increment of 7.31%, 15.94%, 10%, 4.39% in strength at 7, 28, 56 and 90 days of curing, respectively. With 20% replacement, mix C80F20 shows 6.54%, 14.38%, 7.89% and 5.12% improvement in strength at 7, 28, 56 and 90 days of curing, respectively. The findings revealed that 10% replacement is the optimum ratio which reported the highest improvement in strength. This improvement can be attributed to enhancements in the ITZ and the cementitious matrix within the concrete, facilitated by the pozzolanic reactions of silica with Calcium Hydroxide (CH), which leads to the formation of additional calcium silicate hydrate (Prakasam et al., 2019). The pozzolanic activity and micro-filling capacity of the little ferrock particles improve the production of hydrates that reinforce concrete by increasing the amount of calcium and alumina silicates in both the silicate and amorphous phases. Inadequate production of calcium hydroxide, which is necessary for the development of C-S-H in the concrete matrix, could impact performance when FA and MK are used together in concrete, resulting in unreacted silica particles and potentially leading to a reduction in strength (Jeffy Pravitha et al., 2023).

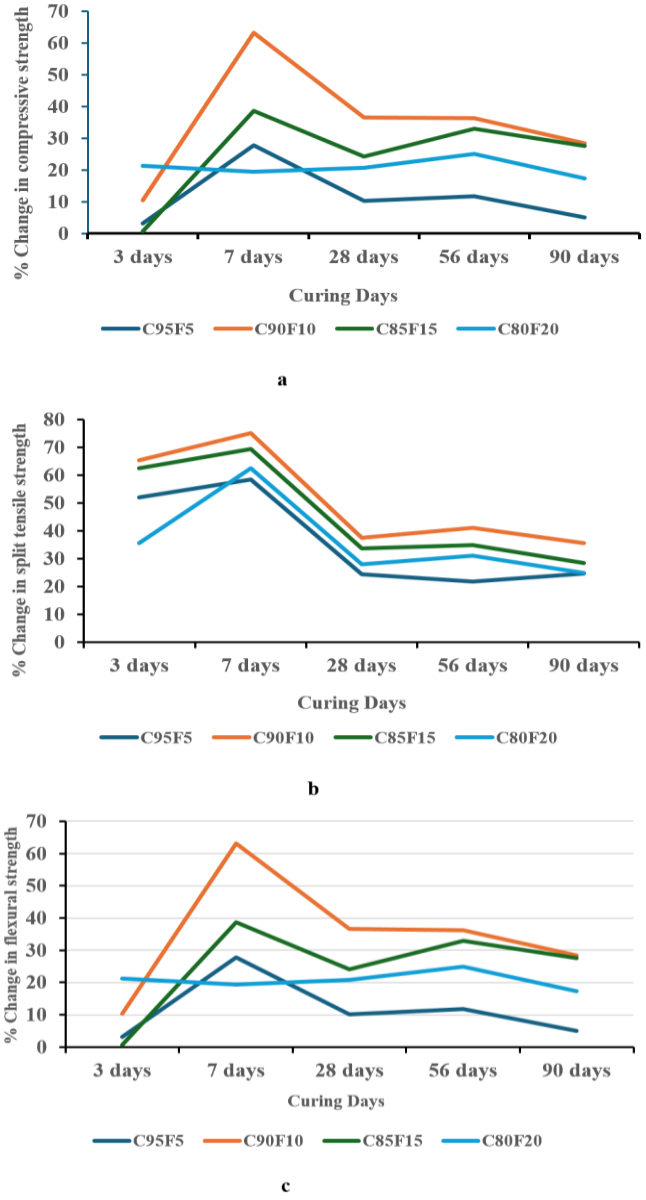


Figure (3): Percentage change in (a) CS, (b) ST, and (c) FS with mix notation

Previous studies concluded that the incorporation of FA in concrete and cement mortar lowers the risks of expansion due to alkali silica reaction (Shi et al., 2018). The use of MK in concrete reduces the expansion till the optimum ratio of replacement (Aquino et al., 2001). Previous research mentioned that 25%-40% of FA proved to be effective in significantly reducing expansion and cracking as compared to the control sample (Thomas et al., 2011). The expansion due to alkali silica reaction also depends on calcium content, a lower calcium content leads to lower expansion, and EDS analysis of ferrock shows that it has a lower calcium content as compared to OPC (Williamson & Juenger, 2016).

Results of Carbonation Test

The findings of the carbonation test of the ferrock-concrete specimens provide clear insights into the carbonation process and the material behavior under CO_2 exposure. After exposure to 100% CO_2, the freshly split surfaces of the specimens were treated with phenolphthalein as a pH indicator to assess the extent of carbonation. The carbonated and non-carbonated areas of the specimens were prepared from mixes C100F0, C95F5, C90F10, C85F15 and C80F20, as shown in Figures 4(a), 4(b), 4(c) and 4(d), respectively. Mix C95F5 indicated a significantly large non-carbonated area of concrete, as shown in Figure 4(a).

The maximum carbonated area was found in mix C80F20 with 20% replacement, which absorbs CO_2 in significantly large amounts as compared to C100F0, as illustrated in Figure 4(d). With increasing the replacement of cement with ferrock, the carbonated area also increases. Consequently, incorporating ferrock, the into concrete could enhance its capacity to absorb CO_2, with higher percentages of ferrock leading to greater CO_2 absorption. Previous studies also used phenolphthalein as an indicator for carbonated and non-carbonated areas in concrete (Chinchón-Payá et al., 2016; Lo & Lee, 2002).

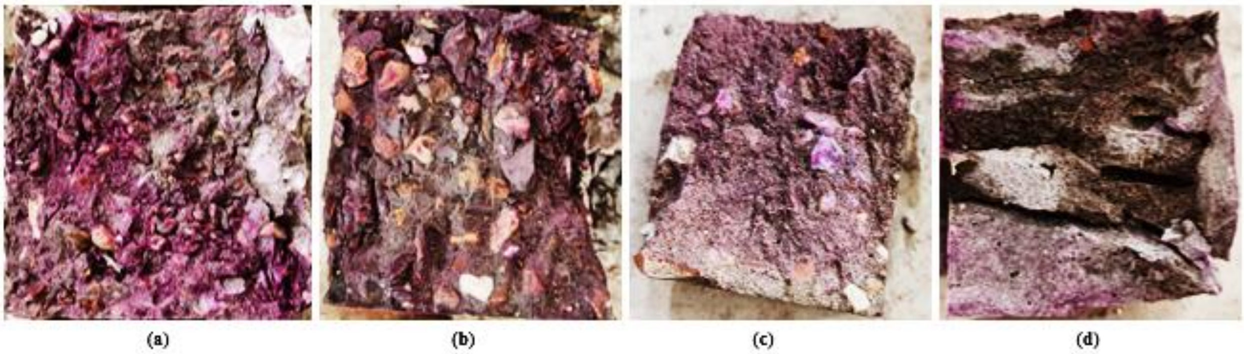


Figure (4): Carbonated area of mix (a) C95F5, (b) C90F10, (c) C85F15 and (d) C80F20

CONCLUSIONS

The present study used iron-based binder to enhance waste utilization, hence minimizing cement use and fostering sustainable development *via* the reduction of non-renewable resource usage. 10% replacement of cement with ferrock was found to be optimum in terms of mechanical strength of concrete.

The results of mechanical strength tests indicated a significant improvement at 28 days of curing, with CS increasing by 10% to 36.5%, TS increasing by 24.4% to 37.5% and FS increasing by 13.7% to 19.3%.

The carbonation test findings indicated that ferrock efficiently absorbs CO_2, rendering concrete with ferrock a feasible choice for CO_2 sequestration and enhancing sustainability to make it a carbon-negative material. This study advocates for the minimization of steel waste in landfills by its recycling into concrete, consequently augmenting concrete strength and fostering environmental sustainability. These findings provide significant insights for engineers, architects, and construction professionals in formulating sustainable construction strategies and reducing environmental consequences. The utilization of ferrock aligns with the Sustainable Development Goals (SDGs), supporting SDG 9 by enabling the development of resilient materials, SDG 11 by minimizing environmental impact, and SDG 13 by serving as a carbon-negative alternative to conventional cement and recycling waste.

Acknowledgments

The authors are thankful to the University for their generous support and assistance throughout this study. Thanks are extended to department of University for FESEM analysis.

Conflict of Interests

The authors affirm their adherence to ethical standards. No conflict of interests exists, and the review was conducted objectively, free of any external influences.

Funding

This research was not funded or supported by any external funding source.

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