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Original Research Article

Performance Study of Glassfibre Reinforced Concrete (GRC) with Ferric Oxide Waste Additive

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Abstract

Portland cement production is a major contributor to carbon emissions in the construction sector because the high-temperature calcination process produces CO_2 emissions that are nearly equivalent to the mass of cement produced. This study focuses on evaluating the potential of ferric oxide waste material in glass fiber-reinforced concrete as a filler to reduce carbon emissions, making it more environmentally friendly. An experimental method was used with a 1:1 binder-to-aggregate ratio and a constant 3% glass fiber addition. The percentage of ferric oxide replacement in the cement was 0–40%. X-ray fluorescence, X-ray diffraction, particle size distribution analysis, sand gradation testing, and mud content were used to obtain the material data. Tests were also conducted to determine compressive strength, flexural strength, water absorption, and dry and wet bulk density. Based on the results obtained, the addition of ferric oxide improved the mechanical properties of glass fiber-reinforced concrete and added to the aesthetic value of the final product. These findings indicate that the application of Glassfibre Reinforced Concrete is environmentally friendly.

Keywords: Ferric oxide waste; flexibly; glassfibrel; glassfibre reinforced concrete (GRC)

1. Introduction

The construction sector is the main contributor to most carbon emissions in the cement production process because the calcination process requires high temperatures. The CO2 emissions produced were almost the same as the weight of the cement water produced. This raises the potential to search for other materials that can reduce clinker use and greenhouse gas emissions. Previous studies have shown that partial replacement of semen with secondary materials can save process energy and reduce carbon emissions by 1-94% depending on the type of replacement material and amount of replacement material used (Akintayo et al., 2023).

Ferric oxide (FO), a waste product from the steel coating and thinning industry, has great potential as a building material. This waste is produced during the hot rolling and pickling processes at temperatures of 800–1200 °C. Fine ferric oxide particles are produced as a result. To prevent damage, such as corrosion and excessive wear on rolling equipment, it is necessary to remove the scale on the steel surface. This scale removal process involves pickling or soaking steel in an aqueous acidic solution. The acid solutions used include hydrochloric, sulfuric, and hydrofluoric acids. However, hydrochloric acid is the most commonly used acid in the steel industry (Khanna et al., 2023). Indonesia's steel production capacity reached 13.67 million tons in 2020, which can produce between 341,750 and 390,571 tons of factory-scale waste (Nurjaman et al., 2019). Government Regulation No. Appendix IX of Law No. 22 of 2021 stipulates that mill scale produced from ore smelting or ferrous and steel processing is classified as B3 waste from specific sources, with waste code B406 and hazard category 2. Mill scale contains ferric oxides, one of which is ferric oxide (Fe_2O_3). However, there is no clear classification for ferric oxide waste from the thinning process.

The main component of ferric oxide compounds is ferric (Fe). Cahyono et al. (2024) reported that the solidification-stabilization method can be used to reduce the amount of heavy metals released into the environment. This method is used to treat liquid and semi-solid wastes, resulting in a more stable solid form. This process is carried out by adding a binding agent such as cement to the waste. This material then interacts with the waste items and creates a solid form that keeps harmful substances trapped inside.

Glassfiber Reinforced Concrete (GRC) is a type of concrete made from cement and sand, with glass fiber added to strengthen it further. Because of its strong ability to handle pressure, attractive appearance, and good protection against weather, GRC is commonly used for building panels and exterior wall parts. The method of matrix preparation and the type of filler used can significantly affect the performance of the matrix. Using fly ash as a partial substitute for cement in GRC can lower the carbon footprint and add more value because of its natural reddish color. The mineral composition of the cement remains unchanged (Okoh & Dim, 2024).

Ferric oxide can be added as a filler or color component in mortar and concrete; however, there is little research on its use in GRC. According to the Glassfibre Reinforced Concrete Association International (2017) standard, there have been very few studies on how fiber oxide affects the mechanical and physical properties of GRC. This indicates that there is insufficient research on the performance of FO-based GRC, particularly in terms of compressive strength, freezing conditions, and air permeability, which are crucial for non-structural applications. Therefore, this study aims to investigate the effect of replacing some of the material with ferric oxide on the strength, flexibility, and ability of GRC to hold water. This study shows that FO is a better choice for the environment than cement and will help make ferric scrap more valuable in a circular economy.

2. Methods

The research flowchart illustrates the method used to carefully examine the subjects step by step. In this study, the impact of using ferric oxide waste as a replacement was examined on the mechanical and physical characteristics of glass fiber-reinforced concrete (GRC) through laboratory-based quantitative testing. All tests were performed in a building materials laboratory following the appropriate ASTM and SNI standards.

2.1 Materials

Ferric oxide (FO) waste was a fine red powder with a specific gravity of 2.475 g/cm3 and an average particle size of 8 μm. FO was obtained from a steel industry in East Java. In the GRC mixture, Portland composite cement (PCC) with an average particle size of 3.4 μm was used as the main binder. Glass fiber (E-glass) was used as a superplasticizer. The fine aggregate consisted of Lumajang sand with a specific gravity of 2.841 g/cm3 (SNI 1969-2008), a fineness modulus of 2.07 (ASTM C33), and a silt content of 3.3% (ASTM C117-95). Glassfiber (E-Glass) with a length of 3 cm was used as reinforcement with a fixed dosage of 3% of the total mixture weight. The selection of 3% refers to GRCA (2017), which recommends this content to achieve the best balance between flexibility and ease of workmanship. To improve workability at low water-cement ratios, it is necessary to use a high-range water reducer (HRWR) type superplasticizer, polycarboxylate ether type (Sika Viscocrete® 3115N) added at 1.5% of the cement weight. The mixing process used clean water that met the concrete quality standards of SNI 7656:2012. The water-cement ratio applied was 0.31, following the GRCA (2017) recommendations.

2.2 Mix Design

The Glassfibre Reinforced Concrete Association (GRCA, 2017) guidelines specify a mix design with a cement-to-aggregate ratio of 1:1, water-to-cement ratio of 0.31, and 3% glass fiber. This study used 0-40% FO substitution, which is the acceptable mechanistic limit of the additive. This is based on the substitution range reported in previous studies on ferric oxide-based materials.

Table 1. Mix design proportions of glassfibre reinforced concrete

Specimen Code	Composition Ratio by Weight				Superplasticizer (%) by Cement Weight	Glass Fiber (%) by total mix weight
	Cement	Ferric Oxide	Lumajang Sand	Water Cement Ratio		
FO_0	1	0	1	0.31	1.5	3
$FO_{0,2}$	0.8	0.2	1	0.31	1.5	3
$FO_{0,3}$	0.7	0.3	1	0.31	1.5	3
$FO_{0,4}$	0.6	0.4	1	0.31	1.5	3

2.3 Sample Preparation

Sample preparation included compressive strength testing (without glass fiber addition), flexural testing (with glass fiber), water absorption, and dry and wet bulk density. Each variation prepares 3 specimens (n = 3). The compressive strength test was conducted using a 5 × 5 × 5 cm cube mold at 28 d (ASTM C39). The flexural strength test was conducted at 28 days (ASTM C947) using an initial mold measuring 62 × 46 × 1 cm after the specimen curing process was cut to 47 × 5 × 1 cm. The water absorption and dry and wet bulk densities were tested following ASTM C948. All specimens were cured by undergoing a drying process covered with burlap sacks, following the ASTM C945 standard.

2.4 Data Analysis

Data analysis in this study included means, MANOVA, correlation analysis, and significance levels. The means, significance levels, and standard deviations were calculated for all test results. Furthermore, MANOVA was conducted to assess the impact and significance of FO substitution on several response variables. After that, they did a correlation analysis to see how the percentage of FO replacement affected the mechanical properties, and they used a significance level of $\alpha = 0.05$

2.5 Validity and Replication

Each test was performed on three samples for every variation to ensure the accuracy of the data. The reported values are shown as average values.

3. Result and Discussion

3.1 Particle Size Distribution (PSD) Analysis of FO Waste and PCC Cement

Particle size distribution tests were performed on the ferric oxide waste and Portland Composite Cement to identify the size of the particles in these materials. The results of the PSD tests are presented in Table 2.

Table 2. Particle size distribution results of ferric oxide waste and portland composite cement

Sample Code	Median (μm)	Mean (μm)	Modulus (μm)	Absorbance	Std Dev
Fe_2O_3	12.33	8.016	17.138	0.035	0.565
	11.694	8.055	17.138	0.046	0.521
PCC	3.996	3.465	5.348	0.233	0.523
Cement	3.985	3.46	5.348	0.239	0.522

From the PSD results, the ferric oxide waste had an average particle size of 8 μm, which might have acted as a filler in the cement mixture. According to Taylor (1997), particles that are 1 to 100 micrometers in size can make the mixture thicker and decrease the number of tiny holes in the cement paste. This is because, depending on the size and physical features of the particles, ferric oxide can partly replace cement when used as an added material in concrete or mortar mixes. These results are in line with those of Yuwana and Purnomo (2022), who stated that because smaller particles can fill the voids between larger particles in the mixture, finer particles play an important role in increasing the density and strength of concrete. This mechanism produces a denser and more homogeneous microstructure than the other mechanisms. As a result, the number of air voids in the matrix is reduced and the bond between the constituent particles in the concrete is improved.

3.2 X-Ray Diffraction (XRD) Analysis of Ferric Oxide Waste

X-Ray Diffraction (XRD) testing on ferric oxide (FO) waste showed that the hematite, maghemite, and magnetite contents were 99.4 %, 0.01%, and 0.05 %, respectively. The results of the XRD analysis of the ferric oxide waste are listed in Table 3.

Table 3. X-Ray diffraction of ferric oxide waste results

Cystal Name	Chemical Formula	Content % Fe Oxide
Magnetite	Fe_3O_4	0.05
Maghemite	Fe_2O_3	0.01
Hematite	Fe_2O_3	99.94

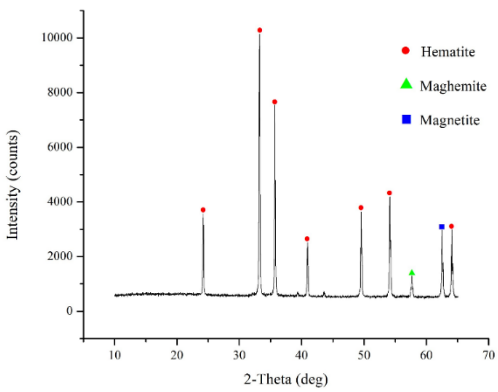

Figure 2. XRD pattern of ferric oxide waste

Figure 2 showed intensity peaks at 2θ angles of 24.15°, 33.15°, 35.61°, 40.85°, 49.46°, 54.06°, and 64.0°. These peaks correspond to the main hematite peaks based on the JCPDS No. 33-0664. On the other hand, the intensity peak of magnetite (Fe_3O_4) at 2θ angle according to JCPDS No. 19-0629 is approximately 62.48°, and the intensity peak of maghemite (Fe_2O_3) at 2θ angle according to JCPDS No. 39-1346 is approximately 57.2°. The dominance of the hematite phase indicates that the material has a stable crystal structure. Through the pore-filling mechanism (filler effect) and increased interparticle contact in the cement matrix, the presence of hematite as the main phase plays an important role in increasing the material density and compressive strength of concrete (Deepa et al. 2018). Hematite can accelerate the reaction of cement with water by offering a surface that helps create the compounds formed during this reaction, making the concrete stronger and more durable. The magnetic behavior of the material changes because it contains a small amount of magnetite. These magnetic properties could help during impurity discussions and improve the quality of the processed material. However, according to Budiman et al. (2015), it does not have as strong an impact on the mechanical properties of concrete as the hematite phase. Although maghemite is not the main component, it is still beneficial because it is stable, environmentally friendly, and has good magnetic properties. When added to concrete mixtures, it can help maintain the structure of the material, as found in Rodliya's 2018 study. Overall, the XRD analysis shows that mixing hematite as the main component with some magnetite and maghemite can work together to improve the physical and mechanical properties of concrete. This is especially true for the density, compressive strength, and stability of the microstructure.

3.3 Analysis of Lumajang Sand Gradation Test

Gradation curve of Lumajang sand that has passed sieve number. Figure 3 explains 8 and compares it with the upper and lower limits of each gradation zone as stated in SNI 03-2834-2000. The analysis showed that the particle size of Lumajang sand was mainly in Zone 2 and was getting closer to the lower part of Zone 1. The overall percentage of material that passed through the sieves increased significantly when the sieve size was between 0.3 and 1.18 mm, indicating that medium-to-coarse sand was the main component of the material. The characteristics of Zone 2 show that Lumajang sand has a particle size that fits the requirements for fine aggregates used in concrete. Owing to this gradual change, the spaces between the particles become smaller, and the concrete mix becomes more compact. In addition, the gradation curve approaching the lower limit of Zone 1 indicates the presence of more coarser sand particles. Using the method correctly can help particles fit better together and make the concrete stronger when it is squeezed. The use of cement paste was also affected by the smooth transition of Lumajang sand from medium to coarse particle sizes. Denser concrete with better microstructural stability can be prepared using fine aggregates with good gradation, which reduces the amount of air and cement required (Mehta & Monteiro, 2014). Therefore, the gradation of Lumajang sand that meets the requirements of SNI 03-2834-2000 indicates that, both in terms of technical requirements and the mechanical performance of the resulting concrete, this material is suitable for use as a fine aggregate in concrete mixtures.

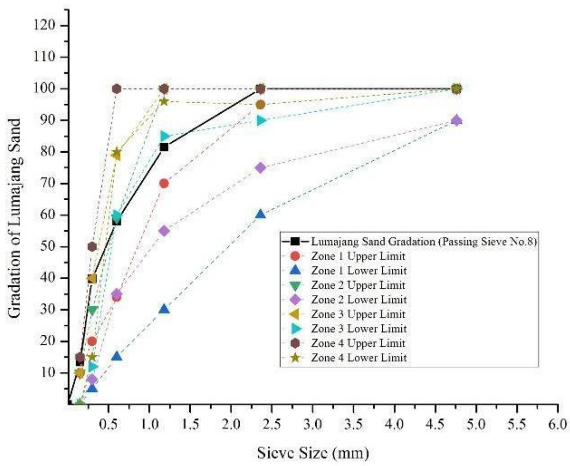

Figure 3. Gradation curve of lumajang sand

3.4 Compressive Strength

This study aimed to analyze the effect of variations in material composition, especially the content of ferric oxide (FO) waste as a filler. Figure 4 shows the compressive strength results for the ferric oxide (FO) waste mixture.

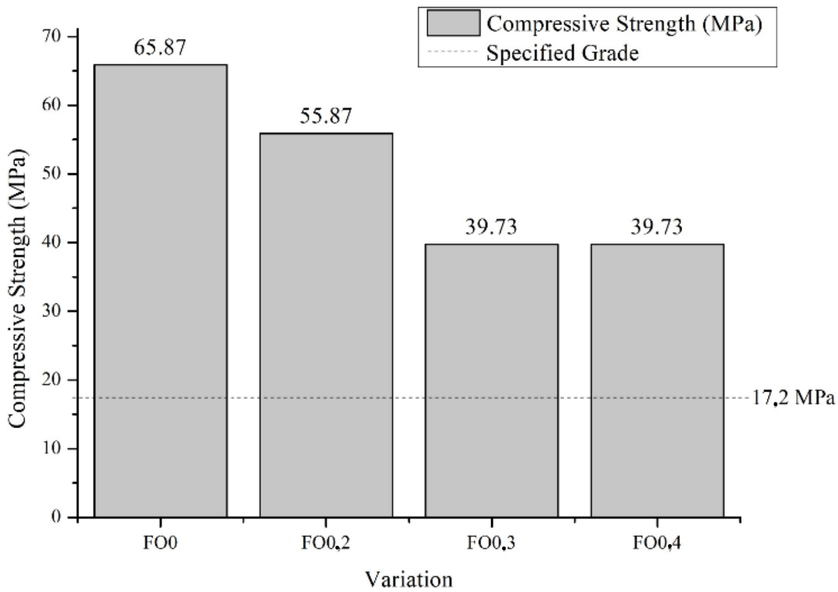

Figure 4. Compressive strength graph of ferric oxide waste

Figure 4 shows that the mixture without the addition of ferric oxide waste (FO0) produced the highest compressive strength of 65.87 MPa; however, in the FO0.2 variation, the compressive strength decreased to 55.87 MPa; and in the FO0.3 and FO0.4 variations, the compressive strength obtained was comparable, namely, 39.73 MPa. This implies that the strength of the mortar decreases when more ferric oxide waste is added.

Ferric oxide affects the structure of the cement matrix, lowering its ability to resist compression. At low levels, ferric oxide can act as a filler by filling the spaces between particles and making the material denser. However, when there is a lot of ferric oxide, it can cause problems with how the semen is mixed with water and increase the air needed for the mix. This leads to larger holes forming in the mortar, making it less strong overall (Mehta & Monteiro, 2014). In addition, when there are more ferric oxide particles, they do not spread out evenly, which weakens the bonds between the particles. This can lead to a lower compressive strength in the matrix.

All the mix variations had compressive strength results that were higher than the target strength of 17.2 MPa, but the addition of ferric oxide lowered the compressive strength. This value satisfies the standards set by ASTM C270-80a, which requires a minimum compressive strength of 175 kg/cm^2 (17.2 MPa) for Type M mortar. This type of mortar is commonly used in reinforced masonry, pound, and other reinforced concrete walls (Sihombing et al., 2019). These results show that when GRC is mixed with ferric oxide waste, it meets the required strength requirements, which means it can be used for both structural and non-structural building purposes.

The strength of mortar when compressed depends on the materials and aggregates used. A low amount of silt in the aggregate can strengthen the concrete or mortar by helping the cement paste adhere better to the aggregate. However, having a lot of silt can prevent particles from sticking together and weaken the material. Therefore, the achievement of a relatively high compressive strength in all mixture variations studied is supported by the use of aggregates with a low silt content (Purwanto & Priastiwi, 2017).

3.5 Flexibility

The goal of this test was to examine how changes in the materials used, especially the use of ferric oxide waste as a filler, affected the outcome. The test results are shown in Figure 5.

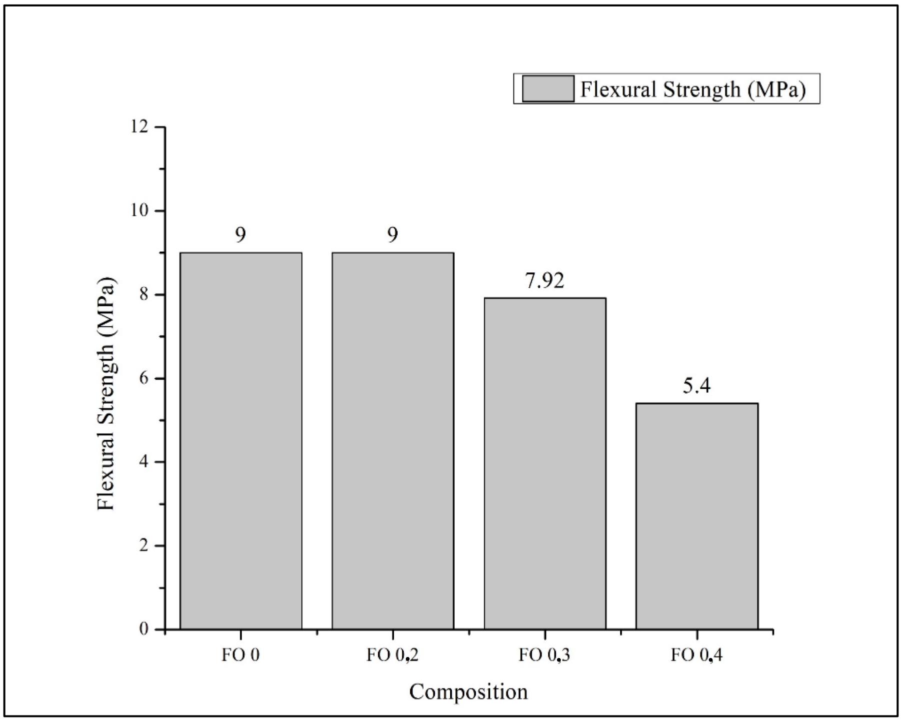

Figure 5. Flexibility of ferric oxide waste mixtures

As shown in Figure 5, the test results show that the FO0 and FO0.2 variations had the highest value of 9 MPa, while the FO0.3 variation dropped to 7.92 MPa, and the FO0.4 variation decreased to 5.4 MPa. This shows that as the amount of material used decreases, the amount of ferric oxide waste in the GRC mixture also decreases. At lower amounts, ferric oxide can work as a filler to make the matrix denser and improve the adhesion of the parts. At higher levels, ferric oxide can lead to uneven structures in the material and create areas where stress builds up more, making the material less able to withstand bending forces (Mehta and Monteiro, 2014). Adding more non-reactive particles to the cement mix can result in weaker bonding between the cement and fibers. This can affect the durability of the GRC over time.

The results showed that adding 20% ferric oxide waste (FO0.2) maintained the initial value as the mixture without any substitution (FO0). This means that the iron oxide particles are spread out fairly evenly at this level of substitution and do not disrupt the way the material regrows or spreads. According to composite material theory, having a uniform structure and strong bonds between the different parts of the material affects how well it can bend (Utami & Cahyo, 2022). The FO0.2 mix was the top choice because it offered the best mechanical performance and made the most use of waste materials. This is because it can keep the ecosystem healthy without getting badly hurt, while also helping to use industrial waste in a way that is sustainable. These results show that using ferric oxide waste to make GRC can work as a green building material and perform well mechanically.

3.6 Water Absorption

This test was performed to determine how changes in the materials used, especially the amount of ferric oxide waste acting as a filler, affect the outcome. Figure 6 shows the results of the tests that measured the amount of air absorbed by the mixtures that included ferric oxide waste. According to the

Glassfibre Reinforced Concrete Association International (2017), the amount of ferric oxide waste used was between 5% and 11%.

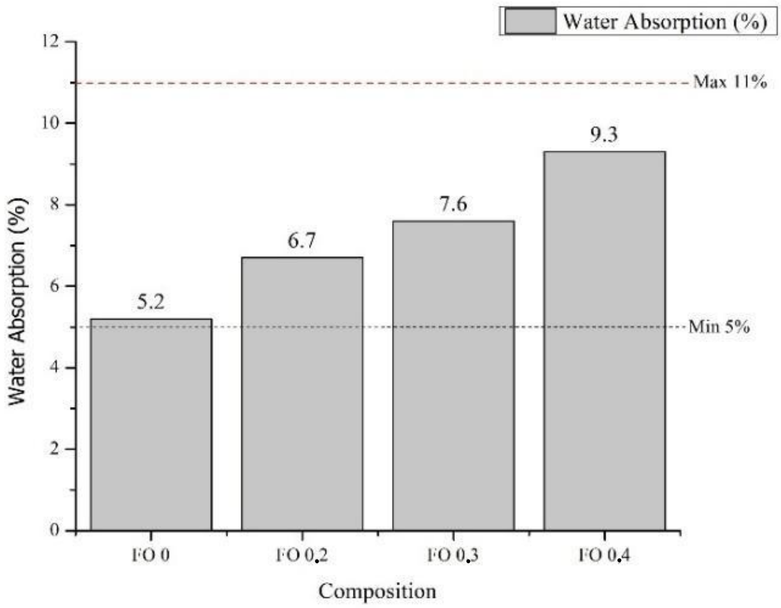

Figure 6. Water absorption of ferric oxide waste mixtures

The test results indicate that there is more ferric oxide waste in the GRC mixture, as shown in Figure 6. The FO0 variation yielded an air absorption value of 5.2%, which was the lowest among all variations. The FO0.2 variation resulted in an air absorption of 6.7%, which increased to 7.6% in the FO0.3 variation, and reached the highest level of 9.3% in the FO0.4 variation.

Adding more ferric oxide particles at higher levels can lead to changes in the material structure, which may result in more air being absorbed. At low levels, ferric oxide can still act as a filler by filling small pores and making the matrix denser; however, when there is more of it, the less reactive ferric oxide particles can interfere with semen hydration, leading to higher air demand and the creation of new pores. This condition helps the material hold more air, according to Mehta and Monteiro (2014).

In addition, adding more ferric oxide can affect the area between the cement and glass fibers, which is called the interfacial transition zone. Because the ITZ is less dense owing to the uneven particle arrangement, air can pass through more easily, making GRC materials more breathable (Bentur and Mindess, 2007). Studies have found that when cement-based materials have higher air absorption, they usually have more pores and uneven structures (Li et al., 2019).

Even though there is more sound absorption in the air, all the results are still within the range that the Glassfibre Reinforced Concrete Association International stated in 2017, which is between 5% and 11%. This shows that each version satisfies the air absorption standards for GRC materials, and the range of air absorption suggests a level of porosity and density that is still suitable for use in construction, either as a separate component or as part of a building structure.

The results indicate that even when the amount of ferric oxide waste is increased by up to 40%, it is still possible to produce GRC with air absorption properties that satisfy the required standards. The air absorption values show that the GRC is sufficiently strong to handle environmental changes, especially when it goes through wet and dry cycles. These results suggest that ferric oxide waste can be used as a substitute for GRC. This is because the material works well and lasts a long time, and it is good for the environment, as shown by Pacheco-Torgal et al. in 2014.

3.7 Dry and Wet Bulk Density

This test was performed to determine the density of the material when it is wet and dry. Figure 7 shows the results of the dry and wet bulk density tests for a mix that included ferric oxide waste. The Glassfibre Reinforced Concrete Association International (2017) states that the minimum bulk density is 1800 kg/m³ and the wet density is 2000 kg/m³.

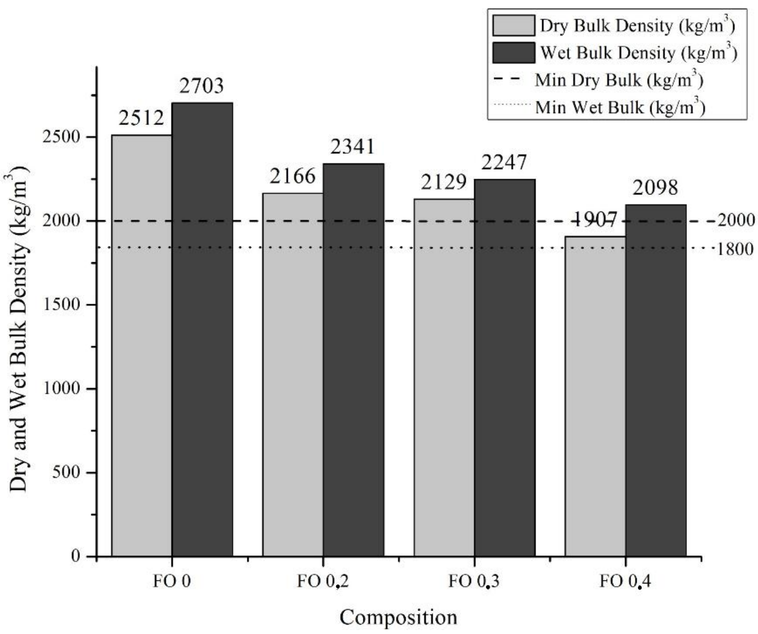

Figure 7. Dry and wet bulk density of ferric oxide waste mixtures

For each different mix used in the GRC tests, the results showed that the dry rainfall density decreased slowly, as shown in Figure 7. The FO0 variation resulted in a dry rainfall density of 2512 kg/m3, whereas the FO0.2 variation dropped to 2166 kg/m3. The FO0.3 variation was 2129 kg/m3, and the FO0.4 variation had the lowest value of 1907 kg/m3. The Glassfibre Reinforced Concrete Association International (2017) states that the minimum dry density required is 1800 kg per cubic meter. The measured values satisfied this requirement.

Therefore, it can be concluded that each mix variant produced GRC with a dry density that met the quality standards. Dry density values that meet these criteria indicate that the material has sufficient compactness and volume stability for use in construction projects. These values also indicate that all mix variations complied with applicable standards.

The wet density results also showed a decreasing trend for each ferric oxide composition. The wet density of the FO0 variation was 2703 kg/m³. It then decreased to 2341, 2247, and 2098 kg/m3 at FO0.2, FO0.3, and to 2098 kg/m³ at FO0.4, respectively. According to the Glassfibre Reinforced Concrete Association International (2017), the minimum wet density of GRC products is 2000 kg/m³. The test results showed that this minimum limit was met for all mixture variations. Consequently, all the GRC mixtures met the wet density requirements. Consequently, they can be used for various GRC applications that require strength, durability, and stability. Thus, it can be concluded that the addition of ferric oxide increased both the dry and wet bulk densities. The Glassfibre Reinforced Concrete Association International (2017) showed that the manufactured materials met the established standards because all variations tested were within the specified range.

3.5 Glassfibre Reinforced Concrete (GRC)

The results showed that the addition of ferric oxide (FO) waste significantly affected the compressive strength and stiffness of the GRC, as shown in Figure 7. In the FO0 variation, which was controlled without FO waste, the compressive strength was 65.87 MPa and the bond was 9.0 MPa; however, with the addition of FO, these values decreased gradually, reaching 39.73 MPa for compressive strength and 5.4 MPa for implementation on the FO0.4 mixture. There was a strong correlation between compressive strength and stiffness. A greater compressive strength was associated with a larger error and vice versa. However, the sensitivity of the decrease increased at FO substitution levels of 0.3 and 0.4. This indicates that when excessive FO was added, the material lost its strength and toughness more easily than its compressive strength.

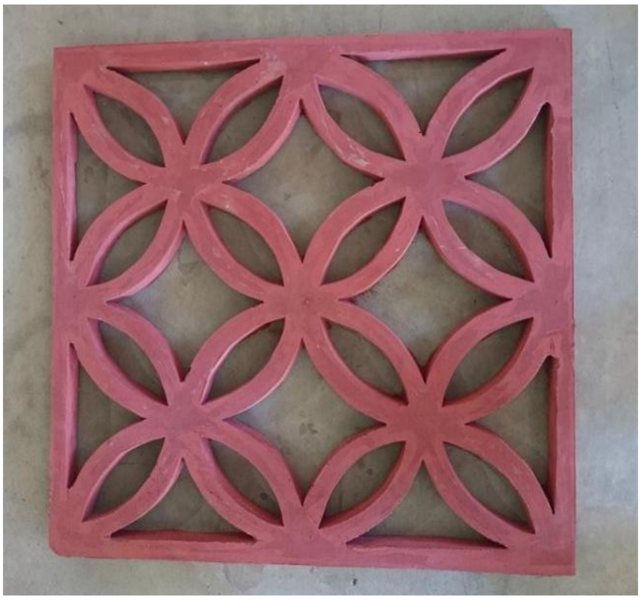

Figure 8. Glassfibre Reinforced Concrete (GRC) products from Krawangan

The results showed that the addition of ferric oxide (FO) significantly affected the mechanical and physical properties of GRC. MANOVA revealed that variations in FO substitution significantly affected compressive strength, curing, air absorption, and density ($p < 0.05$). The compositions of FO0.3 and FO0.4 showed significant differences; the compressive and cooling strengths decreased by more than 30% compared with those of the control. This decrease was not only a descriptive trend but also had a mechanical correlation with the decrease in the amount of active binder because non-reactive FO was used as a cement substitute. As reported by Hansu and Etli (2025) and Rasikbhai Thoriya et al. (2023), this condition inhibits the formation of C–S–H gel and increases the voids between agglomerates. Consequently, the resistance of the material to compressive loads decreased.

These results are in line with Amalia's (2009) research, which explains that excess Fe_2O_3 can slow down the finishing process and produce a denser microstructure. In addition, the effectiveness of the filler only affects the best dosage; if the dosage is more than 20% FO, microcracks appear, reducing the interaction of cement between particles and reducing the integrity of the matrix (Noori & Ibrahim, 2018). According to the analysis of the relationship parameters, the decrease in compressive strength was related to sudden decreases. This indicates a strong relationship between the microstructural conditions and material capacity.

Conversely, an uneven fiber distribution can reduce the flexural performance, particularly in FO compositions. However, the role of glass fibers as a crack-bridging mechanism, which can bridge cracks and strengthen the ITZ, as well as the presence of fine Fe_2O_3 particles as micro-fillers, increases the matrix density and flexural toughness (Jose et al., 2023). However, uneven fiber distribution potentially reduces flexural performance, particularly at high FO compositions (Cheng et al., 2024).

From the perspective of physical properties, excess FO increases air absorption owing to greater open porosity. Non-reactive FO, on the other hand, increases pixel clusters without increasing the interparticle bond density (Pereira et al., 2011) and (Hassani & Kazemian, 2024). This is consistent with the increase in air absorption at the FO0.4 composition from 5.2% to 9.3%. The increase in wet and dry densities does not directly indicate a decrease in porosity, as this increase is more related to the intrinsic density of FO than to an improvement in the microstructure (Wang et al., 2022).

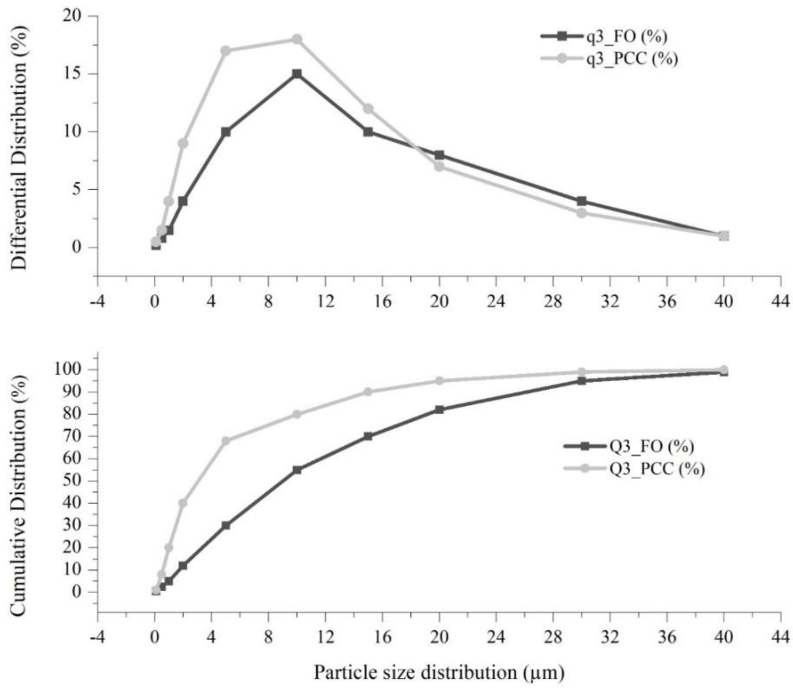

Figure 9. Particle Size Distribution (PSD) of ferric oxide and PCC

The mechanical and physical properties of GRC are significantly influenced by the particle size distribution. The test results show that ferric oxide (FO) and PCC particles have a variety of sizes that can form a better stacking density. As fine particles fill the gaps between larger particles, the voids in the matrix are reduced. This resulted in a denser microstructure and a stronger interfacial transition zone (ITZ). Consequently, crack initiation is more difficult and can be inhibited by the crack-bridging mechanism reinforced by glass fibers (Singh et al., 2021).

The mechanical properties of composite materials are significantly affected by an increase in particle density. If the particle sizes are not balanced, it can cause the particles to separate, filling up all the empty spaces, which then lowers porosity. Therefore, the ability of the material to withstand compression improves, and the manner in which stress is transferred between the particles becomes more effective. In addition, there are fewer empty spaces in the material that can initiate cracks (Mehta & Monteiro, 2014). This occurred because the compressive strength and signature dropped in the mixtures with FO0.3 and FO0.4, respectively.

Increasing density also affects physical properties, such as the amount of air absorbed. A thicker matrix implies fewer open spaces and pathways for water movement. Consequently, the ability of air to absorb things becomes very weak. When a material has lower porosity, air can pass through it more easily. Consequently, the wet-dry cycles made the material more difficult to damage. These findings are consistent with Neville (2011), who highlighted that fine fillers help lower the capillarity of cement paste and that a denser matrix leads to higher air absorption.

The dry and wet densities indicate the extent to which the particles are spread out. When the spaces between the particles are filled with a mixture of large and small particles, the material becomes denser. Wet density indicates that the material can hold its shape better when wet, whereas dry density indicates that there is less empty space inside the material. This matches the findings of Hansu and Etli (2025), who noted that cementitious materials have a higher bulk density when the packing density is higher. Therefore, when the packing density in the GRC matrix increases, the particle size distribution, presence of organisms, air absorption, and density are all connected to each other.

Moreover, when a material has more pores, it creates more tiny pathways inside, which helps it absorb more air. (Wang et al., 2022) The data shows that the mix with too much filler had an air absorption value of 9.3%. This implies that more empty spaces are present. To obtain the best strength and performance from the material while keeping as much air out as possible, it is important to have the right level of material packed together. This occurs because the increase in density when there is a lot of PCC is mainly because there are more particles packed together, not because the material has less empty space. Using 20% fossil fuels instead of cement is beneficial for the environment.

Replacing 20% of cement can lower CO_2 emissions by approximately 0.16 tons of CO_2 for every ton of cement used or 0.8 tons of CO_2 for each ton of cement. This shows that using the appropriate amount of FO can boost mechanical performance, reduce carbon emissions, and support recycling efforts in construction.

4. Conclusions

This study indicates that waste from ferric oxide can be used as a filler material. Glassfiber Reinforced Concrete (GRC) has a composition of 20% and provides an average compressive strength of 9 MPa, which is higher than the strength of the mixture that does not include ferric oxide. According to the GRCA (2017), every mix variation satisfied the standards for air absorption and had a minimum dry and wet density. This demonstrates that these materials are suitable for use in construction. If the amount of ferric oxide waste is increased beyond 20%, tiny empty spaces are created and the amount of active binder is reduced, which leads to a significant decrease in compressive strength and hardenability. Using ferric oxide as a filler is helpful because it lowers the amount of cement required, and cement is a major cause of CO_2 emissions in the construction industry. Ferric oxide is a compound made up of Fe_2O_3, and it is stable, not harmful, and works as a small filler that helps make the matrix denser. Compared with using only cement, this method is better for the environment. This helps manage waste from the steel industry sustainably and lowers the amount of carbon emissions from building materials. The findings indicate that industrial construction can apply the concept of a circular economy and help achieve the aim of lowering greenhouse gas emissions in the infrastructure industry. Further studies are required to support these results. This may involve checking how long the product lasts over time, testing its performance when made on a larger scale, and conducting a more detailed examination of its effect on the environment.

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Ethics Statement

This study follows the Standard National Indonesian (SNI) to ensure that the product is of good quality. All the people who took part in the study signed a document to show they understood what was involved, and their personal information was kept private and secure during the whole process.

CRedit Author Statement

Vivin Setiani: Conceived and Designed the Analysis, Collected the Data, Contributed Data or Analysis Tools, Performed the Analysis, Wrote the Paper. **Wiwik Dwi Pratiwi**: Collected data, performed the analysis, wrote the paper, and provided GRC characteristics. **Denny Dermawan**: Provided Conceptual

Industrial Coordination to Take Sample Material of GRC. **Luqman Cahyono**: Contributed to the GRC experiment. **Mohamad Hakam**: Contributed Experiment GRC. **Ryan Yudha Adhitya**: Contributed Experiment GRC. **Mochammad Karim Al Amin**: Contributed Experiment GRC. **Nur Fajar Aprilia Sari**: Contributed to the GRC experiment. **Wanda Cahyaning Ati**: Helped Experiment GRC. **Lina Indawati**: Contributed to Data Analysis Based on Statistics.

References

Akintayo, B. D., Akintayo, D. C., & Olanrewaju, O. A. 2023. Material substitution strategies for energy reduction and greenhouse gas emissions in cement manufacturing. Atmosphere, 14(8), 1–14.

Amalia. 2009. Studi eksperimental perilaku mekanik beton normal dengan substitusi limbah debu pengolahan baja (Dry Dust Collector). Program Magister Teknik Sipil, 56.

Bentur, A., & Mindess, S. 2007. Fiber-reinforced cementitious composites (2nd ed.). London: Taylor & Francis.

Budiman, A., Trilismana, H., Fisika, L., Jurusan, B., & Andalas, U. 2015. Effects of oxidation on the concentration of superparamagnetic grains of magnetite in iron sand. 9–15.

Cahyono, L., Carina, A., Pratiwi, W. D., Fardina, F., Widiana, D. R., Utomo, A. P., & Fahmi, M. R. 2024. Sustainable materials melalui solidifikasi-stabilisasi limbah sandblasting menjadi beton ferosemen. 04(02), 108–118.

Cheng, C., He, J., Li, X., & Hong, S. 2024. Flexural behavior of glass fiber-reinforced cement incorporating foam. Journal of Engineered Fibers and Fabrics, 19.

Deepa, R., Geethamozhi, E., Monika, S., Shalina, S. P., & Swathy, K. (2018). Experiment on high-density concrete incorporating hematite. Indian Journal of Scientific Research, 20(2), 49–53.

Glass Fiber Reinforced Concrete Association International. 2017. GRC specifications and quality manuals. International Glass Fiber Reinforced Concrete Association.

Hansu, O., & Etli, S. 2025. Evaluation of the usability of scms produced by adding aluminum and iron oxide to mortar waste powder under different conditions. Buildings, 15(17), 1–25.

Hassani, A., & Kazemian, F. 2024. Case studies in construction materials investigating geopolymer mortar incorporating industrial waste using response surface methodology : a sustainable approach for construction materials. Case Studies in Construction Materials, 21(May), E03609.

Jose, P. A., Alex, A. G., Gebrehiwet, T., & Murugan, S. 2023. Influence of Fe2o3 nanoparticles on the characteristics of cement mortar mixed with waste marble powder International Journal of Concrete Structures And Materials, 17(1).

Khanna, R., Konyukhov, Y., Li, K., Jayasankar, K., Maslennikov, N., Zinoveev, D., Kargin, J., Burmistrov, I., Leybo, D., Kravchenko, M., & Mukherjee, P. S. 2023. Innovative transformation and valorisation of red mill scale waste into ferroalloys: carbothermic reduction in the presence of alumina. Sustainability (Switzerland), 15(24).

Li, G., Zhao, X., Rong, H., & Wang, Z. 2019. Effect of porosity on water absorption and mechanical properties of cement-based materials. Construction and Building Materials 215: 831–840.

Mehta, P. K., & Monteiro, P. J. M. 2014. Theoretical concepts of stress-wave propagation in solids. in concrete: Microstructure, properties, and materials.

Neville, A. M. 2011. Properties of Concrete (5th ed.). Harlow: Pearson Education Limited.

Noori, K. M., & Ibrahim, H. H. 2018. Mechanical properties of concrete using iron waste as a partial replacement for sand. Eurasian Journal of Science and Engineering, 3(3), 75–82.

Nurjaman, F., Prilitasari, N. M., Prasetyo, A. E., & Nugroho, E. 2019. Pemanfaatan limbah industri baja sebagai bahan baku pembuatan logam pig iron: peleburan mill scale menggunakan submerged arc furnace. 37–48.

Okoh, J. S., & Dim, P. E. 2024. P066 - Investigation of the effect of iron oxide (Feo 3) pigment on the production of colored cement 9(7), 66.

Pacheco-Torgal, F., Labrincha, J. A., Leonelli, C., Palomo, A., and Chindaprasirt, P. 2014. Handbook of

Recycled Concrete and Demolition Waste. Cambridge: Woodhead Publishing.

Pereira, F. M., Carlos, J., Verney, K. De, & Lenz, D. M. 2011. Evaluation of the use of mill scale as a fine aggregate in concrete. 64(4), 463–469.

Purwanto & Priastiwi, Y. A. 2017. Pengaruh kadar lumpur pada agregat halus dalam mutu beton. Jurnal Teknik Sipil Universitas Diponegoro, 33, 46–52

Rasikbhai Thoriya, K., Singh, A., Agrawal, V., & Chandra Gupta, R. 2023. Preliminary study on the utilization of steel mill scale in concrete. materials today: Proceedings.

Rodliya, L. S. 2018. Sintesis pigmen maghemit (Γ-Fe2o3) dari limbah bubut industri kerajinan besi dengan variasi suhu kalsinasi. 1–120.

Sihombing, A. P., Afrizal, Y., & Gunawan, A. (2019). Pengaruh penambahan arang batok kelapa terhadap kuat tekan mortar. Inersia, Jurnal Teknik Sipil, 10(1), 31–38.

Singh, B., Pathania, A., Gupta, M., Saini, A., & Shukla, A. (2021Si21 Influence of the packing density of fine particles in ternary, quaternary and quinary blends on high performance concrete. Rilem Bookseries, 29(January), 465–482.

Taylor, H. F. W. 1997. Cement chemistry. 2nd Ed. Academic Press, 20(4), 335.

Utami, N., & Cahyo, E. 2022. Sifat mekanik komposit fiberglass melalui uji lentur. Teknika Sttkd: Jurnal Teknik, Elektronik, Engine, 8(2), 322–329.

Wang, Y., Li, L., An, M., Sun, Y., Yu, Z., & Huang, H. 2022. Factors influencing the capillary water absorption characteristics of concrete and their relationship to pore structure. Applied Sciences (Switzerland), 12(4).

Yuwana, H. P., & Purnomo, S. 2022. Pengaruh gradasi pasir terhadap kekuatan tekan mortar dalam perencanaan sementasi limbah radioaktif. Jurnal Pengawasan Tenaga Nuklir, December, 42–51.