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Green Concrete: Ferrock Applicability and Cost- Benefit Effective Analysis

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ABSTRACT

This research aims to assess the viability and suitability of Ferrock as an alternative to concrete for constructing foundations. The study evaluates the performance of Ferrock in foundation applications, compares its costs with traditional concrete, and examines the benefits of using Ferrock for foundations. To achieve these objectives, the utilization of Staad Pro and Foundation software is done to analyze the performance of Ferrock foundations. A cost-benefit analysis, considering factors like material costs, construction techniques, and maintenance requirements to determine the economic feasibility of Ferrock as a substitute for concrete and the potential to reduce carbon emissions, and promote environmentally friendly construction practices is also done. The research findings indicate that Ferrock exhibits promising performance characteristics for building foundations. It demonstrates comparable strength to traditional concrete while offering potential environmental benefits. Although implementing Ferrock may require an initial investment, the long-term advantages of reduced maintenance costs and improved sustainability contribute to its overall value proposition.

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1. INTRODUCTION

Concrete has emerged as the most widely used building material globally, owing to its affordability, ease of use, durability, versatility, and local availability (Ngugi *et al*., 2017; Latha *et al*., 2015). However, the production of cement, the main component of concrete, has led to significant carbon dioxide emissions. In 2021, these emissions from cement manufacturing were estimated to reach 1.7 billion MtCO2, with a steady increase observed since the 1960s, more than doubling since the start of the 21st century. Presently, annual global cement production surpasses 4 billion metric tons. The growing global population, urbanization trends, and infrastructure demands have fueled the demand for cement and concrete, placing increased pressure on policymakers to expedite efforts in reducing the carbon footprint associated with cement production. Even if countries were to consider their publicly stated energy efficiency goals and commitments to carbon emission reduction, the cement industry would still experience a 4% rise in direct CO2 emissions by 2050, despite an anticipated 12% increase in cement production during that period. Therefore, more aggressive measures would be necessary to achieve the climate targets set for the world. The construction of foundations is a significant part of any project, often accounting for one-third to half of the overall working cycle and costs. It is important to analyze the suitability of using green materials in foundation construction to accurately control carbon emissions and protect the environment. Additionally, the environmental impact of foundations is seldom assessed as part of the overall evaluation of structures.

Today, there is a growing focus on finding ways to reduce atmospheric concentrations of greenhouse gases, particularly CO2. As a result, the world is exploring alternative materials that can provide similar benefits to concrete in terms of strength, endurance, and durability while also being cost-benefit effective. In this study, an analysis of the performance of foundations and assessing the cost-benefit effectiveness of using a concrete alternative material named Ferrock (which is an environmentally friendly material crafted from recycled resources like steel dust and other industrial byproducts), is done to contribute to the goal of lowering greenhouse gas emissions.

In response to the global warming crisis, engineers are actively seeking alternatives to concrete. The current state of the world demands the creation, development, and improvement of new materials that offer enhanced performance, durability, sustainability, and eco-friendliness, all while remaining cost-effective. By designing structures using alternative materials to concrete, engineers can work towards achieving these goals. This approach also enables the development of tools and methods to evaluate the entire life cycle of building processes, including business dealings, procurement, construction, and result evaluation. Until now, there has been a lack of research investigating the use of Ferrock as an alternative to concrete in footing design. To address this gap, a performance-based design approach is proposed as a direct replacement for traditional material design. Consequently, this study aims to examine the performance of the foundations of a building using both Concrete and Ferrock and conduct a cost-benefit effective analysis.

Questions are in the following:

(i) Is Ferrock material a viable alternative to concrete for building foundations?
(ii) Does Ferrock material have a lower cost compared to concrete?
(iii) Does Ferrock material have more benefits compared to concrete?

This research aims to assess the feasibility and suitability of Ferrock as a viable alternative to concrete for building foundations. The specific objectives of the study are as follows:

(i) Assess the performance of Ferrock material when used in building foundations.

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(ii) Compare the cost of implementing Ferrock as a foundation material with traditional concrete.
(iii) Compare the benefit of implementing Ferrock as a foundation material with traditional concrete.

2. LITERATURE REVIEW

Cement is widely used in the construction industry due to its durability, high compressive strength, and resistance to chemical and weathering effects. However, the environmental impact of cement production has raised concerns. If the use of cement continues without changes, it is estimated that the world will produce 3.5 billion metric tons of cement by 2050. To address this issue, alternative approaches such as increasing energy efficiency and incorporating alternative raw materials need to be explored. In this study, an investigation is done for Ferrock, an alternative material for concrete that utilizes by-products from various industries. Ferrock was discovered by Dr. David Stone in 2002 while working on preventing iron from rusting and hardening. Initially, he didn't pay much attention to the material but later decided to focus on developing an environmentally friendly substance with properties similar to concrete. To conduct tests on Ferrock, Stone partnered with the Tohono O'odham Nation Reservation in Arizona to obtain the necessary silica and received grants from the Environmental Protection Agency. After successful development, Ferrock won a competition but faced a patent infringement lawsuit filed by Pantang Fodrino in 2013. Stone eventually reached a licensing agreement in 2014 with the University of Arizona to commercialize Ferrock, facilitated by Tech Launch Arizona (Manjunath & Prasanna, 2021).

Ferrock is a carbon-negative material and a useful tool for waste management. It incorporates waste materials such as iron powder (60% of its weight), fly ash or glass (20%), metakaolin (8%), limestone (10%), and oxalic acid (2%). These materials are obtained from sources like construction waste and discarded ground silica glass. By utilizing waste products, Ferrock avoids additional carbon dioxide emissions during its manufacturing process. It emits significantly less CO2 than traditional concrete and can absorb CO2 as it hardens, resulting in a carbon-negative impact. Ferrock is also stronger and more flexible than Portland cement, with a faster setting time and the ability to withstand stress and seismic activity without fracturing. Compared to Ordinary Portland Cement (OPC), Ferrock requires only 8-10% of the clay and limestone while being more cost-effective, stronger, and more versatile in construction applications. Its curing process is expedited using compressed carbon dioxide, eliminating the need for additional heat. Ferrock's quick setting time makes it suitable for projects where speed is essential. While it may not be readily available everywhere, Ferrock proves to be an excellent alternative to concrete in areas where it is accessible. It typically has a compressive strength ranging from 5,000 to 7,500 psi, and a unit weight of 16.3 Kg/m3. To date, there have been limited studies conducted to establish the validity of proposed alternative materials for concrete. Furthermore, none of these studies have specifically examined the suitability of such materials as alternatives for concrete in foundations. Therefore, the purpose of this research is to ascertain the validity of utilizing Ferrock as an alternative to concrete in foundations.

3. METHODOLOGY

3.1. General Approach

To properly analyze the selected material, a concrete building is modeled using STAAD.Pro V8i software. Subsequently, the geotechnical analysis of this building is conducted using

STAAD Foundation V8i (version 5.3), making use of the chosen material. STAAD.Pro V8i is a powerful design program licensed by Bentley. It is commonly used for structural analysis and design, with any load-bearing structure falling under its purview. The initial step involves defining the structure's shape, followed by an analysis to identify the types of loads acting on the beams and calculate shear forces and bending moments. The design process incorporates the chosen material and its proportions to ensure it can withstand the applied load.

For tank structures, STAAD.Pro is considered an excellent option due to its efficiency, completing the task in just one hour. Currently, STAAD.Pro is widely utilized for designing various structures, making it crucial for civil engineers to possess knowledge of this program. Additionally, the program supports several country codes for different design requirements. On the other hand, STAAD Foundation (version 5.3) is a robust software utilized for calculating different types of foundations. Also licensed by Bentley, this program complements the analysis, design, and post-processing capabilities of STAAD. It provides load information at various support locations, which are then inputted into the program to determine footing specifications, including geometry and reinforcing data.

3.2. Method

3.2.1. Foundation Analysis

The primary objective of the building design is to ensure a safe and environmentally sustainable structure. The design approach follows the limit state method, aiming to establish a level of confidence that the structure will not deteriorate over time and will continue to function as intended. This method considers all relevant states to achieve a desired level of safety and serviceability. The limit state of collapse represents the maximum load-bearing capacity of the structure. If this limit state is violated, it indicates potential issues in the structure's integrity, although it does not necessarily imply complete failure. This limit state encompasses flexural, compressive, shear, and torsion forces.

The design geometry involves a 3D concrete building with two floors (floor 1: 10 x 10 x 4 m^3 and floor 2: 10 x 10 x 3 m^3) and a roof (6*10*3 m^3). The building is supported by a rectangular concrete beam with a cross-sectional area of 0.45 x 0.3 m^2 and a slab with a thickness of 0.2 m. The beam rests on nine rectangular columns with dimensions of 0.3 x 0.3 m^2 and nine isolated foundations (see **Figure 1**).

The design notations and assumptions follow the ACI 318-19 standards. Partial safety factors are considered for loads, with a factor of Υ_t=1.52, and for concrete or alternative materials (1.5) and steel (1.15) according to ACI 318-19. The partial safety factors are determined based on load combination clauses of ACI 318-19. The loads and combinations are crucial considerations in the design process. Loads are categorized into vertical and horizontal loads, depending on their direction of structural action or forces. Properly accounting for loads is essential to ensure the structure's safety and serviceability throughout its useful life. The specific loads imposed on a structure are influenced by factors such as occupancy, function, layout, location, climate, and site conditions. Design choices, including material selection, construction details, and architectural arrangements, are influenced by the type and magnitude of these design loads.

In this structure, two loads are considered: dead loads and live loads. Dead loads refer to the permanent construction material loads that compress the slab, beams, columns, and foundation systems. They typically do not vary over time. Live loads, on the other hand, are caused by the use and occupancy of the structure and include loads from occupants, construction, and maintenance activities. In this design, a live load of 3 kN/m^2 is considered. Dead and live loads are calculated according to the guidelines specified in ACI 318-19. By

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accurately applying these design loads, the completed structure's value can be maximized. The dead and live loads are allocated to the structural members using STAAD PRO software, considering the properties and characteristics of the materials involved. ACI considers all load cases by incorporating load factors and analyzing the building in different load combinations. The results are obtained and the load combination with the highest magnitude is selected for the design. **Table 1** illustrates the load combination.

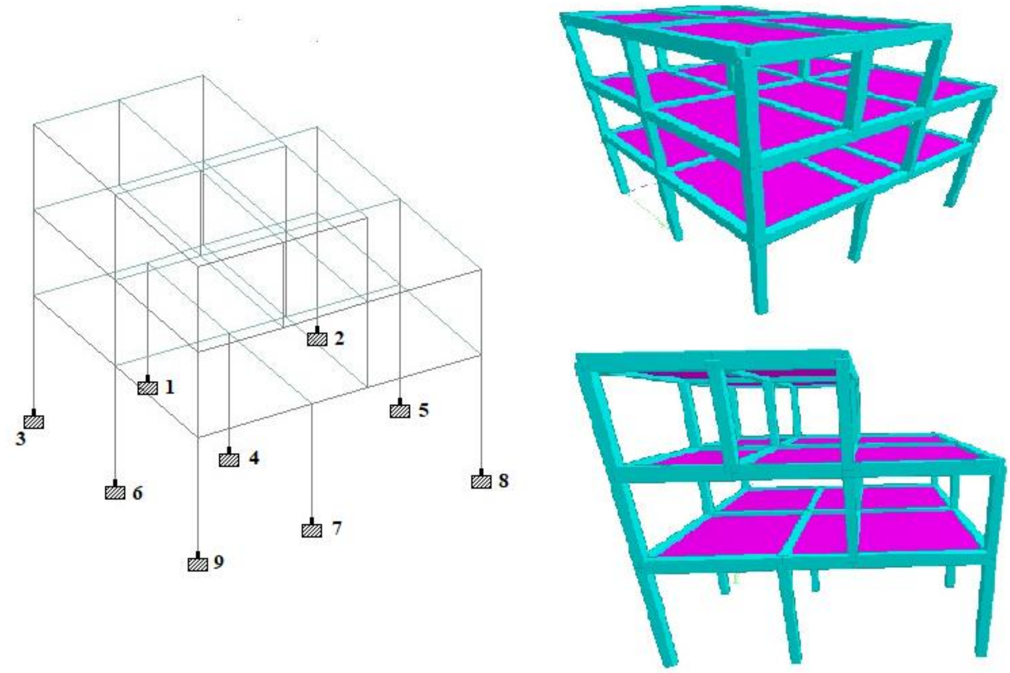

Figure 1. Geometry and Foundation.

Table 1. Load combination

	Combination
1	1.4 DL + 0 LL
2	1.2 DL + 1.6 LL
3	1.2 DL + 1 LL
4	1.2 DL + 0 LL
5	0.9 DL + 0 LL

A foundation is a crucial structural element that carries the load from a building or individual column and transfers it to the underlying soil. To ensure the stability and integrity of a structure, foundations must be designed and constructed carefully to prevent excessive settlement, rotation, and differential settlement, and to provide adequate protection against sliding and overturning. The size of the foundation is determined by the allowable bearing capacity of the soil, which defines the maximum load per square foot that the soil can support without experiencing significant settlements. To design the footings, engineers often employ specialized software such as Staad Foundation. Once the structural analysis is completed, the column reactions are imported into Staad Pro using the import button. In Staad Foundation, various input data are required, including information about soil properties (**Table 2**), foundation properties (**Table 2**), mechanical properties of materials (**Table 3**), rebar properties (**Table 4**), and safety factors (**Table 5**). For the design of isolated footings, the guidelines specified in the ACI 318-05 code are typically followed.

Table 2. Soil and foundation properties.

Soil Properties	
Type of soil	Undrained condition
Unit weight of soil (kN/m^3)	20
Bearing capacity of the soil (kN/m^2)	100
Depth of soil above footing (m)	0.5
Depth of water table (ft)	120
Foundation Properties	
Type of foundation	Isolated
Clear cover (in)	2
Minimum length (in)	40
Maximum length (in)	500
Minimum width (in)	40
Maximum width (in)	500
Minimum thickness (in)	12
Maximum thickness (in)	60

Table 3. Material Properties**.**

Material	Unit weight (KN/m^3)	Compressive strength (MPa)
Concrete	25.0	27.58
Ferrock	16.0	51.71
Steel	78.5	415.00

Table 4. Rebar Properties.

Rebar Properties	
Yield strength of steel (N/mm^2)	415
Minimum rebar spacing (cm)	10
Maximum rebar spacing (cm)	100
Minimum rebar size	#6
Maximum rebar size	#18

Table 5. Safety conditions.

Safety conditions	
Safety against friction	0.5
Safety against overturning	1.5
Safety sliding	1.5

3.2.2. Cost-Benefit Effective Analysis

Cost-Benefit Analysis (CBA) is a methodical strategy employed to assess the economic feasibility of a project or decision by carefully examining its costs and benefits. It entails a comparative analysis of the expenses associated with implementing a specific course of action and the anticipated advantages it is likely to yield. The fundamental objective of conducting a cost-benefit analysis is to equip decision-makers with relevant information to make informed choices and establish priorities for projects or policies based on their economic implications (Sudarsan & Sridharan, 2021). It's important to note that the availability and pricing of concrete and Ferrock can differ depending on the geographical location and the specific project requirements. Furthermore, market dynamics and advancements in

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manufacturing processes can influence the relative costs of these materials as time progresses. Thus, in this research, we will use the decision matrix analysis method.

Decision matrix analysis, also known as a decision-making matrix, is a tool that can be used to compare and rank different alternatives. A decision matrix is a structured tool or technique used in decision-making processes to analyze and evaluate different options or alternatives systematically. It helps in making well-informed decisions by considering multiple criteria or factors. Each criterion will be ranked according to its importance to the research objectives. Thus, the ratings assigned to the cells can be based on our opinions. Numerical value 1 and 2 is assigned to each cell, reflecting the importance of the option for that specific criterion where 2 reflects the best option. A value of "0" will be assigned if both materials are found to be equal when compared.

3.2.2.1. Criteria

The criteria used are the following:

(i) Cost of Materials
(ii) Maintenance cost
(iii) Steel Cost
(iv) Energy Consumption Cost
(v) Transportation Cost
(vi) Construction Requirements Cost
(vii) Lightweight
(viii) Durability
(ix) Environmental Impact.

Environmental impact is focused on the following: (i) Production Process; (ii) Carbon footprint; (iii) Life Cycle; and (iv) Recycling and Reusability.

3.2.2.2. Determine the Weighting

In this step, the assignment of the weights to each criterion based on their relative importance must be done. However, in this research, we decided to give equal weight to each criterion. This choice is made because we believe that all the listed criteria have an equal impact on determining the best material, based on their perspective. **Table 6** shows the weight of each criterion.

Table 6. Weighing of criteria.

Criteria		Weight (%)
Cost of Materials		12.500
Maintenance cost		12.500
Steel Cost		12.500
Energy Consumption Cost		12.500
Transportation Cost		12.500
Construction Requirements Cost		12.500
Lightweight		12.500
Durability		12.500
Environmental Impact	Production Process	3.125
	Carbon footprint	3.125
	Life Cycle	3.125
	Recycling and Reusability	3.125

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4. RESULTS AND DISCUSSION

4.1. Foundation Results

The applied loads for service stress level and strength level for the most critical foundation (foundation number 4) are shown in **Table 7** as calculated by STAAD Pro V8i. The most critical foundation is Foundation 4.

Table 7. Service stress level and strength level.

Load	Axial (kip)	Shear X (kip)	Shear Z (kip)	Moment X (kip-ft)	Moment Z (kip-ft)
DL	86.195	-2.293	0	0	10.612
LL	40.321	-0.994	0	0	4.609
COMB 1	120.673	-3.211	0	0	14.857
COMB 2	167.948	-4.342	0	0	20.109
COMB 3	143.755	-3.746	0	0	17.344
COMB 4	103.434	-2.752	0	0	12.735
COMB 5	77.576	-2.064	0	0	9.551

Following analysis, the results of the pressure at four corners for concrete footing are shown in **Figure 2** and **Table 8.**

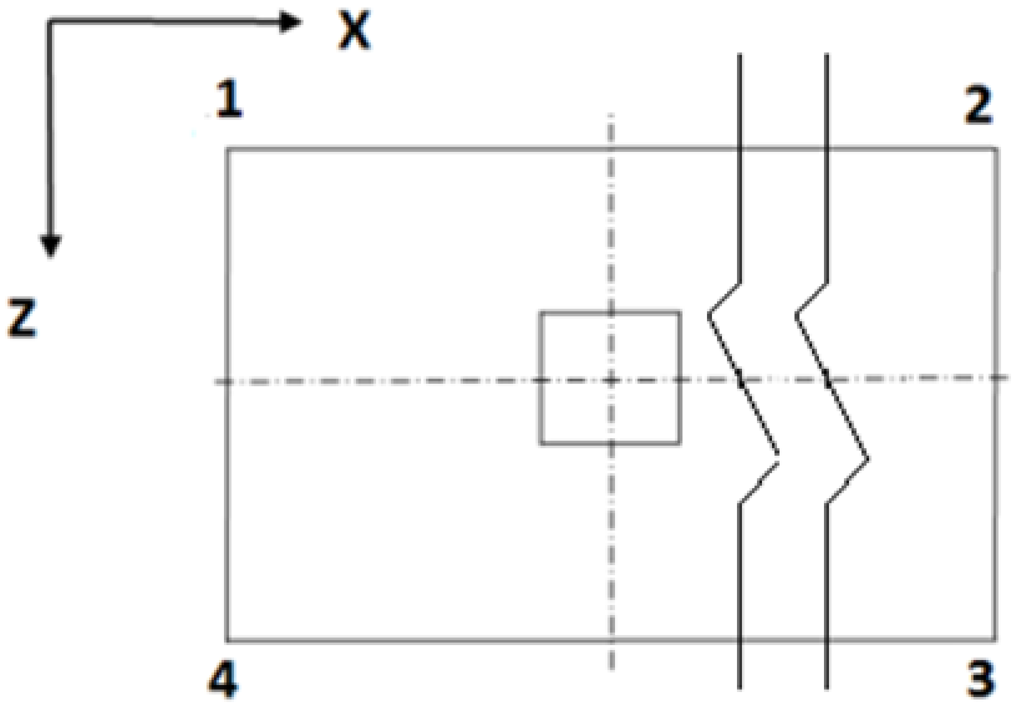

Figure 2. Pressure at four corners for concrete footing.

Table 8. Pressure at four corners for concrete footing.

Load Case	Pressure at corner1 (q1) (kip/ft^2)	Pressure at corner2 (q2) (kip/ft^2)	Pressure at corner3 (q3) (kip/ft^2)	Pressure at corner4 (q4) (kip/ft^2)	Area of footing in uplifting (Au) (ft^2)
Comb2	2.0719	1.8060	1.8060	2.0719	0

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Table 9 shows the dimensions of all the concrete footings and **Table 10** shows the reinforcement details according to ACI 318-05 Clause No-10.6.4. Results for checking the stability against overturning and sliding for concrete footing are shown in **Table 11**.

Table 7. Footing geometry details for concrete material.

Group ID	Foundation Geometry		
	Length (m)	Width (m)	Thickness (m)
1	2.54	2.54	0.31
2	2.08	2.08	0.31
3	1.93	1.93	0.31
4	3.15	3.15	0.31
5	2.59	2.59	0.31
6	2.54	2.54	0.31
7	2.54	2.54	0.31
8	2.08	2.08	0.31
9	1.93	1.93	0.31

Table 8. Footing reinforcement details for concrete material.

Group ID	Top Reinforcement (Mz)		Bottom Reinforcement (Mz)		Top Reinforcement (Mx)		Bottom Reinforcement (Mx)	
	Bar	Spacing (in)	Bar	Spacing (in)	Bar	Spacing (in)	Bar	Spacing (in)
1	#6	24	#6	24	#9	39	#6	32
2	#8	39	#8	39	#8	39	#8	39
3	#6	36	#8	39	#8	39	#6	36
4	#6	13	#6	13	#8	39	#6	30
5	#6	24	#6	24	#9	39	#6	33
6	#8	39	#6	24	#9	39	#6	32
7	#6	24	#6	24	#9	39	#6	32
8	#8	39	#8	39	#8	39	#8	39
9	#6	36	#8	39	#8	39	#6	36

Table 9. Checking the stability against overturning and sliding for concrete footing.

Load Case	Factor of safety against sliding		Factor of safety against overturning	
	Along X-Direction	Along Z-Direction	Along X-Direction	Along Z-Direction
DL	27.313	20.89*10^6	45.42*10^6	50.156
LL	39.953	13.24*10^6	24.25*10^6	73.23
COMB1	24.879	19.97*10^6	41.97*10^6	45.685
COMB2	23.84	12.93*10^6	24.5*10^6	43.748
COMB3	24.405	15.24*10^6	28.34*10^6	44.794
COMB4	25.893	23.75*10^6	44.86*10^6	47.548
COMB5	28.26	29.17*10^6	49.88*10^6	51.895

Following analysis, the results of the pressure at four corners for Ferrock footing are shown in **Figure 3** and **Table 12**.

Table 10. Pressure at four corners.

Load Case	Pressure at corner1 (q1) (kip/ft^2)	Pressure at corner2 (q2) (kip/ft^2)	Pressure at corner3 (q3) (kip/ft^2)	Pressure at corner4 (q4) (kip/ft^2)	Area of footing in uplifting (Au) (ft^2)
Comb2	2.0177	1.7417	1.7417	2.07177	0

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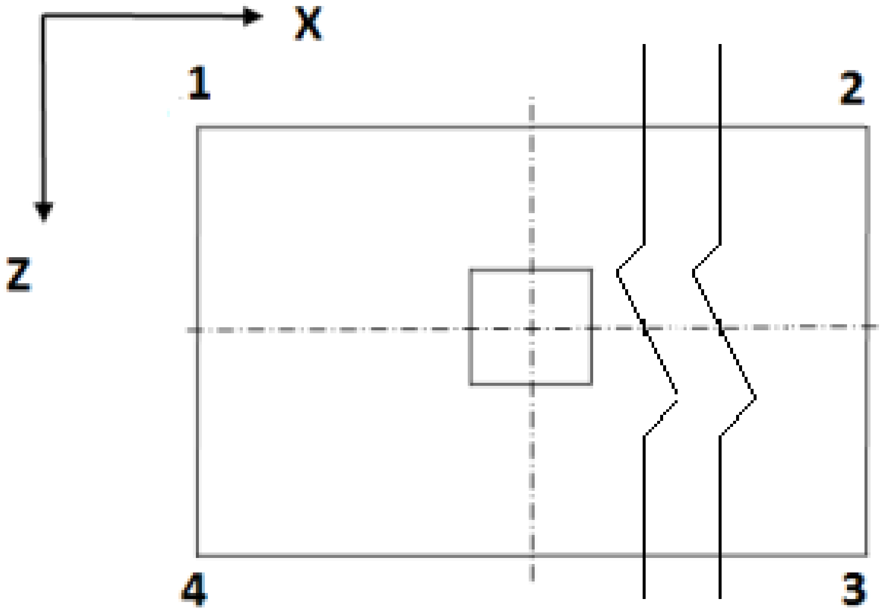

Figure 2. Pressure at four corners.

Table 13 shows the dimensions of all the Ferrock footings and **Table 14** shows the reinforcement details according to ACI 318-05 Clause No-10.6.4. Results for checking the stability against overturning and sliding for Ferrock footing are shown in **Table 15**.

Table 11. Footing geometry details for Ferrock material.

Group ID	Foundation Geometry		
	Length (m)	Width (m)	Thickness (m)
1	3.03	3.00	0.50
2	3.03	3.00	0.50
3	3.03	3.00	0.50
4	3.10	3.20	0.50
5	3.03	3.00	0.50
6	3.03	3.00	0.50
7	3.03	3.00	0.50
8	3.03	3.00	0.50
9	3.03	3.00	0.50

Table 12. Footing reinforcement details for Ferrock material.

Group ID	Top Reinforcement (Mz)		Bottom Reinforcement (Mz)		Top Reinforcement (Mx)		Bottom Reinforcement (Mx)	
	Bar	Spacing (in)	Bar	Spacing (in)	Bar	Spacing (in)	Bar	Spacing (in)
1	#7	23	#10	39	#10	39	#7	23
2	#7	23	#10	39	#10	39	#7	23
3	#7	23	#10	39	#10	39	#7	23
4	#8	31	#7	20	#7	20	#8	31
5	#7	23	#10	39	#10	39	#7	23
6	#7	23	#10	39	#10	39	#7	23
7	#7	23	#10	39	#10	39	#7	23
8	#7	23	#10	39	#10	39	#7	23
9	#7	23	#10	39	#10	39	#7	23

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Table 13. Checking the stability against overturning and sliding for Ferrock footing.

Load Case	Factor of safety against sliding		Factor of safety against overturning	
	Along X-Direction	Along Z-Direction	Along X-Direction	Along Z-Direction
DL	27.889	21.32*10^6	41.47*10^6	47.230
LL	41.281	13.67*10^6	22.89*10^6	69.790
COMB1	25.290	20.3*10^6	38.39*10^6	42.828
COMB2	24.144	13.1*10^6	22.58*10^6	40.862
COMB3	24.758	15.46*10^6	26.22*10^6	41.910
COMB4	26.373	24.19*10^6	41.6*10^6	44.660
COMB5	28.900	29.83*10^6	46.91*10^6	48.940

4.2. Cost-Benefit Effectiveness Results
4.2.1. Criteria results
4.2.1.1. Cost of Materials

Concrete is a readily accessible building material, and its price can fluctuate based on various factors like the specific concrete mix, geographical location, and the amount needed. Generally, concrete is considered to be a cost-effective option when compared to many other construction materials. On the other hand, Ferrock is an environmentally friendly material crafted from recycled resources like steel dust and other industrial byproducts. As a relatively new material with limited widespread availability, Ferrock might presently be more expensive in comparison to traditional concrete. The cost can also vary based on the geographical area and the accessibility of raw materials. However, other researches show that Ferrock utilizes waste materials that are often available at low or no cost. This can contribute to reducing the overall material cost. Therefore, in this study, concrete and Ferrock are assumed to have equal material costs. In the provided example, the volume of concrete and Ferrock needed to be calculated manually according to Equation 1.

$$Volume\ of\ Concrete = Volume\ of\ Footing - Volume\ of\ steel \quad (1)$$

The volume of concrete and Ferrock materials are 2.97 m^3 and 4.57 m^3 respectively. This means that the cost of ferrock material is higher than concrete material.

4.2.1.2. Maintenance cost

Ferrock is a relatively new material that is still being researched and developed, so its long-term maintenance costs are not yet well-documented. Concrete, on the other hand, has been widely used for many years and has a more established track record in terms of maintenance. Concrete is known for its durability and low maintenance requirements. Once it is properly cured and hardened, concrete structures generally require minimal upkeep. Regular cleaning and occasional repairs or sealing may be needed to address cracks or other issues that can occur over time. The maintenance costs for concrete structures are typically considered to be relatively low. Since Ferrock is a more recent development, there is less information available regarding its long-term maintenance costs. Ferrock is an eco-friendly material made from industrial waste products, including steel dust and silica. It has shown promising potential in terms of strength and sustainability, but its long-term performance and maintenance requirements are still being evaluated. Given the lack of extensive data on Ferrock's maintenance costs, it is challenging to provide a direct comparison with concrete. However, it is reasonable to assume that Ferrock may require similar or slightly higher maintenance than concrete, especially considering its potential for corrosion due to the steel content.

Proper monitoring and maintenance will likely be required to ensure the longevity and structural integrity of Ferrock structures.

4.2.1.3. Steel Cost

The steel cost is calculated manually in this research according to equations 2 and 3.

$$Volume\ of\ steel = \pi * radius^2 * length \tag{2}$$
$$Steel\ Weight = \gamma steel * volume\ of\ steel * Number\ of steel\ bars \tag{3}$$

The total volume of steel needed is 830.1 Kg and 859.98 Kg in concrete and Ferrock footing number 4 respectively. As seen, 3.5% of steel is added in the case of Ferrock footing. Suppose that this % is equal to all footings. Then, an addition of 31.5% is needed in total. Thus, the cost of steel in the case of Ferrock material use is higher.

4.2.1.4. Energy Consumption Cost

Concrete, commonly made with Portland cement, is manufactured by heating limestone and clay at high temperatures, a process that consumes substantial energy. This procedure also results in the release of carbon dioxide (CO_2), contributing to the emission of greenhouse gases. On the other hand, Ferrock incorporates waste steel dust, often obtained from steel mills, and combines it with other components such as iron oxide and industrial byproducts. Manufacturing Ferrock generally demands less energy compared to the production of concrete.

4.2.1.5. Transportation Cost

Concrete is a widely used construction material composed of cement, aggregates (such as sand and gravel), and water. The transportation costs of concrete can vary based on factors like the distance between the production site and the construction site, the availability of raw materials, and the mode of transportation. Since Ferrock is typically produced using locally available materials, transportation costs may be lower compared to concrete in certain cases. However, the overall transportation costs would still depend on the specific logistics involved, including the distance traveled and the mode of transportation used. Thus, both materials are considered to have equal transportation costs.

4.2.1.6. Construction Requirements Cost

Concrete is versatile and widely used in construction. It can be poured into formwork and used for foundations, walls, slabs, and various structural components. It requires formwork, reinforcement (such as steel bars), and curing time for strength development. Ferrock has similar construction requirements to concrete. It can be poured, molded, or used in precast forms. It requires formwork for shaping and support during curing. Thus, both materials are considered to have equal construction costs.

4.2.1.7. Lightweight

Traditional concrete is commonly known for its relatively high density, typically falling within the range of 2200 to 2500 kilograms per cubic meter (kg/m^3). In contrast, lightweight concrete offers a reduced density, typically ranging from 800 to 2000 kg/m^3, depending on the specific lightweight aggregates employed. Ferrock, on the other hand, possesses a density that is comparable to or slightly lower than that of traditional concrete. With a density approximately ranging from 1900 to 2200 kg/m^3.

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4.2.1.8. Durability

Ferrock and concrete are both construction materials, but they have different compositions and properties. Concrete is a widely used material known for its strength and durability, while Ferrock is a newer material that aims to provide an environmentally friendly alternative to traditional concrete. In terms of durability, concrete is a proven and well-established material. It has been used for centuries in various construction projects and has demonstrated excellent performance over time. Its long-term durability depends on factors such as the quality of materials used, proper design and construction practices, and maintenance. Ferrock, a recently developed material, is currently undergoing extensive research and evaluation to determine its long-term durability. Numerous studies are being conducted to investigate the advantages of Ferrock, including its weather resistance, durability, resistance to cracking, and long-term structural stability. These studies have demonstrated the benefits of Ferrock over traditional concrete materials (Vijayan *et al*., 2020).

4.2.1.9. Environmental Impact
4.2.1.9.1. Production Process

Concrete production involves extracting raw materials like limestone, sand, and clay, resulting in energy consumption and habitat destruction. Additionally, the use of high-temperature kilns in the process contributes to carbon dioxide emissions. On the other hand, Ferrock is an innovative material that utilizes recycled components, such as steel dust (a byproduct of steel manufacturing) and silica (a prevalent element found in sand). By employing recycled materials, Ferrock minimizes the necessity for extracting new resources and helps divert waste away from landfills.

4.2.1.9.2. Carbon footprint

The manufacturing of cement, an essential ingredient in concrete, results in considerable carbon dioxide emissions. The chemical reaction involved in cement production releases carbon dioxide as a byproduct, contributing to the emission of greenhouse gases. Ferrock offers the potential to actively sequester carbon dioxide. During its production, Ferrock absorbs carbon dioxide, which is then chemically bound and stored within the material. This carbonation process aids in reducing the overall carbon footprint associated with Ferrock (Niveditha *et al*., 2020).

In a study conducted by Sanjuán *et al*. (2020), it was found that OPC has a carbon emission rate of 1040 Kg CO_2-eq/metric ton of production, indicating a positive impact on the environment. In contrast, Ferrock, another material examined in the study, exhibited a negative carbon emission rate of -50 Kg CO_2-eq/metric ton of production, implying a beneficial effect on carbon emissions. **Figure 4** provides a visual representation of the carbon emission levels associated with Ferrock and Ordinary Portland cement.

4.2.1.9.3. Life Cycle

Concrete is renowned for its durability and extended lifespan, resulting in reduced replacement needs. However, it's important to consider the overall environmental impact of concrete throughout its life cycle. This impact encompasses not only concrete production but also maintenance, repair, and eventual demolition, which can contribute to waste generation and energy consumption. On the other hand, Ferrock holds promise for a long lifespan. What sets Ferrock apart is its unique chemical composition, which enables it to reabsorb carbon

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dioxide in case of damage or exposure to the elements. This feature extends its carbon sequestration potential.

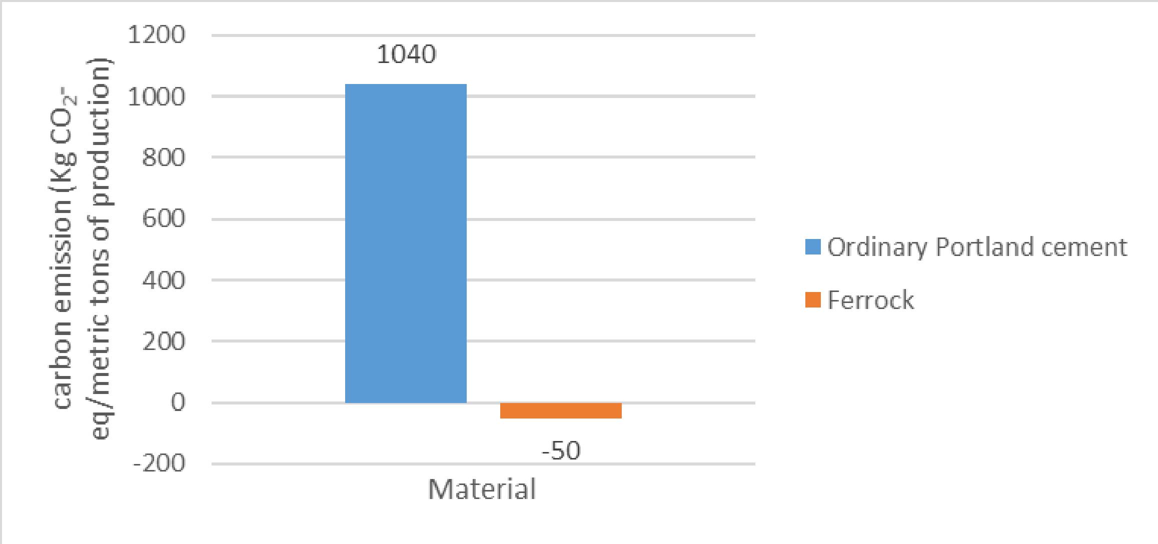

Figure 4. Carbon emission of Ferrock and OPC.

4.2.1.9.4. Recycling and Reusability

Concrete can be repurposed by crushing it into aggregate, which can then be used in the production of new concrete or for road construction. However, the recycling process necessitates energy and transportation, and not all concrete can be efficiently recycled. On the other hand, Ferrock presents a more sustainable alternative. It is created from recycled materials and is designed to be recyclable. When Ferrock reaches the end of its life cycle, it can be crushed and utilized as a raw material for the production of new Ferrock. This approach fosters a circular economy, minimizes waste generation, and contributes to a more environmentally friendly future.

4.2.2. Decision-Matrix Results

The decision matrix results are shown in **Table 16**. As seen in this table, the score of Ferrock material is 137.5 which exceeds that of concrete material by 12.5. Thus, according to the cost-benefit analysis, Ferrock material is better than concrete.

Table 14. Decision matrix results.

Criteria	Concrete	Ferrock	Weight (%)	Concrete	Ferrock
Cost of Materials	2	1	12.500	25.000	12.50
Maintenance cost	2	1	12.500	25.000	12.50
Steel Cost	2	1	12.500	25.000	12.50
Energy Consumption Cost	1	2	12.500	12.500	25.00
Transportation Cost	0	0	12.500	0.000	0.00
Construction Requirements Cost	0	0	12.500	0.000	0.00
Lightweight	1	2	12.500	12.500	25.00
Durability	1	2	12.500	12.500	25.00
Production Process	1	2	3.125	3.125	6.25
Carbon footprint	1	2	3.125	3.125	6.25
Life Cycle	1	2	3.125	3.125	6.25
Recycling and Reusability	1	2	3.125	3.125	6.25
Score	-	-	100.000	125.000	137.50

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4.2.3. The answer to posted questions

There are several questions raised:

(i) Q_1: Is Ferrock material a viable alternative to concrete for building foundations? After gathering mechanical data about Ferrock material from the literature review, software simulation was done. As seen by **Tables 9 and 13**, an isolated footing with acceptable length, width, and thickness can hold the designed building. **Tables 10 and 14** also show the reinforcement of the footing where they are also acceptable.

(ii) Q_2: Does Ferrock material have a lower cost compared to concrete? According to the decision matrix method, if the cost of material is only taken into account, it is noticed that Ferrock is more expensive than concrete.

(iii) Q_3: Does Ferrock material have more benefits compared to concrete? According to the decision matrix method, if the benefit of the material is only taken into account, it is noticed that Ferrock is more beneficial than concrete.

5. CONCLUSION

In summary, both concrete and Ferrock are utilized in construction, but they possess distinct characteristics and environmental implications. Concrete is a widely adopted material known for its strong structural properties, yet its production negatively impacts the environment. Conversely, Ferrock presents a more sustainable alternative that tackles some of the drawbacks associated with concrete. Nevertheless, Ferrock is still in its nascent stages of development and is not as prevalent or easily accessible as concrete. As technology progresses and sustainable construction practices gain prominence, Ferrock and other alternative materials may assume a more significant role in the construction industry.

6. AUTHORS' NOTE

The authors declare that there is no conflict of interest regarding the publication of this article. Authors confirmed that the paper was free of plagiarism.

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