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Glass Fibre–Reinforced Concrete as a Structural Material

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ABSTRACT

Glass Fiber-Reinforced Concrete (GFRC) has emerged as a sustainable and versatile building material. This paper provides a comprehensive overview of GFRC, encompassing its composition, construction techniques, and unique properties. A detailed life cycle assessment (LCA) is conducted to evaluate its environmental impact, considering factors such as energy consumption, greenhouse gas emissions, water usage, and waste generation. GFRC's potential to reduce the environmental footprint of construction is highlighted by comparing it to traditional concrete. A detailed cost analysis is presented to assess the economic viability of GFRC. Both initial and long-term costs, including maintenance, repair, and replacement, are considered. The analysis reveals that while GFRC may have higher initial costs, its superior durability, reduced maintenance requirements, and longer lifespan can lead to significant long-term cost savings. The paper discusses the diverse applications of GFRC in architecture and construction, including its use in cladding systems, facades, sculptural elements, and structural components. By understanding the advantages, limitations, and economic implications of GFRC, architects, engineers, and construction professionals can make informed decisions to leverage this innovative material for sustainable and aesthetically pleasing building projects.

1. Introduction:

In an era marked by the pursuit of sustainable and innovative building materials, glass fiber–reinforced concrete (GFRC) has emerged as a compelling option in the construction industry. By blending the time-tested principles of concrete with the strength and versatility of glass fibers, GFRC offers a unique solution to the evolving demands of modern architecture. This introduction sets the stage for an in-depth exploration of GFRC, delving into its composition, construction techniques, advantages, disadvantages, diverse applications, and the conclusions drawn from its utilization in structural projects, see Figs 1and 2 [1-6]. As the construction landscape continues to evolve, understanding the intricacies of GFRC becomes essential for architects, engineers, and builders seeking to harness its potential in creating structures that are both durable and aesthetically appealing.

Fig. 1 Glass fiber

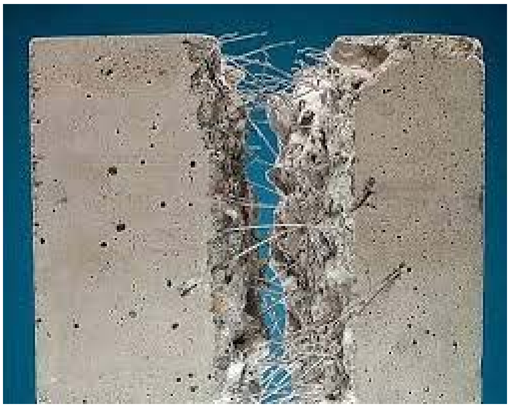

Fig. 2 Glass fiber in reinforced concrete

2. Types of GFRC

There are generally two main types GFRC each offering distinct characteristics and applications: Sprayed GFRC: Sprayed GFRC involves the application of a mixture of cement, glass fibers, water, Fig. 3 and other additives onto molds or formwork using specialized spraying equipment. This method allows for the creation of thin, lightweight panels with consistent thickness and surface finish. Sprayed GFRC is commonly used for architectural cladding, decorative elements, and complex shapes due to its ability to conform to intricate designs and contours Figs 4 and 5 [7-12].

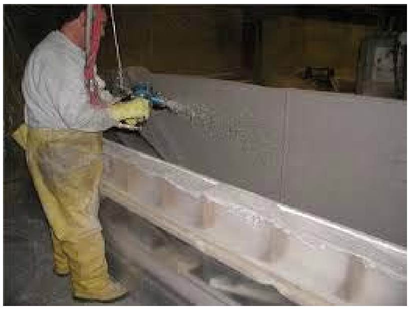

Fig. 3 Sprayed GFRC

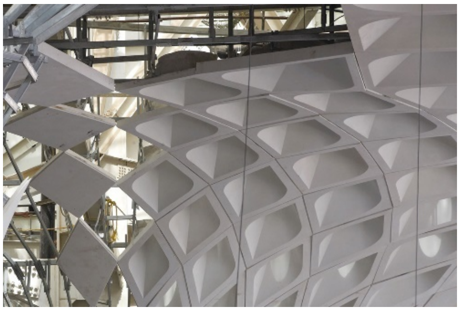

Fig. 4 GFRC architectural cladding

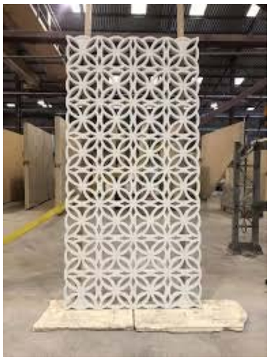

Fig. 5 GFRC decorative elements

Premixed GFRC: Premixed GFRC is manufactured by blending pre-chopped glass fibers with dry concrete mixtures, which are then mixed with water and other additives to form a workable paste Fig. 6. This type of GFRC is typically hand-packed or poured into molds, offering greater control over the placement and consolidation of the material. Premixed GFRC is often preferred for larger structural elements such as panels, columns, and facades, where uniformity of strength and thickness is crucial Fig. 7 [1-14].

Fig. 6 Pre-chopped glass fibers mixed with concrete

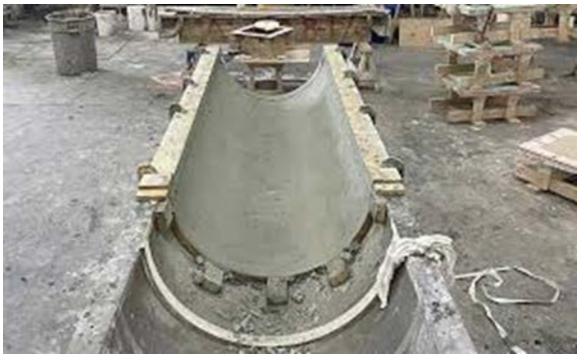

Fig. 7 Premixed GFRC

Both types of GFRC offer advantages such as high strength-to-weight ratio, durability, and versatility in design. However, the choice between sprayed and premixed GFRC depends on factors such as project requirements, complexity of design, and construction methods.

3. **Material used**

GFRC typically consists of several key materials, including:

Cementitious Materials: GFRC usually incorporates Portland cement as the primary binder, which provides the material with its structural integrity and durability Fig. 8. Other cementitious materials, such as silica fume or fly ash, slag, natural pozzolans may also be added to enhance properties like strength and impermeability Fig. 9 [1-14].

Fig. 8 Portland cement

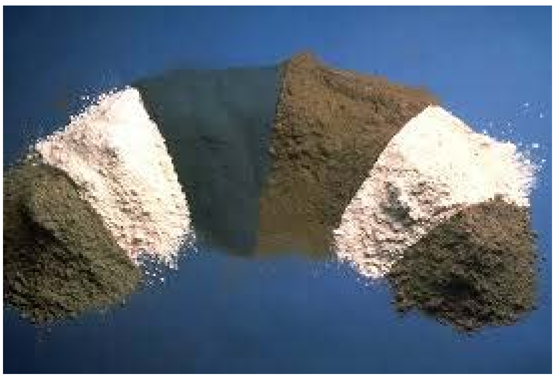

Fig. 9 Other cementitious materials

Aggregates: Aggregates such as sand, crushed stone, or lightweight aggregates are added to the concrete mix to provide bulk and stability Figs 10 and 11. The choice of aggregates can influence properties such as density, texture, and finish of the GFRC.

Fig. 10

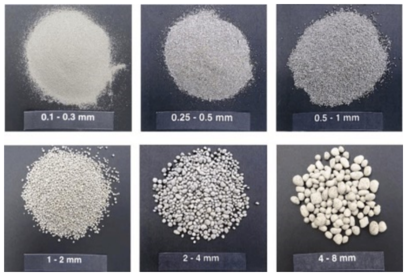

Fig. 11

Admixtures: Various chemical admixtures may be incorporated into the GFRC mix to modify properties such as workability, setting time, and water content. These may include plasticizers, accelerators, retarders, and air-entraining agents.

Glass Fibers: The reinforcement in GFRC comes from alkali-resistant glass fibers, which are typically made of either E-glass or AR-glass (alkali-resistant glass). These fibers are dispersed throughout the concrete matrix to improve tensile strength, flexural strength, and impact resistance [1-14].

The types of glass commonly used in GFRC include:

E-Glass: E-glass, or electrical-grade glass, is one of the most used types of glass fibers in GFRC. It offers excellent tensile strength, chemical resistance, and thermal stability, making it suitable for a wide range of applications Fig. 12.

Fig. 12

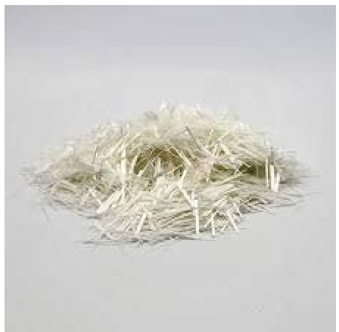

Fig. 13

AR-Glass (Alkali-Resistant Glass): AR-glass fibers are specially designed to withstand the highly alkaline environment of concrete. These fibers have a special chemical composition that prevents them from reacting with the alkaline cement matrix, ensuring long-term durability and performance in GFRC applications Fig. 13.

Both E-glass and AR-glass fibers are widely available in various forms, including chopped strands, roving's, and mats, allowing for flexibility in designing and manufacturing GFRC products tailored to specific project requirements.

4. Construction procedures and precautions

Construction procedures for glass fiber–reinforced concrete (GFRC) involve several key steps and precautions to ensure successful fabrication and installation:

Mix Design: Develop a precise mix design tailored to the specific project requirements, considering factors such as desired strength, workability, and aesthetics. Ensure that the mix design includes the appropriate proportions of cementitious materials, aggregates, glass fibers, and admixtures.

Fiber Distribution: Properly disperse the glass fibers throughout the concrete mix to ensure uniform reinforcement and consistent mechanical properties. Avoid clumping or segregation of fibers by using appropriate mixing equipment and techniques.

Mold Preparation: Prepare molds or formwork meticulously to achieve the desired shape, dimensions, and surface finish of the GFRC elements. Apply suitable release agents to the molds to facilitate easy demolding without damaging the finished product, see Figs 14 and 15.

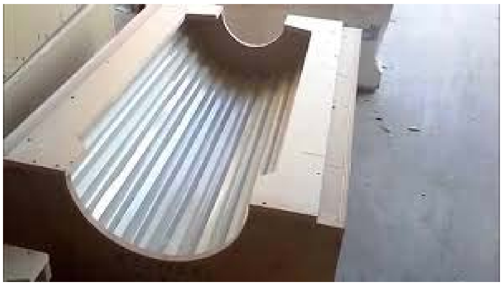

Fig. 14

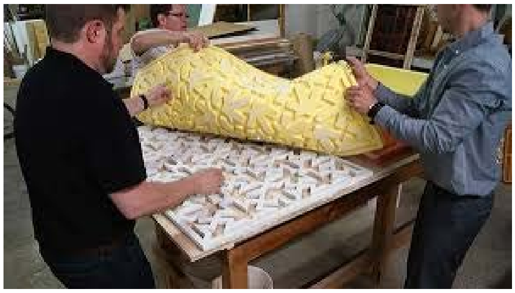

Fig. 15

Mixing: Mix the GFRC ingredients thoroughly using either a batch mixer or a continuous mixer, depending on the scale and complexity of the project. Control mixing time, speed, and sequence to achieve a homogeneous mix with optimal fiber dispersion and minimal air voids.

Spraying or Casting: Depending on the chosen construction method (sprayed or premixed GFRC), apply the concrete mix into the molds or onto the substrate using appropriate techniques. Ensure consistent thickness and coverage while avoiding overworking or excessive vibration that could cause segregation or fiber misalignment.

Curing: Proper curing is essential to achieve the desired strength and durability of GFRC. Implement curing methods such as moist curing, steam curing, or application of curing compounds to maintain adequate moisture levels and temperature during the initial curing period.

Handling and Transportation: Handle GFRC elements with care during demolding, handling, and transportation to prevent cracking, chipping, or other damage. Use appropriate lifting equipment and protective measures to safeguard the integrity of the finished products, see Figs 16-19.

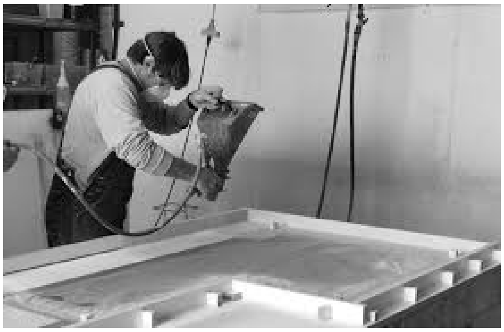

Fig. 16

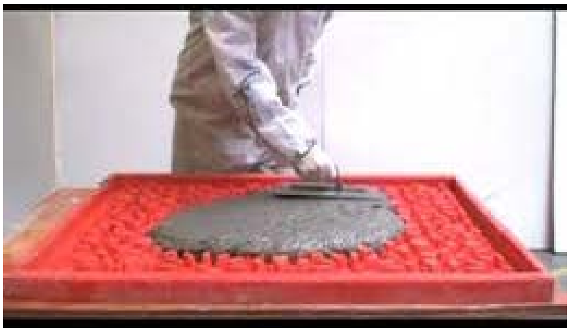

Fig. 17

Fig. 18

Fig. 19

Surface Treatment: After installation, consider applying surface treatments such as sealers, coatings, or protective finishes to enhance durability, weather resistance, and aesthetics of the GFRC elements, see Fig. 20.

Fig. 20

5. Precautions:

Safety: Adhere to proper safety protocols and guidelines when handling cementitious materials, glass fibers, and chemical admixtures to minimize health risks associated with dust inhalation, skin contact, or exposure to hazardous substances.

Quality Control: Implement stringent quality control measures throughout the construction process to monitor mix consistency, fiber distribution, mold preparation, and curing conditions. Conduct regular inspections and testing to identify and address any deviations or defects promptly.

Environmental Conditions: Consider environmental factors such as temperature, humidity, and wind conditions, which can affect the workability, curing, and performance of GFRC. Take appropriate precautions, such as providing shade, wind barriers, or temperature control measures, to mitigate adverse effects on construction quality.

By following these construction procedures and precautions diligently, contractors and builders can ensure the successful fabrication and installation of high-quality GFRC elements that meet the desired performance, aesthetic, and durability requirements of the project.

6. Advantages of GFRC:

High Strength-to-Weight Ratio: GFRC offers impressive strength properties while being significantly lighter than traditional concrete, making it suitable for applications where weight reduction is desired without compromising structural integrity Table 1.

Table 1 Results of strength testing of concrete

Per centage addition of fibre	Strength (MPa)					
	7 days			28 days		
	Compressive	Split tensile	Flexural	Compressive	Split tensile	Flexural
0.0	23.10	2.91	6.66	31.53	3.34	7.24
0.5	24.01	3.61	9.66	35.66	4.04	10.29
1.0	26.07	3.83	10.66	42.87	4.66	12.67

Fiber content (V_f) %	Compressive strength (MPa)		% Increase in compressive strength	
	7 days	28 days	7 days	28 days
0.0	24.22	31.48	–	–
0.5	24.44	31.99	0.90	1.62
1.0	25.21	34.03	4.08	8.10
1.5	26.16	35.31	8.00	12.16
2.0	27.05	36.50	11.68	15.94
2.5	27.20	36.50	12.30	15.94
3.0	27.25	37.40	12.51	18.80
3.5	27.39	38.19	13.08	21.31
4.0	28.27	39.50	16.72	25.47
4.5	28.46	40.44	17.50	28.46

Durability and Weather Resistance: The incorporation of glass fibers enhances GFRC's resistance to cracking, impact, and environmental factors such as freeze-thaw cycles, UV exposure, and chemical corrosion, resulting in long-term durability and minimal maintenance requirements.

Versatility in Design: GFRC can be molded into a wide variety of shapes, textures, and surface finishes, allowing for intricate designs, decorative elements, and complex architectural features that may be difficult or impractical to achieve with other materials, see Fig. 21.

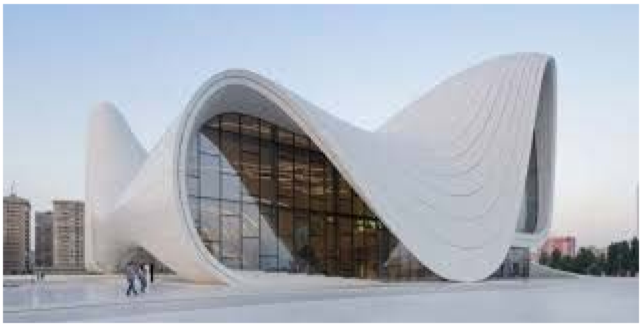

Fig. 21

Thin and Lightweight Construction: GFRC panels and elements can be manufactured with reduced thicknesses compared to conventional concrete, resulting in space-saving solutions and easier handling during transportation, installation, and retrofitting.

Fire Resistance: GFRC exhibits inherent fire-resistant properties due to the non-combustible nature of its constituent materials, providing added safety and compliance with fire regulations in building applications.

6. Disadvantages of GFRC:

Cost: The initial cost of GFRC materials and fabrication processes may be higher compared to conventional concrete, primarily due to the expense of glass fibers and specialized manufacturing techniques. However, long-term savings can be realized through reduced maintenance and lifecycle costs.

Complexity of Manufacturing: The production of GFRC requires specialized equipment, skilled labor, and precise quality control measures to ensure proper fiber distribution, mix consistency, and curing conditions, which may pose challenges and increase production time and costs.

Limited Load-Bearing Capacity: While GFRC exhibits excellent tensile and flexural strength, its compressive strength may be lower compared to traditional concrete, limiting its suitability for certain structural applications requiring heavy loads or high bearing capacities.

Surface Vulnerability: GFRC surfaces may be susceptible to scratching, chipping, or surface abrasion if not properly handled, protected, or maintained, requiring careful consideration of surface treatments, coatings, and protective measures to enhance durability and aesthetics.

Material Compatibility: Compatibility issues may arise when GFRC is combined with other building materials or finishes, necessitating thorough testing and coordination to ensure proper adhesion, expansion, and contraction characteristics to prevent delamination or compatibility issues over time.

7. Applications:

Glass Fiber–Reinforced Concrete (GFRC) finds diverse applications across various industries and architectural projects due to its unique combination of properties, including strength, durability, versatility, and aesthetic appeal. Some common applications of GFRC include:

Architectural Cladding: GFRC panels are widely used as exterior cladding systems for buildings, providing weather resistance, thermal insulation, and architectural enhancement. The lightweight nature of GFRC allows for easy installation and reduces structural loads on the building envelope, see Figs 24-27.

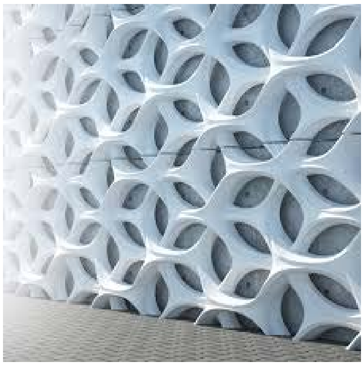

Fig. 24

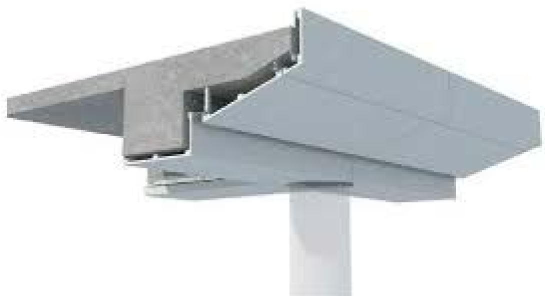

Fig. 25

Façade Systems: GFRC façade elements such as cornices, columns, pilasters, and decorative moldings add architectural detailing and visual interest to building exteriors. GFRC's moldability allows for the replication of intricate historical designs or the creation of contemporary architectural features.

Fig. 26

Fig. 27

Precast Concrete Elements: GFRC is used to manufacture precast concrete elements such as panels, balustrades, parapets, and window surrounds, offering design flexibility, durability, and ease of installation for both new construction and renovation projects, see Figs 28-31.

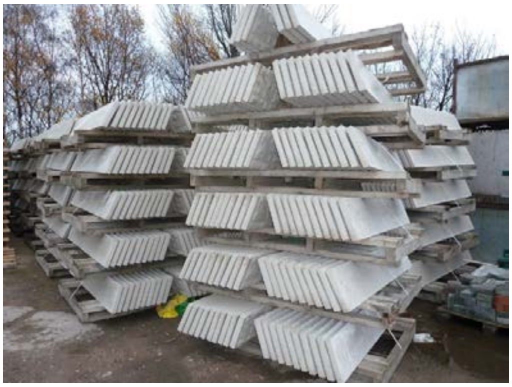

Fig. 28

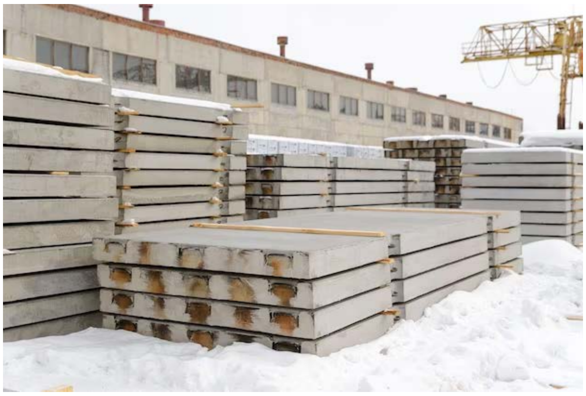

Fig. 29

Sculptural Art and Ornaments: GFRC is favored by artists and sculptors for creating sculptures, statues, ornamental features, and public art installations due to its ability to achieve intricate shapes, textures, and surface finishes with enhanced durability and weather resistance.

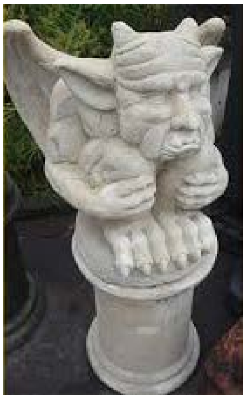

Fig. 30

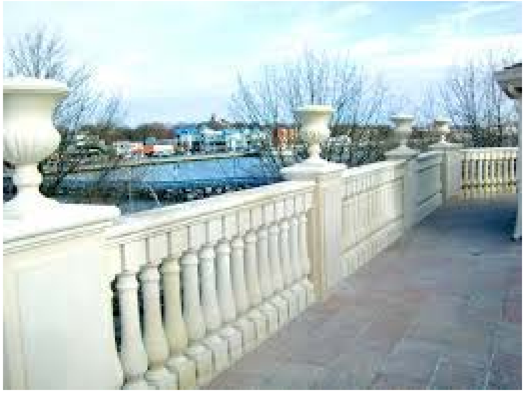

Fig. 31

Interior Design Elements: GFRC is utilized in interior design applications such as wall panels, room dividers, fireplace surrounds, countertops, and furniture pieces, offering customizable design options, seamless integration, and resistance to moisture and staining, see Figs 32-33.

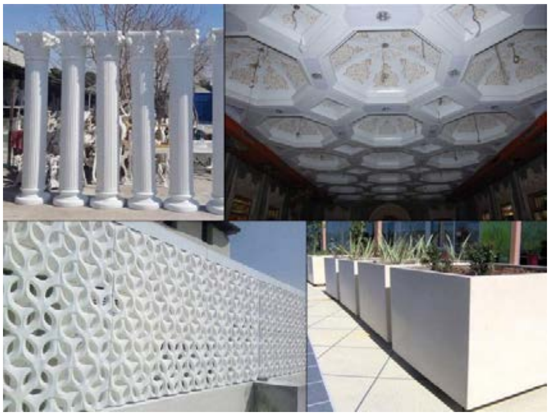

Fig. 32

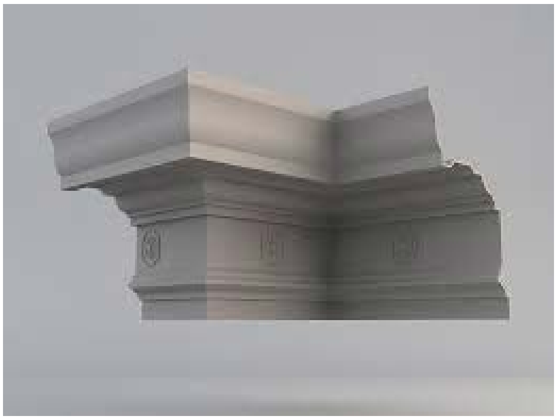

Fig. 33

Landscaping and Urban Design: GFRC is employed in landscape architecture and urban design projects for applications such as planter boxes, seating elements, retaining walls, and decorative paving, providing durability, aesthetics, and low maintenance in outdoor environments, see Figs 34-35.

Fig. 34

Fig. 35

Structural Elements: While GFRC is primarily used as cladding and decorative elements, it can also serve as structural components such as beams, lintels, and canopies in certain architectural designs, particularly in conjunction with other structural materials for lightweight construction.

Restoration and Rehabilitation: GFRC is utilized in the restoration and rehabilitation of historic buildings and structures, offering the ability to replicate intricate architectural details, match existing finishes, and provide durable replacements for deteriorated elements, see Figs 36-37.

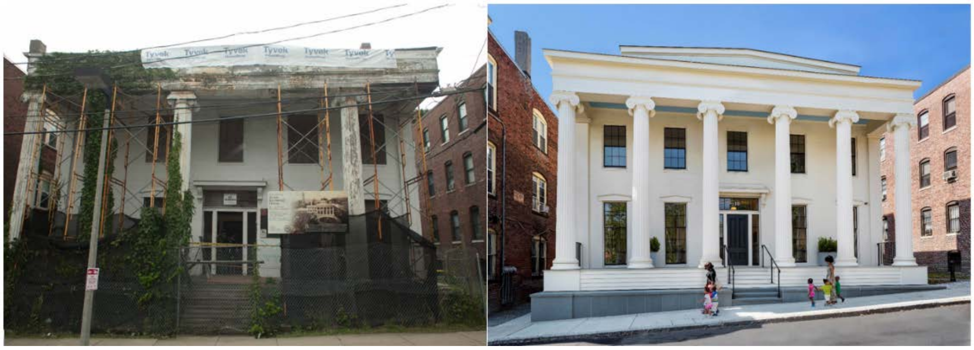

Fig. 36

Fig. 37

7. Environmental Impact of Glass Fiber-Reinforced Concrete (GFRC)

A comprehensive life cycle assessment (LCA) will be conducted to evaluate the environmental impact of GFRC. The LCA methodology will follow the ISO 14040 and 14044 standards. The following stages will be considered:

1. Raw Material Acquisition:
   - Extraction of raw materials, including cement, sand, glass fibers, and additives.
   - Energy consumption and emissions associated with mining and quarrying.
2. Material Processing and Manufacturing:

- Energy consumption and emissions associated with cement production, glass fiber manufacturing, and GFRC component production.
- Water usage and wastewater generation.

3. Transportation and Construction:
   - Energy consumption and emissions associated with transportation of raw materials, components, and finished products.
   - Construction activities, including energy consumption, water usage, and waste generation.
4. Use and Maintenance:
   - Energy consumption for maintenance and repair.
   - Water usage for cleaning and maintenance.
   - Potential for recycling and reuse of GFRC components.
5. End-of-Life:
   - Energy consumption and emissions associated with demolition and disposal.
   - Potential for recycling and recovery of materials.

Expected Environmental Impacts and Benefits

Potential Environmental Impacts:

- Energy Consumption: Energy is required for raw material extraction, processing, transportation, and construction activities.
- Greenhouse Gas Emissions: The production of cement, a major component of concrete, is a significant source of greenhouse gas emissions, particularly CO_2.
- Water Usage and Pollution: Water is used for various stages of GFRC production and construction, and wastewater may be generated.
- Waste Generation: Construction and demolition activities can generate significant amounts of waste, including construction debris and demolition waste.

Potential Environmental Benefits:

- Reduced Carbon Footprint: GFRC can have a lower carbon footprint compared to traditional concrete due to its reduced cement content and lightweight nature.

- Increased Durability and Longevity: GFRC is highly durable and weather-resistant, reducing the need for frequent repairs and replacements, thereby extending its lifespan and reducing associated environmental impacts.
- Energy Efficiency: GFRC can contribute to energy-efficient buildings by providing thermal insulation and reducing heat loss or gain.
- Reduced Transportation Costs: The lightweight nature of GFRC can reduce transportation costs and associated emissions.
- Potential for Recycling and Reuse: GFRC components can be recycled or reused at the end of their service life, reducing waste and conserving resources.

8. Detailed Cost Analysis: GFRC vs. Traditional Concrete

A comprehensive cost analysis is essential to assess the economic viability of GFRC compared to traditional concrete. This analysis will consider both initial costs and long-term costs, including maintenance, repair, and replacement. By comparing these factors, a more accurate assessment of the overall cost-effectiveness of GFRC can be made.

Initial Costs GFRC, see Table 2 and Table3.

- Material Costs:

1. Glass fibers
2. Cement
3. Aggregates
4. Admixtures

- Manufacturing Costs:

1. Molding and casting
2. Curing and finishing
3. Quality control

- Labor Costs:

1. Skilled labor for fabrication and installation

Traditional Concrete

- Material Costs:

1. Cement
2. Aggregates
3. Admixtures

- Labor Costs:

1. Formwork construction and removal
2. Concrete placement and finishing
3. Reinforcement installation

Table 2 Initial Costs

Category	GFRC Cost	Traditional Concrete Cost
Material Costs	\$150/m²	\$100/m²
Labor Costs	\$50/m²	\$40/m²
Manufacturing Costs (GFRC only)	\$20/m²	-
Total Initial Cost	\$220/m²	\$140/m²

Table 3 Long-Term Costs (Per 10 Years)

Category	GFRC Cost	Traditional Concrete Cost
Maintenance Costs	\$10/m²	\$20/m²
Repair Costs	\$5/m²	\$15/m²
Replacement Costs	\$0/m²	\$20/m²
Total Long-Term Cost	\$15/m²	\$55/m²

Comparative Analysis:

While the initial costs of GFRC may be higher due to the additional cost of glass fibers and specialized manufacturing processes, it can be offset by several factors:

- Reduced Material Usage: GFRC often requires less material, particularly cement, compared to traditional concrete, leading to lower material costs.
- Faster Construction Time: GFRC can be prefabricated and installed more quickly, reducing labor costs and accelerating project timelines.
- Design Flexibility: GFRC's versatility allows for intricate designs and architectural features that may require additional labor and materials with traditional concrete.

- **Long-Term Costs for GFRC**
- Maintenance Costs:

1. Lower maintenance requirements due to high durability and resistance to weathering.
2. Reduced cleaning and repair costs.

- Repair Costs:

1. Easier and less costly repairs due to the modular nature of GFRC components.

- Replacement Costs:

1. Longer lifespan, reducing the frequency of replacements.

- **Long-Term Costs for Traditional Concrete**
- Maintenance Costs:

1. Higher maintenance requirements, including regular cleaning, sealing, and repair.
2. Potential for cracking, spalling, and corrosion, leading to increased maintenance costs.

- Repair Costs:

1. More complex and costly repairs, often requiring specialized techniques and materials.

- Replacement Costs:

1. Shorter lifespan, necessitating more frequent replacements.

Comparative Analysis over the long term, GFRC can offer significant cost savings due to its durability, reduced maintenance requirements, and longer lifespan. While the initial costs may be higher, the long-term benefits can outweigh these initial investments.

- Factors Affecting Cost-Effectiveness
- Project Scale and Complexity: Large-scale projects with complex designs may benefit more from the advantages of GFRC.
- Local Material Availability and Costs: The availability and cost of raw materials can influence the overall cost of GFRC and traditional concrete.
- Skilled Labor Availability: The availability of skilled labor for GFRC fabrication and installation can impact labor costs.

- Design Considerations: The design choices, including the complexity of the structure and the desired aesthetic, can affect the cost of both GFRC and traditional concrete.

9. Conclusions

While this paper provides a comprehensive overview of GFRC, there are still areas for further research and analysis:

1. Comparative Studies with Other Sustainable Materials: A more in-depth comparison of GFRC with other sustainable building materials, such as bamboo concrete or recycled aggregate concrete, would provide a clearer understanding of its relative advantages and disadvantages.

2. Standardized Life Cycle Assessment: The development of standardized LCA methodologies specifically tailored to GFRC would enhance the accuracy and comparability of environmental impact assessments.

3. Long-Term Performance Studies: Long-term studies are needed to monitor the durability and performance of GFRC structures in various climatic conditions.

4. Innovative Design and Construction Techniques: Further research is required to explore innovative design and construction techniques that can optimize the use of GFRC and minimize its environmental impact.

5. Socioeconomic Impact Assessment: A comprehensive assessment of the socioeconomic impact of GFRC, including job creation, local economic development, and community benefits, would provide a holistic view of its potential.

GFRC emerges as a promising sustainable building material, offering a blend of aesthetic appeal, durability, and environmental benefits. While GFRC presents several advantages over traditional concrete, challenges such as initial cost and specialized manufacturing techniques remain. However, the long-term benefits, including reduced maintenance costs, increased durability, and potential for recycling, make GFRC a compelling choice for sustainable construction.

Future research should focus on addressing the identified gaps, such as conducting comparative studies with other sustainable materials, developing standardized LCA methodologies, and exploring innovative design and construction techniques. By advancing our understanding of GFRC and its applications, we can contribute to the development of more sustainable and resilient built environments.

References

[1] Javier Manso-Morato, Nerea Hurtado-Alonso, Víctor Revilla-Cuesta, Marta Skaf, Vanesa Ortega-López, Fiber-Reinforced concrete and its life cycle assessment: A systematic review, Journal of Building Engineering, Vol. 94, 110062, 2024.

[2] Rania F. Ismail, Ahmed Abouzied, “The Impact of Using Fiberglass Reinforced Concrete (FRC) on Sustainable Design and Construction Future”, Environmental Design, Material Science, and Engineering Technology Conference, UAE, July 2024.

[3] Rodsin, K.; Ejaz, A.; Hussain, Q.; Parichatprecha, R. Experimental and Analytical Studies on Low-Cost Glass-Fiber-Reinforced-Polymer-Composite-Strengthened Reinforced Concrete Beams: A Comparison with Carbon/Sisal Fiber-Reinforced Polymers. *Polymers* **2023**, *15*, 4027. https://doi.org/10.3390/polym15194027.

[4] Muñoz Pérez, S.P., Santisteban Purizaca, J.F., Castillo Matute, S.M. *et al*. Glass fiber reinforced concrete: overview of mechanical and microstructural analysis. *Innov. Infrastruct. Solut.* **9**, 116 (2024). https://doi.org/10.1007/s41062-024-01429-1

[5] Y. Tao, S.A. Hadigheh, Y. Wei, Recycling of glass fibre reinforced polymer (GFRP) composite wastes in concrete: A critical review and cost benefit analysis, Structures, Vol. 53, pp. 1540-1556, 2023.

[6] Ahmad, J.; González-Lezcano, R.A.; Majdi, A.; Ben Kahla, N.; Deifalla, A.F.; El-Shorbagy, M.A. Glass Fibers Reinforced Concrete: Overview on Mechanical, Durability and Microstructure Analysis. *Materials* **2022**, *15*, 5111. https://doi.org/10.3390/ma15155111

[7] P J M Bartos, Glassfibre Reinforced Concrete: a Review, 2017 *IOP Conf. Ser.: Mater. Sci. Eng.* **246** 012002 doi:10.1088/1757-899X/246/1/012002

[8] Blazy, J.; Blazy, R.; Drobiec, Ł. Glass Fiber Reinforced Concrete as a Durable and Enhanced Material for Structural and Architectural Elements in Smart City—A Review. *Materials* **2022**, *15*, 2754. https://doi.org/10.3390/ma15082754

[9] F. Soltanzadeh, A.E. Behbahani, K. Hosseinmostofi, C.A. Teixeira, Assessment of the sustainability of fibre-reinforced concrete by considering both environmental and mechanical properties, Sustainability 14 (2022) 6347, https://doi.org/10.3390/su14106347.

[10] United Nations, Sustainable Development Goals, Department of Economic and Social Affairs, 2023. https://sdgs.un.org/goals. (Accessed 12 November 2024).

[11] W. Xing, V.W. Tam, K.N. Le, J.L. Hao, J. Wang, Life cycle assessment of sustainable concrete with recycled aggregate and supplementary cementitious materials, Resour. Conserv. Recycl. 193 (2023) 106947, https://doi.org/10.1016/j.resconrec.2023.106947.

[12] GCCA, The GCCA 2050 Cement and Concrete Industry Roadmap for Net Zero, 2021.

[13] ANEFHOP, Guide for the Carbon Footprint Reduction in the Prepared Concrete Industry (GU´IA PARA LA REDUCCION ´ DE LA HUELLA DE CARBONO DE LA INDUSTRIA DEL HORMIGON ´ PREPARADO), 2022. www.anefhop.com.

[14] S.K. Kirthika, S.K. Singh, A. Chourasia, Alternative fine aggregates in production of sustainable concrete- A review, J. Clean. Prod. 268 (2020) 122089, https:// doi.org/10.1016/j.jclepro.2020.122089.