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Original Research Paper

Flexural Strengthening of Reinforced Concrete Beams with Prestressed L-Shaped Sections: A Numerical Investigation

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Abstract

This study introduces and numerically validates a novel method for the flexural strengthening of reinforced concrete (RC) beams using prefabricated, L-shaped prestressed concrete sections. A Finite Element model was developed in Abaqus and validated against existing experimental data for an unstrengthened RC beam. A comprehensive parametric study was then conducted to assess the performance of the strengthened system, focusing on the effects of prestress level and tendon arrangement. The results demonstrate the exceptional efficacy of the proposed technique. The beam's flexural capacity was significantly increased, with the optimal configuration showing a 428.7% enhancement in yield moment compared to the reference beam. Furthermore, the method substantially improves the structure's ductility and energy dissipation capacity, with inelastic energy dissipation increasing by up to 59.9% and damage-related energy dissipation by up to 191%. A direct comparison revealed that the proposed method's performance is approximately 2.5 times greater than strengthening with advanced Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) jackets. This numerical proof-of-concept confirms that the proposed technique is a highly promising and efficient solution for structural retrofitting.

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INTRODUCTION

Concrete is one of the most widely used construction materials globally due to its economic advantages and the accessibility of its raw materials (Al Khaffaf et al., 2025; Althoey et al., 2023; Favier et al., 2018). It is utilized in a vast array of structures, including buildings, bridges, dams, and offshore platforms. While concrete exhibits high compressive strength, it is notably weak in tension. This weakness leads to the formation of cracks under tensile stresses induced by applied loads, shrinkage, or temperature variations. To counteract this, steel reinforcement is embedded within the concrete to carry the tensile forces. An advanced approach involves prestressing, where high-strength steel tendons are tensioned to induce a pre-compressive force in the concrete, thereby delaying the onset of cracking (Nawy, 1988).

Over time, many existing concrete structures suffer from degradation, material fatigue, or exposure to harsh environmental conditions, necessitating repair or strengthening (Mirzaee et al., 2021; Sharif et al., 1994). The need for strengthening also arises from changes in building codes, modifications in the structure's use, or errors during the initial design and construction phases. Consequently, various strengthening techniques have been developed. Common methods for enhancing the seismic resistance and ductility of concrete beams include the application of fiber-reinforced polymer (FRP) jackets, steel jackets or plates, and reinforced concrete (RC) jackets (Attari et al., 2019; Esmaeeli et al., 2015; Gergely et al., 2000; Gkournelos et al., 2021; Hadi & Tran, 2014; Kabashi et al., 2025; Karbhari, 2001; Ma et al., 2017; Raza et al., 2019; Singh & Murty, 2024). While RC jacketing is a traditional and effective method for increasing flexural and shear strength, it has notable drawbacks, such as a significant increase in the member's weight and dimensions, which can reduce usable space and is contrary to the goal of weight reduction in seismic retrofitting (Attari et al., 2019; Shahbazpanahi & Manie, 2006).

Previous research has explored various strengthening techniques. Hassani Tabar *et al*., (Hassani Tabar et al., 2014) experimentally investigated the use of prestressed CFRP plates and found that prestressing improved load-bearing capacity. Similarly, Haji Hashemi studied near-surface mounted (NSM) prestressed CFRP strips, noting an 11.5% to 15% increase in ultimate load capacity for prestressed samples compared to a 10% increase for non-prestressed ones (Hajihashemi, 2008). Lampropoulos *et al.*, (Lampropoulos et al., 2016) explored the use of Ultra-High Performance Fiber Reinforced Concrete (UHPFRC) layers and jackets, finding that a three-sided UHPFRC jacket provided the best performance.

This paper introduces a novel strengthening method using pre-fabricated, prestressed concrete beams. This approach offers several potential advantages over conventional post-tensioning methods that often rely on shotcrete, which is not considered a high-strength concrete. The proposed method benefits from:

- **Quality Control:** The prestressed beams are fabricated in a controlled factory environment, ensuring higher quality compared to on-site methods.
- **Durability:** The high-quality fabrication and strong bond between steel and concrete in pre-tensioned members eliminate the need for periodic inspections and reduce the risk of stress loss over time.
- **Cost-Effectiveness:** The proposed technique is potentially more economical than post-tensioning or FRP-based methods.

Therefore, the primary objective of this paper is to conduct a numerical investigation to establish a proof-of-concept for this novel strengthening technique. A detailed parametric study is performed to quantify its potential benefits and identify key behavioral trends, thereby laying the groundwork for future experimental validation.

Research Methodology

The research process involved numerically modeling a reference RC beam in the Finite Element software Abaqus (Abbassi et al., 2023; Abdolpour & Sawicki, 2025; Al-Ashmawy et al., 2023; Bouakaz et al., 2014; Chen et al., 2023; Elsalakawy et al., 2025; Habibi et al., 2022; He et al., 2025; Islam, 2020; Kim et al., 2025; Laib et al., 2021; Lewiński & Więch, 2020; Mobasseri & Janghorban, 2024; Mobasseri et al., 2022; Mobasseri & Mobasseri, 2016; Mobasseri et al., 2020; Mobasseri et al., 2024; Ni et al., 2025; Sadeghi & Hesami, 2018; Shakor et al., 2021; Tan et al., 2025; Wang et al., 2024) and then simulating its strengthening with the proposed method. A parametric study was conducted to evaluate the effects of the number of prestressing tendons and the level of prestress.

Reference Model

The reference model for this study is based on the experimental work detailed in Lampropoulos *et al.*, (Lampropoulos et al., 2016) which serves as the validation benchmark. The base RC beam has a cross-section of 150 mm × 250 mm and a total length of 2200 mm, with an effective span of 2000 mm. It is reinforced with two 12 mm diameter steel bars in the tension zone, having a yield strength of 500 MPa and a concrete cover of 25 mm. The 28-day cylindrical compressive strength of the concrete is 39.5 MPa. The beam was subjected to a four-point bending test. Details of the base model beam are shown in Figure 1 and the experimental setup is depicted in Figure 2.

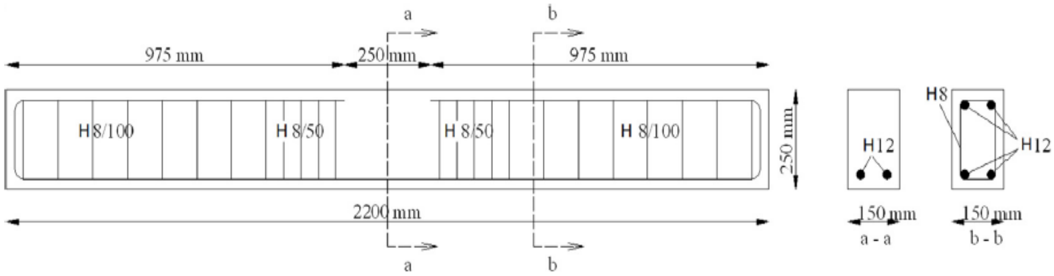


Fig 1. Base Model

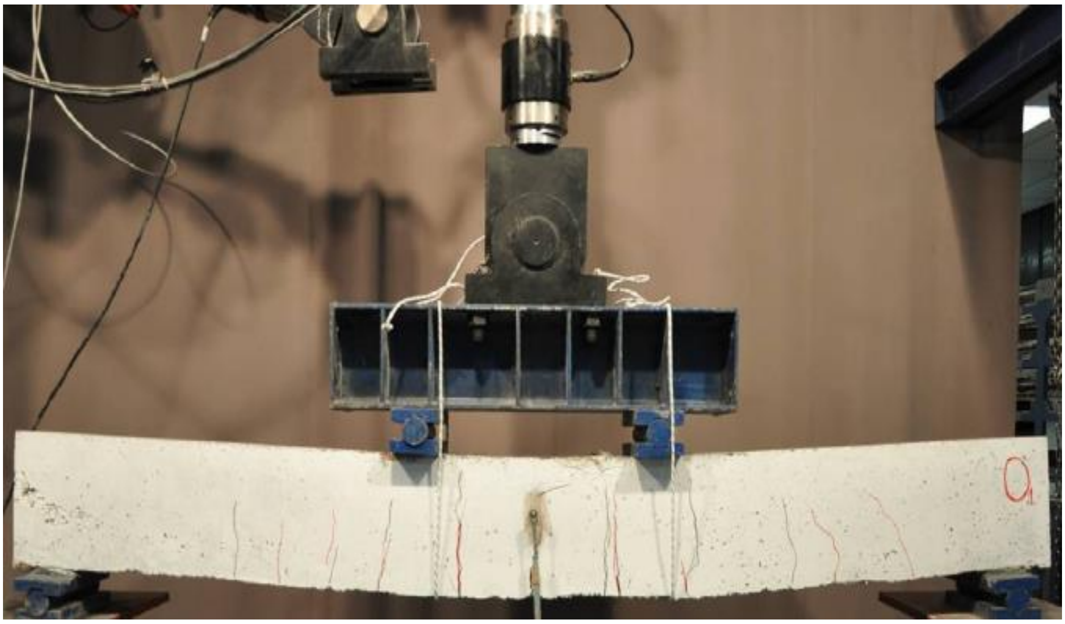


Fig 2. Experimental Setup

[redacted] performed using ABAQUS software (v.2016) (Abbassi et al., 2023; Mobasseri & Janghorban, 2024; Mobasseri et al., 2022; Mobasseri & Mobasseri, 2016; Mobasseri et al., 2020; Mobasseri & Soltani, 2013; Mobasseri et al., 2024; Systèmes, 2016). The analysis was conducted using a Dynamic Explicit step over a duration of 80 seconds.

Component Modeling (Part Module)

All components, including the main RC beam, the L-shaped strengthening beams, reinforcing bars, and prestressing tendons, were modeled as 3D deformable parts. The loading and support plates were modeled as 3D discrete rigid bodies to prevent deformation during analysis. A view of the modeled RC beam is shown in Figure 3, the reinforcement cage in Figure 4, and an L-shaped strengthening beam in Figure 5.

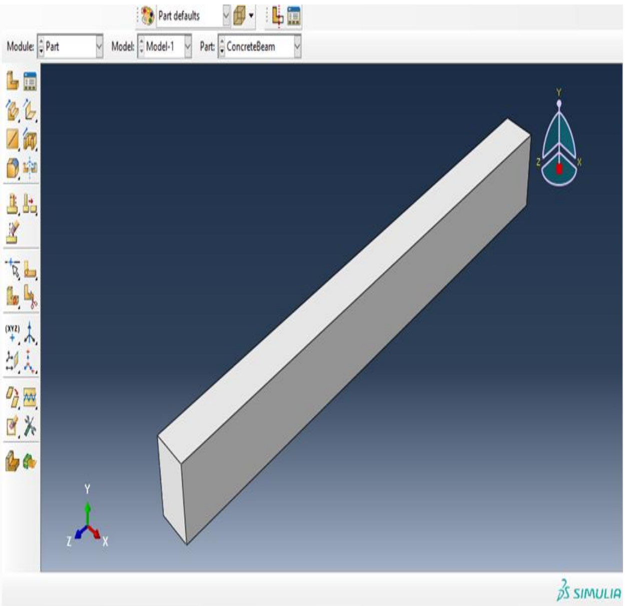


Fig 3. Modeled RC Beam

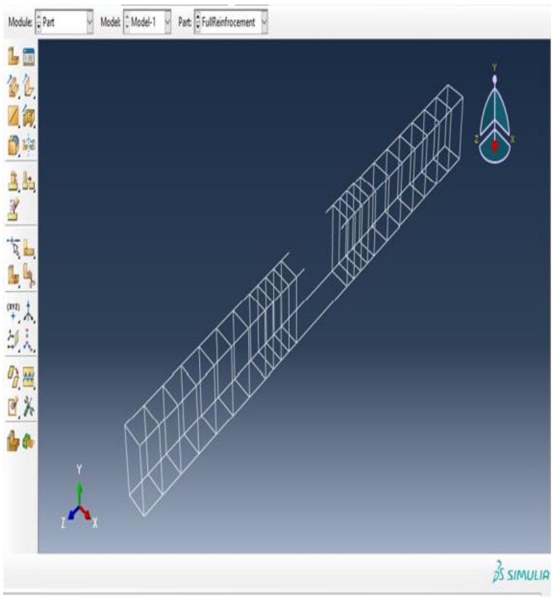


Fig 4. Reinforcement Cage

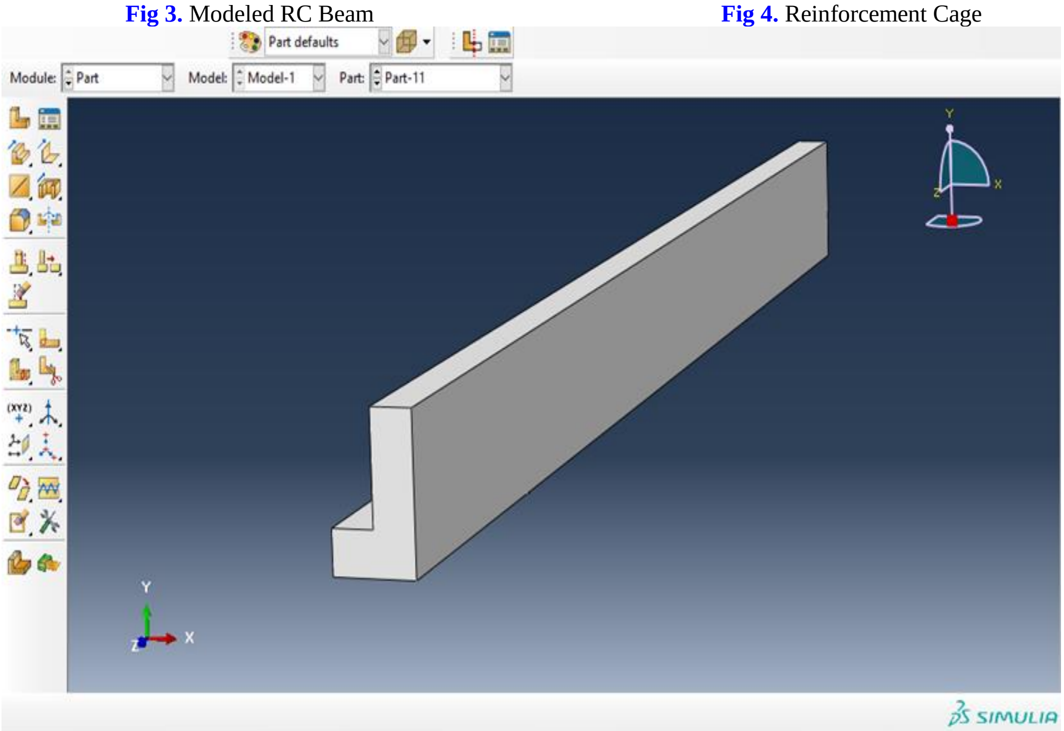


Fig 5. L-shaped Strengthening Beam

Material Properties (Property Module)

Concrete: The concrete was modeled using the Concrete Damage Plasticity (CDP) model. The material parameters were based on the reference paper and relevant literature (Jankowiak & Lodygowski, 2005; Sümer & Aktaş, 2015). The density, Young's modulus, and Poisson's ratio were defined as per Table 1. The specific parameters for the CDP model, including compressive behavior and damage evolution, are illustrated in Figures 6, 7, and 8. A single concrete type (C40) was used for both the main beam and the strengthening beams.

Table 1. Concrete Parameters

Density ($tonne/mm^3$)	Young's modulus (MPa)	Poisson's ratio
2.5e-09	36000	0.2

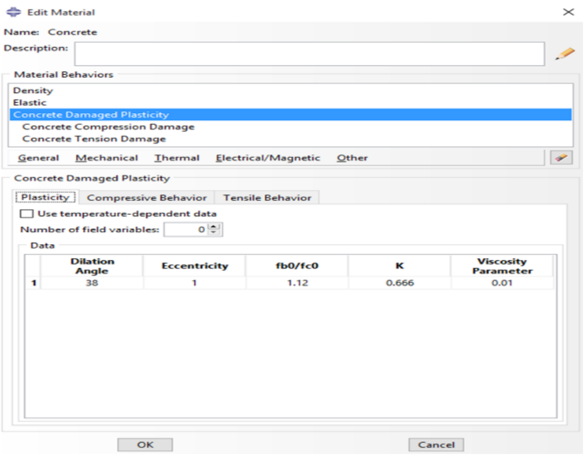
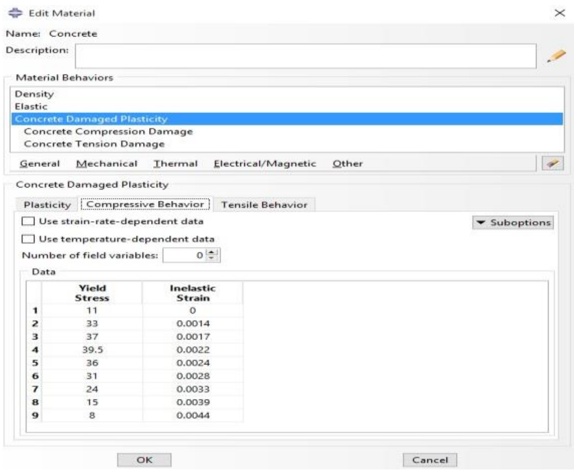


Fig 6. Specific Parameters for CDP Model



Figu 7. Concrete Compressive Behavior

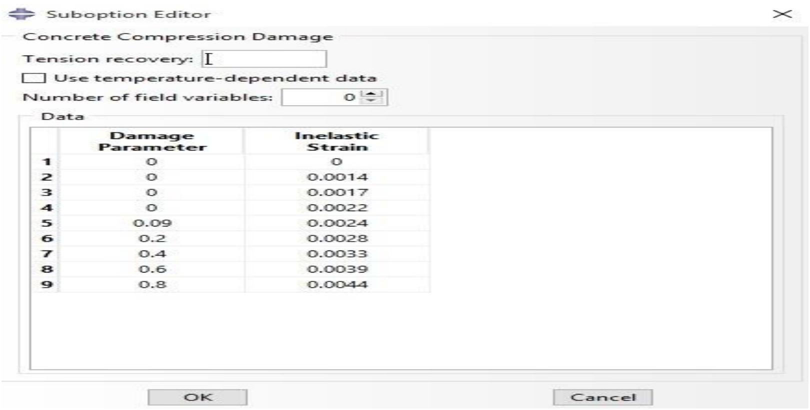


Fig 8. Concrete Compressive Damage Evolution

Steel Reinforcement: The reinforcing steel was modeled with properties as listed in Table 2, with a specified yield strength of 500 MPa.

Table 2. Reinforcing Steel Properties

Density $(tonne/mm^3)$	Young's modulus (MPa)	Poisson's ratio
7.85e-09	205000	0.3

Prestressing Tendons: The tendons were modeled based on the ASTM A416 standard for low-relaxation, Grade 270 strands (International, 2018), with a nominal diameter of 9.53 mm. Their mechanical properties are given in Table 3.

Table 3. Grade 270 Strands Properties

Density $(tonne/mm^3)$	Young's modulus (MPa)	Poisson's ratio
7.85e-09	196508	0.3

Assembly and Interactions

The individual parts were assembled to create the final model, as shown in Figure 7. A perfect bond was assumed between the strengthening beams and the main RC beam by using a tied interface. This assumption was made to evaluate the theoretical maximum performance of the fully composite section and to isolate the effects of the prestressing parameters. The analysis of interfacial slip and the design of shear connection mechanisms are complex issues that are considered beyond the scope of this initial proof-of-concept study and are recommended for future experimental investigation. Reinforcing bars and prestressing tendons were embedded within the concrete host regions using the "Embedded Region" constraint, as shown for the rebar in Figure 8. A general contact algorithm was used for all other interactions.

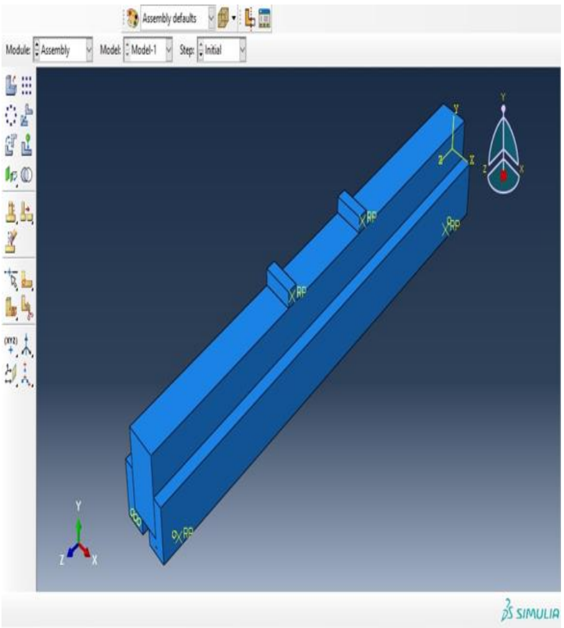


Fig 9. Assembled Model

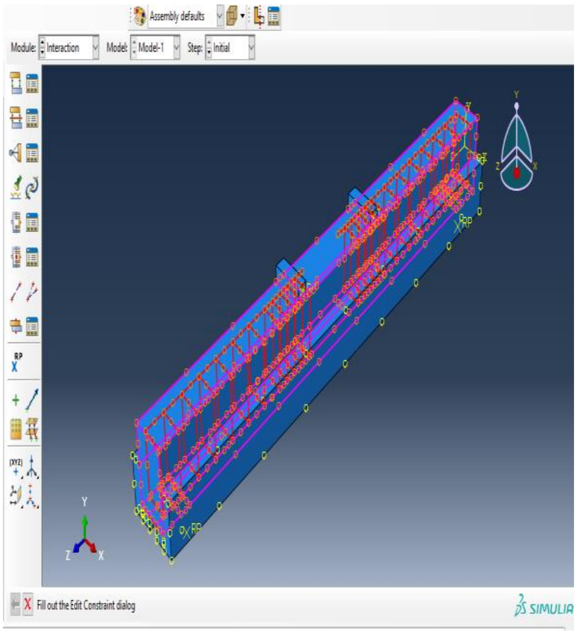


Fig 10. Embedded Region Constraint

Loading and Boundary Conditions (Load Module)

The simulation was displacement-controlled to replicate the experimental test. A vertical displacement was applied to the top loading plates at a rate of 0.5 mm/s, up to a total of 40 mm. This is depicted in 9 and 10. The prestressing force was applied to the tendons as an initial stress condition using the "Predefined Field" option, as shown in Figure 11.

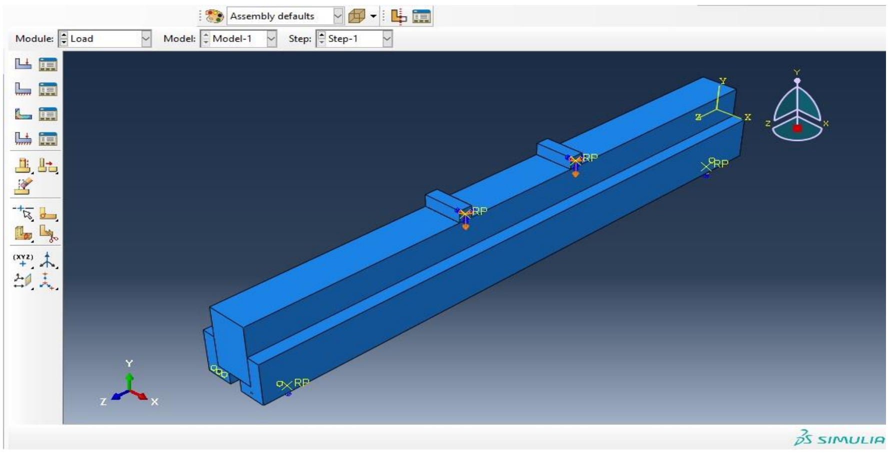
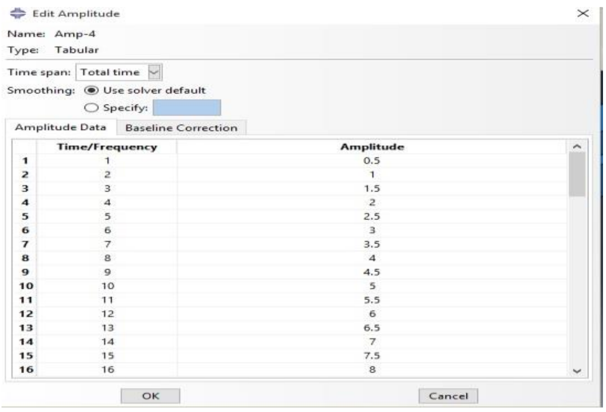


Fig 11. Applied Vertical Displacement in Model



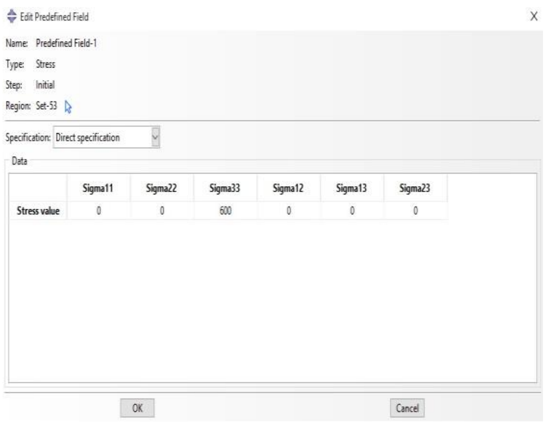


Fig 12. Applied Vertical Displacement Data

Fig 13. Initial Stress Condition in Predefined Field

Parametric Study and Naming Convention

A total of 10 models were analyzed. The unstrengthened beam is named Base. The strengthened models were organized into three series based on the number of prestressing tendons (1, 2, or 3) and three levels of total prestress (300, 600, or 900 MPa). The naming convention is detailed in Table 4. For instance, model 2s-600 refers to a beam strengthened with two tendons, each carrying a stress of 300 MPa, for a total equivalent stress of 600 MPa. Visual representations of the different strengthened models are provided in Figures 12, 13, and 14.

Table 4. Models Naming Convention

Model Name	Description
Base	**Unstrengthened beam**
1S-300	Strengthened Beam with one tendon, carrying a stress of 300 MPa
1S-600	Strengthened Beam with one tendon, carrying a stress of 600 MPa
1S-900	Strengthened Beam with one tendon, carrying a stress of 900 MPa
2S-300	Strengthened Beam with two tendons, each carrying a stress of 150 MPa
2S-600	Strengthened Beam with two tendons, each carrying a stress of 300 MPa
2S-900	Strengthened Beam with two tendons, each carrying a stress of 450 MPa
3S-300	Strengthened Beam with three tendons, each carrying a stress of 100 MPa
3S-600	Strengthened Beam with three tendons, each carrying a stress of 200 MPa
3S-900	Strengthened Beam with three tendons, each carrying a stress of 300 MPa

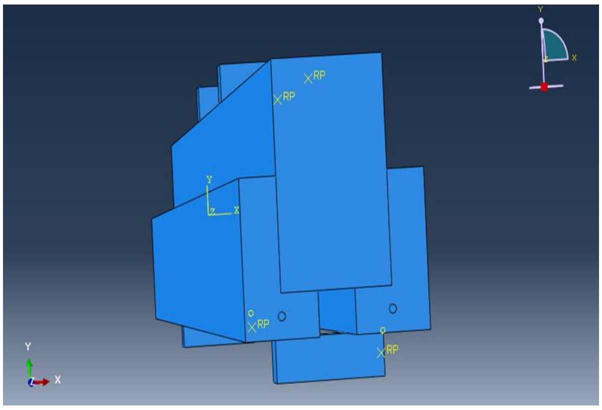


Fig 14. 1S Models

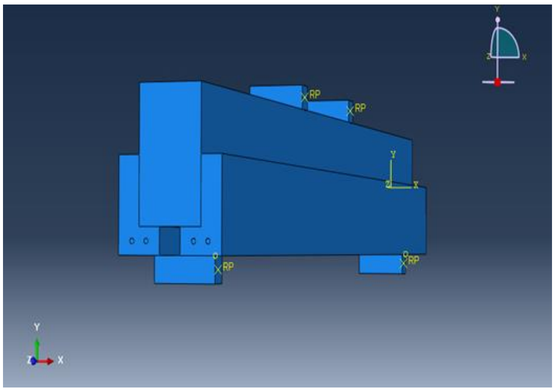


Fig 15. 2S Models

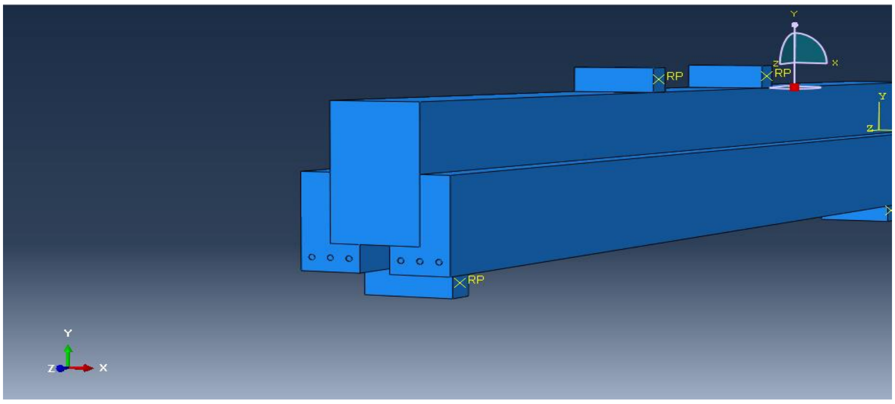


Fig 16. 3S Models

Model Validation

Verification of the Base Model

The first step was to validate the numerical model by comparing the simulation results of the Base model with the experimental (IBexp) and numerical (IBnum) results from the reference paper (Lampropoulos et al., 2016). As shown in Figure 15, the load-deflection curve of the Abaqus model shows good agreement with the benchmark data. The maximum error of the Abaqus model relative to the experimental results was approximately 2.5%, whereas the error in the reference paper's numerical model was 3.9%. This level of accuracy was deemed sufficient for proceeding with the parametric study.

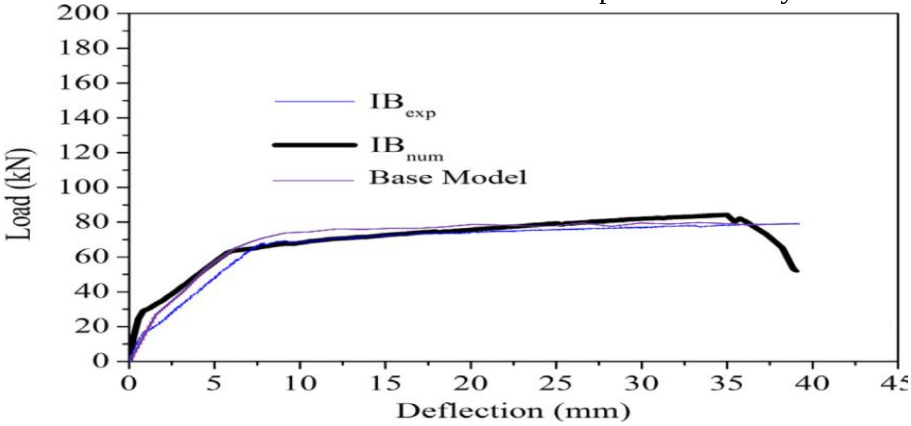


Fig 17. Verification of the Base Model

Mesh Sensitivity Analysis

To ensure the results were independent of mesh size, a sensitivity analysis was performed using three different mesh sizes: 40 mm, 50 mm, and 60 mm. The resulting load-deflection curves are plotted in Figure 17. As the results showed convergence, the 50 mm mesh size was selected as the optimal choice, providing a balance between accuracy and computational cost.

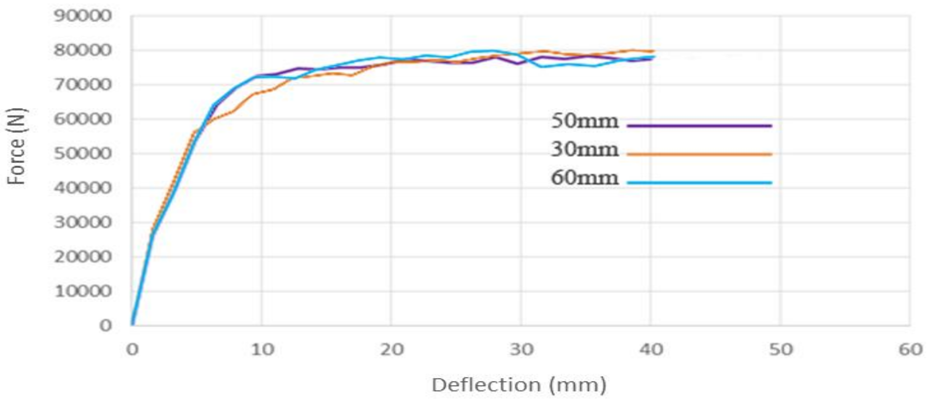


Fig 18. Mesh Sensitivity Analysis

Research findings

The performance of the strengthened models was evaluated based on their yield moment, load-deflection behavior, and energy dissipation capacity.

Flexural Capacity and Yield Moment

The yield moments for all models are summarized in Tables 5, 6 and 7. The Base model had a yield moment of 9.52 kNm. All strengthened models showed a substantial increase in flexural capacity.

The applied prestressing force induces a state of pre-compression in the tension zone of the composite section. This initial compression must be overcome by the applied load before tensile stresses can initiate cracking, thereby significantly increasing the cracking moment of the section. This delay allows for greater utilization of the concrete's compressive strength and postpones the yielding of the main tensile reinforcement, resulting in a substantially higher flexural capacity.

Table 5. 1S Models Yield Moments

Yield Moments (kNm)	Model Name
34.93	1S-300
36.46	1S-600
40.1	1S-900

Table 6. 2S Models Yield Moments

Yield Moments (kNm)	Model Name
36.33	2S-300
42.78	2S-600
48.87	2S-900

Table 7. 3S Models Yield Moments

Yield Moments (kNm)	Model Name
45.04	3S-300
47.65	3S-600
50.33	3S-900

Effect of Prestress Level

For a fixed number of tendons, increasing the prestress level consistently increased the yield moment. For the 1-tendon series (1s), increasing the total prestress from 300 to 900 MPa resulted in a 14.8% increase in yield moment. For the 2-tendon series (2s), the same increase in prestress led to a 34.5% improvement in yield moment. This trend, however, was accompanied by a reduction in ductility, as the load-deflection curves (Figures 19, 20, and 21) show a more brittle response at higher prestress levels.

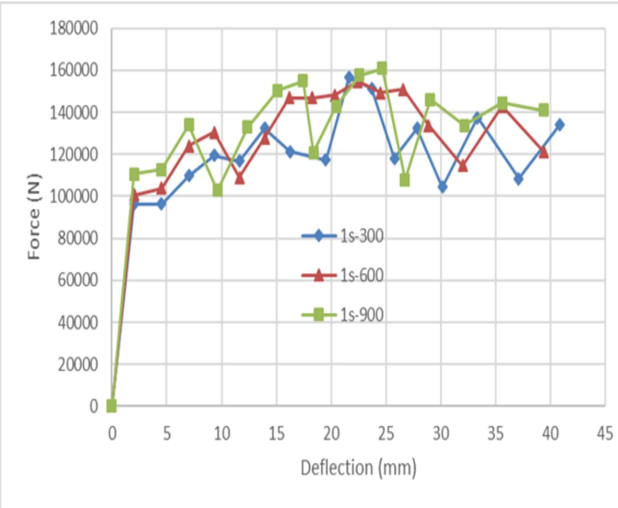


Fig 19. 1S Models Load-Deflection Curves

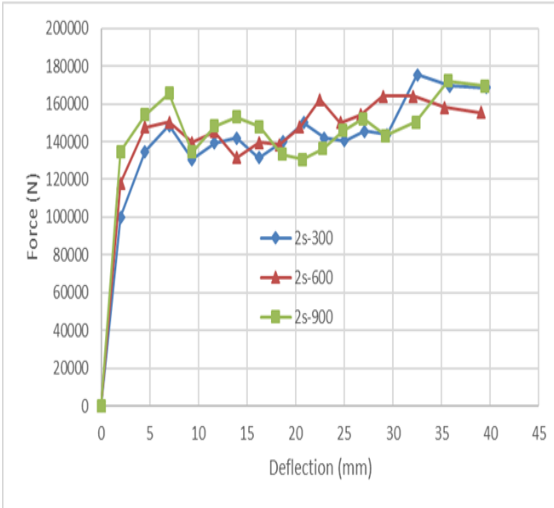


Fig 20. 2S Models Load-Deflection Curves

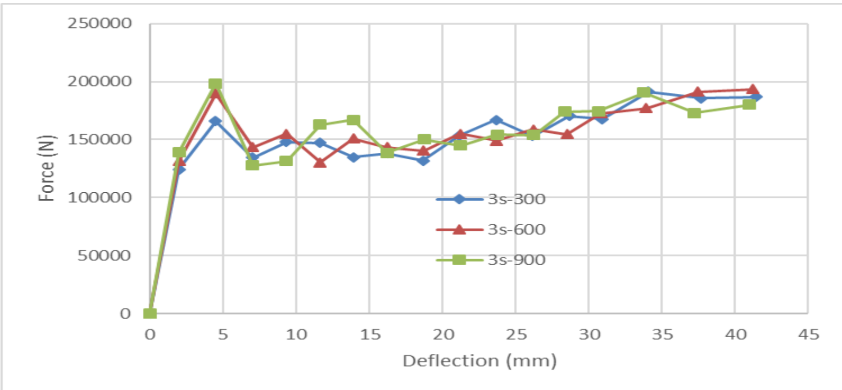


Fig 21. 3S Models Load-Deflection Curves

Effect of Tendon Number

Comparing models with the same total prestress but different numbers of tendons reveals that distributing the force among more tendons improves performance. For a total prestress of 300 MPa, using two tendons (model 2s-300) and three tendons (model 3s-300) increased the yield moment by 4% and 30%, respectively, compared to the single-tendon model (1s-300).

This is likely due to a more uniform distribution of the pre-compressive stress. The highest flexural capacity was achieved by model 3s-900, with a yield moment of 50.33 kNm. This represents a remarkable 428.7% increase compared to the Base model. This result is approximately 2.5 times greater than the enhancement reported for the UHPFRC jacketed beam in the reference study (Lampropoulos et al., 2016), highlighting the significant advantage of incorporating prestressing.
The load-deflection curves for models with the same prestress level but varying tendon numbers are compared in Figures 22, 23, and 24.

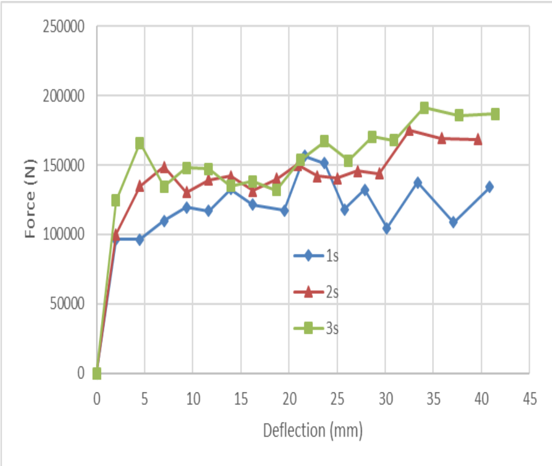


Fig 22. 300 MPa Prestressed Models Load-Deflection Curves

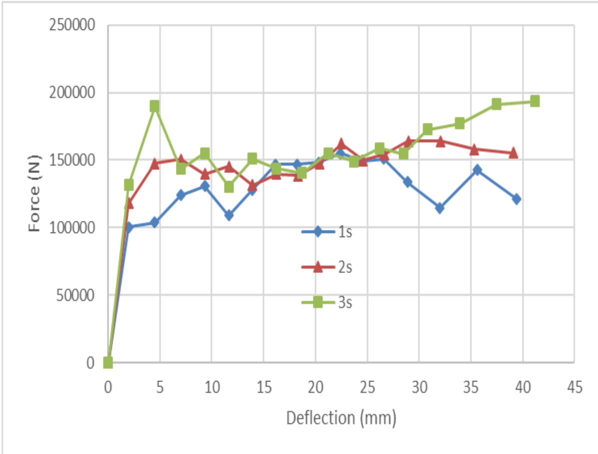


Fig 23. 600 MPa Prestressed Models Load-Deflection Curves

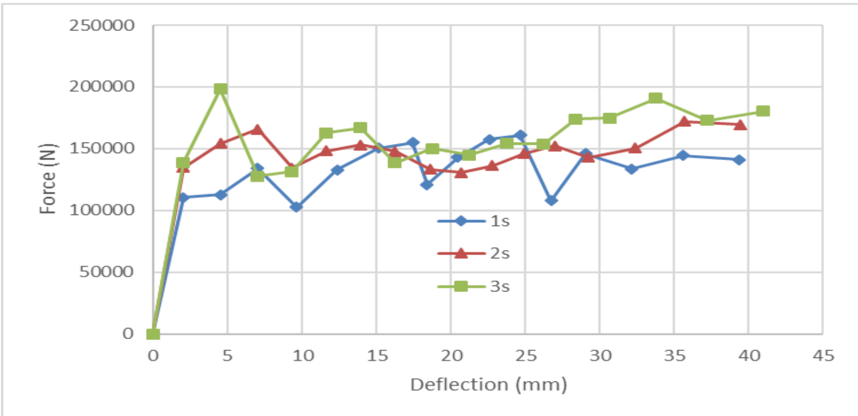


Fig 24. 900 MPa Prestressed Models Load-Deflection Curves

Energy Dissipation

The capacity of a structure to dissipate energy is critical for its performance under seismic loading. Two energy metrics were evaluated: inelastic dissipated energy (ALLPD) and energy dissipated by damage (ALLDMD).
The significant increase in energy dissipation is attributed to the composite action and the controlled, distributed cracking behavior enabled by the prestressed sections. The system is able to undergo larger inelastic deformations before failure, and the damage is spread over a wider area rather than being localized, allowing for greater absorption and dissipation of input energy, which is a critical attribute for seismic resilience.

Inelastic Dissipated Energy

The values are presented in Table 8. The proposed strengthening method increased the inelastic energy dissipation by 15.5% (for model 1s-300) to a maximum of 59.9% (for model 3s-900) compared to the Base model.

Table 8. Inelastic Dissipated Energy

Model Name	Energy (J)	Increase (%)
Base	96587.4	-
1S-300	111606.4	15.5
1S-600	121262.8	25.5
1S-900	133549.5	38.3
2S-300	123851.2	28.2
2S-600	131219.4	35.8
2S-900	142664.8	47.7
3S-300	135104.7	39.9
3S-600	144909.5	50
3S-900	154414.7	59.9

Energy Dissipated by Damage

The values are listed in Table 9. The increase in this metric was even more pronounced, ranging from 49.5% (for model 1s-300) to 191% (for model 3s-900) relative to the Base model.

Table 9. Energy Dissipated by Damage

Model Name	Energy (J)	Increase (%)
Base	6520.9	-
1S-300	8264.7	49.5
1S-600	8436.5	54.4
1S-900	8882.9	67.1
2S-300	11396.9	138.5
2S-600	11626.6	145
2S-900	11656.5	145.9
3S-300	11966.7	154.7
3S-600	12715.9	176
3S-900	13234	191

These results indicate that the proposed method not only strengthens the beam but also substantially improves its ability to dissipate energy, which can help prevent catastrophic failure during severe loading events like earthquakes.

Results

This numerical proof-of-concept study has successfully demonstrated the significant potential of using prefabricated prestressed beams for strengthening RC beams. Based on the Finite Element Analysis (FEA), the following conclusions are drawn:

1. The proposed strengthening method provides a very significant increase in the flexural capacity of RC beams. The maximum observed yield moment increased by 428.7% compared to the unstrengthened base model.
2. Both the level of prestress and the number of tendons are critical parameters. Increasing the prestress level boosts the yield moment but tends to result in more brittle behavior. Distributing the prestressing force among a larger number of tendons leads to a higher cracking moment and better overall performance.
3. The method substantially enhances the energy dissipation capacity of the beams. Inelastic energy dissipation increased by up to 59.9%, and energy dissipated through damage mechanisms increased by up to 191%. This improvement is crucial for seismic resilience.
4. When compared to advanced strengthening techniques like UHPFRC jacketing (Lampropoulos et al., 2016), the proposed method demonstrates superior performance in terms of flexural strength enhancement, largely due to the beneficial effects of prestressing.

Overall, the results confirm that strengthening with prefabricated prestressed concrete sections is a highly effective retrofitting technique. The compelling performance demonstrated in this study strongly justifies experimental research to validate these numerical findings and develop practical guidelines for its implementation.

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Original Research Paper

An Introduction to Solar Energy, Solar Radiation, and their Measurement Methods: A Review Study

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Abstract

The amount of solar radiation is one of the important climatic parameters that has a direct and close relationship with many hydrological and meteorological processes. This parameter is a fundamental element for designing and developing various solar energy systems and conducting applied solar energy research. To estimate the amount of solar radiation, researchers have proposed various models that eliminate the need for expensive equipment in meteorological stations. When measured data is not available, meteorological parameters such as maximum and minimum temperatures, wind speed, sunshine hours, rainfall, air pressure, and humidity can be used at different meteorological stations. In this review article, a series of research conducted in this field will be discussed.

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INTRODUCTION

The radiant energy of the sun is a source of promising and renewable energy on the planet (Basurto et al., 2019). Solar radiation is a crucial parameter used in hydrology, water resources management, water balance models, and plant growth simulation models (Ball, Purcell & Carey, 2004; Seyedian et al., 2017; Besharat, Dehghan & Faghih, 2013; Huang et al., 2021; Budyko, 1969; Islam et al., 2009). The amount of total solar radiation (GSR) is the most important parameter in the design and development of various solar energy systems, which affects numerous water and soil processes, including evaporation, snowmelt, and plant growth (Tiris & Erdalli, 1997; Bagheri, Moradi & Bagheri, 2013; Sabziparvar & Bayat Varkeshi, 2019; HoushmandRad & Mokhtari, 2022). The concept of total radiation refers to the amount of solar energy absorbed by a horizontal surface within a specific period of time in a given region (Almorox & Hontoria, 2004; Wang et al., 2011).The first and most important need in solar energy application designs is the accurate observation and estimation of solar radiation components. Unfortunately, in some countries around the world, there are insufficient solar radiation measurement stations, and in some cases, the measurements are of poor quality.

In developing countries (such as Iran), direct measurement of GSR is usually done in limited sites, and in some cases, the measurements are not of the desired quality; because in these countries, the number of meteorological stations is limited, and in addition, expensive equipment is needed to directly obtain the amount of solar radiation (Tiris & Erdalli, 1997; Bagheri, Moradi & Bagheri, 2013; Chen et al., 2004). To overcome this problem, numerous studies have aimed to predict the amount of solar radiation using geographical and meteorological parameters, such as minimum and maximum temperatures, sunny hours, relative humidity, altitude, rainfall, and wind speed, by various researchers (Bristow & Campbell, 1984). These studies have led to the presentation of different models for evaluating solar radiation (Almorox, 2011).

Literature Review

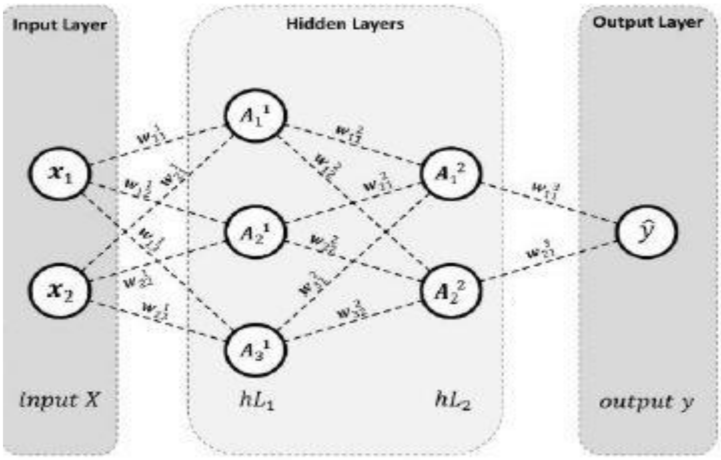
An extensive and practical study of solar energy has been conducted since the 1970s in most parts of the world. According to the climatic and geographical conditions of different regions, suitable models have been proposed. The significant difference in geographical latitude in Iran is a significant factor in the substantial variation in solar radiation across the country. Appropriate modeling to estimate solar energy in different regions of the country, and its correct use, will play a crucial role in determining the country's required energy (Bagheri, Moradi, & Bagheri, 2013).

Studies have been done to estimate the total amount of radiant energy received on a horizontal surface. The first empirical relationship to calculate GSR based on sunshine hours over a long period was presented by Angstrom (1924) (Seyedian et al., 2017; Angstrom, 1924). By using atmospheric data, such as sunshine hours, he developed a simple model to estimate the total amount of solar radiation reaching the Earth's horizontal surface. After Angstrom, many researchers attempted to improve and modify the Angstrom model, whose conversion coefficients and input data were dependent on climatic conditions (Prescott, 1940). Prescott improved the Angstrom model, and his proposed model is known as the Angstrom-Prescott model. Page (1979) presented the coefficient of the Angstrom-Prescott model in a way that can be used everywhere in the world. Ogelman et al. (1984) modified the results of the Angstrom-Prescott equation by using the quadratic relationship. Almorox and Hontoria (2004) presented a power relationship based on the n/N ratio (n: number of sunny hours, N: maximum number of sunny hours). They demonstrated that the results are in good agreement with actual values, making them suitable for estimating monthly solar radiation. Wanxiang et al. (2014), in order to estimate solar radiation, studied 108 different relationships based on the n/N ratio in Shanghai, China, and selected three relationships as the best relationships. Yin et al. (2008) showed that Angstrom's relationship is suitable for estimating radiation in China in order to predict evaporation-transpiration. Bahel et al. (1987) developed a general relationship based on radiation data and sunshine hours for 48 stations, representing diverse geographical and meteorological conditions worldwide.

In Ninomiya's research (1994), the effect of rainy days is also considered. Burari et al. (2001) employed a solar radiation estimation model with specific regression coefficients tailored to the Bauchi region. Chandel et al. (2005) proposed a model based on temperature. Saffaripour and Mehrabian (2008) analyzed the analytical models of other researchers and calibrated some of these models for the climatic conditions of Iran according to the experimental data; also, they investigated the combined effect of geometrical, geographical, astronomical, and meteorological factors on the amount of solar radiation received in Yazd city by using the compound regression method, and by presenting a seven-parameter model, they predicted the intensity of the total daily radiation very accurately.

Research Methodology

Artificial Neural Network (ANN): Artificial neural networks are computational methods that, through a learning process using simple processors called neurons, identify inherent relationships within data and map input spaces to desired output spaces (Figure 1) (Huang et al., 2021). In designing artificial neural networks, a structure inspired by human bio-structure is adopted to enable learning, generalization, and decision-making capabilities (Abbassi et al., 2023; Habibi et al., 2022; Mobasseri & Janghorban, 2024; Mobasseri et al., 2022; Mobasseri et al., 2020; Mobasseri et al., 2024). Hidden layers process information from the input layer and pass it to the output layer. Training involves adjusting connection weights so that predicted values match observed values within an acceptable margin (Sabziparvar & Bayat Varkeshi, 2019). These trained networks can then predict outputs for new datasets.



Figu 1. A sample of artificial neural network with two hidden layers (Rahbar et al., 2020).

Adaptive Neuro–Fuzzy Inference System (ANFIS): ANFIS combines neural network algorithms and fuzzy logic to create a non-linear mapping between input and output spaces. Its strength lies in the combination of fuzzy linguistic capabilities with the numerical power of neural networks for complex process modeling (V & K, 2008). In recent years, AI techniques such as ANN and ANFIS have been widely used for simulating complex phenomena including solar radiation prediction, due to its non-linear nature and dependence on atmospheric parameters (Caudill, 1987).

Application of ANN in Solar Radiation Modeling: The use of ANN for solar radiation prediction was first proposed by Kalogirou et al. (Kalogirou et al., 1998). Subsequent studies demonstrated the effectiveness of ANN in various countries: Fadare (Fadare, 2009) highlighted its superiority in predicting solar radiation; Alfa et al. (Alfa et al., 2001) successfully predicted hourly solar radiation in Nigeria; Sozen et al. (Sözen et al., 2004) applied it for radiation potential zoning in Turkey; Jiya and Alfa (Jiya & Alfa, 2002) also utilized ANN for zoning; Mellit et al. (Mellit et al., 2006) used an adaptive microwave network; and Moghaddamnia et al. (Moghaddamnia et al., 2009) applied gamma test for parameter selection before ANN and ANFIS modeling. Rehman and Mohandes (Rehman & Mohandes, 2009) found that combining relative humidity and average temperature provides the most accurate estimation.

Estimation Procedure: Meteorological parameters such as minimum and maximum temperature, relative humidity, wind speed, and sunshine hours are commonly used as input for ANN and ANFIS models. Networks are trained on historical data to adjust weights for minimizing prediction errors, and the trained models are then validated using independent datasets.

Research findings

(Lazzús et al, 2011) demonstrated, using wind speed, relative humidity, and air and soil temperatures, that the neural network has a remarkable ability in hourly estimation of solar radiation. AbdulAzeez (AbdulAzeez, 2011) estimated the monthly mean solar radiation using a neural network with reasonable accuracy, incorporating data from sundial, maximum temperature, and relative humidity. SabziParvar and Bayat (Sabziparvar & Bayat Varkeshi, 2019) conducted research to evaluate artificial intelligence models for predicting the total amount of solar radiation reaching the horizontal surface of the Earth. In that study, an artificial neural network and an Adaptive Neuro-Fuzzy Inference System were employed to simulate the total amount of solar radiation. The information used included minimum temperature, maximum temperature, average relative humidity, sunny hours, and daily solar radiation recorded at four similar stations in the country (Isfahan, Kerman, Urmia, and Shiraz) from 1992 to 2006. Their results indicated that the amount of solar radiation can be predicted by using intelligent models. Additionally, the predicted results of the artificial neural network were more accurate than those of the neural-fuzzy inference system. Also, using the linear regression model, the most effective factors affecting the amount of solar radiation at each station were identified. The results of their research indicate that in all the studied stations, the parameter of sunny hours had the most significant effect on the amount of solar radiation. Additionally, in most stations, the minimum air temperature and average relative humidity had the least effect on the total amount of solar radiation. Bagheri et al. (Moradi, & Bagheri, 2013) presented a new method to estimate the daily average solar radiation on a horizontal surface for a given month, based on the Angstrom model and using the bees algorithm with programming in the MATLAB software environment. They calculated the experimental coefficients of the Angstrom model for four different climatic regions of Iran in the MATLAB software environment. They presented the average daily amount of total solar radiation estimated by the proposed method for each month in the sample areas. To validate their results, they used the results obtained from the proposed method in conjunction with other methods to determine solar radiation for all four sample regions of Iran.

Table 1. The proposed BA coefficients and its corresponding R^2 & RMSE values

City	A	B	R^2	RMSE
Hamedan	0.36710	0.30821	0.9912	0.0011
Khur and Biabanak	0.3329	0.39008	0.9908	0.0014
Mashhad	0.32846	0.30162	0.9786	0.0175
Tabriz	0.33372	0.42148	0.9745	0.0194

Table 2. Comparison between BA and SRT outputs

City	Method	A	B	R^2	The difference between the values R^2 (%)
Hamedan	BA	0.36710	0.30821	0.9912	2.58
	SRT	0.38250	0.24580	0.9662	
Mashhad	BA	0.32846	0.30162	0.9786	7.06
	SRT	0.32200	0.31100	0.9140	
Tabriz	BA	0.33372	0.42148	0.9745	8.84
	SRT	0.33870	0.42140	0.8953	
Khur and Biabanak	BA	0.3329	0.39008	0.9908	4.81
	SRT	0.4101	0.3154	0.9453	

Source: Bagheri et al, 2013

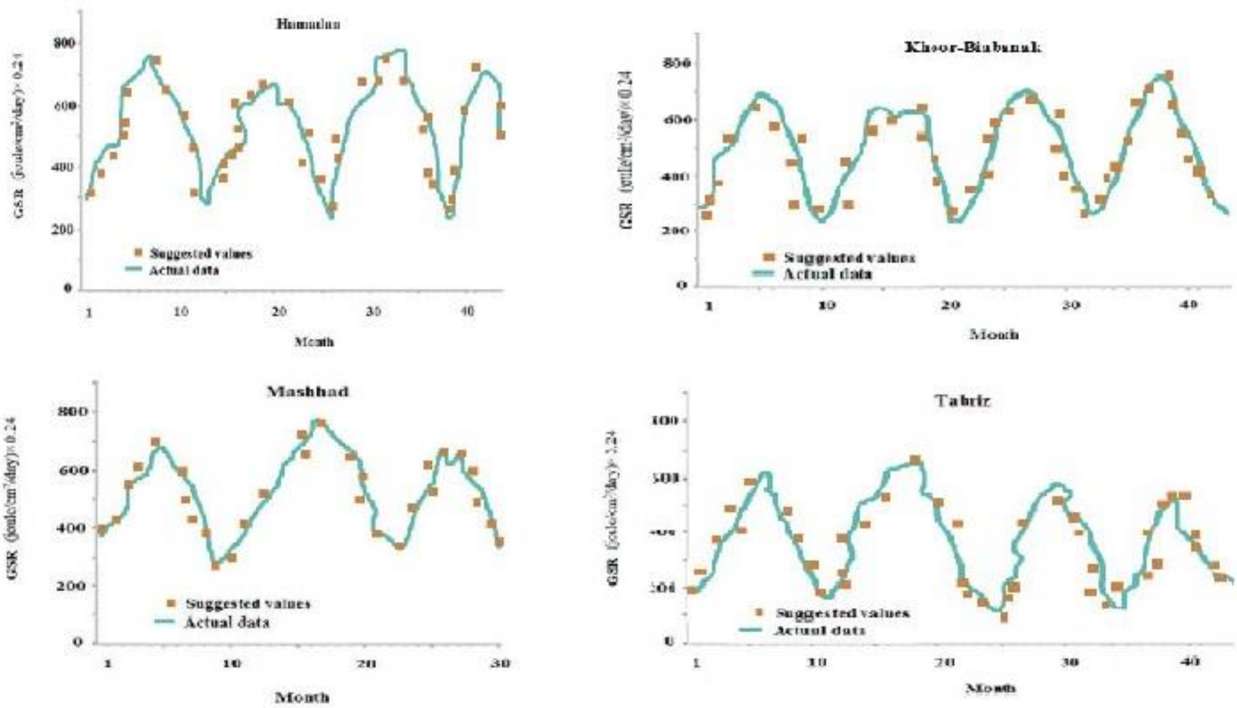


Fig 2. Comparison between average daily GSR values in the month predicted by BA and actual values in four sample cities (Bagheri et al, 2013)

Gamma test: Gamma test was first proposed by Koncar (1997) and later developed by many researchers such as Durrant (2001). Gamma test is a non-linear modeling tool that can be used to check the appropriate combination of input parameters to model the output data and create a model. It is also a developer tool for estimating the mean squared error resulting from the modeling of various phenomena using observational data sets. Gamma test estimates the mean square of the output error for different combinations of parameters:

$$\gamma = A\delta + \Gamma \qquad (1)$$

There is useful information on the regression of relation (1). The width from the origin of the line indicates the value of gamma (Γ), which represents that part of the variance of the output data that cannot be estimated by the model. The slope of the regression line indicates the complexity of the model, and the steeper this slope is, the more complex the model is. The results of the gamma test can be checked by another parameter ($Vratio$), obtained by equation (2):

$$V_{ratio}=\frac{\Gamma}{(y)\sigma 2} \qquad (2)$$

The denominator of the fraction is the variance of the output values (y) and (V_{ratio}) is a number between zero and one that shows the constant error value. Seyedian et al. (2017) collected meteorological data, including maximum and minimum temperatures, wind speeds, solar hours, rainfall, air pressure, and humidity, at six meteorological stations in Mashhad, Isfahan, Ramsar, Zahedan, Urmia, and Shiraz. Using the gamma test, they determined the meteorological parameters that affect solar radiation at each station. The results of their research showed that, in all stations, maximum temperature and sunshine hours are among the parameters affecting solar radiation. Additionally, at five stations, air pressure and wind speed are also among the parameters that affect solar radiation. The most important influencing parameters differ at each station; therefore, wind speed in four stations and sun hours in three stations are the first and second most important factors. Examining the parameters revealed that the maximum temperature has a significant impact on solar radiation, but compared to sun hours and wind speed, these are less important parameters (Tables 3, 4, and 5).

Table 3. Average data used to estimate solar radiation

	Zahedan	Shiraz	Ramsar	Urmia	Mashad	Isfehan
Number of days	4725	2384	2400	4079	4624	5488
Minimum temperature (ºC)	10.9	10.8	14.0	5.8	9.6	9.7
Maximum temperature (ºC)	27.2	26.5	20.2	18.5	23.1	24.5
Sunshine duration (hr)	9.4	9.4	4.6	8.3	8.6	9.3
Air pressure (mb)	862.1	850.9	1017.4	867.4	903.0	843.6
Relative humidity (%)	28.8	37.7	83.2	57.1	49.6	34.9
Rainfall (mm)	0.2	0.6	3.3	0.7	0.7	0.4
Wind speed (m/s)	3.3	1.8	1.8	1.9	2.5	1.5
Cloudiness	1.5	1.7	4.7	2.6	3.0	1.8
Solar radiation ($MJm^{-2}d^{-1}$)	7.6	7.3	5.5	5.4	6.7	6.2

Table 4. Parameters affecting on solar radiation

Station	Cloudiness	Wind Speed	Rainfall	Relative humidity	Air pressure	Sunshine duration	Maximum temperature	Minimum temperature
Isfehan				✓	✓	✓	✓	
Mashad	✓	✓				✓	✓	✓
Urmia	✓	✓			✓	✓	✓	
Ramsar	✓	✓				✓	✓	
Shiraz	✓	✓			✓	✓	✓	
Zahedan	✓			✓	✓	✓	✓	

Table 5. Ranking parameters effect on solar radiation in the stations

Station	Parameters	Gamma(Γ)	Slop (A)	Error	V_{ratio}
	All	0.171	0.342	0.0079	0.683
	All-RH	0.179	-0.601	0.0042	0.790
Isfehan	All-n	0.192	0.088	0.0048	0.768
	All-p	0.187	-0.591	0.0083	0.748
	All-T_{max}	0.186	0.086	0.0088	0.745
	All	0.165	0.192	0.0062	0.663
	All-n	0.205	-0.329	0.0028	0.820
Mashad	All-w	0.180	0.294	0.0083	0.719
	All-T_{min}	0.176	0.095	0.0111	0.706
	All-Cl	0.170	0.548	0.0064	0.679
	All-Tmax	0.168	0.194	0.0058	0.672
	All	0.174	0.146	0.0075	0.695
	All-p	0.179	0.254	0.0068	0.714
Urmia	All-w	0.183	0.108	0.0045	0.734
	All-n	0.191	0.241	0.0060	0.765
	All-Cl	0.195	-0.093	0.0053	0.781
	All-T_{max}	0.186	0.147	0.0062	0.745
	All	0.179	0.302	0.0088	0.716
	All-w	0.230	-0.056	0.0052	0.919
Ramsar	All-n	0.208	0.029	0.0047	0.832
	All-T_{max}	0.199	0.245	0.0079	0.795
	All-Cl	0.186	0.401	0.0101	0.746
	All	0.150	0.348	0.0176	0.598
	All-w	0.209	-0.351	0.0131	0.835
Shiraz	All-p	0.192	-0.136	0.0077	0.770
	All-Cl	0.195	0.115	0.0121	0.780

Station	Parameters	Gamma(Γ)	Slop (A)	Error	V_{ratio}
	All-T_{max}	0.190	-0.014	0.0128	0.762
	All-n	0.190	0.147	0.0124	0.761
	All	0.194	0.198	0.0074	0.775
	All-RH	0.217	-0.062	0.0055	0.868
Zahedan	All-Tmax	0.211	-0.019	0.0050	0.844
	All-p	0.211	0.129	0.0081	0.844
	All-n	0.208	0.260	0.0050	0.832
	All-Cl	0.199	0.364	0.0068	0.799

Minimum temperature (Tmin), maximum temperature (Tmax), sunny hours (n), air pressure (P), relative humidity (RH), rainfall (R), wind speed (R) and solar radiation (Rs) in six stations of the country Is. The number of days with data and the average of the studied parameters are given in Table 1.

Results

This review article examines several studies conducted in the field of solar radiation, along with an analysis of their results. Considering the importance of radiation in the applied sciences of solar energy and the numerous problems associated with measuring this parameter, as well as the success of innovative models in predicting complex parameters, the need to utilize intelligent neural models in predicting the radiation parameter becomes increasingly important. Therefore, several user methods have been introduced in this field, including Artificial Neural Networks, Adaptive Neuro-Fuzzy Inference Systems, and the gamma test. This article provides a brief introduction to the field of solar energy, introducing researchers to some standard methods in the field.

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Original Research Paper

Evaluation of the Position of Roller Compacted Concrete as a Green Material Based on Sustainable Development Criteria (Economic, Social and Environmental)

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Abstract

Asphalt pavements are associated with severe environmental problems including energy consumption and greenhouse gas emissions. Roller compacted concrete (RCC) is one of the recently developed materials in pavement construction and can be used as an apt alternative for asphalt to tackle the mentioned problems. However, previous studies did not quantitatively calculate three pillars of sustainable development on RCC simultaneously. This study targets to investigate the sustainable development impacts of RCC and asphalt pavements to show that positive economic, social and environmental effects of RCC pavements are much higher than asphalt pavements. Questionnaire was prepared and green materials factors were identified through experts and then were ranked in order to select the most important factors for green materials in RCC, including 'durable pavement', 'useful life', 'life cycle cost', 'reuse of pavement' and 'fossil fuels reduction' with scores of 0.495, 0.247, 0.06, 0.12 and 0.03, respectively, using Stepwise Weight Assessment Ratio Analysis (SWARA) method. A matrix calculated through Excel was used to analyze sustainable development criteria. Also, Green Road Standard was used for both RCC and asphalt pavements. Finally, economic, social and environmental comparisons of concrete and asphalt pavements show 2 negative effects, 15 positive effects and 4.52 effects average for concrete pavement, and 8 negative effects, 10 positive effects and -0.28 effects average for asphalt pavement. The obtained results of this study prove the superiority of RCC for using in road construction projects in terms of sustainability.

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INTRODUCTION

Roller Compacted Concrete (RCC) is a Portland Cement product and a kind of concrete admixture, usually zero-slump, which has recently been widely used due to its low construction cost and faster performance than asphalt (Taylor, 2012; Calis & Yıldızel, 2019). RCC pavement was first introduced for a runway construction in North America (Kokubu & Anzaki, 1989). After that, pavement projects using RCC have expanded in recent years, such as parking lots, highways, roadway shoulders, etc. (Hossain, Ozyildirim, & Celik, 2016). RCC has identical strength features and basic components to conventional concrete, but with different mixture proportions and lower paste for sustainable pavement construction, which has made it a suitable material for constructing pavements that can sustain burdensome loads and bad weathers with very slight maintenance requirement and a very short construction period (Roller-Compacted Concrete Pavements, 2010; Ali & Abbas, 2022; Topli, Grdi, Risti, & Grdi, 2015; Schrader, 1987; Pavements, 2015; Khayat & Libre, 2014). Moreover, materials and gradation of Roller Compacted Concrete Pavement (RCCP) are similar to conventional concrete and hot mix asphalt pavement, respectively, and a wider variety of materials can be used by RCC as compared to conventional concrete (Keleş & Akpinar, 2022; Scanlon, Tarbox, Hess, & Hulshizer, 1999). Another feature is that due to the dryness and stiffness of RCCP mixture, the construction method of RCCP is different from conventional concrete pavements and similar to asphalt pavements, and since RCC is much stiffer than asphalt concrete (AC), tensile fatigue will not occur in AC (Hunan & Guangdong, 2014; Sok, Kim, Park, & Lee, 2022). From an economic standpoint, the primary costs of RCC pavement are much lower than asphalt pavements and conventional concrete, and since the use of asphalt pavements might lead to some inefficiencies, using RCCP may be reasonable, economically and technically, and even a long life can be achieved for the asphalt pavement on RCC base (Rezaei, Kordani, & Zarei, 2022; Moradi & Shahnoori, 2021; Liu, Wu, Li, & Xu, 2021). This benefit is mainly due to its low cement volume, which has made RCCP an economical and eco-environmentally alternative for pavements (Kalhori & Ramezanianpour, 2021). The credibility of RCCP concrete mixture for constructing the road pavement is dependent on the mechanical features of RCCP, such as compressive strength and splitting tensile strength (Zhang, Hamzehkolaei, Rashnoozadeh, Band, & Mosavi, 2022; Abbasi, Shafigh, & Baharum, 2021). However, the utilization of asphalt in concrete might be detrimental to its mechanical properties (Dareyni, Mohammadzadeh Moghaddam, & Delarami, 2018). The compressive strength and split tensile strength of RCC can be increased in a variety of ways, such as the rise of cement content (Teja & Ramesh, 2021), the need of low water with high workability and compaction (Rakesh, Maddala, Priyanka, & Barhmaiah, 2021), and using metakaolin with or without steel fiber (Abu-Bakr, Mahmood, & Mohammed, 2022). In addition, the compressive strength of RCC including Compaction is very essential in the formation of RCC structure, and RCCP applications have similar compaction to asphalt pavements (Issa & Zollinger, 2022; Selvam, NSSP, Kannan, & Singh, 2023). The implication of sustainable development is based on three dimensions namely ecological, social and economic pillars of sustainability (Klarin, 2018). Some approaches were investigated for improving the sustainability of pavements with concrete materials, and their economic, environmental and societal impacts were also considered qualitatively (Snyde et al, 2016; Siva Rama Krishna & Tadi, 2022). Sustainable development can be obtained for concrete mixtures in a number of ways, such as using recycled alternative materials (Zamora-Castro et al., 2021), the use of stone dust as an alternative to sand (Turuallo et al, 2020), using waste tyre rubber due to the cost efficiency and reduction of CO2 emissions (Ince et al, 2022), and using waste materials with the conservation of mechanical properties (Helmy et al, 2023). There are also some materials which can improve the sustainability of RCC, such as several alternative aggregates including recycled concrete aggregates (RCA), reclaimed asphalt pavement (RAP) aggregates, crumb rubber, electric-arc furnace steel slag aggregates (Selvam et al, 2022), utilization of waste materials, such as RAP (Debbarma et al, 2022), cold reuse of RAP (Boussetta et al, 2020), RAP and red mud (Ram Kumar &

Ramakrish, 2022), using coal waste (Modarres et al, 2018), coal bottom ash (Tighe, Haas, & Ningyuan, 2006), the utilization of ceramic and coal waste powders (Shamsaei et al, 2019), using fly ash as a cementitious material (Hashemi & Shafigh, 2018), a mixture of fly ash, crumb rubber and nano-silica (Adamu, Mohammed, & Liew, 2018), circulation fluidized bed combustion (CFBC) fly ash (CFA) (Lin et al., 2019), using copper slag (CS) waste fine aggregates (Sheikh, Mousavi, & Afshoon, 2022), using steel slag materials (Gallant & Asce, 2019), a mix of coconut shell ash and eggshell powder as a cement substitution (Ogbonna, 2021), using coarse RCA (Lopez-uceda et al, 2016), recycled aggregates and recycled steel fibers (Muscal et al, 2013), a natural pozzolan namely Trass (Ghahari, Mohammadi, & Ramezanianpour, 2017), the utilization of cross-linked polyethylene (XLPE) waste (Shamsaei, Aghayan, & Kazemi, 2017), using recycled tire rubbers and shredded rubber tire aggregates (Fakhri & Farshad, 2016; Meddah, Beddar, & Bali, 2014). Furthermore, sustainable RCCP mixtures would be designed in a range of ways, such as soil compaction, concrete consistency, consistency-compaction, etc (Selvam & Singh, 2022).

Some approaches were investigated for improving pavement sustainability with concrete materials production. Moreover, a literature review was conducted on sustainable pavements for roads with low volume, using sustainable materials like pervious concrete pavements, and generally their economic, environmental, and societal impacts were also considered qualitatively (Snyder et al., 2016; Krishna & Tadi, 2022). Rakesh et al. (2021) investigated that various materials can be used for RCC, including crusher dust, which is obtained from mining and quarrying with fine particles. However, environmental and social impacts of RCC were ignored. According to Hashemi et al. (n.d.) producing large amounts of RCCP for infrastructure development might lead to an increase in CO2 emissions. Fardin and Santos (2020) focused on studying the mechanical and physical characteristics of RCC utilized with RCA as an alternative for natural coarse aggregate. Marzouk et al. (2017) conducted an investigation about the application of methodology based on BIM to evaluate the environmental impacts in road construction projects. Anwer and Zena (2022) reviewed RCC according to four factors, such as environmental impact, cost, inclusion of fiber, and particular RCC utilization for the country. But the evaluation of economic and social impacts of RCC and road construction projects were not investigated and reviewed (Ali & Abbas, 2022; Hashemi et al., n.d.; Fardin & Santos, 2020; Marzouk et al., 2017). Debbarma et al. (2020) provided a set of studies relating to the utilization of RAP aggregates for RCCP. Ameli et al. (2021) investigated the application of waste materials, such as RAP and crumb rubber, into RCCP, which contributes to sustainable development while having economic and environmental advantages. Debbarma and Ransinchung (2021) reviewed that the utilization of RAP in RCCP mixtures may provide economic and environmental advantages, such as depletion in RAP stockpiles and reduction in carbon footprints, respectively. Moradi and Shahnoori (2021) studied the impacts of substituting sands acquired from mines on the properties of RCCP. Teja and Kumar (2021) conducted a literature review regarding the utilization of various sustainable materials into RCC mixes for rigid pavement construction, such as natural aggregates and red mud, which reduce CO2 emissions. However, there were no investigations and reviews about societal impacts of RCC (Moradi & Shahnoori, 2021; Teja & Kumar, 2021; Debbarma et al., 2020; Ameli et al., 2021; Debbarma & Ransinchung, 2021). Aghayan et al. (2021) studied the environmental life cycle of RCCP containing ceramic waste aggregate and coal waste powder. However, their study lacked consideration of the economic impacts of RCCP.

Although the above mentioned studies were accomplished to qualitatively investigate the sustainability of RCC based on the sustainable development dimensions, none of which quantitatively calculated three pillars of sustainable development on RCC simultaneously. The chief target of this research is to investigate the application of RCC in improving economic, social and environmental effects on roads construction. The study aims to identify and rank effective factors of selecting green materials in concrete pavements at the first stage. According to the identified factors, as well as by using the questionnaire and its distribution among the statistical population, and by using the SWARA decision criterion method, the factors of green materials are ranked, and the most important factors are selected. Moreover, ecological, social and economic factors of sustainable development are evaluated and calculated quantitatively to prove RCC as a sustainable pavement in various projects. In the third stage, sustainable development effects of RCC are calculated and compared with asphalt in which economic, users and maintenance costs of both RCC and asphalt are investigated in a certain period. Altogether, this paper targets to evaluate the position of RCC as a green material to achieve sustainable development.

Research Methodology

This part provides information concerning the specific method utilized to recognize, elicit, prepare, and analyze data about the interest phenomenon, making readers able to evaluate the reported results sufficiently. Due to the multiplicity of contents in this research, an explanation of the various tools and methods employed is given in the subsequent parts to improve transparency.

The process and stages of this study are described according to its objectives, and in Fig. 1.

1. Identification of effective factors in selecting green materials in concrete pavements: Effective factors in selecting green materials in concrete pavements are identified using the literature review of Green Road Standard and the distribution of checklists (Table 5).

2. Ranking the effective factors in selecting green materials in concrete pavements: Green materials factors are ranked according to the identified factors, as well as by using the questionnaire and its distribution among the statistical population and the SWARA decision criterion method, the most important factors for green materials in RCC are selected.

3. Evaluation of roller compacted concrete from the standpoint of sustainable development factors (economic, social and environmental impacts): Using the calculated matrix through Excel, economic, social and environmental impacts of concrete and asphalt pavement designs are evaluated.

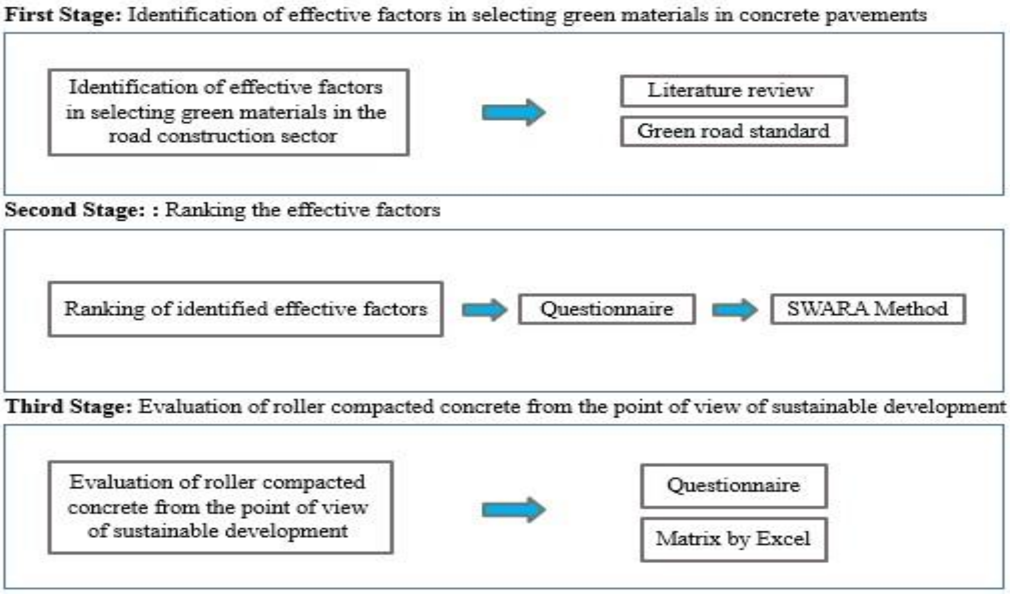

Fig 1. Steps of research

Questionnaire

In this study, a questionnaire was designed to identify effective factors in selecting green materials in concrete pavements. In this questionnaire, the respondents were asked to weigh the identifications of effective factors in selecting green materials in the identified concrete pavements according to the evaluation criteria. For this purpose, a 5-point Likert scale was utilized. In this scale, 1 and 5 were the least and the most important, respectively. The information obtained from this questionnaire was used for analysis in the SWARA method.

Identification of factors contributing to sustainability criteria

Selection criteria for the experts

In the research compiled based on the questionnaire, the selection and determination of the statistical sample is an important factor. The statistical population of this research consisted of experts working in the road construction department, totaling 120 people. Sampling from the statistical population is used when the number of individuals and geographical coverage are large (Al-Tmeemy et al., 2011). The sample size was calculated based on the following formula (Al-Tmeemy et al., 2012). The minimum number of experts required to complete the questionnaires was specified according to Equation (1), where SS, z, p, and c represent sample size, confidence level coefficient, confidence interval, and selection percentage, respectively.

$$SS = \frac{z^2 p(1-p)}{c^2} \quad (1)$$

Equations (2) and (3) were utilized to create a corrected sample size (SS), and *rr* defines the response rate:

$$Corrected\ SS = \frac{SS}{1+\left(\frac{SS-1}{pop}\right)} \quad (2)$$

In Equation (2), *pop* is the population and the corrected sample size (SS) for the response rate was measured using Equation (3), while *rr* is the response rate:

$$Corrected\ SS\ for\ rr = rr * corrected\ SS \quad (3)$$

Reliability

In this study, Cronbach's alpha test was utilized to determine the questionnaire reliability. Reliability signifies that to what extent the measurement tool gives the same results in the same conditions. In order to determine the reliability and measurement tool, there are also many different methods that one of which is estimating its internal consistency. The internal consistency of measurement tool can be measured by Cronbach's alpha coefficient. The most commonly used reliability coefficient is the Cronbach's alpha value, which ranges from 0 to 1, and higher values indicate higher reliability. Table 1 shows the domain of Cronbach's alpha coefficients and its reliability level.

Table 1. Reliability domain and Cronbach's alpha coefficients

Reliability Level	Cronbach's Alpha Coefficient
Very much	1
Much	0.8-0.99
Medium	0.6-0.79
Low	Less than 0.59

SWARA method

In numerous multi-factor decision-making problems, weighing the factors is one of the most significant steps in solving the problem (Hafezalkotob et al., 2018). Based on this, experts play an important role in evaluating the factors and their weights, and they are responsible for an unavoidable part of the decision-making process. The SWARA method is one of the most recent approaches introduced by Keršuliene et al. (2010), enabling the decision maker to select, assess, and weigh the factors. The most significant advantage of this method compared with other similar approaches is its ability to assess the precision of experts' perceptions about the weighted factors during the process. Furthermore, experts are able to consult with one another, and such consultation makes the obtained results more precise than those achieved by other decision-making criteria (Zolfani et al., 2013). This method is understandable and requires fewer pairwise comparisons than ANP and AHP methods (Hafezalkotob et al., 2018). Therefore, in the current research, using this method to calculate the weight of criteria, the steps of weighing by the SWARA method are illustrated in Fig. 2. In this method, each expert ranks the criteria first. The most significant criterion is ranked first, and the least significant is assigned the last rank. Finally, the criteria are prioritized based on the average values of respective significance. In this method, the expert plays an essential role in evaluating the calculated weights, and each expert determines the significance of each criterion based on their implicit knowledge, information, and experience. Then, according to the average value of group ranks acquired from experts, the weight of each criterion is specified.

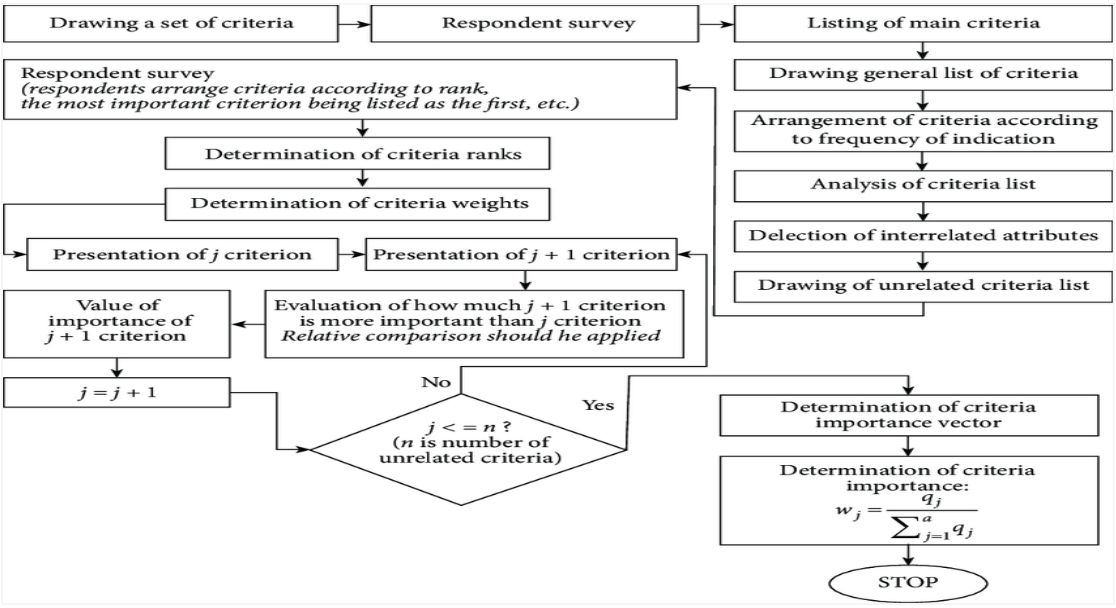

Fig2. The stages of weighing factors in the SWARA method

The calculated matrix is used to identify, investigate, predict and evaluate the effects and consequences of the activities of a plan or a project on the components and parameters of the environmental factor and policymaking and final decision-making about options. At this stage of the matrix process, the proposed different options are examined and compared, and finally, the option that has the least negative effects or its negative effects can be prevented and controlled more, and in terms of comparison, receives a higher positive score, will be selected as the best option. In the mentioned matrix calculated through Excel, rows and columns represent environmental factors and project activities, respectively. Environmental factors are classified according to physical, chemical, biological, social, economic and cultural environments, and in each environment, the impressionable micro-factors of the implementation of the project are determined according to the existing study records of the plan and field visits. Negative effects that are in the range of (-5) to (-3.1) are considered as destructive and significant effects, and should be reduced as much as possible by providing a corrective option. The point that is necessary to mention in this section is that in the implementation of projects and development plans, in addition to trying to reduce negative environmental effects and outcomes, efforts should also be made to increase and strengthen the positive effects and outcomes of the project. Then, the mutual effects of project activities and environmental factors on each other are determined and loaded as numbers in the +5 to -5 ranges. The number +5 illustrates a positive effect (high usefulness or favorability), and the number -5 illustrates negative effects (high demolition or undesirability).

Research findings

Statistical society analysis

In a research that is designed based on a questionnaire, it is necessary to determine the number of respondents from the existing statistical population in order to value the answers and results. In this study, the acceptable number of respondents was determined using Equations (1), (2) and (3). The size of the statistical population in this study was 120 people working in road construction projects, who were in the contracting and employer sectors and consultants. According to Equations (1), (2) and (3) and the statistical population, 54 valid questionnaires are sufficient to refer to the answers of the questionnaire, and in this research, 96 valid questionnaires were collected. The analysis results of the statistical population valid numbers are illustrated in Table 2.

Table 2. The number of valid responses

Safety distance (C)	0.1	0.975
Percentage of selecting an option (P)	0.5	
Safety factor (Z)	95%	1.96
Response rate (rr)	92%	
Population	250	
The number of valid responses		54

In this section, the demographic statistics and the characteristics of respondents are discussed. In a research where the results of the questionnaire are effective in determining the final result, it is necessary to select people who have sufficient experience in the field of research, therefore, the information of the respondents' career history is stated, and only the information related to valid questionnaires was analyzed. Table 3 shows the frequency and percentage of respondents based on their professional career history. The respondents were divided into four groups based on their work experience. According to the obtained statistics, about 67 people, which is equivalent to 69.8 percent of the respondents, had work experience of 10 years or more in the road construction projects field. The majority of respondents were operating engineers, contractors and designing engineers. Based on Table 3 information, 25%, 20.8% and 14.5% were operating engineers, contractors, and designing engineers, respectively.

Table 3. Frequency and percentage of the number of respondents based on job experience and responsibility

The amount of work experience	Frequency	Frequency percentage	Responsibility in the project	Frequency	Frequency percentage
1-5 years	15	15.7%	Operating engineers	24	25%
6-10 years	14	14.5%	Contractors	20	20.8%
10-15 years	48	50%	Project managers	8	8.3%
More than 15 years	19	19.8%	Consulting engineers	11	11.4%
Total	96	100	Designing engineers	14	14.5%
			Employers	10	10.4%
			Supervisor engineers	9	9.3%
			Total	96	100%

Pilot study

Pilot study is prepared before distributing the main questionnaire to evaluate the reliability of the questions. These questionnaires were distributed among a small group of experts in road construction projects, whose number was 10 people. After collecting the questionnaires and using experts' opinions, the questionnaire was modified for final distribution. Cronbach's alpha test was utilized to analyze the questionnaires reliability. The cumulative test result for the questionnaire is shown in Table 4. Cronbach's alpha coefficients for the questionnaire reliability should be higher than 0.70. After collecting the questionnaires, the necessary corrections were made in the questions. Finally, the coefficients obtained from Cronbach's alpha show that the designed questionnaire is valuable, and has acceptable sustainability for distribution. According to the number of identified statistical society, which was 96 people, in this research, 96 questionnaires were distributed among them. 75 and 21 questionnaires were distributed manually and online, respectively, and 90 questionnaires were returned. The return rate of the questionnaire was 93.75%, which is an acceptable rate. Among the completed questionnaires, 4 questionnaires were incomplete and invalid.

Table 4. Cronbach's alpha coefficients for the questionnaire

Title	Cronbach's alpha coefficient
Questionnaire for weighing sustainability factors	0.812

Identification of effective factors in selecting green materials in concrete pavements

The first step in this research is the effective factors in selecting green materials in concrete pavements. In order to obtain an encyclopedic list of factors in these projects, comprehensive studies were conducted using the literature review. At this stage, 27 factors were finally identified by using the prepared checklists (Table 5). Eventually, according to the causing factors, the factors were divided into 3 economic and technical, environmental and social groups.

At this stage, by using the Green Road Standard, the effective factors in selecting green materials are identified, and based on this standard, these criteria are scored based on the scores of this standard.

Table 5. The weight of sustainability factors in the economic and technical, environmental and social groups

Row	Group	Factors	Code
1	Economic and Technical	Durable pavement	A1
2		Safety	A2
3		Early performance and exploitation	A3
4		Materials on site	A4
5		Useful life	A5
6		Life cycle cost	A6
7	Environmental	Reuse of pavement	A7
8		Light pollution reduction	A8
9		Habitat and nesting	A9
10		Vegetation	A10
11		Surface water quantity	A11
12		The Earth shape and topography	A12
13		Residual status	A13
14		Landscape situation	A14
15		Fossil fuel reduction	A15
16		Recyclable materials	A16
17		Soil erosion	A17
18		Groundwater quality	A18
19		Air quality	A19
20		Sound status	A20
21		Energy resources consumption	A21
22	Social	Transportation and traffic	A22
23		Social welfare facilities and services	A23
24		Effect on economic activities	A24
25		Employment	A25
26		Increasing income and improving the living standard	A26
27		Development plan in the region	A27

Weighing the effective factors in selecting green materials

One of the purposes of this research was to rank the effective factors. The target of this work is to identify important factors so that the beneficiaries of this type of projects can plan to identify the effects of these factors. For this purpose, a questionnaire was first prepared and distributed among road projects experts. Respondents were asked to rank the causes of identified sustainability. The valuation scale was based on a 5-point analogy that 5 and 1 represent the greatest and the least effects, respectively. At this stage, after collecting the questionnaires, the answers average was calculated. The answers average was sorted from ascending to descending, and then, the factors were ranked based on the SWARA method stages. In Table 5, the weighing of sustainability factors is discussed. The weight of factors is classified into three economic/technical, environmental and social groups, and the most important factors of each group are determined. Table 5 shows the ranking of factors and the weight of sustainable development factors in concrete pavements. Among the factors, the 5 most important identified factors were durable pavement, useful life, life cycle cost, reuse of pavement and fossil fuel reduction.

Table 6. Ranking the sustainability factors in concrete pavements

Factors	Average	s_j	$K_j=s_j+1$	$W_j=k_j-1/k_j$	$C_i=w_j/w$	Rank
A1	7.33	-	1	1	0.495	1
A5	7.30	1	2	0.5	0.247	2

Factors	Average	s_j	$K_j=s_j+1$	$W_j=k_j-1/k_j$	$C_i=w_j/w$	Rank
A7	7.26	0.990	1.99	0.25	0.12	3
A6	7.15	0.980	1.98	0.13	0.06	4
A15	6.96	0.950	1.95	0.07	0.03	5
A3	6.93	0.947	1.947	0.03	0.02	6
A21	6.87	0.940	1.940	0.02	0.01	7
A4	6.83	0.930	1.930	0.009	0.004	8
A14	6.80	0.929	1.929	0.005	0.002	9
A2	6.74	0.920	1.920	0.002	0.001	10
A11	6.70	0.910	1.910	0.001	0.0006	11
A8	6.53	0.905	1.905	0.0007	0.0003	12
A22	6.59	0.900	1.900	0.0003	0.0002	13
A19	6.57	0.896	1.896	0.0002	0.0001	14
A18	6.48	0.880	1.880	0.0001	0.00005	15
A16	6.41	0.875	1.875	0.00005	0.00003	16
A9	6.35	0.870	1.870	0.00003	0.00001	17
A25	6.33	0.864	1.864	0.00001	0.000007	18
A24	6.30	0.861	1.861	0.000008	0.000004	19
A20	6.28	0.860	1.860	0.000004	0.000002	20
A13	6.26	0.855	1.855	0.0000023	0.0000012	21
A26	6.24	0.850	1.850	0.0000013	0.000006	22
A27	6.21	0.847	1.847	0.000007	0.0000034	23
A17	6.19	0.844	1.844	0.000004	0.0000020	24
A23	6.16	0.840	1.840	0.000002	0.0000010	25
A10	6.13	0.836	1.836	0.000001	0.0000005	26
A12	6.12	0.832	1.832	0.0000006	0.0000003	27

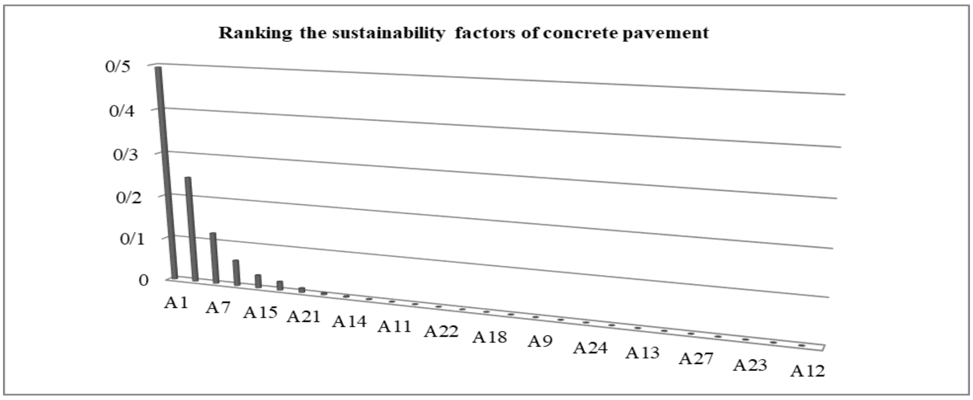

Fig 3. Ranking the sustainability factors of concrete pavement

Table 6 and Fig. 3 show the weight of sustainability factors in three economic/technical, environmental and social groups. According to the obtained results, durable pavement, reuse of pavement, and transportation and traffic factors with scores of 0.495, 0.12 and 0.0000006, respectively, were the most stable factors in these groups.

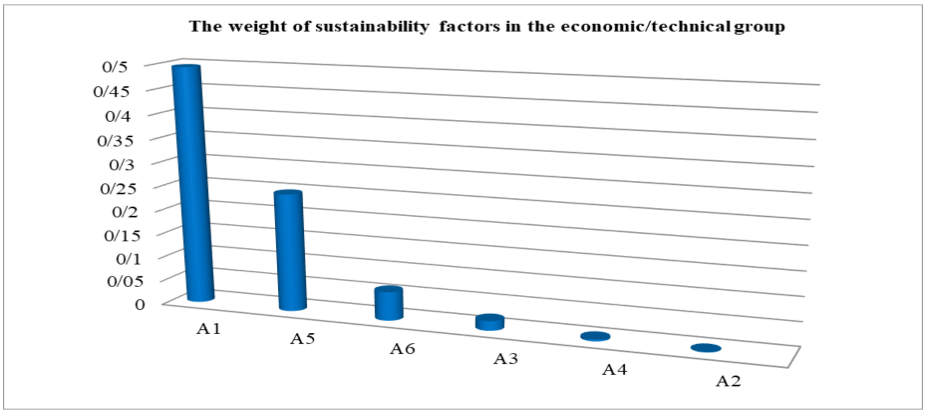

Fig 4 . The weight of sustainability factors in the economic/technical group

Fig. 4 shows the weight of sustainability factors in the economic and technical group. According to the obtained results, durable pavement, useful life and life cycle cost factors had the scores of 0.495, 0.247 and 0.06, respectively in this group.

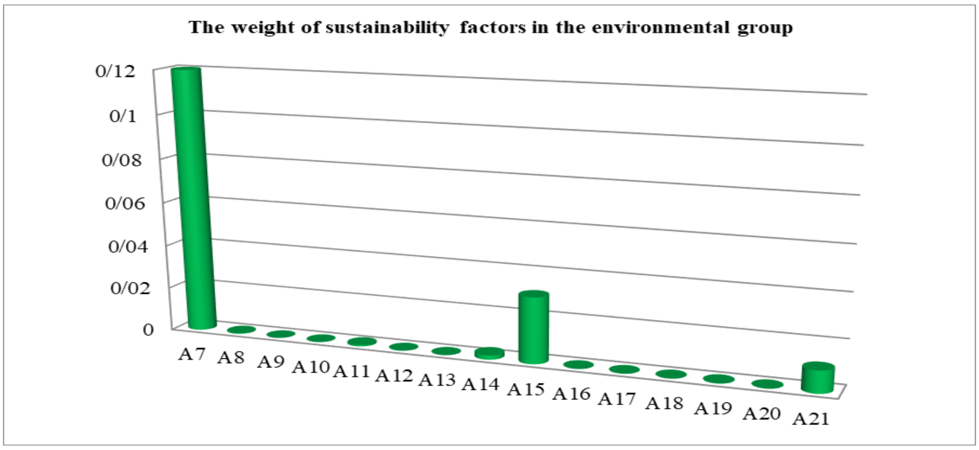

Fig 5. The weight of sustainability factors in the environmental group

Fig. 5 shows the weight of sustainability factors in the environmental group. According to the obtained results, reuse of pavement, fossil fuel reduction and energy resources consumption factors had the scores of 0.12, 0.03 and 0.01, respectively in this group.

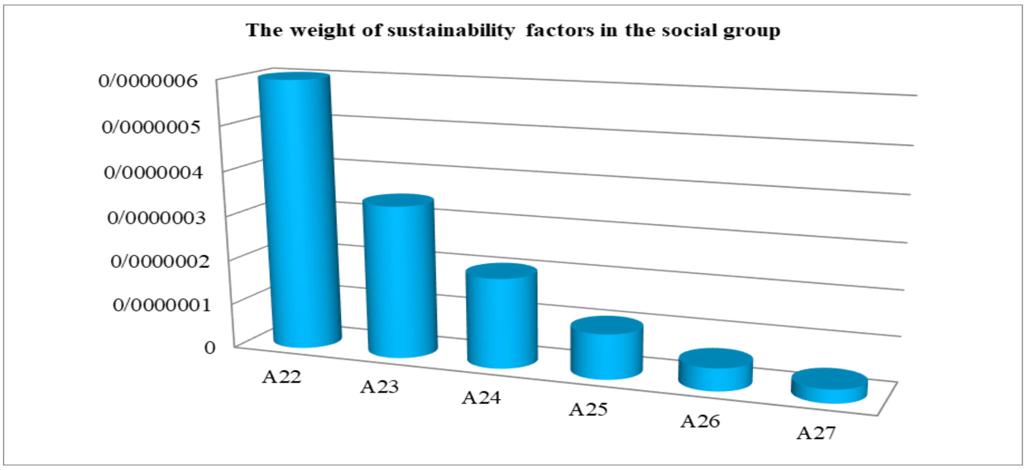

Fig 6. The weight of sustainability factors in the social group

Fig. 6 shows the weight of sustainability factors in the social group. According to the obtained results, transportation and traffic, social welfare facilities and services and effect on economic activities factors had the scores of 0.0000006, 0.00000034 and 0.0000002, respectively in this group.

3.5. Roller compacted concrete and asphalt pavements analysis using the calculated matrix by Excel

In this section, in order to draw conclusions from the studies on the evaluation of the effects of RCC and asphalt pavements, and to find out the activities positive and negative effects of these pavements during operation, based on the existing criteria, they were converted into quantitative effects, and were analyzed using the calculated matrix.

In the first stage, 27 identified criteria are categorized into economic/technical, physical/chemical, biological and social/cultural groups.

In the second stage, each of the criteria categorized based on their effects, is qualitatively evaluated with the intensity of high, medium and low effects in the form of positive or negative effects in Table 7.

In the third stage, this qualitative evaluation is converted into a numerical evaluation, which is shown in Table 7.

Table 7. Concrete pavement descriptive and numerical rating

	Environment	Sub-criterion	Operation time	Total number of results	Algebraic sum of results	Results average	Positive result numbers	Negative result numbers
1	Physicochemical	Soil quality						
2	Physicochemical	Soil stability						
3	Physicochemical	Soil erosion	2-	1	2-	2-	0	1
4	Physicochemical	Land shape and topography	2-	1	2-	2-	0	1
5	Physicochemical	Region drainage pattern						
6	Physicochemical	Natural hazards such as flood, slip and drift						
7	Physicochemical	Air quality	2-	1	2-	2-	0	1
8	Physicochemical	Groundwater quality	3	1	3	3	1	0
9	Physicochemical	Surface water quality						
10	Physicochemical	Surface water quantity	3	1	3	3	1	0
11	Physicochemical	Groundwater quantity						
12	Physicochemical	Hydrography						
13	Physicochemical	Sound status	3-	1	3-	3-	0	1
14	Physicochemical	Residual status	2-	1	2-	2-	0	1
15	Physicochemical	Fossil fuel reduction	3	1	3	3	1	0
16	Physicochemical	Landscape situation	3	1	3	3	1	0
17	Physicochemical	Light pollution reduction	3	1	3	3	1	0
18	Biological	Vegetation	2-	1	2-	2-	0	1
19	Biological	Areas under management						
20	Biological	Habitat and nesting	2-	1	2-	2-	0	1
21	Biological	Endangered plant species						
22	Biological	Endangered animal species						
23	Social/Cultural	Migration to the region						
24	Social/Cultural	Preventing migration out of the region						
25	Social/Cultural	Environmental and residents' health						
26	Social/Cultural	Development plans in the region	3	1	3	3	1	0
27	Social/Cultural	Native culture and customs						
28	Social/Cultural	Conflicts caused by water harvesting						
29	Social/Cultural	Social welfare facilities and services	3	1	3	3	1	0
30	Social/Cultural	Early performance and exploitation	4	1	4	4	1	0

	Environment	Sub-criterion	Operation time	Total number of results	Algebraic sum of results	Results average	Positive result numbers	Negative result numbers
31	Social/Cultural	Transportation and traffic	3	1	3	3	1	0
32	Economic/Technical	Useful life	4	1	4	4	1	0
33	Economic/Technical	Materials on site	3	1	3	3	1	0
34	Economic/Technical	Recyclable materials	3	1	3	3	1	0
35	Economic/Technical	Reuse of pavement	4	1	4	4	1	0
36	Economic/Technical	Energy resources consumption	3	1	3	3	1	0
37	Economic/Technical	Safety	4	1	4	4	1	0
38	Economic/Technical	Employment	3	1	3	3	1	0
39	Economic/Technical	Durable pavement	3	1	3	3	1	0
40	Economic/Technical	Increasing income and improving the living standard	3	1	3	3	1	0
41	Economic/Technical	Effect on economic activities	3	1	3	3	1	0
42	Economic/Technical	Life cycle	3	1	3	3	1	0
	Impacts	Total number	27					
	Impacts	Algebraic sum	49					
	Impacts	Average	1.8					
	Impacts	Positive effect numbers	20					
	Impacts	Negative effect numbers	7					

Operation time: it can be divided into low, medium and high impacts

Low negative impact: Soil erosion, Land shape and topography, Air quality, Residual status, Vegetation, Habitat and nesting

Medium negative impact: Sound status

Medium positive impact: Groundwater quality, Surface water quantity, Fossil fuel reduction, Landscape situation, Light pollution reduction, Development plans in the region, Social welfare facilities and services, Transportation and traffic, Materials on site, Recyclable materials, Energy resources consumption, Employment, Durable pavement, Increasing income and improving the living standard, Effect on economic activities, Life cycle

High positive impact: Early performance and exploitation, Useful life, Reuse of pavement, Safety

According to Table 7, the micro-criteria for the descriptive rating of concrete pavement are placed in the table, and the positive and negative evaluations with high, medium and low intensities are given to each of the criteria separately, and regarding the numerical ranking of the concrete pavement according to the calculated matrix, concrete pavement has been evaluated with 20 positive effects and 7 negative effects from the set of 27 effects and a positive average of 1.8, which indicates less destructive effects than the asphalt pavement.

3.6. Economic evaluation of roller compacted concrete and asphalt pavements

One of the effective factors in evaluating engineering projects is the economic parameters. Therefore, in this research, the costs of asphalt and RCC pavements are compared with each other based on the costs of construction and performance, repairs and maintenance, and users (depreciation of vehicle and tires, time spent for travel, cost spent in case of an accident due to the incomplete operation of pavement, fuel consumption cost, etc.).

The cost of road users includes the following items, which is then calculated in Table 8 and Fig. 7:

a) Vehicle operating cost: Physical characteristics and pavement conditions are effective in the speed and the amount of fuel and oil consumption and tire depreciation (vehicle operating cost). Due to the rigidity of concrete pavements, vehicle operating cost (the amount of fuel and oil consumption and tire depreciation) on these pavements is lower than on asphalt pavement.

b) Personal cost: This cost basically includes the costs of delaying users due to slowing down, stopping and blocking the road. The cost of users is mainly considered to be about one third of the construction cost in exploiting the route.

According to Table 8 and Fig. 7, RCC is 16% more economic than asphalt pavement

Table 8. Users cost on concrete and asphalt pavements

Row	Pavement	Performance cost	Increase percentage	Users cost
1	Concrete	1,719,055 IRR	30%	515,864 IRR
2	Asphalt	2,063,776 IRR	30%	619,132 IRR

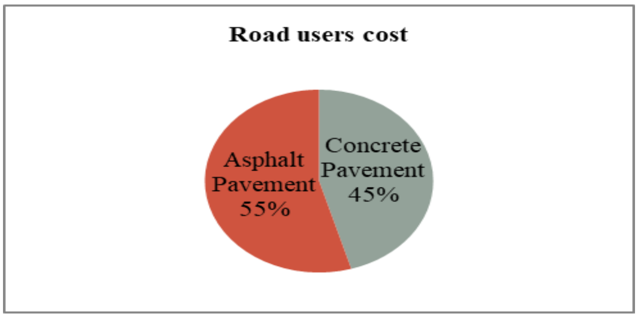

Fig 7. Users cost on concrete and asphalt pavements

Estimating the maintenance cost

In relation to the maintenance cost of roller compacted concrete pavements, no detailed study has been done so far, but it can be said that considering the concrete exposed to the weather and the passing traffic, it gradually leads to cracking during many years, and requires maintenance, as the asphalt changes drastically under the effect of temperature and traffic, and despite various damages with different intensity, it does not have the ability to have a high service life, and therefore the concrete can have a higher life according to its properties. While concrete needs maintenance after 5 years or more, asphalt usually needs maintenance after 2 to 3 years. In Table 9, the cost of the maintenance period, which is the maintenance and repair cost for the 20-year period with an annual increase rate of 15% is calculated with the cost of 5% of the performance cost for the asphalt pavement, and 2.5% of the performance cost for the concrete pavement in the first year. As it is shown in Fig. 8, the cost of asphalt pavement maintenance will be much higher than that of RCC pavement.

Table 9. The cost of asphalt and concrete pavements maintenance period

Asphalt		Concrete	
Year	Cost	Year	Cost
1	103,188 IRR	1	42,988 IRR
2	118,666 IRR	2	49,436 IRR
3	136,465 IRR	3	56,851 IRR
4	156,934 IRR	4	65,378 IRR
5	180,474 IRR	5	75,184 IRR
6	207,545 IRR	6	86,461 IRR
7	238,676 IRR	7	99,430 IRR
8	274,477 IRR	8	114,344 IRR
9	315,648 IRR	9	131,495 IRR
10	362,995 IRR	10	151,219 IRR
11	417,444 IRR	11	173,901 IRR
12	480,060 IRR	12	199,986 IRR
13	552,069 IRR	13	229,984 IRR
14	634,879 IRR	14	264,481 IRR
15	730,110 IRR	15	333,476 IRR
16	839,626 IRR	16	383,947 IRR

17	965,659 IRR	17	441,471 IRR
18	1,110,494 IRR	18	507,691 IRR
19	1,277,068 IRR	19	583,884 IRR
20	1,468,628 IRR	20	671,420 IRR
	10,571,105 IRR		4,662,981 IRR

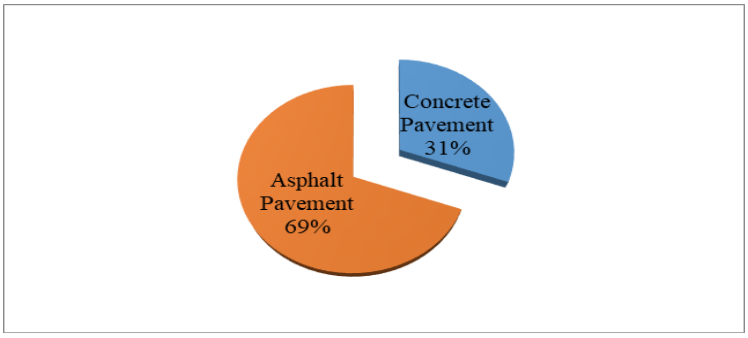

Fig 8. The cost of concrete and asphalt pavements maintenance period

Estimating the total cost

In the end, estimating the final cost of concrete and asphalt pavements, which includes the overall cost of performance, maintenance, and users is illustrated in Table 10.

Table 10. The total cost of concrete and asphalt pavements

Title	Performance cost	Users cost	Maintenance cost	Total cost
Concrete pavement	1,719,055 IRR	515,864 IRR	4,662,981 IRR	6,897,900 IRR
Asphalt pavement	2,063,776 IRR	619,132 IRR	10,571,105 IRR	13,254,013 IRR

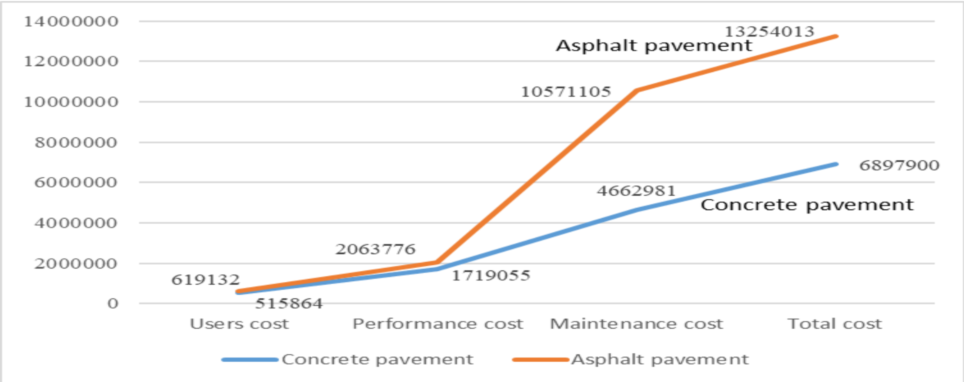

Fig 9. Economic comparison of concrete and asphalt pavements

According to Table 10 and Fig. 9, the cost of concrete construction and performance compared to asphalt, the cost of concrete users compared to asphalt, and the cost of concrete maintenance compared to asphalt reduced by 16%,16% and 55%, respectively. Therefore, according to the costs estimation in the performance, users and maintenance sections, RCC pavement can be considered as a more economical pavement than asphalt pavement.

Table 11. Biological, social and economic/technical comparisons of concrete and asphalt pavements

Title	Environmental conditions				
Pavement type	Different effects	Biological	Social	Economic/Technical	Total
Concrete pavement	Negative effect	2	0	0	2
	Positive effect	0	4	11	15
	Effects average	-2	3.25	3.27	4.52
Asphalt pavement	Negative effect	3	0	5	8
	Positive effect	0	4	6	10
	Effects average	-2.33	2.5	-0.45	-0.28

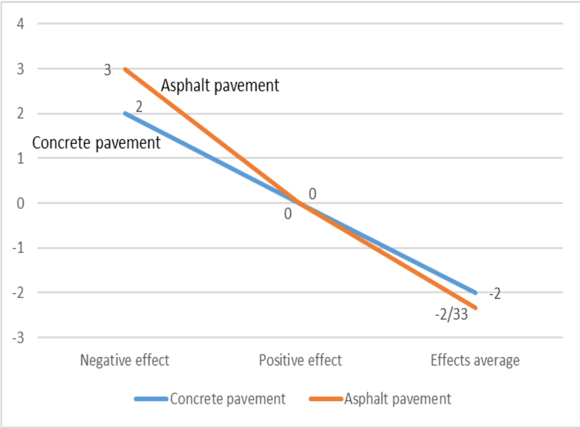

Fig 10. Biological comparison of concrete and asphalt pavements

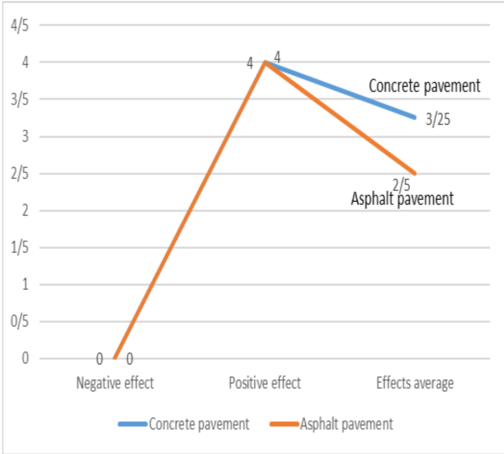

Fig 11. Social comparison of concrete and asphalt pavements

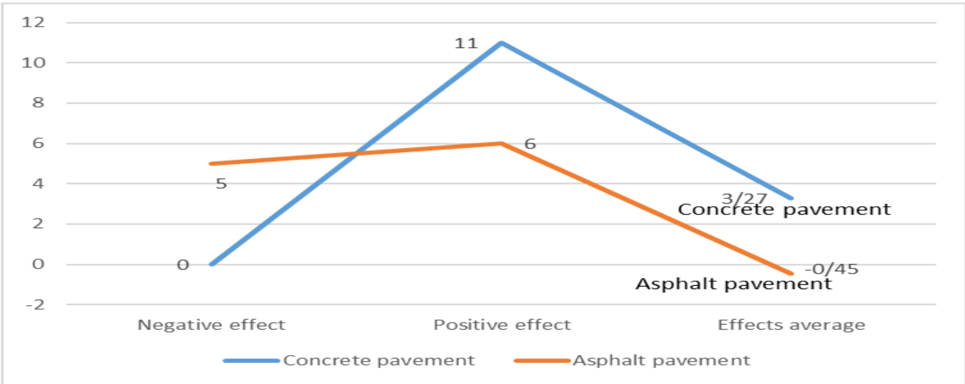

Fig 12. Economic/technical comparison of concrete and asphalt pavements

Based on Table 11, Fig. 10, Fig. 11, and Fig. 12 information, concrete and asphalt pavements are compared with each other in different environmental conditions, including biological, social and economic/technical conditions, and also negative and positive effects and effects average are calculated, which show 2 negative effects, 15 positive effects and 4.52 effects average for concrete pavement, and 8 negative effects, 10 positive effects and -0.28 effects average for asphalt pavement in biological, social and economic/technical conditions.

The hydraulic conditions of WDNs are generally evaluated by using demand-driven modeling (DDM) models as a demand function in normal operational conditions and additional pressure-driven modeling (PDM) implementations that have better responded to WDNs (WDN) analysis in operating conditions. Water distribution calculations were investigated by an under-pressure model, as it provided a better description of the system's conditions than the classical model formulas in the event of a pipe failure.

Table 12. Suitability classes of factors for dam site

Factors	Categories	Ranking	Suitability
Slope	≤ 3.1	4	High Suitable
	3.1- 7.9	3	Suitable
	7.9 – 12.9	2	Low suitable
	12.9- 19.7	1	Not Suitable
Distance from Roads	≤ 1 000 m	4	High Suitable
	1 000 m – 2 000 m	3	Suitable
	2 000 m – 3 000 m	2	Low

Factors	Categories	Ranking	Suitability
			suitable
	> 3 000 m	1	Not Suitable
Distance from Settlements and markets	< 10 km	4	High Suitable
	5-10 km	3	Suitable
	1-5 km	2	Low suitable
	> 1km	1	Not Suitable
Soil Type	Masooka rock land	4	High Suitable
	Rough mountainous land	3	Suitable
	Pirsbak	2	Low suitable
	Kamala complex	1	Not Suitable
Distance from Agricultural fields	> 500 m	4	High Suitable
	400 m – 500 m	3	Suitable
	200 m – 400 m	2	Low suitable
	> 200 m	1	Not Suitable

Results

This study had four main goals. The first goal was to identify the effective factors in selecting green materials in concrete pavements. In this step, the factors were identified utilizing the literature review, which included books, articles and Green Road Standard. In the second step, the results obtained about the factors were confirmed and proved. Finally, after collecting the results, 27 factors were identified. The factors were classified into 3 groups based on the factors of their existence, which included ‘economic and technical’, ‘social’ and ‘environmental’ groups.

The second goal of this research was to rank the effective factors in selecting green materials in concrete pavements identified in road construction projects. For this purpose, a questionnaire was first prepared and distributed among the experts of road construction projects. At this stage, after collecting the questionnaires, the answers average was calculated, and then the most important factors for selecting green materials in concrete pavements, including ‘durable pavement’, ‘useful life’, ‘life cycle cost’, ‘reuse of pavement’ and ‘fossil fuels reduction’ with scores of 0.495, 0.247, 0.06, 0.12 and 0.03, respectively were ranked based on SWARA method stages.

The third target of this study was to assess RCC from the standpoint of sustainable development factors (economic, social and environmental). At this stage, calculated matrix was used, positive and negative effects, and effects average of both concrete and asphalt pavements were analyzed, and the results have been obtained numerically in the asphalt pavement with 8 negative effects, 10 positive effects and -0.28 effects average compared to 2 negative effects, 15 positive effects and 4.52 effects average in the concrete pavement.

The final target of this research was to analyze the comparison of sustainable development effects, and using RCC than asphalt that in addition to the environmental and social effects resulting from the matrix evaluation of two pavements, economic analysis (construction, users and maintenance costs) was calculated, and presented in the form of tables and graphs, and finally, the percentages of construction and performance cost, users cost, and maintenance cost of concrete pavement compared to asphalt pavement show 16%, 16% and 55% reductions, respectively. In general, the positive economic, social and environmental effects of RCC pavements are far more than asphalt pavements, and can be used as an apt substitute in several different road construction projects.

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Original Research Paper

Developing a Method for Managing Construction Defect Risk in the Residential Sector Case Study: Shiraz Mass Housing Complexes

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Abstract

This study examines structural defects in mass housing complexes in Shiraz and identifies the factors influencing their occurrence. Given the importance of construction quality and its impact on the lifespan of buildings, this research aims to propose effective solutions for reducing defects. The goal of this study is to identify and analyze the factors contributing to structural defects in mass housing complexes in Shiraz. The research follows a qualitative approach, and data has been collected through questionnaires, interviews, observations, and archival research. The study population includes project managers, engineers, and construction industry experts, with sampling conducted using a purposive method. The collected data has been processed and analyzed using MaxQDA software and statistical tools. The research findings indicate that low-quality materials, inadequate supervision, and time pressure to complete projects are key factors leading to structural defects. Additionally, insufficient employee training and adverse weather conditions play a significant role. These findings can contribute to improving construction quality and reducing defects in future projects. By implementing training programs for workers, utilizing high-quality materials, and ensuring continuous supervision of construction processes, maintenance and repair costs can be minimized.

Keywords: *Risk Management, Structural Defects, Residential Sector, Mass Housing Complexes, Shiraz.*

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INTRODUCTION

Building construction plays a crucial role in urban development, demanding careful attention to quality and safety. Despite these efforts, defects and potential failures in the construction process can still arise, impacting the building's overall quality and reliability (Okoye, 2022). There is ample evidence showing that new residential buildings often exhibit defects, which require serious consideration due to their significant consequences for all parties involved in construction projects, as well as for end users. These defects also contribute to the generally low perception of quality within the housing sector in many countries. Researchers have offered various definitions of building defects. Generally, a defect is described as a shortfall in a building's ability to fulfill its intended functions or comply with regulatory standards and occupancy requirements. It can also be defined as a failure to meet the specifications outlined in contract documents, site reports, and other project records, in addition to established building codes and regulations. While it is nearly impossible to eliminate defects entirely in construction, minimizing their recurrence is critical for stakeholders, as it helps avoid unnecessary costs. In the construction industry, defects are classified by different criteria, such as severity, construction stage, type, and cause. Latent defects are those not immediately visible and require thorough inspection to detect, whereas visible defects are apparent upon standard inspection (Shah et al., 2024).

Construction defects are a frequent occurrence in construction projects, particularly in those with poor site performance and inadequate project management. These defects often result from insufficient planning. Within the construction industry, defects are recognized as a significant issue that can diminish the value of a project (Kutsch & Hall, 2010). The industry has long faced criticism for substandard construction and performance, often caused by a combination of rushed work, flawed design, and inadequate maintenance. Employers and end users frequently express dissatisfaction, stating that their housing fails to meet their needs and expectations. Providing high-quality housing is crucial as it fosters social, educational, and economic opportunities, helping to create more equitable communities. However, construction defects remain a persistent challenge, especially in residential projects. Previous research highlights defects as a major contributor to poor quality outcomes, increased costs, and extended schedules. Defects requiring rework are a common concern when evaluating project success because they negatively affect stakeholder satisfaction. Studies indicate that many construction defects are often unavoidable, stemming from both hidden and direct causes. These defects significantly impact the project success criteria cost, time, and quality as well as stakeholder satisfaction. Therefore, timely and effective management of defect resolution is essential. Construction defects usually involve multiple shortcomings in areas such as design, planning, supervision, and execution. Buildings that develop defects during construction typically fail to meet consumer demands. Technically defective work can be viewed as non-compliance with the contractual agreements. The quality of construction execution plays a vital role in the likelihood of defects and failures. Mistakes in the supply or use of materials like concrete, steel, or other structural components can cause structural issues. Additionally, insufficient knowledge of proper construction methods can contribute to defects. Material selection must align with project specifications, as using substandard materials compromises construction quality and leads to defects. Defect management encompasses the planning, coordination, and monitoring of construction activities to minimize inefficiencies, costs, and delays caused by these issues (Kutsch & Hall, 2010).

From the initial design phase through to project completion, construction quality depends on the collaborative efforts of multiple participants working together. The construction industry often faces criticism for the poor quality of its projects, both in terms of the final outcomes and the processes used during design and construction. Common issues include defects such as roof leaks, wall deformation and cracking, insufficient floor thickness, bulging flooring, and the cracking or detachment of interior and exterior facade coatings. Additionally, accidents on construction sites frequently result from unlicensed professionals working without proper authorization. Key functional requirements of any building include strength, stability, climate control, indoor comfort, efficient use, and durability. To meet these requirements, buildings are planned, developed, constructed, and managed according to standards and specifications established by regulatory authorities, professional organizations, and experts who understand user needs and expectations. Construction defects are a serious concern for all project stakeholders because they can arise at any stage of the project lifecycle, leading to costly rework that impacts both budget and schedule. Beyond financial losses, these defects can undermine stakeholder trust. As noted, the expenses associated with repairing construction defects can represent a significant portion of the overall building cost (Aljassmi, Perera, & Han, 2013). Defects arise from various causes, including faulty planning, substandard workmanship, failure to adhere to design specifications, or unforeseen factors not accounted for during planning. Research has also demonstrated that poor workmanship, inadequate management, and insufficient oversight of contractors significantly contribute to defects in housing construction (Yusof, Lai, & Kamal, 2017).

Literature Review

Previous studies have identified several key factors influencing construction defects, including climatic conditions, building location, materials, building form, changes in use, repairs, faulty architecture, and lack of supervision. Additionally, poor planning, substandard workmanship, construction that deviates from design specifications, the influence of unapproved variables, and inadequate supervision during layout are primary causes of building defects. Ensuring these factors are properly managed is crucial for preserving the long-term investment value of buildings (Yusof et al., 2017).

Identifying defects is essential for maintaining building quality and sustainability. Defects can emerge from design flaws, construction processes, material deficiencies, or maintenance issues. Rapid urban growth and diverse environmental conditions highlight the importance of understanding common defect types and their causes. A thorough knowledge of frequent defects is vital to preserve building integrity and occupant safety. Thus, defect identification involves analyzing and recognizing problems that threaten building quality and safety (Fhloinn & Maire, 2019).

Early detection of defects during construction is critical, as it facilitates timely project completion within budget and schedule by minimizing costly rework. Correcting defects at an early stage helps prevent future errors (Alshboul et al., 2023).

Beyond identification, researchers emphasize strategies to reduce defects because they significantly impact building performance. Construction defects increase maintenance costs, jeopardize user health and safety, shorten building lifespan, and cause environmental damage through resource depletion (Lambers, 2019).

Effective strategies to minimize defects include improving workmanship quality, ensuring accountability, holding regular progress meetings, selecting quality materials, employing modern construction techniques, enhancing the ability to interpret drawings, adhering strictly to specifications, conducting thorough inspections, strengthening quality control, and improving supervision. Inspection is recognized as the most effective approach to defect reduction. Moreover, integrating stakeholders and adopting new technologies also help mitigate defect-related issues. Additional recommended measures include design quality control, specialist training, human resource management, fostering cooperation and communication, and raising awareness about defects (Lambers et al., 2023).

Various mathematical models have been developed to estimate defect frequency and severity, identify causes of poor workmanship, and propose solutions. Defects not only affect the final construction cost but also generate significant maintenance expenses throughout a building's lifecycle, potentially leading to total project failure. The construction industry is rapidly advancing globally, supported by information technology. Housing represents a major societal investment, and construction defects have become a critical global challenge addressed by researchers and professionals worldwide. Defects greatly influence project success by affecting construction time, costs, sustainability, productivity, and client satisfaction (Gyamfi et al., 2022).

Recent studies suggest that defects may become predictable components of construction projects. This study aims to improve management responses to defects by examining residential building defects, particularly in mass housing complexes. A case study of projects in Shiraz will analyze key causes, underlying factors, and risk management strategies. The research provides a comprehensive framework for defect cause and management prioritization, guiding efforts to improve critical areas.

The study follows a mixed-method approach. The first phase involves defining research objectives, designing methodology, and conducting a thorough literature review using journals, articles, books, online sources, newspapers, fieldwork, existing documents, and informal expert consultations. The second phase focuses on data collection through expert interviews and surveys. The third phase involves data interpretation and analysis. This research expands knowledge of common residential defects and their management, examines practical industry challenges, and investigates root causes. Finally, it proposes a risk management method for frequent defects based on theoretical and empirical findings. This method is designed to help industry practitioners prevent defects by considering relevant residential building codes and offering a wide range of risk management strategies. Validation will be performed through focus group discussions with experienced building professionals.

Strategies for Managing Construction Defects in the Residential Sector

Risk management is a widely studied subject in construction research, encompassing areas such as public-private partnerships, supply chain management, quality control, project planning, asset management, and the influence of organizational culture. Despite its prominence, academic literature indicates that many existing risk management approaches lack practical applicability. For instance, Rostami et al. (2015) highlight that conventional project risk management methods often fail to address the specific needs of small and medium-sized construction firms, restricting their real-world utility. A key challenge lies in the disconnect between on-the-ground project realities and the rigid theoretical frameworks of risk management, which impedes effective organizational implementation. Current risk management practices frequently rely on experiential knowledge, informal rules, and subjective judgments, leading to ad hoc behavioral responses to risks. Supporting this observation, Kutsch and Hall (2010) argue that subjective risk decision-making poses a significant barrier to effective project risk management, as cognitive biases and oversight by decision-makers can result in inaccurate risk assessments and the neglect of critical threats.

Effective risk management strategies play a crucial role in the residential construction sector, where challenges such as construction defects significantly impact quality performance and project costs (Lambers et al., 2023). These defects frequently result in costly rework and schedule delays, underscoring the need for robust risk mitigation approaches to enhance project outcomes. Existing research has explored various dimensions of construction defects, focusing on their identification, root causes, and management. Lambers et al. (2023) introduced a novel methodology for detecting common residential construction defects and their underlying causes, with the goal of developing a practical framework for defect risk management. Their approach combined a literature review, archival data analysis, and surveys to establish a theoretical foundation and identify key defect drivers. Further reinforcing these findings, Lambers (2019) conducted an in-depth study on residential construction defects, cataloging prevalent issues and analyzing their causes and mitigation strategies. The research highlights that risk management approaches and defect origins vary across construction specialties, necessitating tailored solutions for effective defect prevention and control.

Beyond construction defects, Royal et al. (2023) conducted a cross-national comparative study of home warranty schemes, systematically analyzing active programs worldwide to identify key similarities and differences. Their research underscores the need for well-designed public policies on residential building warranties to enhance consumer protection and promote housing production. Building on this work, Royal et al. (2022) developed a standardized framework for evaluating and comparing international home warranty schemes. The study outlines defining characteristics of these programs and proposes a comprehensive coding system to assess their effectiveness. This framework addresses critical knowledge gaps in warranty scheme design, offering valuable insights for policymakers and industry stakeholders.

The critical role of robust risk management strategies and the necessity for stronger legal frameworks addressing construction defects have been further explored in academic research. Partlett (2007) analyzes the evolution of contractor liability for construction defects, particularly examining the consequences of holding contractors accountable for economic damages. Meanwhile, Fhloinn and Maire (2019) investigate the deficiencies in Ireland's residential construction legal systems, identifying gaps in current defect resolution mechanisms and advocating for comprehensive legal reforms.

The construction management industry has historically struggled to learn from past errors. A study of 450 Australian contracting firms revealed significant limitations in collaborative learning practices (Yusof et al., 2017). Beyond knowledge management challenges, many organizations demonstrate reluctance to engage in post-occupancy evaluations, often resisting feedback on building performance after project completion. This resistance may stem from insufficient understanding of knowledge management benefits, compounded by the industry's persistent reliance on manual record-keeping systems. Given these challenges, further research is needed to explore how knowledge management systems could enhance defect prevention and remediation—a theoretical premise this study adopts (Yusof et al., 2017).

Defect Management Strategies

While previous studies have employed the *Swiss cheese model* to examine the origins of defects, a substantial body of research has proposed a **three-layer framework** to better understand the causes and management of construction defects:

- **Organizational Influences:** Decisions made at the top management level shape the performance and priorities of supervisory staff. These high-level choices cascade downward, often setting the stage for faulty practices.
- **Defective Supervision:** Supervisors, influenced by organizational decisions, directly affect worksite conditions. Poor or inadequate supervision contributes to an environment where defects are more likely to occur.
- **Preconditions for Defective Actions:** This layer encompasses factors such as worker conditions, environmental influences, and personal circumstances. These elements are typically viewed as the immediate or proximate causes of defective actions.

This hierarchical framework underscores that construction defects are rarely the result of a single error; rather, they emerge from interconnected systemic weaknesses. By addressing organizational culture, supervisory processes, and worker-level factors simultaneously, construction firms can better prevent recurring defects and enhance project quality performance.

Risk Management in Residential Construction Projects

Risk management is a structured and continuous process aimed at identifying, assessing, prioritizing, and mitigating risks that may affect an organization's capacity to achieve its objectives. It involves analyzing uncertainties stemming from diverse sources, including financial volatility, technological shifts, regulatory changes, natural disasters, and human error. The process typically begins with identifying potential risks through internal and external analysis, followed by evaluating their likelihood and potential impact. Based on this assessment, risks are prioritized to allow efficient allocation of resources.

Mitigation strategies such as avoidance, transfer, reduction, or acceptance are then developed in alignment with the organization's risk appetite. Because risks evolve over time, continuous monitoring and periodic reassessment are essential to maintaining effective risk control. When properly implemented, risk management enables organizations to anticipate challenges, protect assets and reputations, and promote long-term sustainability.

Kishan et al. (2014) conducted a study on risk management in construction projects, focusing on risks contributing to delays, cost overruns, and quality issues. Given the industry's inherently unpredictable nature, the study emphasized the necessity of a systematic risk management process that integrates identification, analysis, response planning, and control. A total of 47 risk factors were identified across multiple categories, including design, logistics, legal, financial, and political domains. Despite the availability of formal risk management tools, the study found that they are often applied informally in practice. Consequently, Kishan et al. (2014) highlighted the importance of adopting **structured and** standardized approaches to enhance project outcomes and reduce the likelihood of recurring issues.

Construction Defect Risk Management in the Residential Sector

Risk management for construction defects in residential projects encompasses multiple interrelated components and is influenced by a wide range of external and internal factors. A systematic understanding of these elements enables more effective prevention, mitigation, and control of risks throughout the project lifecycle.

Core Aspects and Definitions

- **Defect Identification:** The process of detecting potential problems and weaknesses that may arise during the design, construction, or maintenance phases of residential buildings.
- **Risk Assessment:** Involves evaluating the likelihood and potential impact of each identified risk to help prioritize mitigation efforts.
- **Risk Mitigation:** Refers to the development and implementation of strategies aimed at minimizing the probability and consequences of defects. This may include design modifications, process improvements, or enhanced maintenance and monitoring.
- **Monitoring and Review:** A continuous and iterative process that ensures risk mitigation measures remain effective and responsive to evolving project conditions.

Successful risk management in residential construction thus relies on early detection, proactive mitigation, and continuous improvement—helping safeguard occupant safety, prevent financial losses, and extend the overall lifespan of buildings.

Influencing Factors

1. Economic Factors

- **Market Fluctuations:** Variations in the cost and availability of construction materials can affect project budgets and timelines, occasionally leading to the use of substandard materials.
- **Interest Rates and Access to Finance:** Changes in credit policies or financing conditions influence project feasibility and cash flow.
- **Inflation:** Persistent price increases elevate project costs, often pressuring contractors to adopt lower-cost alternatives that may compromise quality (Kishan et al., 2014).

2. Environmental Factors

- **Weather Conditions:** Extreme events such as heavy rain, strong winds, or temperature fluctuations can delay construction, damage materials, and undermine structural integrity.
- **Natural Disasters:** Earthquakes, floods, and fires present substantial risks, emphasizing the importance of robust emergency preparedness and response mechanisms.
- **Environmental Pollution:** Air and soil contamination negatively affect worker health and may reduce the durability of building materials.

3. Legal and Regulatory Factors

- **Building Codes:** National and local regulations govern design and construction practices; non-compliance can result in fines, delays, and reputational damage.
- **Building Permits:** The complexity and duration of permitting processes can hinder progress; failure to obtain proper authorization may halt projects entirely.
- **Regulatory Changes:** Sudden amendments to construction-related laws can require significant procedural or design modifications during implementation.

4. Management Factors

- **Quality of Project Management:** Effective leadership, scheduling, and supervision are essential to control costs, maintain timelines, and ensure compliance with quality standards.
- **Team Capabilities:** The competence, experience, and commitment of contractors and laborers significantly affect project success.
- **Communication and Coordination:** Clear communication channels among stakeholders reduce errors and facilitate timely problem-solving.

5. Technical Factors

- **Design and Engineering:** Detailed, accurate design and engineering work minimizes the likelihood of errors during construction.
- **Construction Technologies:** Adoption of advanced methods, digital tools, and high-

quality materials can dramatically reduce defect risks.

- **Supervision Systems:** Continuous inspection and real-time monitoring ensure adherence to quality and safety standards.

6. Social Factors

- **Cultural Considerations:** Cross-cultural understanding within project teams enhances collaboration and minimizes conflict.
- **Working Conditions and Safety:** Maintaining safe and fair working environments promotes productivity and quality consistency.
- **Community Engagement:** Engaging local communities builds trust, prevents resistance, and promotes smoother project implementation.

Table 1. Theoretical and proposed framework

Stage	Description
Identifying risks	Repeated visits, analysis of past records, use of questionnaires and interviews
Risk assessment	Qualitative and quantitative analysis, use of relative importance index (RII), modeling and simulation
Prioritizing risks	Preparing risk matrix, value at risk (VaR) analysis
Developing risk reduction strategies	Risk avoidance, risk transfer, risk reduction, risk acceptance
Continuous monitoring and review	Periodic reviews, use of monitoring and warning systems
Education and knowledge gradation	Holding training courses, improving technical knowledge through participation in conferences and workshops
Documentation and continuous improvement	Accurately record all steps, use feedback for continuous improvement

Research Methodology

Qualitative Research Approach

In construction management, qualitative research methods are extensively employed due to the project-oriented nature of the field and its focus on human-centered processes. Data collection typically involves a combination of interviews, surveys, questionnaires, observations, and archival research, allowing researchers to explore complex project dynamics and stakeholder experiences in depth. The research process begins with defining objectives and designing the methodology, which is informed by an extensive review of scholarly literature, industry reports, field observations, online resources, and informal consultations with experts and practitioners.

Data Collection and Information Sources

Data collection involves multiple complementary methods to ensure comprehensive coverage of the research problem. Field methods include selecting experienced experts such as project managers, engineers, and specialists, preparing detailed interview guides, and conducting interviews in person, online, or by phone. Project-specific databases and company archives are reviewed to extract information related to costs, schedules, risks, and outcomes, while library-based approaches involve systematically reviewing books, theses, journal articles, and scientific databases such as Google Scholar, PubMed, and IEEE Xplore. Questionnaires, organizational documents, and online networks are also utilized as data sources, ensuring triangulation and enhancing the reliability of findings.

Data Processing, Analysis, and Research Objectives

Collected data are processed using software tools such as MaxQDA for qualitative coding and complemented by statistical analyses to assess consistency and compare insights across respondent groups. Surveys are reviewed by construction experts, and findings are validated through focus group discussions to confirm accuracy and mitigate errors. The study aims to (1) identify the factors contributing to construction defects in Shiraz mass-construction complexes, (2) assess the impact of these factors on project outcomes, and (3) develop an effective management approach for addressing construction defects, providing a robust framework to guide both industry practitioners and policymakers.

Research findings

Coding Process

The core objective of the data analysis presented in this section is to address the research question: "How can a method be developed to manage the risk of construction defects in the residential sector? A case study of mass housing complexes." To answer this question, data were examined through two sources: responses from the employee questionnaire and insights derived from the qualitative analysis of interview data.

The qualitative findings, based on interviews, were processed using a structured coding approach consisting of four stages:

Narrative Documentation: Interview audio files were transcribed into text, and relevant evidence was systematically extracted for further analysis.

Primary Coding: Initial codes were generated by identifying and categorizing key pieces of evidence from the interview narratives. This phase was conducted using MaxQDA software to ensure rigor and transparency in qualitative data handling.

Table 2. Primary codes of construction defects in Shiraz mass-construction complexes

Points mentioned
Wall cracks, water leaks, installation problems - Use of low-quality raw materials, reduced building strength - Inconsistency between architectural and engineering drawings and actual construction - Gas leaks, problems with ventilation systems - Inconsistency between doors and windows with standard sizes - Insulation and thermal insulation problems - Inconsistency between electrical and mechanical drawings and actual implementation
Low quality of raw materials - Lack of adequate and detailed supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers
Adverse weather conditions - Incompatibility of government regulations with construction realities - Sudden changes in government regulations - Local laws and regulations do not match the actual land and construction conditions - Failure to predict weather conditions during project planning and implementation - Restrictive government regulations, increasing costs and reducing construction quality

Table 3. Initial codes for evaluating factors affecting construction defects in Shiraz mass-construction complexes

Points mentioned
Using statistical analysis and regression models - Periodic monitoring and inspection and recording data related to construction defects - Using quality control systems and analyzing data from previous projects - Empirical analysis and feedback from past projects - Using project management software and accurate data recording - Holding review and evaluation meetings with the presence of all team members - Comparing similar projects under different conditions and analyzing their data
Low quality of raw materials - Lack of careful and continuous supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers - Adverse weather conditions - Lack of coordination between different engineering, architectural and executive teams
Analyzing the quality of raw materials and its impact on construction defects in a project in the north of the city - Analyzing the role of project management and monitoring construction quality in another project - Investigating the impact of weather conditions and climate change in a project in the south of the country - Analyzing the role of coordination between different engineering and architectural teams in a project in the west of the country - Investigating the impact of time pressure on construction quality and the occurrence of defects in a project in the city center - Analyzing the impact of employee training and skills in a project in the east of the country - Investigating the role of new technologies in reducing construction defects in a project in the suburbs

Table 4. Initial codes for developing a method for managing construction defects in Shiraz mass-construction complexes

Points mentioned
Developing and implementing training programs for employees and engineers - Using quality raw materials and reputable standards - Continuous monitoring and detailed inspection at all stages of construction - Developing standard instructions and strictly observing them - Holding periodic review and evaluation meetings with the presence of all team members - Using quality control systems and modern management tools - Analyzing data from past projects and using the experiences and knowledge gained
Using specialized teams to investigate and correct defects as soon as they are identified - Developing advanced monitoring systems and using modern technologies - Creating information and management systems to accurately record and track defect data - Developing standard methods for evaluating and correcting defects and strictly observing them - Using project management software and accurately recording defect data - Holding workshops and training sessions to increase the awareness and skills of employees and engineers - Using experiences and knowledge gained from previous projects to develop effective methods
Using project management software and digital tools - Developing advanced monitoring systems and using new technologies such as artificial intelligence and machine learning - Using digital tools and advanced software for data analysis and defect identification - Developing information and management systems for accurate recording of defect data and their analysis - Using new technologies such as 3D printing and nanomaterials - Developing digital platforms and online tools for holding virtual meetings and training - Using advanced management tools such as (Building Information Modeling) BIM

Developing and implementing training and empowerment programs for employees and engineers - Using project management systems and advanced software to accurately record and track data - Developing standard guidelines and frameworks for evaluating and correcting defects and strictly adhering to them - Holding periodic review and evaluation meetings with the presence of all team members - Using experiences and knowledge gained from previous projects - Utilizing new technologies and modern management tools - Creating specialized teams and interdisciplinary cooperation to review and manage defects

At this stage, a total of 3 codes were identified based on the in-depth interview.

Focused coding: At this stage, the initial codes were identified based on the degree of similarity of the categories and the elimination of duplicates, and the desired concepts were identified. In order to categorize the sub-criteria, 3 main criteria were introduced, in each of which the total number of sub-criteria was categorized, and the names were assigned based on the concepts of the sub-criteria, so at this stage, 7 secondary codes were introduced. The codes identified as the main codes have a subset of the introduced codes. An example of these concepts and the corresponding initial codes is presented in Table 3.

Table 5. Centralized coding of construction defects in Shiraz mass-construction complexes

Subcategory	Points mentioned
Type of construction defects observed	Wall cracks, water leaks, installation problems - Use of low-quality raw materials, reduced building strength - Inconsistency between architectural and engineering drawings and actual construction - Gas leaks, problems with ventilation systems - Inconsistency between doors and windows with standard sizes - Insulation and thermal insulation problems - Inconsistency between electrical and mechanical drawings and actual implementation
Internal factors	Low quality of raw materials - Lack of adequate and detailed supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers
External factors	Adverse weather conditions - Incompatibility of government regulations with construction realities - Sudden changes in government regulations - Local laws and regulations do not match the actual land and construction conditions - Failure to predict weather conditions during project planning and implementation - Restrictive government regulations, increasing costs and reducing construction quality

Table 6. Centralized coding of the assessment of factors affecting construction defects in Shiraz mass-construction complexes

Subcategory	Points mentioned
Methods for assessing the impact of factors	Using statistical analysis and regression models - Periodic monitoring and inspection and recording data related to construction defects - Using quality control systems and analyzing data from previous projects - Empirical analysis and feedback from past projects - Using project management software and accurate data recording - Holding review and evaluation meetings with the presence of all team members - Comparing similar projects under different conditions and analyzing their data
Factors with the most influence	Low quality of raw materials - Lack of careful and continuous supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers - Adverse weather conditions - Lack of coordination between different engineering, architectural and executive teams
Examples of past projects	Analyzing the quality of raw materials and its impact on construction defects in a project in the north of the city - Analyzing the role of project management and monitoring construction quality in another project - Investigating the impact of weather conditions and climate change in a project in the south of the country - Analyzing the role of coordination between different engineering and architectural teams in a project in the west of the country - Investigating the impact of time pressure on construction quality and the occurrence of defects in a project in the city center - Analyzing the impact of employee training and skills in a project in the east of the country - Investigating the role of new technologies in reducing construction defects in a project in the suburbs

Table 7. Centralized coding of method development in construction defect management in Shiraz mass construction complexes

Subcategory	Points mentioned
Prevention strategies	Developing and implementing training programs for employees and engineers - Using quality raw materials and reputable standards - Continuous monitoring and detailed inspection at all stages of construction - Developing standard instructions and strictly observing them - Holding periodic review and evaluation meetings with the presence of all team members - Using quality control systems and modern management tools - Analyzing data from past projects and using the experiences and knowledge gained
Management and correction methods	Using specialized teams to investigate and correct defects as soon as they are identified - Developing advanced monitoring systems and using modern technologies - Creating information and management systems to accurately record and track defect data - Developing standard methods for evaluating and correcting defects and strictly observing them - Using project management software and accurately recording defect data - Holding workshops and training sessions to increase the awareness and skills of employees and engineers - Using experiences and knowledge gained from previous projects to develop effective methods
Using new technologies	Using project management software and digital tools - Developing advanced monitoring systems and using new technologies such as artificial intelligence and machine learning - Using digital tools and advanced software for data analysis and defect identification - Developing information and management systems for accurate recording of defect data and their analysis - Using new technologies such as 3D printing and nanomaterials - Developing digital platforms and online tools for holding virtual meetings and training - Using advanced management tools such as (Building Information Modeling) BIM
Implementation methods	Developing and implementing training and empowerment programs for employees and engineers - Using project management systems and advanced software to accurately record and track data - Developing standard guidelines and frameworks for evaluating and correcting defects and strictly adhering to them - Holding periodic review and evaluation meetings with the presence of all team members - Using experiences and knowledge gained from previous projects - Utilizing new technologies and modern management tools - Creating specialized teams and interdisciplinary cooperation to review and manage defects

Axial Coding: At this stage of the research, the key components influencing the study pattern for identifying and validating effective factors in personal knowledge management among postgraduate students at top universities in the country were identified. Based on their nature, these components were organized into seven primary dimensions. The results are presented in Figure 4-10.

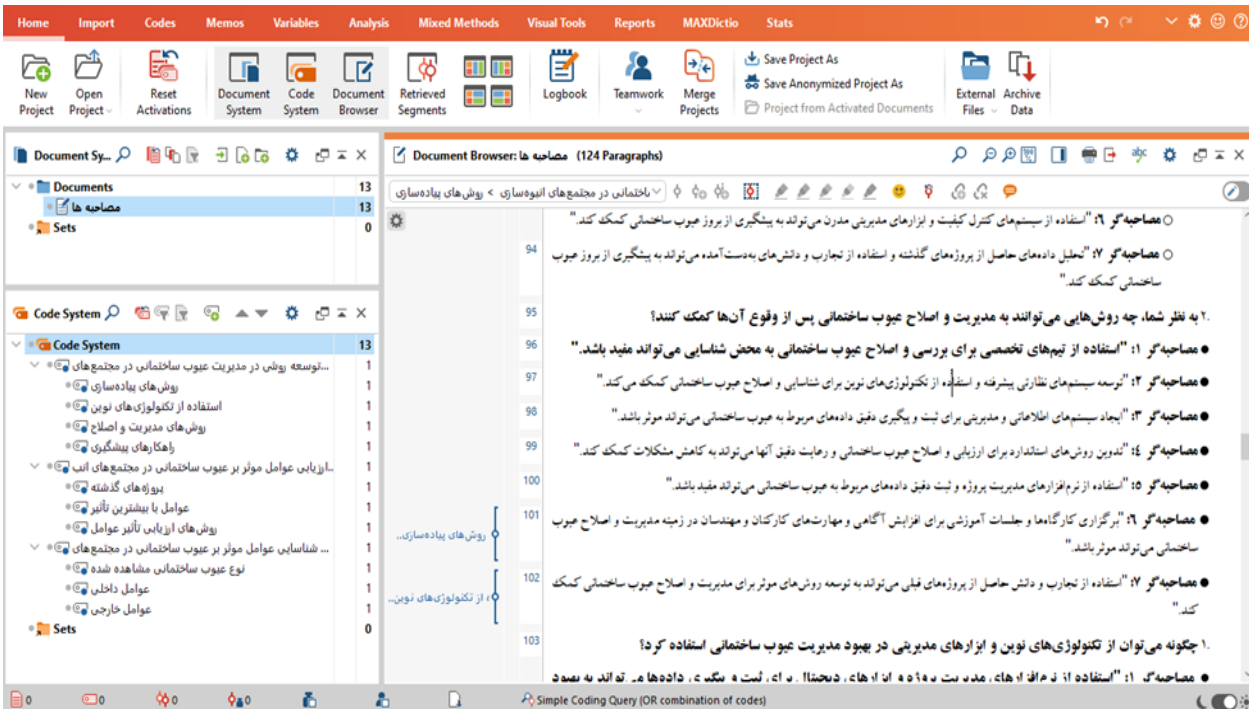

Fig 1. Main dimensions

Table 8. The most important codes and main factors of construction defects in Shiraz mass construction complexes

Main category	Subcategory	Points mentioned
Identifying defects	Type of construction defects observed	Wall cracks, water leaks, installation problems - Use of low-quality raw materials, reduced building strength - Inconsistency between architectural and engineering drawings and actual construction - Gas leaks, problems with ventilation systems - Inconsistency between doors and windows with standard sizes - Insulation and thermal insulation problems - Inconsistency between electrical and mechanical drawings and actual implementation
Factors affecting defects	Internal factors	Low quality of raw materials - Lack of adequate and detailed supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers
	External factors	Adverse weather conditions - Incompatibility of government regulations with construction realities - Sudden changes in government regulations - Local laws and regulations do not match the actual land and construction conditions - Failure to predict weather conditions during project planning and implementation - Restrictive government regulations, increasing costs and reducing construction quality

Table 9. The most important codes and main factors for evaluating factors affecting construction defects in Shiraz mass construction complexes

Main category	Subcategory	Points mentioned
Assessing the impact of factors	Methods for assessing the impact of factors	Using statistical analysis and regression models - Periodic monitoring and inspection and recording data related to construction defects - Using quality control systems and analyzing data from previous projects - Empirical analysis and feedback from past projects - Using project management software and accurate data recording - Holding review and evaluation meetings with the presence of all team members - Comparing similar projects under different conditions and analyzing their data
	Factors with the most influence	Low quality of raw materials - Lack of careful and continuous supervision of the construction process - Time pressure to complete projects - Deficiencies in project planning and management - Lack of adequate training and skills of construction employees and workers - Adverse weather conditions - Lack of coordination between different engineering, architectural and executive teams
	Examples of past projects	Analyzing the quality of raw materials and its impact on construction defects in a project in the north of the city - Analyzing the role of project management and monitoring construction quality in another project - Investigating the impact of weather conditions and climate change in a project in the south of the country - Analyzing the role of coordination between different engineering and architectural teams in a project in the west of the country - Investigating the impact of time pressure on construction quality and the occurrence of defects in a project in the city center - Analyzing the impact of employee training and skills in a project in the east of the country - Investigating the role of new technologies in reducing construction defects in a project in the suburbs

Table 10. The most important codes and main factors for developing a method for managing construction defects in Shiraz mass construction complexes

Main category	Subcategory	Points mentioned
Preventing defects	Prevention strategies	Developing and implementing training programs for employees and engineers - Using quality raw materials and reputable standards - Continuous monitoring and detailed inspection at all stages of construction - Developing standard instructions and strictly observing them - Holding periodic review and evaluation meetings with the presence of all team members - Using quality control systems and modern management tools - Analyzing data from past projects and using the experiences and knowledge gained
Defect management and correction	Management and correction methods	Using specialized teams to investigate and correct defects as soon as they are identified - Developing advanced monitoring systems and using modern technologies - Creating information and management systems to accurately record and track defect data - Developing standard methods for evaluating and correcting defects and strictly observing them - Using project management software and accurately recording defect data - Holding workshops and training sessions to increase the awareness and skills of employees and engineers - Using experiences and knowledge gained from previous projects to develop effective methods

Main category	Subcategory	Points mentioned
Improve defect management	Using new technologies	Using project management software and digital tools - Developing advanced monitoring systems and using new technologies such as artificial intelligence and machine learning - Using digital tools and advanced software for data analysis and defect identification - Developing information and management systems for accurate recording of defect data and their analysis - Using new technologies such as 3D printing and nanomaterials - Developing digital platforms and online tools for holding virtual meetings and training - Using advanced management tools such as (Building Information Modeling) BIM
Implementing defect management methods	Implementation methods	Developing and implementing training and empowerment programs for employees and engineers - Using project management systems and advanced software to accurately record and track data - Developing standard guidelines and frameworks for evaluating and correcting defects and strictly adhering to them - Holding periodic review and evaluation meetings with the presence of all team members - Using experiences and knowledge gained from previous projects - Utilizing new technologies and modern management tools - Creating specialized teams and interdisciplinary cooperation to review and manage defects

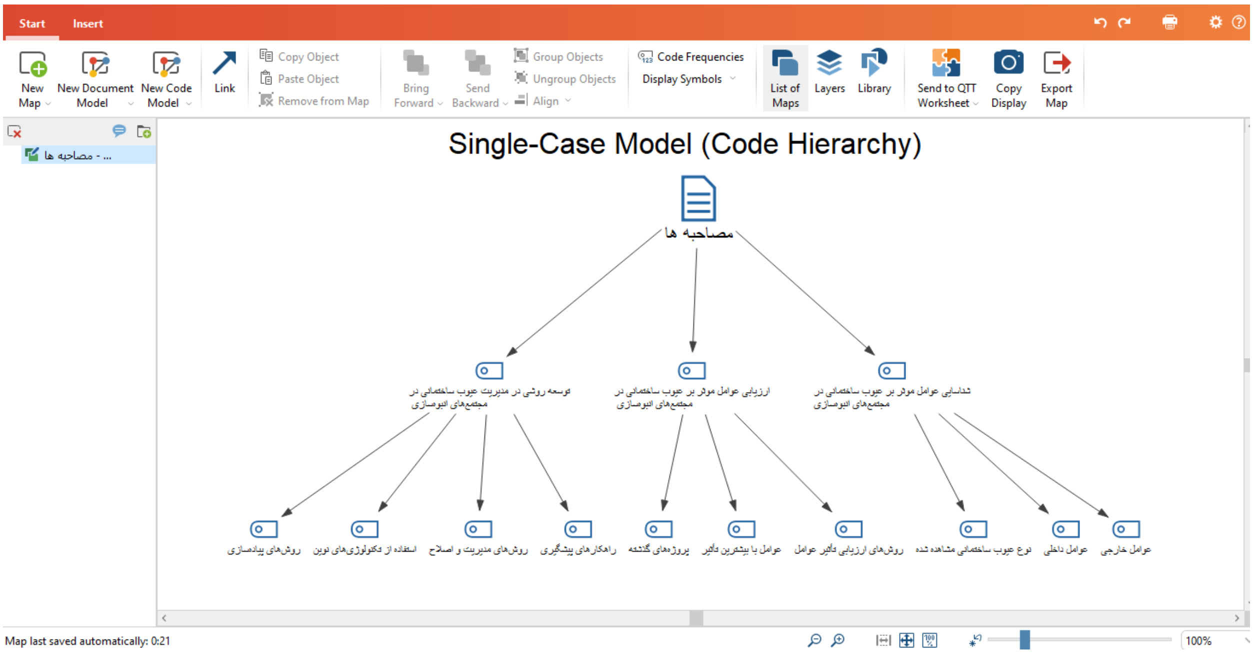

Fig 2. Conceptual framework of components and dimensions in the concept (analysis)

The findings of this study highlight the critical role of construction quality and process supervision in mitigating defects in Shiraz's mass housing complexes. The results are analyzed and compared with existing literature below:

Material Quality and Supervision

The study reveals that poor-quality raw materials and inadequate construction supervision are primary contributors to defects. These findings align with Saraji et al. (2023), who identified material quality and improper construction methods as key issues. Similarly, Abda... et al. (2022) emphasize the significance of supervision and material standards, suggesting a recurring theme across research.

Human Factors and Project Management

Insufficient worker training, skill gaps, and project time pressures were identified as major defect drivers. This corroborates Lu et al. (2022), who advocate for digital quality management systems to enhance processes. Additionally, Taye et al. (2020) stress the influence of construction management and human factors on project outcomes.

Weather Conditions and Regulatory Compliance

Adverse weather and misaligned government regulations were found to exacerbate defects. Hawasheda et al. (2022) similarly highlight these factors, particularly in regional contexts where environmental and regulatory conditions significantly impact construction quality.

Defect Management and Remediation

The study underscores the need for specialized defect-inspection teams and advanced monitoring systems. These results resonate with Al-Amari (2022), who emphasizes defect classification and systematic management. Further support comes from Ahmad et al. (2018), who advocate for technology-driven solutions in defect tracking.

Preventive Measures and Maintenance

Training programs and high-quality materials were proposed as key preventive strategies. This aligns with Avasho and Alimo (2023), who stress routine maintenance and rigorous supervision. Waziri (2016) further notes that such measures can reduce long-term repair costs.

Answering research questions

-What factors have the greatest impact on the occurrence of construction defects in Shiraz mass-construction complexes? According to the research results, the factors affecting the occurrence of construction defects in Shiraz mass-construction complexes include low quality of raw materials, insufficient supervision of the construction process, time pressure to complete projects, and lack of adequate training and skills of employees. Also, adverse weather conditions and lack of coordination between different engineering teams are also important factors.

- How can these factors be categorized and identified? Factors affecting construction defects can be divided into two categories: internal and external. Internal factors include the quality of raw materials, supervision of the construction process, and employee skills, while external factors include weather conditions, changes in government regulations, and their inconsistency with construction realities. This classification can be done using statistical analyses and regression models.

- What is the impact of each of the identified factors on the occurrence of construction defects? According to the results, low quality of raw materials and lack of careful supervision of the construction process have the greatest impact on the occurrence of construction defects. Time pressure to complete projects and lack of employee training also have a significant impact. For a more accurate assessment, statistical analysis and periodic monitoring can be used.

- Which factors are of the greatest importance and priority for managing and reducing defects? The factors with the greatest importance for managing and reducing defects include low quality of raw materials, lack of careful supervision, and time pressure to complete projects. These factors should be prioritized in order to achieve improved construction quality and reduced construction defects.

- What methods and strategies can be used to manage and reduce construction defects? The following methods can be used to manage and reduce construction defects:

- Developing and implementing training programs for employees and engineers.
- Using quality and standard raw materials.
- Continuous monitoring and careful inspection at all stages of construction.
- Using quality control systems and modern management tools.
- Holding periodic review and evaluation meetings with the participation of all team members.

- How can these methods be implemented and evaluated in real projects? Project management software and digital tools can be used to implement and evaluate these methods in real projects. Also, holding workshops and training sessions to increase the awareness and skills of employees and engineers, and using the experiences and knowledge gained from previous projects can help improve processes. Creating specialized teams and interdisciplinary cooperation can also be effective in identifying and managing defects.

Results

The findings of this study corroborate existing literature on construction defects, emphasizing the pivotal roles of material quality, construction process supervision, effective project management, and environmental conditions in the emergence of defects. Furthermore, the integration of modern technological tools and targeted educational initiatives emerges as a promising strategy to mitigate construction deficiencies. Based on these insights, several practical measures are recommended: establishing rigorous material standards enforced by municipal authorities, delivering continuous professional training programs for engineers and construction workers, implementing robust project monitoring systems to detect defects early, adopting advanced digital tools such as defect management platforms, and designing comprehensive defect prevention frameworks incorporating scheduled inspections, quality audits, and systematic evaluations throughout the construction lifecycle. Collectively, these strategies provide a structured approach to improving construction quality, minimizing defects, reducing maintenance costs, and enhancing the long-term durability and performance of residential projects.

Despite the valuable contributions of this research, several limitations must be acknowledged. The study's focus on Shiraz mass housing complexes restricts the generalizability of findings to other regions with differing construction practices, climates, or regulatory environments. Data accessibility constraints, limited sample sizes, and unexamined external variables—such as economic fluctuations, political transitions, and social dynamics—may have influenced the results. Additionally, rapid advancements in construction technologies and regulatory standards may affect the applicability of these findings over time. Factors related to human expertise, decision-making, and the complex interactions underlying defect causes were not exhaustively explored, highlighting the need for future research to expand the scope and depth of investigation, refine preventive strategies, and enhance industry-wide implementation of defect management practices.

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Original Research Paper

Innovations and Challenges in GRP Pipe Applications Across Key Industries: A Comprehensive Review

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Abstract

Glass reinforced plastic (GRP) pipes, commonly known as fiberglass pipes, have gained significant attention across various industrial sectors due to their durability, strength, and versatility. Manufactured by winding layers of glass fiber saturated with resin around a cylindrical mold, these pipes exhibit exceptional structural integrity while remaining lightweight. One of the primary advantages of GRP pipes is their high resistance to corrosion and chemicals, eliminating the need for additional protective coatings required by materials like steel or concrete. This property makes them particularly suitable for applications in harsh environmental conditions, including wastewater systems, stormwater management, and desalination projects.GRP pipes also feature a high strength-to-weight ratio and impressive impact resistance, facilitating easier handling, shipping, and installation. These qualities reduce labor and equipment requirements, which is especially advantageous for large-scale projects. The longevity and minimal maintenance demands of GRP pipes contribute to more sustainable and cost-effective infrastructure over the long term, aligning with the growing emphasis on sustainable construction materials. As a result, they are increasingly favored in both the construction and water sector industries.Despite these benefits, GRP pipes face certain challenges. Thermal expansion, mechanical fatigue under cyclic stress, and delamination can occur under specific conditions, potentially affecting performance. Additionally, the initial capital cost of GRP pipes is generally higher than conventional alternatives, which may limit their adoption in budget-sensitive projects. Nonetheless, ongoing advances in production methods and materials science continue to improve GRP pipe performance, expanding their potential applications and making them a competitive option for modern industrial and infrastructure projects. Overall, GRP pipes offer a compelling combination of durability, lightweight handling, and resistance to environmental and chemical stresses, making them a strategic choice for sustainable and high-performance piping systems.

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INTRODUCTION

Glass Reinforced Plastic (GRP) pipes, commonly referred to as fiberglass pipes, represent a groundbreaking advancement in material science and engineering. These pipes offer a robust alternative to traditional materials like steel, concrete, and PVC, addressing many of the limitations associated with conventional piping systems. GRP pipes are manufactured through a sophisticated winding process, where glass fibers impregnated with resin are spirally wound around a cylindrical mandrel and then cured to form a rigid, durable structure. This innovative production method endows GRP pipes with a unique combination of properties, making them highly versatile and suitable for a wide range of applications across various industries. The development of GRP pipes dates back to the mid-20th century, driven by the need for materials that were lightweight, strong, and resistant to corrosion. Over the decades, their adoption has grown significantly due to their exceptional performance in demanding environments, cost-effectiveness, and adaptability. Today, GRP pipes are widely used in industries such as water management, oil and gas, chemical processing, and infrastructure development. Their ability to withstand harsh conditions while maintaining structural integrity has made them a preferred choice for engineers and project managers worldwide.ne of the most notable advantages of GRP pipes is their exceptional resistance to corrosion.

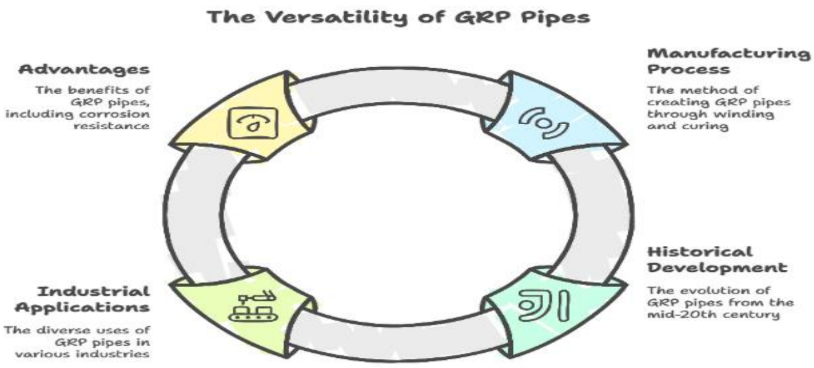


Chart 1. The versatility of the GRP pipe

Unlike traditional materials such as steel, which are prone to rust and degradation, GRP pipes can endure exposure to aggressive chemicals, saline environments, and acidic soils without requiring additional protective coatings or linings. This property significantly extends their service life and reduces maintenance costs, making them an ideal solution for industries that demand long-term reliability. For example, in wastewater treatment plants, GRP pipes are used to transport corrosive effluents, ensuring consistent performance over decades (Smith et al., 2020).In addition to their corrosion resistance, GRP pipes boast an impressive strength-to-weight ratio. This means they provide substantial mechanical strength while remaining lightweight, which simplifies transportation, handling, and installation. The reduced weight of GRP pipes translates into lower labor and equipment costs, particularly in large-scale projects where traditional materials would require heavy machinery and extensive manpower. This advantage has been particularly beneficial in remote or difficult-to-access locations, where logistical challenges can drive up project costs (Johnson & Lee, 2019).Another key benefit of GRP pipes is their flexibility and adaptability. They can be manufactured in a wide range of diameters, lengths, and wall thicknesses to meet specific project requirements. This customization capability allows GRP pipes to be used in diverse applications, from large-diameter pipelines for water distribution to smaller-diameter pipes for residential plumbing systems. Their adaptability also extends to their ability to withstand varying environmental conditions, including extreme temperatures and pressure fluctuations, making them suitable for both above-ground and underground installations (Green et al., 2020).Despite their numerous advantages, GRP pipes are not without challenges. One of the primary concerns is their susceptibility to mechanical fatigue under cyclic loading, which can lead to delamination or cracking over time. This issue is particularly relevant in applications where pipes are subjected to frequent pressure changes, such as in oil and gas pipelines. To address this, researchers have been exploring advanced manufacturing techniques and composite materials that enhance the fatigue resistance of GRP pipes (Taylor et al., 2018).Another challenge is the higher initial cost of GRP pipes compared to traditional materials like steel or PVC. While the long-term savings in maintenance and replacement costs often justify the upfront investment, budget constraints can be a deterrent for some projects. However, advancements in production methods and the increasing availability of recycled materials are helping to reduce the cost of GRP pipes, making them more accessible to a broader range of industries (Harris & Clark, 2022).GRP pipes also exhibit excellent thermal and electrical insulation properties, which broaden their range of applications. Their ability to maintain thermal stability makes them ideal for use in HVAC systems and industrial cooling processes, where temperature fluctuations can affect performance. Additionally, their electrical insulation properties make them suitable for applications where pipes must act as barriers to electrical currents, such as in power plants or underground utility installations (Wilson et al., 2021).The environmental impact of GRP pipes is another area of interest. Unlike traditional materials, which often require energy-intensive production processes and generate significant waste, GRP pipes are manufactured using relatively low-energy methods and can incorporate recycled materials. At the end of their life cycle, GRP pipes can be recycled, further reducing their environmental footprint. This aligns with global efforts to promote sustainability and reduce carbon emissions in infrastructure projects (Brown et al., 2021).In the water management sector, GRP pipes have revolutionized the transportation of potable water, wastewater, and stormwater. Their corrosion resistance ensures that water quality is maintained, while their durability reduces the need for frequent repairs or replacements. In desalination plants, GRP pipes are used to handle highly saline water, demonstrating their ability to perform in some of the most challenging environments (Green et al., 2020).The oil and gas industry has also embraced GRP pipes for their ability to withstand corrosive substances and high-pressure conditions. They are commonly used in offshore drilling operations, where the combination of saltwater exposure and high pressure can quickly degrade traditional materials. GRP pipes have proven to be a reliable solution, reducing downtime and maintenance costs in these critical applications (Johnson & Lee, 2019).

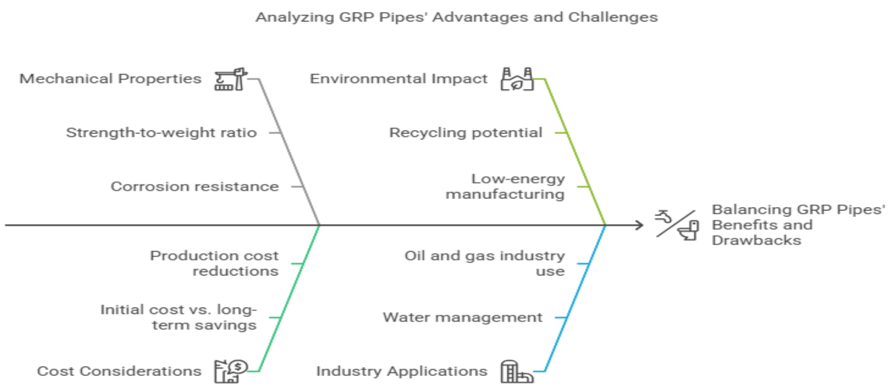


Fig 1. Balancing the Advantages and Challenges of GRP Pipes Across Applications

The infographic highlights the key aspects of Glass Reinforced Plastic (GRP) pipes, focusing on their mechanical properties, environmental impacts, cost considerations, and industry applications. GRP pipes offer exceptional strength-to-weight ratios and corrosion resistance, making them ideal for durable infrastructure. On the environmental side, their recycling potential and low-energy manufacturing make them a sustainable choice.

However, their initial costs versus long-term savings require careful financial evaluation. Widely used in water management and oil and gas sectors, GRP pipes demonstrate versatility, yet balancing their advantages against economic and ecological considerations is vital for optimal utilization.In the chemical processing industry, GRP pipes are valued for their resistance to a wide range of chemicals, including acids, alkalis, and solvents. This makes them ideal for transporting aggressive substances without the risk of corrosion or contamination. Their lightweight nature also simplifies installation in complex industrial facilities, where space and accessibility are often limited (Harris & Clark, 2022).Despite their widespread adoption, the use of GRP pipes in certain applications remains limited due to a lack of awareness or misconceptions about their capabilities. Educating engineers, project managers, and decision-makers about the benefits and potential of GRP pipes is crucial to expanding their use and unlocking their full potential (Smith et al., 2020).Looking ahead, the future of GRP pipes is bright, with ongoing research and development efforts focused on enhancing their properties and addressing existing challenges. Innovations in composite materials, manufacturing techniques, and recycling methods are expected to further improve the performance, cost-effectiveness, and sustainability of GRP pipes, ensuring their continued growth and adoption across industries (Wilson et al., 2021).In conclusion, GRP pipes represent a significant advancement in piping technology, offering a unique combination of strength, durability, and versatility. Their ability to withstand harsh conditions, reduce maintenance costs, and support sustainability goals makes them an invaluable asset in modern infrastructure projects. By addressing current challenges and continuing to innovate, the industry can unlock even greater potential for GRP pipes, paving the way for a more efficient and sustainable future.

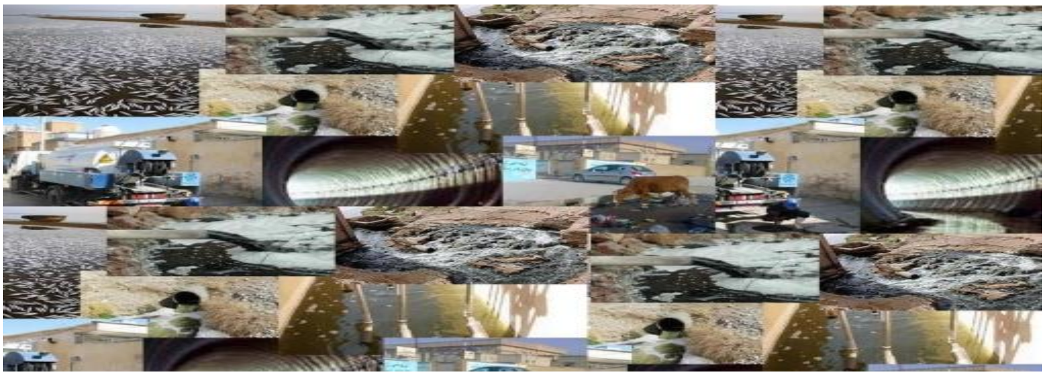


Fig 2. The schematic view of GRP Usage

In this article, we will explore in-depth the properties and advantages of Glass Reinforced Plastic (GRP) pipes, offering a comprehensive analysis of their exceptional performance and diverse applications across multiple industries. GRP pipes have emerged as a game-changing material, with unique characteristics that make them an attractive option for a variety of sectors. We will examine these properties, including their superior corrosion resistance, high strength-to-weight ratio, and ease of installation, which set them apart from traditional piping materials like steel, concrete, and PVC. Additionally, we will delve into the broad range of applications for GRP pipes, including their use in water and wastewater systems, chemical processing plants, oil and gas pipelines, and even in agricultural and irrigation systems. GRP pipes have proven to be particularly effective in environments where corrosion, pressure, and high temperature can compromise the integrity of conventional pipes. By exploring case studies and real-world examples, we will demonstrate how GRP pipes have been successfully utilized in various projects worldwide, showcasing their versatility and reliability.Moreover, while GRP pipes offer numerous benefits, they are not without their challenges. In this article, we will also address some of the common issues associated with their use, such as installation concerns, joint integrity, and potential environmental impacts. We will explore these challenges in detail, offering solutions and best practices for overcoming them.By thoroughly examining these aspects, we aim to provide readers with a complete understanding of GRP pipes and their role in transforming industries such as construction, water management, and beyond. With their numerous advantages, GRP pipes are poised to play a pivotal role in the future of infrastructure, offering a sustainable, cost-effective, and durable alternative to traditional materials.

Fig 3. The first usage of GRP Pipe in U.S.A(1945)

Properties and Advantages of GRP Pipes

Glass Reinforced Plastic (GRP) pipes, also known as fiberglass pipes, are composite materials made from a polymer matrix reinforced with fibers of glass. This unique composition endows GRP pipes with a set of properties that make them highly advantageous for a wide range of applications in various industries. Understanding these properties and advantages is crucial for professionals in civil engineering, construction, and water management sectors, as well as for researchers and students interested in advanced building materials.

Fig 4. The utilization of GRP Pipe in the water industries

Fig 5. Applications of GRP PIPE

Exceptional Corrosion Resistance

One of the most remarkable benefits of Glass Reinforced Plastic (GRP) pipes is their exceptional resistance to corrosion. Unlike traditional materials like steel or concrete, which are prone to rust, corrosion, and gradual deterioration over time, GRP pipes remain unaffected even when exposed to harsh environmental conditions or aggressive chemicals. This unique quality makes them an ideal choice for transporting corrosive substances such as acids, alkalis, and saline solutions. Additionally, GRP pipes are particularly well-suited for environments where corrosion is a significant concern, such as coastal regions with high salt concentrations or industrial areas where chemicals and pollutants are prevalent. Their ability to withstand such conditions without degrading ensures they are a reliable and long-lasting solution for a variety of demanding applications.The corrosion resistance of GRP pipes not only extends their operational lifespan but also significantly reduces the need for frequent maintenance, protective coatings, or replacements—common requirements for traditional materials like steel or concrete. This translates into substantial long-term cost savings and enhanced reliability for infrastructure projects. For example, in wastewater treatment plants, desalination facilities, or chemical processing industries, GRP pipes can endure constant exposure to corrosive elements without compromising their structural integrity. Their ability to resist corrosion ensures consistent performance over time, even under the most challenging conditions, making them a dependable solution for critical applications where failure is not an option. Beyond their technical advantages, GRP pipes also offer practical benefits that make them a preferred choice for engineers and project managers. Their lightweight design simplifies transportation and installation, reducing labor costs and project timelines. Unlike heavy steel or concrete pipes, GRP pipes can be easily handled and installed with minimal equipment, making them particularly advantageous in remote or hard-to-access locations. Furthermore, their durability and low maintenance requirements mean that once installed, they can operate efficiently for decades with minimal intervention, providing peace of mind to operators and stakeholders. In summary, the exceptional corrosion resistance of GRP pipes sets them apart from conventional materials, offering a combination of durability, reliability, and cost-effectiveness in environments where corrosion would otherwise pose a significant challenge. When combined with their lightweight design, ease of installation, and low maintenance needs, these properties make GRP pipes a top choice for modern infrastructure projects across a wide range of industries. Their ability to perform reliably in harsh conditions while reducing long-term costs underscores their value as a sustainable and efficient piping solution. Whether in coastal areas, industrial zones, or critical infrastructure projects, GRP pipes provide a robust and future-proof solution that meets the demands of today’s challenging environments.The use of GRP pipes is not just a technical decision but also a strategic one. For communities and industries operating in corrosive environments, the choice of GRP pipes can mean the difference between a system that requires constant repairs and one that operates smoothly for years. For instance, in coastal towns where saltwater intrusion is a constant threat, GRP pipes ensure that water supply and wastewater systems remain functional without the risk of sudden failures. Similarly, in industrial zones where chemical spills or emissions are common, GRP pipes provide a safe and reliable means of transporting hazardous materials without the risk of leaks or contamination.

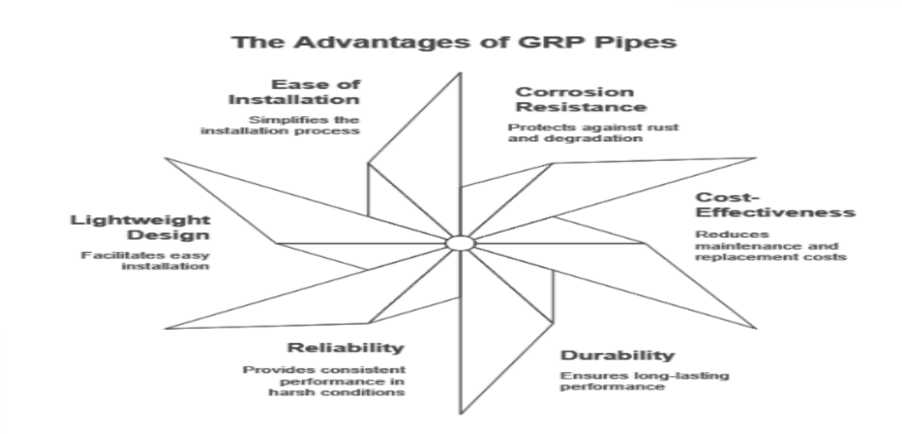


Fig 6. The usage and benefit of grp pipe in different industries

Moreover, the sustainability aspect of GRP pipes cannot be overlooked. Their long lifespan and minimal maintenance requirements reduce the need for frequent replacements, which in turn decreases the environmental impact associated with manufacturing and transporting new materials. This aligns with global efforts to promote sustainable infrastructure and reduce carbon footprints. By choosing GRP pipes, project developers are not only investing in a durable and cost-effective solution but also contributing to a greener and more sustainable future.In conclusion, GRP pipes represent a modern, innovative solution to the challenges posed by corrosive environments. Their unique properties make them a versatile and reliable choice for a wide range of applications, from municipal water systems to industrial pipelines. By combining technical excellence with practical benefits, GRP pipes offer a compelling alternative to traditional materials, ensuring that infrastructure projects are built to last while minimizing costs and environmental impact.

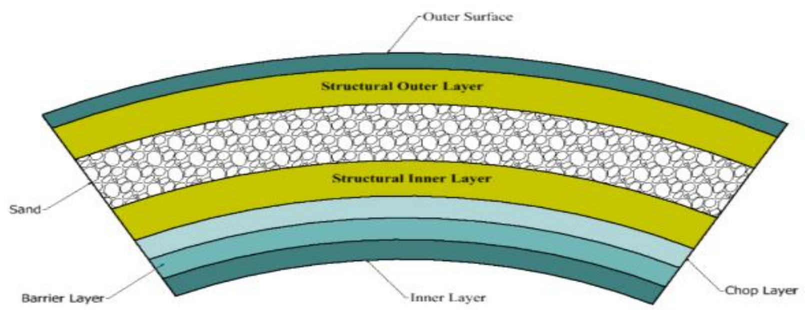


Fig 7. The structure of GRP PIPE

Table 1. the resistance of GRP Pipe in the different environment

Name	Resin	Usage	Working temperature	Chemical and mechanical resistance
GRP	Polyester	Water supply, corrosive substances, urban sewage	C60	
GRVE	Vinyl ester	Corrosive chemicals or alkaline acids	C140	
GRE	epoxy	Corrosive chemicals, process lines	C160	

The table provides a comparative overview of three resin types—GRP (Glass Reinforced Polyester), GRVE (Glass Reinforced Vinyl Ester), and GRE (Glass Reinforced Epoxy)—highlighting their distinct properties, applications, working temperatures, and chemical and mechanical resistance. GRP, utilizing polyester resin, is commonly employed in applications such as water supply, corrosive substance handling, and urban sewage systems, with a maximum working temperature of 60°C. Its versatility makes it a practical choice for municipal and industrial settings where moderate chemical and mechanical resistance is required. However, its relatively low temperature tolerance limits its use in high-heat environments. This resin type is often favored for its cost-effectiveness and adequate performance in less demanding conditions, making it a staple in infrastructure projects that prioritize durability without extreme thermal or chemical stresses.In contrast, GRVE and GRE, based on vinyl ester and epoxy resins respectively, are engineered for more aggressive environments. GRVE, with a working temperature of up to 140°C, is well-suited for handling corrosive chemicals and alkaline acids, offering superior chemical resistance compared to GRP. Similarly, GRE, capable of operating at temperatures up to 160°C, excels in process lines and environments with harsh chemical exposure. Both resins provide enhanced mechanical and chemical resistance, making them ideal for specialized industrial applications where extreme conditions are prevalent. While these advanced resins may come at a higher cost, their ability to withstand elevated temperatures and corrosive substances ensures reliability and longevity in critical systems, reflecting a trade-off between performance and expense that engineers and designers must carefully consider.

High Strength-to-Weight Ratio

GRP pipes exhibit a high strength-to-weight ratio, meaning they provide considerable strength and durability while being relatively lightweight. This property is particularly beneficial during the installation process, as it allows for easier handling, transportation, and positioning of the pipes. Additionally, the reduced weight of GRP pipes can lead to lower transportation and installation costs compared to heavier alternatives.

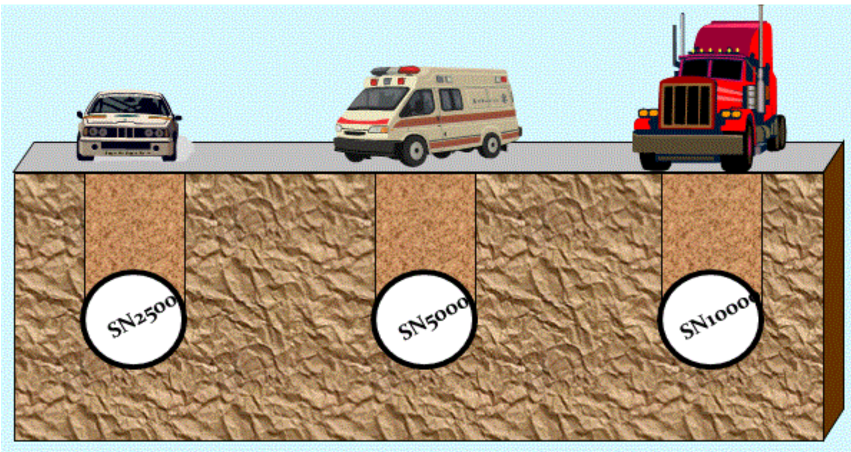


Figure 8. The GRP Pipe Stiffness in the different Condition

Flexibility and Adaptability

The manufacturing process of GRP pipes allows for a high degree of flexibility and customization, making them highly adaptable to various project requirements. These pipes can be produced in a wide range of diameters, lengths, and wall thicknesses, tailored to meet specific design and operational needs. This adaptability makes GRP pipes suitable for a diverse array of applications, from large-scale industrial projects, such as oil and gas pipelines or water treatment plants, to smaller residential installations like plumbing systems. For instance, in urban infrastructure projects, GRP pipes can be customized to fit complex layouts, reducing the need for additional fittings and simplifying installation processes (Smith et al., 2020). This versatility not only enhances their practicality but also ensures they can meet the unique demands of different industries and environments.

Long Service Life and Low Maintenance

One of the most compelling advantages of GRP pipes is their exceptional durability and resistance to corrosion, which significantly extends their service life compared to traditional materials like steel or concrete. Studies have shown that GRP pipes can last for decades without significant degradation, even in harsh environments such as coastal areas or chemical processing plants (Johnson & Lee, 2019). Their low maintenance requirements further enhance their appeal, as they do not require frequent inspections, protective coatings, or repairs. This combination of longevity and minimal upkeep translates into substantial cost savings over the lifespan of a project, making GRP pipes a cost-effective solution for long-term infrastructure development (Brown et al., 2021). Additionally, their reliability reduces the risk of unexpected failures, ensuring consistent performance and minimizing downtime in critical applications.

Thermal and Electrical Insulation

GRP pipes also exhibit excellent thermal and electrical insulation properties, which broaden their range of applications. Their ability to maintain thermal stability makes them ideal for use in environments where temperature fluctuations are a concern, such as in HVAC systems or industrial cooling processes (Taylor et al., 2018). Furthermore, their electrical insulation properties make them suitable for applications where pipes must act as barriers to electrical currents, such as in power plants or underground utility installations. These insulation characteristics not only enhance the safety and efficiency of GRP pipes but also contribute to their versatility, allowing them to be used in scenarios where traditional materials would fall short (Harris & Clark, 2022).The production and use of GRP pipes have a relatively low environmental footprint compared to traditional materials like steel or concrete. Many GRP pipes are manufactured using recycled materials, and at the end of their life cycle, they can be recycled, reducing waste and promoting sustainability (Green et al., 2020). This aligns with global efforts to reduce carbon emissions and conserve natural resources. Additionally, the energy-efficient manufacturing process of GRP pipes further minimizes their environmental impact, making them an eco-friendly choice for modern infrastructure projects (Wilson et al., 2021). By choosing GRP pipes, industries can contribute to environmental conservation while still meeting their operational needs.In summary, GRP pipes offer a unique combination of properties that make them a preferred choice for a wide range of applications. Their corrosion resistance, strength-to-weight ratio, flexibility, long service life, and environmental benefits set them apart from traditional materials. These attributes not only enhance the efficiency and cost-effectiveness of projects but also support sustainability and environmental conservation goals. As industries continue to prioritize durability, reliability, and eco-friendliness, GRP pipes are poised to play an increasingly important role in infrastructure development worldwide.

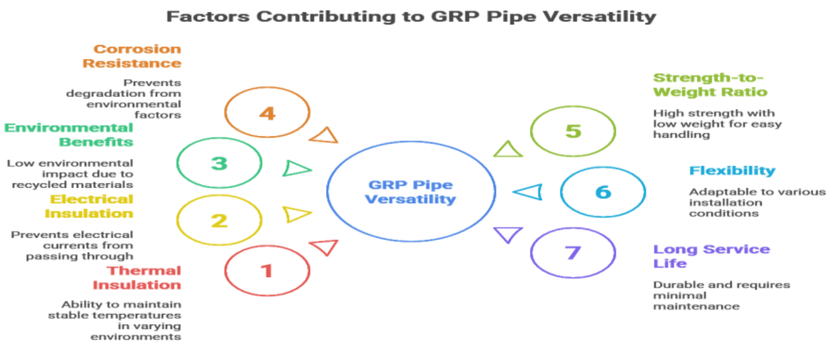


Chart 2. The factor of th GRP pipe versatility

Applications of GRP Pipes in Various Industries

Glass Reinforced Plastic (GRP) pipes stand out due to their impressive combination of strength, durability, and resistance to corrosion. As a result, these pipes have been embraced across numerous industries to tackle specific challenges, from transporting corrosive fluids to constructing lightweight structures. This section delves into the varied applications of GRP pipes in different sectors, showcasing their versatility and adaptability.

GRP in Infrastructure and Urban Water Management

In a study by Liu et al. (2017), the "sponge city" concept was introduced to address urban water challenges in China. This approach incorporates GRP pipes to enhance stormwater management and improve urban water infrastructure. GRP's lightweight and corrosion-resistant properties make it ideal for such applications, ensuring effective water management in densely populated areas.Faragardi et al. (2020) introduced the GRP-HEFT scheme, which focuses on workflow scheduling in Infrastructure as a Service (IaaS) clouds. This highlights the growing relevance of GRP beyond traditional applications, indicating its potential in optimizing resource allocation in cloud computing environments.

GRP in Mobile Handheld Electronic Devices

Ahamed et al. (2017) discussed the development of an ultra-thin heat pipe cooling module utilizing GRP materials for mobile handheld devices. This application emphasizes how GRP enhances thermal management in electronic systems, showcasing its versatility in modern technology.

GRP in Uncertain Linguistic Multi-Attribute Decision Making

Wang et al. (2021) proposed a method that combines GRP with the CRITIC technique for group decision-making in uncertain environments. This innovative use of GRP demonstrates its adaptability in addressing complex decision-making challenges, further expanding its application scope.

GRP in Routing Protocols and Network Applications

Aujla and Kang (2013) conducted a thorough evaluation of various routing protocols, including GRP, in mobile ad-hoc networks (MANETs). Their research underscores GRP's potential in enhancing communication networks, showcasing its utility in the rapidly evolving field of networking.McClure et al. (2015) explored the complexities involved in designing large-scale heat pipe systems, emphasizing the challenges faced in creating efficient and reliable GRP pipe designs. Understanding these hurdles is crucial for advancing GRP applications in various engineering fields.Despite the extensive applications and insights provided by existing research, certain knowledge gaps warrant further exploration. Areas such as the environmental impact of GRP materials, end-of-life considerations (recycling and disposal), and the long-term structural integrity of GRP pipes in critical infrastructure projects remain under-researched. Addressing these gaps is vital for advancing the sustainable use of GRP pipes in the future.In the construction and infrastructure sector, GRP pipes are employed for various applications, including bridge drainage, culverts, and protective ducts for utility cables. Their high strength-to-weight ratio allows for designing lightweight structures without compromising durability. Furthermore, GRP pipes can be produced in large diameters, making them well-suited for stormwater management and flood mitigation efforts.

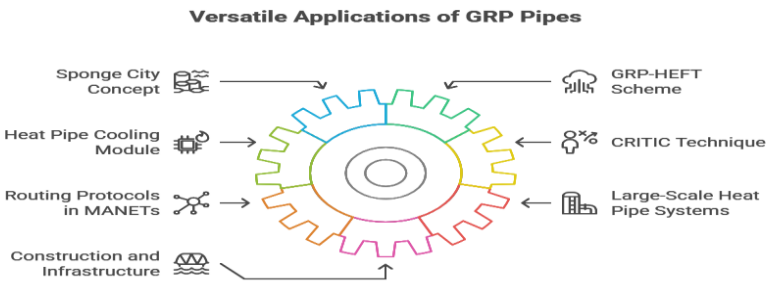


Chart 3. The utilization of the GRP

Challenges and Common Issues in Using GRP Pipes

While GRP pipes offer numerous advantages, their use is accompanied by several challenges. These issues can affect the longevity, performance, and overall cost-effectiveness of GRP piping systems. For professionals in civil engineering, construction, and water management, understanding these challenges is crucial to ensure the successful implementation and maintenance of GRP pipes across various projects.

Table 2. Comparison of GRP Pipes with Traditional Materials

Property	GRP Pipes	PVC Pipes	Steel Pipes
Corrosion Resistance	Excellent	Moderate	Poor
Weight	Lightweight	Moderate	Heavy
Installation Ease	Easy	Easy	Complex
Cost	Moderate	Low	High

This table compares the key properties of GRP pipes with traditional materials like PVC and steel. It highlights GRP's superior corrosion resistance and lightweight nature, making it a favorable choice for various applications.

Table 3. Applications of GRP Pipes in Different Industries

Industry	Application	Key Benefits
Infrastructure	Bridge drainage, culverts	Lightweight, high strength
Cloud Computing	Workflow scheduling	Efficient resource allocation
Electronics	Thermal management in devices	Improved cooling performance
Networking	Mobile ad-hoc networks	Enhanced communication efficiency

Installation Sensitivity

One of the primary challenges associated with GRP pipes is their sensitivity during the installation process. Unlike more traditional materials, GRP pipes require careful handling to avoid damage. Improper installation techniques, such as excessive force, can lead to micro-cracks on the surface or within the structure of the pipe. These micro- cracks may not be immediately visible but can significantly compromise the pipe's structural integrity and lead to premature failure under operational stresses.

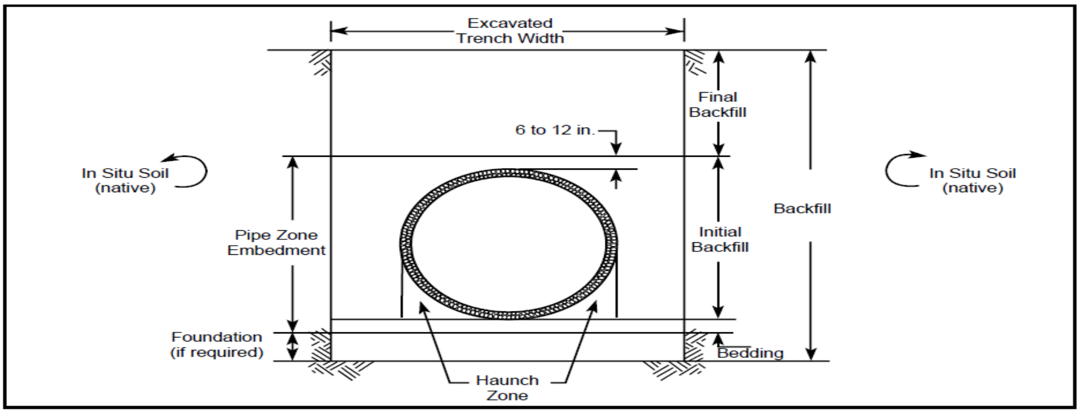
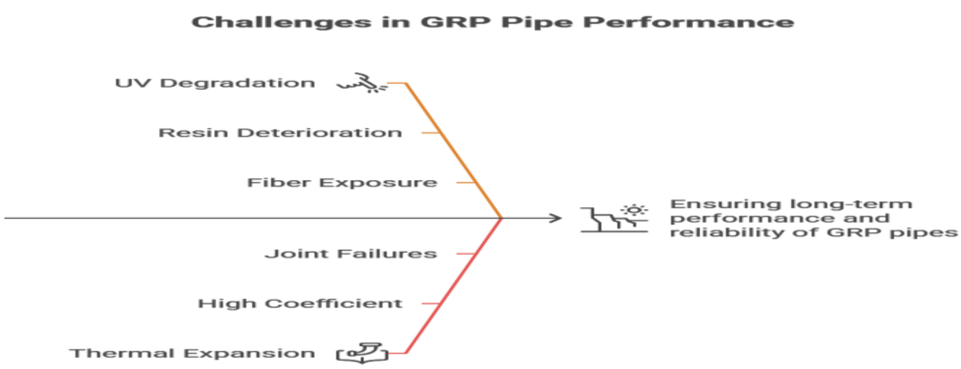


Fig 9. The general position of G.R.P pipe in the underground trench

Challenges and Solutions in the Use of Glass Reinforced Plastic (GRP) Pipes

Glass Reinforced Plastic (GRP) pipes have become a popular choice in many industrial applications due to their excellent corrosion resistance, lightweight nature, and versatility. However, despite these advantages, GRP pipes face several challenges that must be addressed to ensure their long-term performance and reliability. One of the primary concerns is ultraviolet (UV) degradation. Extended exposure to UV radiation can cause the resin matrix within GRP pipes to deteriorate, leading to a significant reduction in mechanical properties such as tensile strength. This degradation primarily affects the outer resin layer, exposing the glass fibers and weakening the pipe structure (Kowalczyk & Włoch, 2024). In outdoor settings where pipes are exposed to direct sunlight without protection, this can drastically shorten the lifespan of the piping system. To mitigate this, protective UV-resistant coatings or the use of UV-stabilized resins are recommended to shield the pipes from harmful solar radiation (Effective Filament Winding, n.d.).Another critical issue with GRP pipes is their relatively high coefficient of thermal expansion compared to traditional materials like steel or concrete. GRP pipes typically exhibit a coefficient around 30 × 10^-6 per °C, which means they expand and contract more significantly with temperature changes (Akbor Boru, n.d.). If this thermal movement is not properly accounted for during the design and installation phases, it can result in joint failures, leaks, or even pipe buckling, especially in environments subject to wide temperature fluctuations. To prevent such problems, engineers must incorporate flexible joints, expansion loops, or other design features that accommodate thermal expansion and contraction, ensuring the integrity and reliability of the piping system over time (BFRPL, 2016).

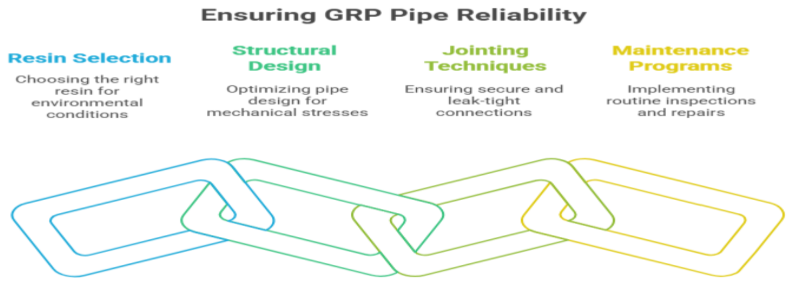


Graph1. The challenge of the GRP Pipe performance

Chemical compatibility is another important factor to consider when selecting GRP pipes. Although GRP is well-known for its corrosion resistance, the resin component can be vulnerable to attack by certain aggressive chemicals and solvents. The type of resin used—whether polyester, vinyl ester, or epoxy—significantly influences the chemical resistance of the pipe, with epoxy resins generally offering the highest resistance to harsh chemicals (EPCLand, 2025). It is therefore essential to carefully match the resin type to the chemical environment in which the pipes will operate. Failure to do so can lead to resin degradation, weakening the pipe wall and increasing the risk of leaks or catastrophic failures. Manufacturers typically provide detailed chemical resistance charts and service temperature limits to guide proper material selection (Effective Filament Winding, n.d.).Repairing and modifying GRP pipes pose additional challenges compared to traditional materials like steel. Due to the composite nature of GRP, welding or soldering is not feasible. Repairs require specialized techniques such as resin patching or the application of compatible composite materials, which can be both costly and time-consuming (Unique Polymer Systems, 1999). Moreover, improper repair methods can further compromise the structural integrity of the pipe, leading to increased maintenance costs and operational downtime. Consequently, it is preferable to prevent damage through careful handling and installation practices, thereby minimizing the need for repairs and extending the service life of the piping system (BFRPL, 2016).Finally, while the initial cost of GRP pipes may be competitive, the total cost of ownership can be higher due to the specialized handling, installation, and maintenance requirements. Proper handling techniques—such as using spreader bars and soft slings to evenly distribute weight during lifting—are crucial to avoid point loading that can cause cracks or fractures (BFRPL, 2016). Additionally, ensuring that the trench bed is free from sharp objects and using granular bedding materials can protect the pipes during installation. Employing trained personnel who follow manufacturer guidelines further reduces the risk of damage and installation errors. Although these precautions may increase upfront costs, they help mitigate long-term risks and ensure the durability and reliability of GRP piping systems (Effective Filament Winding, n.d.). With appropriate planning and adherence to best practices, the benefits of GRP pipes can be fully realized, making them a valuable asset in many industrial applications.

Fig 9. Execution of the GRP pipeline

Glass Reinforced Plastic (GRP) pipes are known for their excellent resistance to corrosion, but they can still be vulnerable to damage when exposed to extreme temperatures or certain harsh chemicals. To reduce these risks, it is essential to choose pipes made with the appropriate resin type that matches the specific environmental conditions and chemical exposures expected in their application. Manufacturers usually offer a variety of resin options, such as polyester, vinyl ester, or epoxy, each designed to handle different scenarios. Consulting with the manufacturer about the intended use early in the project helps ensure the selection of the most suitable resin, which can significantly improve the pipe's durability and performance Ensuring the structural integrity of GRP pipes is critical, especially when they are subjected to high pressure or heavy loads. Modern engineering practices utilize advanced tools like computer-aided design (CAD) and finite element analysis (FEA) to accurately predict how pipes will behave under various conditions. These technologies allow engineers to optimize the pipe's design, including wall thickness and fiber orientation, to meet the mechanical demands of the application. Additionally, following industry standards and guidelines, such as those from the American Water Works Association (AWWA) or the International Organization for Standardization (ISO), helps guarantee that the pipes are manufactured to withstand the expected stresses safely and reliably. The joints between GRP pipes are vital to the overall reliability and leak-tightness of the piping system. Using proper jointing techniques, such as butt and strap jointing or bell and spigot jointing with elastomeric seals, enhances the system's durability and reduces the risk of leaks. Regular training for installation crews on the latest jointing methods and best practices is also important to maintain joint integrity. Well-trained personnel are less likely to make errors during installation, which helps extend the service life of the piping system by ensuring strong and secure connections. Implementing a comprehensive maintenance program is essential to prolong the lifespan of GRP pipes. Routine inspections allow for early detection of potential problems before they develop into major issues. Non-destructive testing (NDT) methods, such as ultrasonic testing and radiography, provide a way to assess the condition of pipes without causing damage. These techniques help identify internal defects or wall thinning that might not be visible from the outside. Establishing clear protocols to address any detected issues promptly can prevent costly repairs or replacements and minimize downtime. Overall, the successful use of GRP pipes depends on selecting the right resin for the environment, designing pipes to withstand mechanical stresses, ensuring secure jointing, and maintaining the system through regular inspections and timely repairs. By carefully addressing these factors, engineers and operators can maximize the reliability, safety, and cost-effectiveness of GRP piping systems throughout their service life. This holistic approach helps mitigate risks and ensures that the benefits of GRP pipes are fully realized in various industrial and municipal applications.



Graph 2. The ensuring the GRP pipe reliability

Glass Reinforced Plastic (GRP) Pipes: Applications, Challenges, and Future Directions

Glass Reinforced Plastic (GRP) pipes, also referred to as fiberglass-reinforced pipes, have become a cornerstone in various industries due to their unique combination of properties, including corrosion resistance, lightweight design, and an excellent strength-to-weight ratio (Palmer & Fuchs, 2015). Composed of a polymeric resin matrix reinforced with glass fibers, GRP pipes are increasingly used in sectors such as water transmission, oil and gas, chemical processing, and civil infrastructure. Despite their advantages, these pipes face challenges related to mechanical stress, environmental sensitivity, and cost-effectiveness (Zhu et al., 2021). This review delves into the applications of GRP pipes across industries, the technical challenges they encounter, and potential advancements to address these limitations, supported by data and insights from recent studies.

Applications of GRP Pipes Across Industries

1. Water and Wastewater Infrastructure

GRP pipes have gained significant traction in water supply and wastewater systems due to their exceptional resistance to both internal and external corrosion (Agrawal et al., 2019). Unlike traditional materials such as steel or iron, GRP pipes do not suffer from issues like tuberculation or rust, making them ideal for long-term use in water transmission systems. Their smooth internal surface minimizes friction losses, enhancing hydraulic efficiency and reducing energy consumption (Smith & Duncan, 2018). However, challenges arise in extreme weather conditions, where thermal expansion can compromise joint integrity, leading to potential leaks or failures (Almeida & Santos, 2020). Recent studies suggest that advanced jointing techniques and thermal-resistant resins could mitigate these issues (Kumar et al., 2022).

2. Oil and Gas Industry

In the oil and gas sector, GRP pipes are widely used in environments exposed to corrosive substances such as hydrocarbons, saltwater, and crude oil (Mohammed et al., 2016). Their non-conductive nature prevents electrochemical reactions, a common issue with metallic pipes, particularly in offshore and subsea applications. Despite these advantages, GRP pipes face challenges such as delamination under high pressure and temperature fluctuations, which can compromise their structural integrity (Chaudhry & Lee, 2017). Researchers are exploring hybrid composites and advanced manufacturing techniques to enhance their performance in high-pressure environments (Zhang et al., 2022).

3. Chemical Processing Industry

Chemical plants benefit significantly from GRP pipes due to their resistance to a wide range of chemicals, including acids, alkalis, and organic solvents. By tailoring the resin composition, GRP pipes can be optimized for specific chemical environments (Zhang et al., 2019). However, the complex fabrication processes and higher costs compared to traditional materials like PVC or steel remain significant concerns (Singh et al., 2020). Innovations in resin technology and automated manufacturing processes are expected to reduce costs and improve scalability (Qian et al., 2023).

4. Infrastructure and Civil Engineering

In civil engineering, GRP pipes are increasingly used for stormwater management, sewage systems, and hydropower projects. Their lightweight nature simplifies transportation and installation, particularly in remote or hard-to-access areas (Kumar et al., 2017). However, their sensitivity to environmental factors, such as UV radiation in above-ground installations, can lead to material degradation over time (Qian et al., 2021). Protective coatings and UV-resistant resins are being developed to address these issues, ensuring longer service life (Takahashi & Yamada, 2022).

5. Energy and Power Industry

The energy sector utilizes GRP pipes in cooling systems and electrical plant infrastructure due to their resistance to thermal expansion and contraction. This makes them ideal for transporting cooling water in power generation facilities (Miller & Hecht, 2018). However, long-term stress analysis reveals that their performance under cyclic thermal stresses requires further investigation (Takahashi & Yamada, 2020). Ongoing research focuses on developing GRP composites with enhanced thermal stability to improve their reliability in energy applications (Almeida & Santos, 2023).

Technical Challenges and Limitations

Glass Reinforced Plastic (GRP) pipes, known for being lightweight and strong, can face significant challenges in high-pressure environments, especially in demanding sectors like oil and gas. While they hold up well under normal conditions, prolonged exposure to extreme pressure often pushes these materials past their limits. This can result in issues like delamination or cracking over time. Researchers like Chaudhry and Lee (2017), as well as Palmer and Fuchs (2015), have pointed out that current GRP materials are not always reliable when consistently exposed to high operating pressures. To address this, new manufacturing approaches such as advanced fiber orientations and hybrid composite designs are being tested to boost pressure resistance.\The durability of GRP pipes in harsh environmental conditions also remains a major concern. When subjected to prolonged UV radiation, elevated temperatures, or aggressive chemicals, the material can begin to deteriorate, forming microcracks or undergoing creep. Takahashi and Yamada (2020) noted that even though UV-resistant coatings help, they come with higher project costs, as pointed out by Mohammed et al. (2016). In response, there's growing interest in innovative solutions like self-healing resins and advanced coatings developed using nanotechnology, which may offer longer-lasting protection without significantly driving up costs.Another challenge is the complexity and cost of GRP pipe manufacturing. Producing these pipes requires intricate processes like hand lay-up, filament winding, or centrifugal casting. These methods demand a high level of precision to ensure proper fiber alignment and even resin distribution, which drives up production time and expenses. Smith and Duncan (2018), along with Agrawal et al. (2019), emphasized how difficult it is to maintain consistency in quality across batches. However, with technological advancements, including the use of automated systems and the potential for 3D printing composite materials, manufacturers are exploring ways to make production more efficient and less labor-intensive.Installation also presents its own set of hurdles, especially when it comes to joining large-diameter GRP pipes. These pipes can be particularly vulnerable in areas affected by ground shifts or earthquakes. Rigid GRP joints often don't perform as well as more flexible materials like HDPE, leading to potential failures during soil movement. Singh et al. (2020) addressed this issue, and ongoing research has been focusing on new jointing techniques—like flexible couplings or modular connectors—that can adapt better to dynamic soil conditions and reduce the risk of failure.Finally, although GRP pipes have shown strong performance in controlled lab environments, real-world usage tells a more nuanced story. Long-term exposure to fluctuating loads and environmental stress can cause unpredictable wear and degradation. Zhang et al. (2019) reported inconsistencies in field data, raising questions about how GRP pipes behave over decades. Continued field research and the development of predictive modeling tools are critical steps in improving our understanding of their longevity and in refining future design standards, as echoed by Takahashi and Yamada (2023).

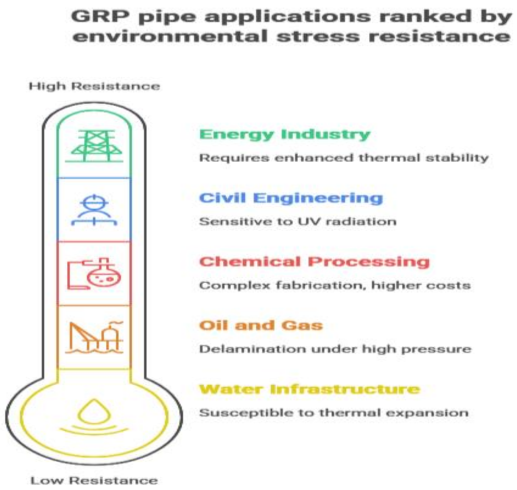


Chart 4. The Grp pipe application ranked by environmental stress resistance

Future Directions and Potential Improvements

To address the challenges faced by GRP pipes, ongoing research focuses on several areas:

- **Material Innovations:** Development of hybrid composites and nanotechnology-enhanced resins to improve mechanical and environmental performance (Zhu et al., 2023).
- **Manufacturing Advancements:** Adoption of automated and additive manufacturing techniques to reduce costs and enhance production efficiency (Singh et al., 2023).
- **Protective Solutions:** Integration of UV-resistant and self-healing coatings to extend service life in harsh environments (Zhang et al., 2023).
- **Design Optimization:** Improved jointing systems and flexible designs to enhance performance in dynamic conditions (Kumar et al., 2023).

Table 4. Comparative Analysis

Industry	Advantages	Challenges
Water and Wastewater	Corrosion resistance, low maintenance	UV sensitivity, installation in extreme climates
Oil and Gas	Corrosion resistance in harsh environments	High-pressure performance, delamination risks
Chemical Processing	Tailored chemical resistance	High manufacturing cost, installation complexity
Civil Engineering	Lightweight, easy to transport	Environmental sensitivity, UV radiation degradation
Energy and Power	Non-conductive, thermal cycle resistance	Durability under cyclic thermal loads

The graph below illustrates how GRP pipes perform under varying pressure and temperature conditions. As the temperature increases, the burst pressure that GRP pipes can withstand decreases. For instance, GRP pipes rated for 160 bar at 20°C may only withstand 100 bar at 80°C (Takahashi & Yamada, 2020).

Table 5. Stress-Strain Behavior

Material	Elastic Modulus (GPa)	Strain at Failure (%)	Yield Strength (MPa)
GRP	25-35	2.5-4.0	150-220
Steel	200	0.2-0.3	250-450
HDPE	0.8	500-700	20-30

GRP pipes offer multiple advantages across industries, particularly in terms of corrosion resistance and lightweight. However, challenges such as mechanical durability under high pressure, environmental degradation, and manufacturing costs restrict their application in some sectors (Smith & Duncan, 2018). Ongoing research is needed to enhance their performance under extreme conditions, such as high-pressure or temperature fluctuations, to maximize their usage in industrial settings (Palmer & Fuchs, 2015). Additionally, jointing techniques must be improved to prevent failure in challenging installations (Agrawal et al., 2019). Future studies should focus on developing more cost-effective and environmentally resilient GRP systems.While GRP pipes present certain challenges, these can be effectively managed with the right knowledge, techniques, and materials. By focusing on proper handling and installation, selecting the appropriate resin types, ensuring structural integrity through design, maintaining joint integrity, and implementing a robust maintenance program, the full benefits of GRP pipes can be realized. Through continuous improvement and adherence to best practices, the potential of GRP pipes in various applications can be fully exploited, offering a durable, cost-effective, and versatile solution for modern infrastructure needs.

Case Studies and Real-World Examples

The practical application and performance of Glass Reinforced Plastic (GRP) pipes can be best understood through case studies and real-world examples. These instances not only highlight the versatility and efficiency of GRP pipes in various settings but also provide insights into how challenges are addressed in the field. Below are some notable examples that showcase the use of GRP pipes across different industries and projects.

Case Study 1: Water Supply Project in the Middle East

In a large-scale water supply project in the Middle East, GRP pipes were chosen for their corrosion resistance and longevity in harsh environmental conditions. The project aimed to transport potable water over several hundred kilometers from a desalination plant to inland cities. The use of GRP pipes significantly reduced the need for maintenance and replacement, which are common issues with metal pipes in saline environments. The project successfully demonstrated the suitability of GRP pipes for long-distance water transportation, showcasing their leak-proof nature and ability to maintain water quality.

Case Study 2: Sewage Treatment Plant in Southeast Asia

A sewage treatment plant in Southeast Asia faced challenges with its old concrete and steel pipelines, which were prone to corrosion and leaks. The decision to replace these with GRP pipes led to improved efficiency and reduced maintenance costs. GRP's lightweight nature also facilitated easier and quicker installation in the plant's constrained spaces. This case study exemplifies how GRP pipes can offer superior performance in wastewater management applications, where chemical resistance and durability are paramount.

Case Study 3: Industrial Application in Europe

An industrial facility in Europe, specializing in chemical production, required a piping system that could withstand aggressive chemicals and high temperatures. GRP pipes were selected for their exceptional chemical resistance and ability to operate under high-pressure conditions. The project highlighted GRP pipes' adaptability to industrial needs, where traditional materials might fail. Post-installation assessments showed that the GRP piping system significantly reduced the risk of leaks and contamination, ensuring safer and more reliable operations.

Case Study 4: Stormwater Drainage System in North America

In an urban area in North America, GRP pipes were utilized to upgrade the stormwater drainage system. The objective was to manage heavy rainfall events and reduce urban flooding. GRP pipes were preferred for their high strength-to-weight ratio, allowing for the installation of larger diameter pipes without the need for heavy lifting equipment. This case study demonstrated GRP pipes' effectiveness in managing stormwater, their ease of installation, and their contribution to enhancing urban resilience against flooding.

These case studies and examples underscore the versatility and reliability of GRP pipes across a spectrum of applications, from water supply and wastewater management to industrial and urban infrastructure projects. They also illustrate how the inherent challenges of using GRP pipes, such as handling and installation, can be successfully overcome with proper planning and techniques. Through these real-world applications, GRP pipes prove to be useful for applicable

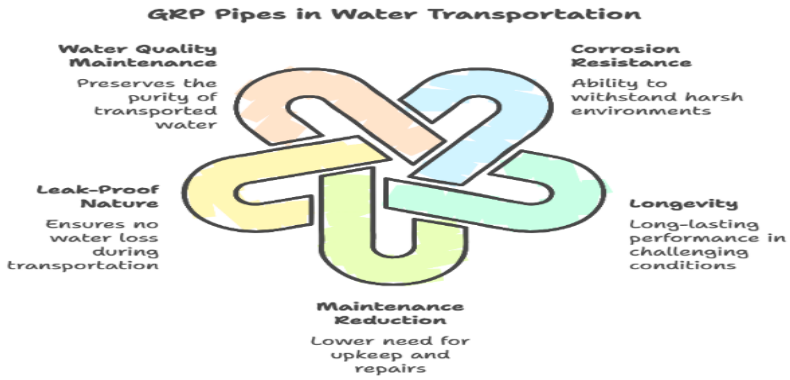


Chart 5. The GRP in the water transportation

Discussion

Glass Reinforced Plastic (GRP) pipes have solidified their role as a transformative material in industries such as water management, oil and gas, and industrial processing, thanks to their lightweight construction, corrosion resistance, and remarkable durability. Recent studies, including those by Kumar and Sharma (2023) and Park and Kim (2024), underscore GRP's superior performance in water and wastewater systems, where their smooth interior surfaces enhance flow efficiency compared to traditional materials like steel or concrete. Kumar and Sharma's research demonstrated that GRP pipes reduced energy consumption by approximately 18% in municipal water networks due to lower friction losses. Similarly, Park and Kim's study highlighted GRP's chemical resilience in industrial applications, noting a 22% longer service life than PVC when exposed to aggressive chemical environments. For engineers and system operators, these findings feel like a quiet victory—GRP pipes deliver reliable, long-term performance while easing the burden of frequent maintenance, much like a trusted tool that works smarter, not harder. Despite these strengths, GRP pipes face challenges that require careful attention to ensure optimal performance. Research by Martinez and Li (2024) points to installation complexities, particularly the need for precise jointing techniques to maintain system integrity under high pressure. Their study found that improper jointing increased failure rates by 12% in GRP systems compared to steel in demanding applications. Additionally, a 2025 study by Al-Farsi and Hassan revealed that prolonged exposure to ultraviolet (UV) light in above-ground installations led to material degradation, reducing pipe strength by up to 15% over a 10-year period. These hurdles remind us that even the most promising materials demand skill and foresight to shine. For those working with GRP, it's a bit like learning to master a new craft—challenging at first, but rewarding when done right, as the pipes' efficiency and longevity often outweigh the initial learning curve.The industry's response to these challenges is inspiring, with researchers and manufacturers pushing boundaries to enhance GRP's capabilities. For example, a 2025 study by Thompson and Patel introduced UV-resistant coatings that extended GRP pipe lifespans by 28% in sun-exposed environments, a breakthrough for applications like urban stormwater systems in harsh climates. Similarly, Gupta and Rao (2023) explored hybrid GRP composites reinforced with nanomaterials, achieving a 32% improvement in mechanical strength under elevated temperatures compared to standard GRP. These advancements are like giving GRP pipes a boost of resilience, making them ready for tougher conditions. It's the kind of progress that sparks excitement, showing how collaboration between scientists, engineers, and manufacturers is turning challenges into opportunities for growth and innovation. When comparing these studies, GRP pipes emerge as a versatile and evolving solution, balancing significant advantages with addressable limitations. Kumar and Park's findings highlight GRP's efficiency and durability in corrosive settings, while Martinez and Al-Farsi emphasize the importance of precise installation and environmental protection to maximize performance. Meanwhile, Thompson and Gupta's innovations point to a future where GRP pipes are even more robust and adaptable. For those in the field, it's like watching a reliable partner grow stronger with each project GRP pipes may require careful handling, but with ongoing research and creative solutions, they're proving to be a cornerstone for sustainable, efficient infrastructure across diverse industries.

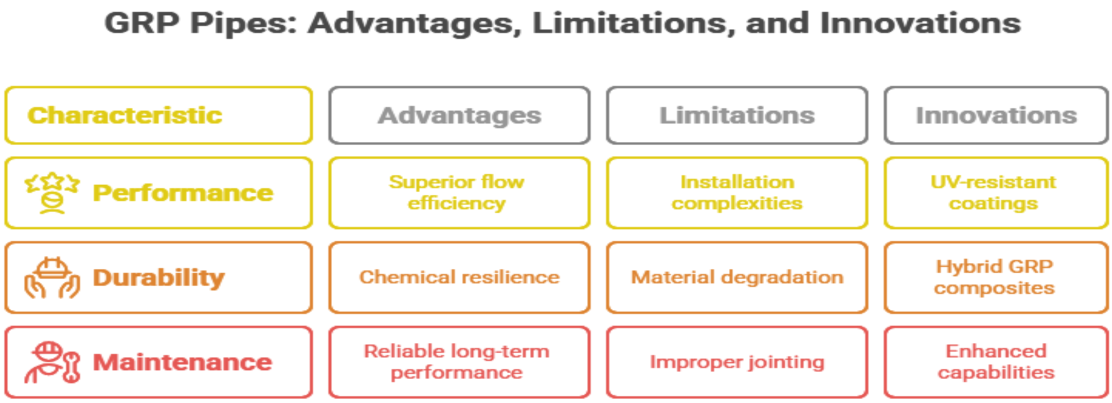


Chart 6. The GRP pipe Advantage and limitation

Results

Glass Reinforced Plastic (GRP) pipes have emerged as a game-changer in modern infrastructure, offering a compelling blend of durability, lightweight design, and environmental sustainability. These pipes, made from polyester resin reinforced with glass fibers, boast exceptional corrosion resistance and a remarkable strength-to-weight ratio, making them a standout alternative to conventional materials like steel, concrete, or PVC. Their eco-friendly profile and adaptability have captured the attention of engineers and project managers, who see GRP pipes as a reliable, cost-effective solution for tackling complex challenges. From sprawling municipal water systems to industrial applications, GRP pipes are proving their worth by delivering long-lasting performance without the heavy resource demands of traditional materials. For those working on civil engineering projects or sustainable infrastructure, these pipes feel like a breath of fresh air a practical yet innovative tool that balances performance with responsibility toward the planet.

The versatility of GRP pipes shines through in their wide-ranging applications, each showcasing their ability to meet demanding engineering needs. In water and wastewater systems, their smooth inner surfaces minimize friction, ensuring efficient flow and reducing energy costs—a small but meaningful win for system operators. In industrial settings, their resistance to harsh chemicals makes them a go-to for safely transporting corrosive substances, while in the oil and gas sector, their non-conductive nature and resilience in punishing environments like offshore platforms are a major draw. Whether it's managing stormwater in urban areas or supporting hydroelectric projects, GRP pipes consistently deliver reliability and efficiency. These real-world successes tell a story of a material that's not just keeping up but pushing boundaries, earning praise from engineers who see it as a trusted partner in building smarter, more resilient infrastructure.Despite their many advantages, GRP pipes come with challenges that demand careful planning and expertise. Installation can be tricky, requiring precise jointing techniques to ensure leak-free, durable systems—something that can feel like a puzzle for even seasoned professionals. Environmental factors, like extreme temperatures or prolonged UV exposure, can lead to issues such as thermal expansion or material degradation, especially in above-ground installations. These hurdles highlight the need for specialized skills and ongoing innovation to keep GRP pipes performing at their best. Fortunately, the industry is stepping up with exciting advancements, from UV-resistant coatings to hybrid composites that boost durability. Collaborative efforts among researchers, manufacturers, and engineers are driving progress, refining installation methods and developing better maintenance practices. With each breakthrough, GRP pipes are solidifying their role as a cornerstone of sustainable infrastructure, paving the way for smarter water networks, resilient energy systems, and a future where innovation meets practicality.

Development and facilitation of sustainable rural development requires knowledge of its components and effective indicators. Theoretically, by relying on two main theoretical approaches in rural studies, the necessary conditions for sustainable development can be provided. These approaches include empowerment and capacity building which can enhance the potential and actual capabilities in rural areas for use in sustainable livelihood development.

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