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Article

Development and characterization of cement paste-coated shape-stabilized phase change materials to achieve net zero energy buildings in desert climates

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Abstract: The development of shape-stabilized phase change materials (SS-PCMs) and their use in construction materials has demonstrated significant potential for improving building energy efficiency and reducing the power consumption of buildings, particularly in desert climates. Despite these benefits, the widespread application of PCMs in civil infrastructure is hindered by their high cost, preparation complexity, leakage issues, and low thermal conductivity. This study addresses these challenges by employing a low-cost, lightweight aggregate (LWA) as a carrier combined with polyethylene glycol (PEG) to develop an LWA/PEG composite PCM. The PEG was incorporated into the LWA pores using a vacuum impregnation technique. Analysis via X-ray diffraction (XRD) and Fourier-transform infrared spectroscopy (FTIR) confirmed that the LWA/PEG composite was successfully prepared without any chemical reactions occurring during the process. However, LWA/PEG composite suffers from leakage problems, which limit its use in building applications. Accordingly, a cement paste coating was developed and applied on LWA/PEG to prepare SS-PCM (CLWA) to prevent the leakage of the composite and enhance its thermal conductivity. Moreover, it was noted that the developed CLWA is chemically stable, and it exhibited outstanding thermal stability after 200 cycles of melting and solidification without signs of leakage. These advantageous characteristics indicate that the CLWA developed can be effectively employed to enhance the thermal efficiency of construction materials to achieve net-zero energy in buildings.

Keywords: shape-stabilized PCMs; lightweight aggregates; polyethylene glycol; thermal energy storage concrete; net zero energy buildings

1. Introduction

The cooling of buildings constitutes a significant portion of energy consumption, particularly in hot and arid regions worldwide. To address this issue, various energy conservation strategies have been explored, including the application of insulation [1], materials, and the development of multi-layered glass windows [2], and the use of phase change materials (PCMs) [3–5]. The use of insulation materials decreases energy consumption by reducing the working time of AC units. However, overheating during the summer increases the energy required to maintain thermal comfort in buildings [6].

Phase change materials (PCMs) are widely utilized as thermal energy storage

mediums. They absorb and store energy during the daytime through the melting process and release it at night through solidification [7]. This cyclic process of melting and solidification enables PCMs to capture and release solar energy, contributing to maintaining a stable ambient temperature within buildings [8]. In desert climates, where ambient temperatures can reach up to 50 °C, the energy demand for air conditioning rises significantly. As a result, renewable energy-based strategies for reducing cooling energy consumption are highly appealing. Thermal energy storage offers a promising renewable energy solution due to the abundant sunlight available in such regions. Utilizing phase change materials (PCMs) to capture and store solar energy as latent heat presents a compelling approach for enhancing energy efficiency. Notably, considerable attention has been directed toward identifying suitable PCMs to improve thermal comfort in buildings [9]. Limited data are available on the use of PCMs in buildings under hot weather conditions. It is essential to develop cost-effective and efficient PCMs tailored for use in temperate and hot weather conditions. PCMs are primarily classified based on their phase transition temperatures into four categories: Solid-liquid, liquid-gas, solid-solid, and solid-gas [10]. Among these, solid-liquid PCMs are preferred for energy storage in buildings due to their stability and compatibility with construction materials [11].

A shape-stabilized phase change material (SS-PCM) is a composite system where the PCM is embedded within a porous supporting medium, enhancing its thermal conductivity, chemical stability, and fire resistance while minimizing the risk of leakage [12–14]. The choice of an appropriate PCM combined with a compatible carrier is crucial for applications in hot weather conditions. Studies indicate that desert regions, such as the Arabian Gulf, experience average peak temperatures reaching up to 50 °C during the summer period [15]. Accordingly, A limited number of organic PCMs, such as paraffins, fatty acids, and polyethylene glycol, are suitable for use [16]. Several studies have explored the incorporation of paraffin with various carriers, owing to its exceptional enthalpy and broad operating temperature range [17–22]. However, paraffin experiences significant volume changes (12.5%) [23] during phase transitions, which can compromise the long-term stability of the PCM system. On the other hand, the high cost of fatty acids restricts their commercial use in building applications. The use of PEG is a better candidate for PCM to be utilized in buildings under desert climates. Depending on its molecular weight, PEG has a broad melting temperature range of 3 °C to 69 °C and is chemically stable. Moreover, PEG is cost-effective, non-toxic, and resistant to erosion [24]. In addition, it does not show phase segregation, has a high degree of chemical and physical stability, and a low supercooling value. Furthermore, PEG has a lower vapor pressure and less volumetric change than paraffin [25]. Those advantages make PEG a good PCM candidate for the development of SS-PCM for building applications.

In building applications, the use of lightweight aggregates as a thermal storage carrier is a relatively new topic. To regulate the temperature inside buildings, Memon et al. [26] used a porous lightweight aggregate as a supporting element in conjunction with paraffin. They came to the conclusion that by lowering building interior temperatures, the produced concrete reduced overall energy use [26]. Comparable results have been

noted with PCM made using lightweight particles and lauryl alcohol [27]. To stop leaks, they applied an epoxy coating to their created SS-PCM. Such a technology is not practical for large-scale applications since it needs specific handling, which raises the cost. In order to attain net-zero energy structures, it is necessary to develop a low-cost SS-PCM by combining lightweight aggregates for building applications in desert regions. Scoria is a naturally occurring lightweight aggregate (LWA) with a gray to black hue that finds use in a variety of applications, including filtering media, lightweight concrete, and cost-effective paint filler [28]. In contrast to other pozzolanic materials, scoria is a natural source of pozzolan that can be utilized in mass concretes, according to Alhozaimy et al. [29]. Additionally, various investigations on the application of scoria in lightweight concrete have been conducted [30–32]. Tchamdjou et al. [32] reported that the use of scoria in concrete enhances its properties, such as improving temperature resistance and decreasing shrinkage [30, 31]. Additionally, it has been confirmed that scoria aggregate can be utilized as an ingredient in Portland cement, to make lightweight concrete, and to make blocks [28].

Several methods can be used to penetrate PCM into the carrier. When compared to alternative impregnation techniques, the vacuum impregnation method demonstrated superior PCM absorption [33–35]. According to Ramakrishnan et al. [36], the paraffin/expanded perlite composite made by the impregnation approach has a 30% higher PCM absorption capacity than the same composite made by the direct method. However, they heat the expanded perlite for 24 h at 105 °C, which is inefficient and energy-intensive.

The current research presents the possibilities of using LWA/PEG composite PCM in building applications for desert climates. Using the vacuum impregnation process, LWA has been utilized as a carrier in conjunction with PEG to develop the LWA/PEG composite. Furthermore, the visibility of using a cement paste coating for the developed composite has been addressed to prepare the SS-PCM (CLWA). The results showed the possibility of the developed CLWA to be utilized in construction applications to achieve net-zero energy buildings under desert climates. Furthermore, the developed CLWA has a high melting temperature of 57.7 °C, which significantly exceeds the melting temperature range of most other PCMs (12–31 °C), as summarized in **Table 1**. The elevated melting point of the developed CLWA makes it particularly suitable for applications in hot weather conditions, where lower melting temperature PCMs would be ineffective.

Table 1. Comparison of characteristics of the developed FS-PCM with those reported in the literature.

PCM	Carrier	Melting Temp (°C)	Melting Enthalpy (J/g)	Impregnation method	Coating	Ref
Paraffin	Macro-PCM	18	N/A	N/A	N/A	D'Alessandro et al. [37]
Fatty acids	Diatomite	31.14	154.97	Direct	N/A	Wang et al. [38]
Paraffin	Expanded clay	29.01	102.5	Vacuum	Epoxy/silica	Memon et al. [39]
Butyl stearate	Expanded perlite	12.56	29.26	Impregnation	N/A	Ma and Bai [40]

Table 1. *Cont.*

PCM	Carrier	Melting Temp (°C)	Melting Enthalpy (J/g)	Impregnation method	Coating	Ref
Lauryl alcohol	Lightweight aggregate	22.96	96.65	Vacuum	Epoxy	Cui et al. [41]
Octadecane	Graphite	28	256.5	Vacuum	N/A	Min et al. [42]
Butyl stearate	Lightweight aggregate	20.09	172	Vacuum	N/A	Niall et al. [43]
Capric acid	Expanded Perlite	N/A	12.13	Vacuum	N/A	Kumar et al. [44]
Fatty acid	Pumice + Graphite	31.14	154.97	Vacuum	Epoxy/Cement	Ren et al. [45]
Paraffin	Commercial PCM	28	180	Microencapsulation	N/A	Lecompte et al. [46]
Myristic acid	Attapulgite	22.12	74.97	Direct mix	N/A	Gencel et al. [47]
PEG	Scoria	57.7	35.8	Vacuum	Cement	Current study

2. Materials and techniques

2.1. Materials

The polyethylene glycol (PEG) used was ultrapure (Purity > 99%), with a molecular weight of 6000 g/mol. A quarry in Saudi Arabia's Western Province provided the lightweight aggregate (Scoria), which has a specific gravity of 1.5, a thermal conductivity of 0.27 W/m·K, and an 11% water absorption rate. The aggregate was coated with ordinary Portland cement (OPC), which ASTM C150 classifies as Type I and has a unit weight of 3150 kg/m^3. Fine sand with a specific gravity of 2.56 and a water absorption of 0.60% by weight was utilized as a fine aggregate.

2.2. Fabrication of LWA/PEG composite

The LWA/PEG composite was prepared using the vacuum impregnation method as shown in **Figure 1**. Varying mass fractions of PEG, starting with 20% up to 100% with 20% increments. The impregnation process was conducted using a vacuum pump with a pressure of 0.1 MPa. First, the LWA particles were placed in a conical glass flask, and then the solid PEG was added while applying the vacuum pressure for 10 min. Then a conical vessel was placed in a hot water bath maintained at a temperature of 70 °C for 2 h. The PEG starts melting and impregnating into the pores of LWA due to the applied vacuum and elevated temperature. After 2 h, the PEG ceases to impregnate into the LWA, as can be noticed by the disappearance of air bubbles in the conical glass flask, which indicates that the pores in the LWA are fully filled with PEG. Accordingly, an impregnation time of 2 h, a temperature of 70 °C, and a pressure of 0.1 MPa were selected as optimum conditions. After several trials, it was observed that adding more than 60% PEG led to a greater loss of PEG compared to the weight gained by the LWA pores, without significantly impacting the overall weight gain of the LWA particles. This loss occurred because the pores of the LWA became fully saturated with PEG, preventing further absorption. Therefore, 60% PEG was identified as the optimal quantity for developing the LWA/PEG composite.

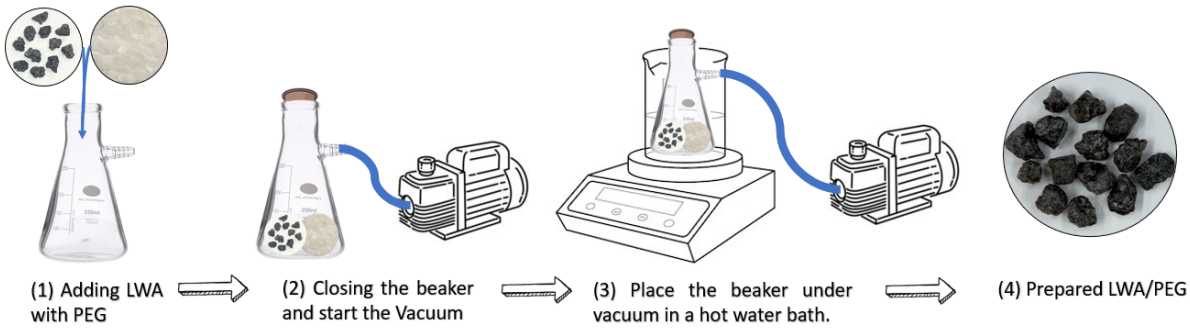


Figure 1. Sketch of the setup used to prepare the LWA/PEG composite.

2.3. Characterization

The mineralogical composition of the materials was determined using a Rigaku X-ray diffractometer (XRD), which used Cu-Kα radiation and operated at 15 mA and 30 kV with a scan rate of 2°/min. A Perkin Elmer (16F PC) spectrophotometer was used to record the Fourier Transform Infrared (FTIR) spectra. The material's morphological analysis was evaluated with a JEOL JSM-6400F FE-SEM running at 10 kV of acceleration voltage. An X-mass detector was also used to record energy-dispersive X-ray spectra (EDS). Differential scanning calorimetry (DSC) measurements were performed by heating 10 mg sealed samples in aluminum pans at a rate of 5 °C/min, under a continuous argon flow of 20 mL/min.

3. Results and discussion

3.1. Particle size distribution of OPC, sand and LWA

The particle size distribution of LWA and fine sand was obtained using sieve analysis, while that of cement was determined using laser diffraction spectroscopy (LDS) using a Microtrac® S3500 laser particle size analyzer, as shown in **Figure 2**. LWA retained on sieve #4 (4.75 mm) was used in the preparation of concrete mixtures. About 84% of LWA was retained on the #4 sieve.

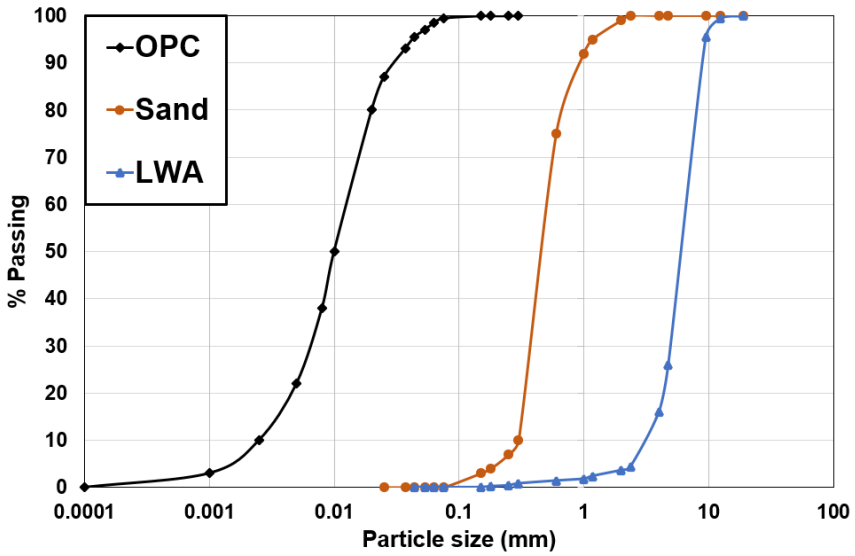


Figure 2. Particle size distribution of OPC, sand, and LWA.

3.2. XRD and FTIR analysis of the LWA, PEG, and the LAW/PEG composites

The XRD peaks for LWA, PEG, and LWA/PEG are shown in **Figure 3**. The peaks located in the range of 20° to 30° 2θ are attributed to the presence of hematite (Fe_2O_3) and anorthite ($Ca(Al_2Si_2O_8)$). The peaks at an angle of 34° 2θ can be ascribed to the formation of aluminum silicate, and those at 60° 2θ indicate the presence of magnetite [48–51]. The LWA/PEG composite exhibited very intense diffraction peaks at 18° and 23° 2θ, which match those obtained for PEG. Moreover, only PEG peaks are present in the LWA/PEG composite, indicating that the developed LWA/PEG formed without any chemical transformation during the injection of PEG into the pores of LWA.

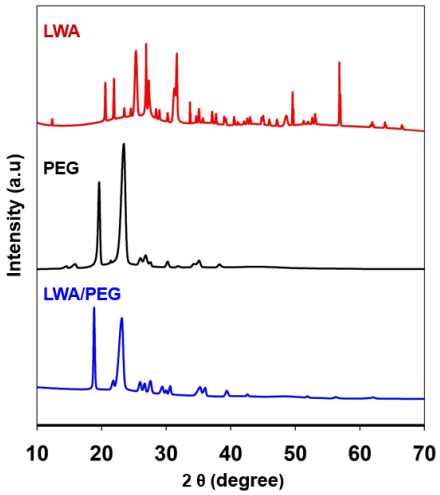


Figure 3. XRD patterns of LWA, PEG, and LWA/PEG composite.

Figure 4 shows the FTIR spectra of LWA, PEG, and LWA/PEG. A broad band in the range of 950 cm^{-1} to 1200 cm^{-1} can be noticed in LWA, which is assigned to the stretching of (Si–O–Si), confirming that SC is mostly composed of silica [49–51]. The spectrum of LWA/PEG closely resembles that of PEG. The lack of significant new peaks in the LWA/PEG spectrum compared to PEG suggests that the formation of the LWA/PEG composite occurs without any accompanying chemical reactions.

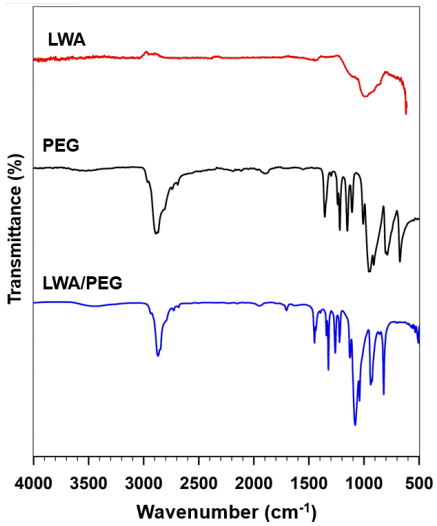
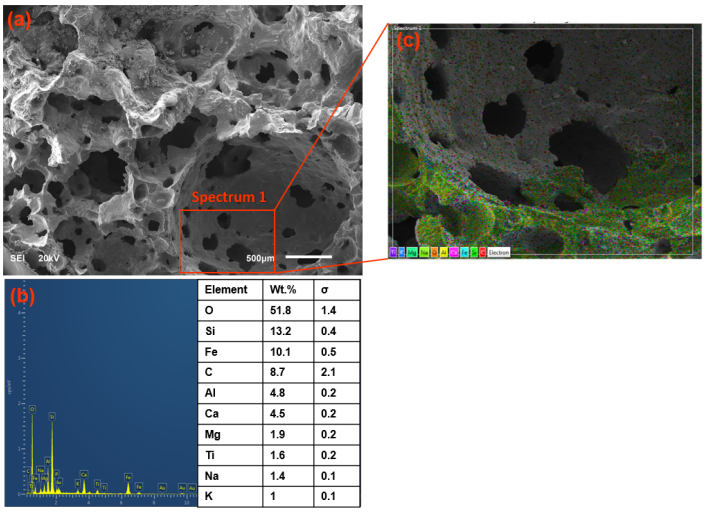


Figure 4. FTIR patterns of LWA, PEG, and LWA/PEG composite.

3.3. Morphology of LWA and LWA/PEG composite

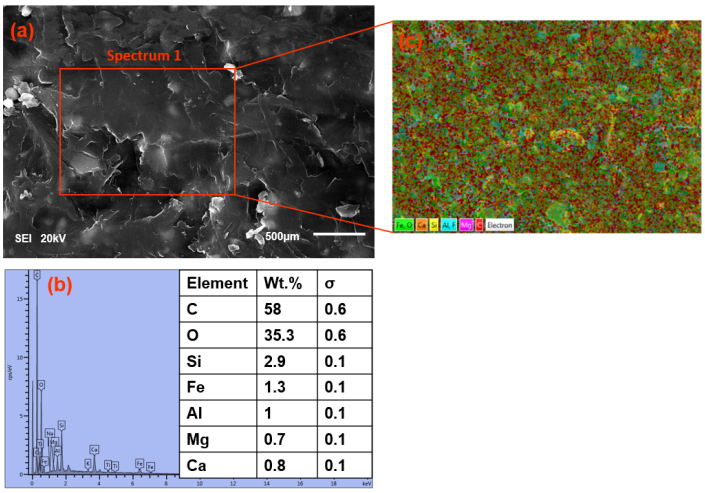
LWA has a highly porous structure, as shown in **Figure 5a**. Varying sizes of Micropores and Mesopores can be noted. This makes the selected LWA have the ability to accommodate a larger quantity of PEG inside these pores to enhance the thermal properties of the developed system. The EDS results in **Figure 5b** show that LWA contains mainly Oxygen (O), Silica (Si), and Iron (Fe), which align with the results obtained from XRD and FTIR. Additionally, the elemental distribution of LWA is shown in **Figure 5c**.



Element	Wt.%	σ
O	51.8	1.4
Si	13.2	0.4
Fe	10.1	0.5
C	8.7	2.1
Al	4.8	0.2
Ca	4.5	0.2
Mg	1.9	0.2
Ti	1.6	0.2
Na	1.4	0.1
K	1	0.1

Figure 5. **(a)** FE-SEM images of LAW and its respective: **(b)** EDS; **(c)** Mapping analysis.

After vacuum impregnation, the pores of the LWA were completely filled with PEG, as illustrated in **Figure 6a**. The elemental analysis of LWA (**Figure 5b**) and the LWA/PEG composite (**Figure 6b**) revealed similar compositions. However, the LWA exhibited higher concentrations of Si, Fe, and Aluminum (Al) compared to the LWA/PEG composite. This reduction is likely due to the presence of PEG occupying the pores of the LWA. Furthermore, the elemental distribution analysis of the LWA/PEG composite presented in **Figure 6c** indicates a uniform distribution of elements, confirming that PEG effectively and comprehensively filled the LWA pores.



Element	Wt.%	σ
C	58	0.6
O	35.3	0.6
Si	2.9	0.1
Fe	1.3	0.1
Al	1	0.1
Mg	0.7	0.1
Ca	0.8	0.1

Figure 6. **(a)** FE-SEM images of LAW/PEG composite and its respective; **(b)** EDS; **(c)** Mapping analysis.

3.4. Differential scanning calorimetry (DSC)

The DSC curves for the melting and solidification processes of LWA, PEG, and the LWA/PEG composite are presented in **Figure 7**. Enthalpy values were calculated from the areas under the DSC curves corresponding to the melting and solidification cycles. PEG exhibited melting and solidification enthalpies of 192.4 J/g and 191.1 J/g, respectively, aligning with values reported by several researchers [52, 53]. The LWA/PEG composite demonstrated a reduction of approximately 64% and 65% in melting and solidification enthalpies, respectively, compared to pure PEG. This reduction can be attributed to the negligible enthalpy contribution of LWA, because the LWA has no latent heat values (No phase change occurs in the LWA before and after heating). This fact reflects the absence of PCMs in the LWA before the impregnation of PEG. Furthermore, the high melting temperature of the LWA/PEG composite of 58.4 °C makes it an appropriate energy storage system for desert climates.

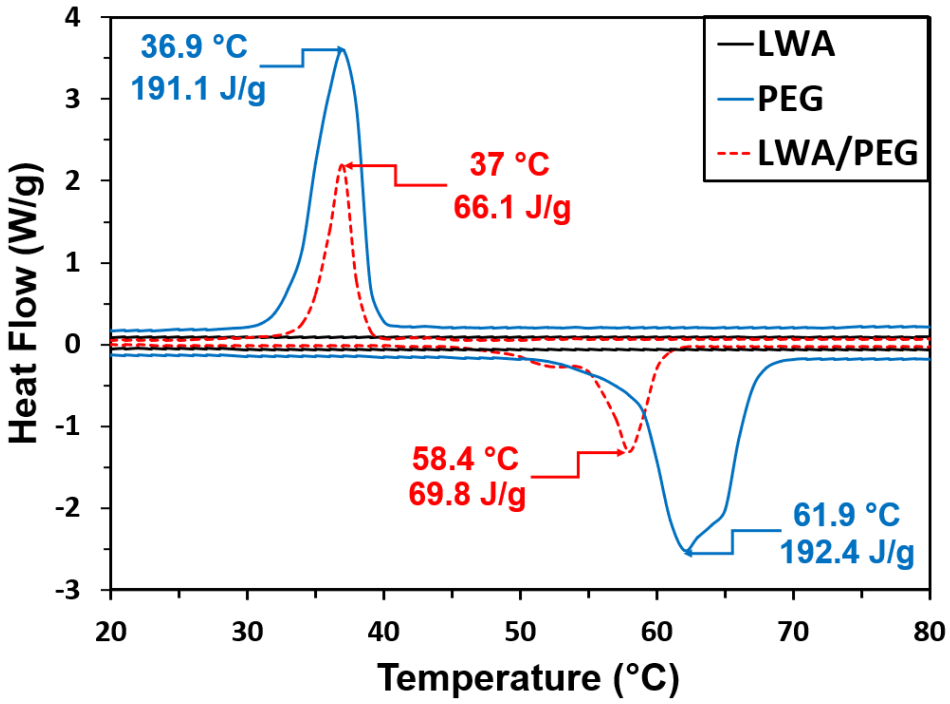


Figure 7. DSC analysis of LWA, PEG, and LWA/PEG.

3.5. Leakage test

Figure 8 illustrates the behavior of PEG and the LWA/PEG composite after exposure to a temperature of 70 °C for 30 min. While PEG completely melted under these conditions, the LWA/PEG composite exhibited minimal leakage, attributed to the presence of PEG on the surface of LWA particles. This observed leakage, as shown in **Figure 8**, highlights a critical limitation, preventing the direct application of leaked PCM into cementitious mixtures due to significant PEG loss [54]. Accordingly, a cement paste coating has been developed to accommodate and prevent the leakage of PEG to obtain the SS-PCM.

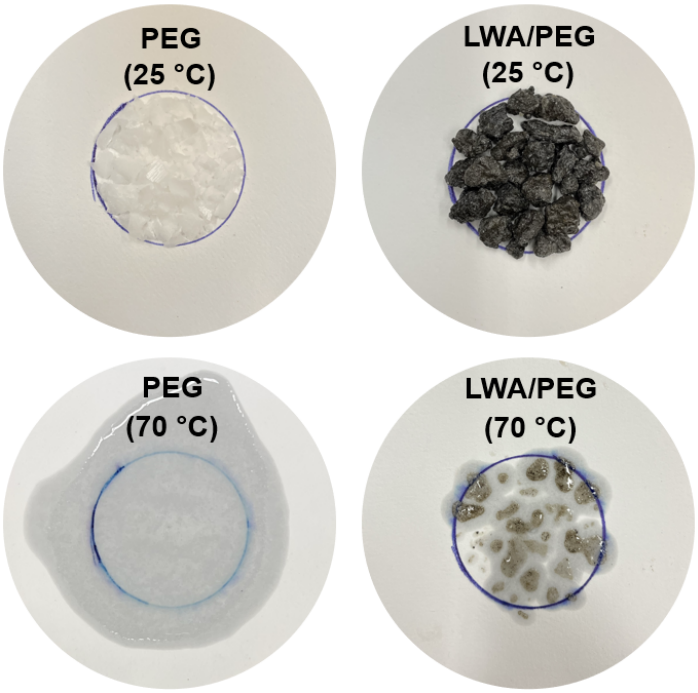


Figure 8. Leakage performance of PEG and LWA/PEG composite.

3.6. Preparation and testing of SS-PCM (CLWA)

3.6.1. Preparation process of CLWA

The cement paste coating was developed by optimizing the LWA/PEG-to-cement ratio through multiple trials. The selected ratio ensured complete coverage of the LWA/PEG particles without leaving excess cement paste. A water-to-cement (w/c) ratio of 0.35 was consistently maintained across all trial mixtures. Initially, the cement and water were mixed for 5 min to achieve a homogeneous paste. Subsequently, the LWA/PEG particles were added to the cement paste and mixed for an additional 5 min until all particles were uniformly coated with a 0.5 mm thick layer of cement paste. The coated LWA (CLWA) was then separated using a sieve and allowed to dry at room temperature for 24 h. After drying, the water absorption and specific gravity of the CLWA were measured in accordance with ASTM C127 [55]. The results showed a water absorption rate of 5.5% and a specific gravity of 1.8, demonstrating the effectiveness of the coating process.

3.6.2. Leakage performance and morphology characteristics of CLWA

The leakage performance of the developed CLWA is presented in **Figure 9**. The CLWA composite exhibited no signs of leakage, even after being subjected to a temperature of 70 °C for 30 min. This result demonstrates that the cement paste effectively encapsulates the PEG within its matrix, successfully preventing any leakage.

The cross-section of CLWA depicted in **Figure 10a** provides insights into the composite inner core structure. As shown in **Figure 10b**, the right portion of the image reveals the formation of calcium silicate hydrate (C–S–H) of the cement coating layer. This observation is further supported by the mapping analysis presented in **Figure 10c**. Additionally, the inner core of the CLWA is filled with PEG, while the cement coating effectively encapsulates the PEG, preventing any leakage from the LWA/PEG

core. This structural configuration highlights the effectiveness of the cement coating in stabilizing the LWA/PEG composite.

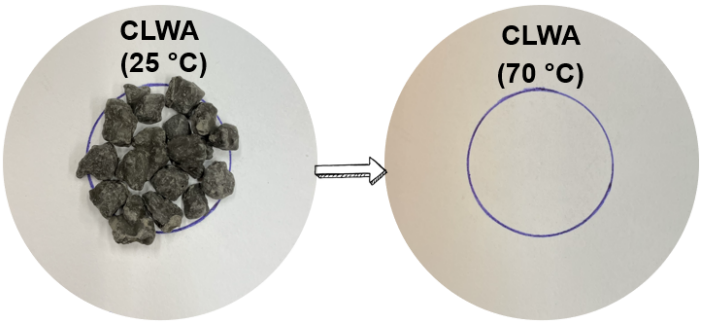


Figure 9. Leakage performance of CLWA.

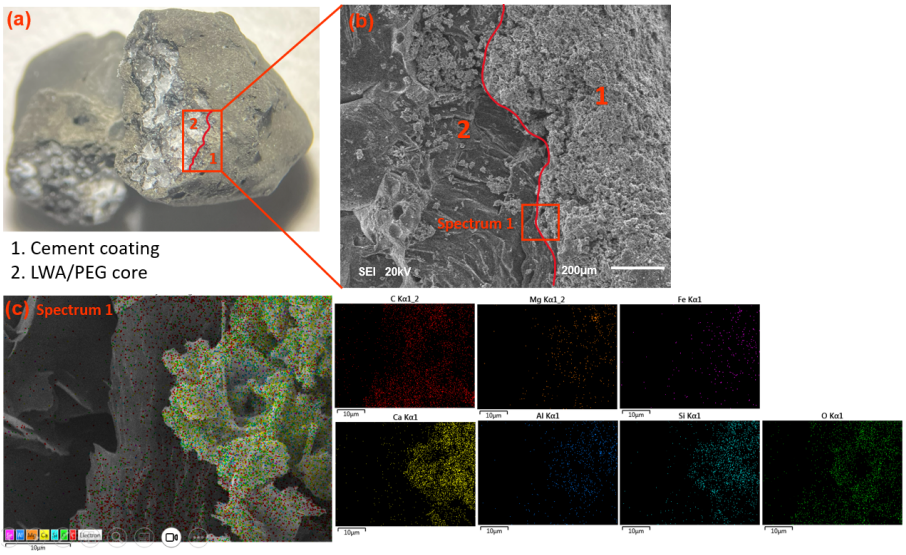


Figure 10. **(a)** Cross-section of CLWA; **(b)** SEM picture of CLWA; **(c)** Mapping analysis of spectrum 1.

3.6.3. Thermal reliability and stability

The thermal reliability of CLWA particles was evaluated by subjecting them to 200 thermal cycles. The DSC results, presented in **Figure 11**, demonstrate that CLWA retains its structural integrity even under rigorous thermal cycling conditions. The material successfully withstood 200 cycles of melting and solidification without significant alterations in its phase change temperatures or enthalpy values. This confirms the excellent thermal stability of the developed CLWA, making it a promising latent heat thermal energy storage material for building applications. Additionally, the melting and solidification temperatures of 56.8 °C and 37.2 °C, respectively, are well-suited for the high ambient temperatures experienced in desert climates during the summer, enhancing the potential of CLWA in reducing energy consumption.

TGA analysis was conducted to assess the thermal stability of the developed CLWA composite. As shown in **Figure 12**, the LWA particles demonstrated no weight loss, indicating their stable thermal behavior. In contrast, the CLWA composite began to lose weight at approximately 350 °C, with the weight loss completing around 400 °C. This loss is attributed to the evaporation of the PEG component from the composite

pores. After this point, the weight of the sample remained constant, indicating that the thermal degradation process had ceased.

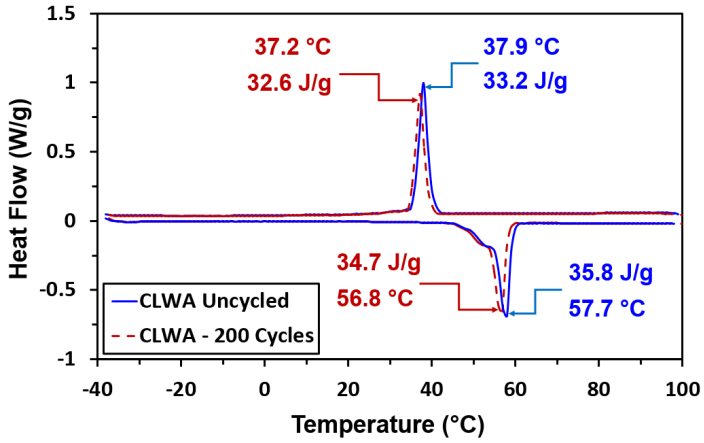


Figure 11. DSC of CLWA composite before and after exposure to 200 thermal cycles.

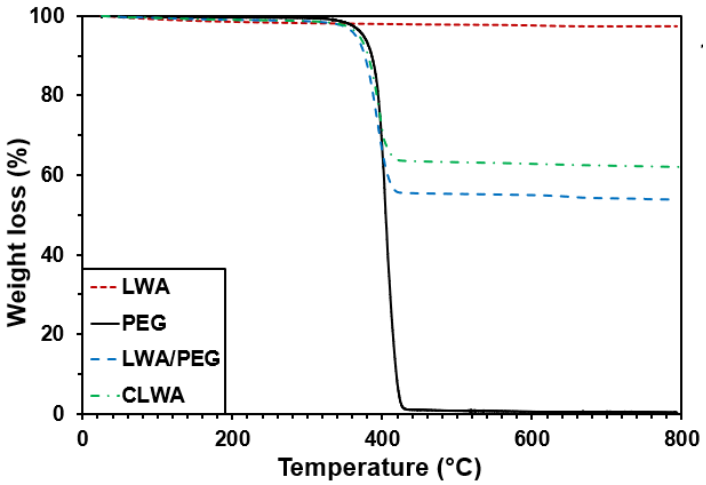


Figure 12. TGA curves of LWA, PEG, LWA/PEG, and CLWA composites.

The weight loss observed in the LWA/PEG composite was 45%, while the weight loss of the CLWA composite was lower. This difference highlights the uniform distribution of PEG within the LWA/PEG composite and supports the conclusion that the preparation process resulted in a homogeneous material. Furthermore, the lower weight loss in CLWA can be attributed to the cement coating applied to the CLWA particles. The cement coating adds mass and enhances the overall stability of the composite, making it more resilient to thermal degradation.

These findings suggest that the developed CLWA composite exhibits robust thermal stability, making it suitable for thermal energy storage applications, particularly in environments such as desert climates. Additionally, the stable thermal behavior of the CLWA composite ensures its long-term reliability in energy storage systems, contributing to efficient thermal regulation in buildings.

Table 2 lists the thermal activity values of PEG and the prepared composites with/without coating.

Table 2. Thermal activity of PEG, LWA/PEG, and CLWA.

Sample	Melting process		Solidification process		Thermal properties					
	T_m (°C)	ΔH_m (J/g)	T_f (°C)	ΔH_f (J/g)	ΔT_s (°C)	E_{eff} (J/g)	R (%)	E (%)	φ (%)	Γ (%)
PEG	61.9	192.4	36.9	191.2	24.9	192.4	-	-	-	100
LWA/PEG	58.4	69.8	37.0	66.1	21.4	148.5	36.3	35.4	97.6	77.2
CLWA	57.7	35.8	37.9	33.2	19.8	76.2	18.6	17.9	96.7	39.6

All the parameters were derived from the following equations:

$$R = \frac{\Delta H_{m,\,com}}{\Delta H_{m,\,PEG}} \times 100\% \tag{1}$$

$$E_{eff} = \frac{\Delta H_{m,\,com}}{X_{PEG}} \tag{2}$$

$$E = \frac{\Delta H_{m,\,com} + \Delta H_{f,\,com}}{\Delta H_{m,\,PEG} + \Delta H_{f,\,PEG}} \times 100\% \tag{3}$$

$$\varphi = \frac{\frac{\Delta H_{m,\,com} + \Delta H_{f,\,com}}{R}}{\Delta H_{m,\,PEG} + \Delta H_{f,\,PEG}} \times 100\% \tag{4}$$

$$\gamma = \frac{\Delta H_{m,\,PEG}}{(x_{PEG} \times \Delta H_{m,\,PEG})} \times 100\% \tag{5}$$

Where: T_m = Melting temperature, ΔH_m = Melting latent heat, T_f = Solidification temperature, ΔH_f = Solidification latent heat, ΔT_f = Supercooling, E_{eff} = Efficient energy per unit mass of PEG as shown in Equation (2) were calculated according to Li et al. [56], R = Impregnation ratio, E = Impregnation efficiency and φ = Energy storage capacity [57] and γ = Heat storage efficiency. In the above equations, com indicates PCM composite (LWA/PEG, CLWA) and X_{PEG} = PEG weight fraction in PCM.

The melting enthalpies of LWA/PEG and CLWA composites decreased by 31% and 64%, respectively, compared to pure PEG, as detailed in **Table 2**. This reduction is attributed to the negligible enthalpies of LWA and the cement paste in CLWA composites. However, the supercooling values of CLWA and LWA/PEG composites were reduced by 14% and 20.5%, respectively, compared to PEG. Notably, the high heat storage efficiency of the CLWA composite makes it a promising candidate for efficient thermal energy storage systems. These characteristics demonstrate the feasibility of employing CLWA in building applications under desert climate conditions. Furthermore, the utilization of CLWA can deliver significant environmental, economic, and sustainable benefits, enhancing and improving the overall quality of buildings subjected to high temperatures in desert environments.

4. Conclusion

In this study, a novel cement-coated LWA/PEG-based PCM was developed to improve the thermal performance of buildings. The following conclusions can be drawn from experimental work.

- A vacuum impregnation technique was effectively utilized to impregnate

polyethylene glycol (PEG) into lightweight aggregate (LWA). The developed LWA/PEG composite exhibited uniform PEG distribution within its pores without any chemical transformations during preparation, as confirmed by XRD and FTIR analyses.

- Cement coating was successfully applied to LWA/PEG composites, addressing the critical issue of PCM leakage. The cement paste encapsulated the PEG, ensuring structural stability and preventing leakage, even under elevated temperatures.
- The CLWA composite exhibited excellent thermal reliability, retaining its structural and thermal properties after 200 cycles of melting and solidification. The negligible changes in phase change temperature and enthalpy demonstrate its suitability for long-term thermal energy storage applications.
- The CLWA composite achieved high heat storage efficiency (96.7%) and demonstrated significant reductions in supercooling compared to pure PEG. These attributes make it a viable material for efficient latent heat thermal energy storage (LHTES) systems.
- The melting and solidification temperatures of CLWA (57.7 °C and 37.9 °C, respectively) align well with the high ambient temperatures experienced in desert climates. This makes it particularly effective in reducing cooling energy consumption in buildings under such conditions.
- The developed CLWA composite is a promising candidate for net-zero energy buildings in desert climates. Its ability to store and release thermal energy efficiently enhances the thermal performance of construction materials, ensuring comfort and sustainability in extreme weather conditions.

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Article

Exploring the factors contributing to public sector building construction delays and mitigation solutions in Pakistan

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Abstract: The construction industry worldwide experiences significant project delays, particularly in the public sector of the construction industry. Construction delays have a substantial effect on the economic development of areas and employment opportunities for the local population, particularly in underdeveloped regions like Balochistan, Pakistan. This research examines the most significant and influential factors causing delays in government building construction within Balochistan, Pakistan. The study presents mitigation solutions and strategies proposed by experts using a Delphi technique for the critical and influential delay factors. The questionnaire survey to collect responses from participants consists of 24 delay factors, which are derived from existing literature and experts' consultation. A satisfactory degree of data reliability was demonstrated by the survey's 78% response rate. Cronbach's alpha and split-half reliability tests were used in SPSS to assess internal consistency. Delay factors were categorized and ranked based on perceived relevance using the Relative Importance Index (RII). Additionally, to provide an alternate prioritizing of delay variables, the Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was used with Microsoft Excel and common mathematical formulations. To confirm the stability and robustness of the rankings, a comparison of the RII and TOPSIS results was done. The results establish the groundwork for further studies on building delays and give insightful information for decision-making in the public sector.

Keywords: construction delays; public sector; mitigation solutions; data analysis; expert stakeholders; Pakistan

1. Introduction

The construction sector is crucial for a nation's economic growth. Nations with robust economies invariably possess highly advanced construction sectors [1]. The worldwide construction industry is experiencing rapid expansion, with its market value projected to rise from USD~15.2 trillion in CY23 to USD~16.0 trillion in CY24, demonstrating a compound annual growth rate (CAGR) of ~5.1%. In fiscal year 2023, Pakistan's construction industry reached a market size of roughly PKR 2190 billion, accounting for 2.7% of the country's overall GDP [2]. Balochistan, Pakistan's largest and resource-rich province, offers significant potential for trade and connectivity. The China-Pakistan Economic Corridor (CPEC) is creating new job opportunities for locals in various sectors [3], particularly construction and transportation. Numerous infrastructure projects, encompassing road networks, port

facilities, and power generation plants, are employing skilled workers, which in turn benefits the local community and contributes to the Country's economy.

Construction projects usually take a long time to complete and are carried out on temporary sites by teams that are brought together just for that specific job. These teams often include multiple parties with different goals and priorities, and they disband once the project is finished, making the construction process even more complex and unpredictable. The construction industry is project-based, highly complex, and often slow to embrace change. Its processes are typically fragmented, which contributes to frequent delays. These delays usually stem from a mix of causes that are often interconnected [4]. While the main stakeholders in a construction project, the owner, consultant, and contractor, are often seen as the primary sources of delays, it's important to recognize that other parties involved can also play a role in causing delays [5]. In the field of construction, a delay is defined as an extension beyond the agreed-upon completion date or a time overrun in project delivery that exceeds the timeline established by all involved parties. Most construction projects fail to meet their scheduled completion dates. Globally, the construction industry faces significant challenges due to these delays in project timelines [6]. A construction delay is generally understood as the failure to complete a project within the agreed timeframe. Even with modern technology and advanced project management and engineering tools, delays remain a common and challenging issue in the industry [7–9]. In Pakistan, numerous projects have experienced delays in the past and continue to face delays. These projects include the reconstruction of roads damaged by earthquakes and floods, the development of Chinese industrial zones in Punjab, the CPEC roadways in Sindh, KPK, and Baluchistan, the Port Tower Complex by KPT, Pakistani Motorways and National Highways, and the Kalabagh Dam, among others. These instances highlight a widespread pattern of construction delays and challenges in Pakistan's infrastructure development efforts [10, 11]. China's Belt and Road Initiative is a major infrastructure development effort across Asia, with large-scale projects like the China-Pakistan Economic Corridor (CPEC) at its core. Valued at over USD 60 billion, CPEC is primarily aimed at boosting infrastructure development in Pakistan [12]. Clients and contractors are affected differently by construction delays. Negative outcomes for clients include lower income, lower productivity, prolonged dependency on current facilities, and a lack of available rental spaces. Conversely, contractors have to deal with issues such as greater labor prices, longer workdays, higher material and equipment costs, and increased expenses [10]. Construction delays frequently result in disagreements, schedule and money overruns, and even project termination. These detrimental effects demonstrate the necessity of efficient methods for delay analysis and management. Accurately identifying delay mitigation strategies is critical for project success because proactive project management helps prevent issues early and promotes continual improvement [7].

The authors investigated the reasons behind building delays in cold storage projects in the Philippines. The study found a number of key causes of these setbacks, such as labor shortages, permit delays, rework requirements, procurement problems, and challenges with testing protocols. The study emphasized the importance of anticipatory risk management using the Relative Importance Index (RII) approach.

In order to improve project efficiency, it also urged industry stakeholders to address these key delay drivers [9]. The 37 major causes were found in a study on delay factors in public, mixed, and private construction projects in Bangladesh. Weather, contract modifications, and construction errors were the main causes of delays, which varied depending on the form of funding. The study provided professional recommendations for reducing delays in various situations [1]. Workforce shortages, decreased productivity, budgetary difficulties, and client-requested modifications were shown to be the main causes of delays in Indian building construction. In order to reduce setbacks and improve project outcomes in the residential building industry, they promoted improved project organization, supervisory procedures, and continuous monitoring using the RII technique [13]. Another study on construction delays in Malaysia analyzed 52 common causes and identified 20 critical factors. A survey of 148 professionals revealed top causes like poor planning, client changes, financial issues, and communication failures. The study highlighted the significant role of contractor-related problems and provided valuable insights for improving project management and reducing construction delays [14]. The authors studied delays in Sri Lanka's public-sector building projects. A survey of clients, consultants, and contractors identified key delay causes, with improper project management topping the list. Other factors included labor shortages, financial issues, scope changes, delays in payments, approvals, and communication breakdowns. Spearman's test showed agreement among stakeholders [15]. A similar study investigated delay causes in Indonesia's EPC projects, surveying 41 owners, 14 contractors, and 12 consultants. Key factors included procurement delays, financial issues, poor planning, and communication problems. The study found contractor-related delays were most significant, with strong agreement among respondents on the ranking of factors [16]. Another research conducted in Nigeria investigated the factors contributing to construction project delays. The study identified several causes, including modifications to designs, financial challenges, and ineffective management practices. These delays resulted in various negative outcomes, such as prolonged project durations, cost overruns, and conflicts in resource allocation. To improve the performance of the construction industry and reduce disruptions, the researchers suggested implementing more effective budgeting strategies, ensuring prompt communication, finalizing designs before commencement, and enhancing project management techniques [17]. Another study investigated delay factors in Iran's construction industry using hierarchical analysis and data from 64 experts. Key issues include sanctions, government policies, financial insolvency, design flaws, managerial inefficiencies, and technical challenges. The study prioritized these factors and proposed solutions to optimize project timelines and costs [18]. Similarly, another study discovered critical causes of delays. They studied and arranged them into three categories: contractor delays, owner delays, and external delay factors. This study was concluded that Contractor-related delays are the most common and often cause the most serious disruptions to construction projects. In addition, delays caused by owners and material shortages are also considered major risks. On the other hand, delays related to labor, equipment, and external factors are seen as less critical

concerns [5]. The reasons behind delays and disruptions in construction projects were explored along with their effects. The study adopted the relative importance index to identify and rank the delay factors. The study discovered that poor project management, funding problems, design changes, delay in payment to contractors, information delays, disagreement on the valuation of work done, and compensation issues are the main reasons for construction delays and disruption [19]. The causes of the delay factor and their interaction in construction projects were explored which identified 65 causes of delays and categorized them as client, plant or equipment, labour, design team or consultant, external factors, communication, and contractor issues. The top 4 delay factors in this study, identified and ranked, are Contractors' excessive workload, poor planning and scheduling by the contractor, change orders by the client, and financial issues [20]. The study determined the critical factor of delays using Z-number theory for the evaluation and prioritization of delay factors. The critical delay factors identified and ranked are cost inflation, contractor financial issues, inadequate project supervision and management, adverse weather conditions, insufficient skilled labour, delays in government document approvals, and unforeseen cost escalations [21]. The authors investigate the causes of time overruns in residential construction projects across Pakistan, using the Relative Importance Index (RII) to evaluate key factors identified by industry experts. The study identified that material price fluctuation, financial difficulties of contractors, and underestimation of project duration are the key factors in the construction industry [22]. The study conducted to explore the main factors causing delays in high-rise project delivery in Nigeria, using a case study approach to identify the core reasons behind these delays. The collected data were analyzed using the Relative Importance Index (RII), mean score, Kruskal–Wallis test, and content analysis. Lack of credit facilities, cash flow problems, and client-related issues are critical delay factors identified in this study [23]. The examined delays in Pakistan's construction industry identified key causes like poor coordination, material shortages, compressed schedules, inexperienced contractors, and an unskilled workforce. The study provides valuable insights to help stakeholders address these issues and improve project outcomes effectively [24].

There are studies conducted on the construction industry of Pakistan, but there is no single study on the construction industry of Balochistan due to multiple reasons, like security concerns. Our research discovered a region-specific delay factor in the construction industry of Balochistan. Flood, security challenges, political unrest, and lack of development are the delay factors that exist in Balochistan. The World Bank [25] granted a $213 million fund for reconstruction in Balochistan to recover from the loss of the flood that occurred in 2023. The Asia development Bank and Japan [26] granted a $5 million fund for loss recovery in Balochistan due to the flood that occurred in 2023. Similarly, security challenges, political unrest, and lack of development are the delay factors unique and specific to this region. The study [27] highlights that the China-Pakistan Economic Corridor (CPEC), particularly through the development of Gwadar Port in Balochistan, is expected to significantly boost the region's growth. However, the study also points out that security threats pose a serious challenge to the successful implementation and overall impact of this major project.

While a lot of research has been done on construction delays in developing nations, political unrest and security threats are typically considered minor considerations. This work fills an obvious research vacuum because there is still a dearth of empirical research on areas where these elements are structural rather than incidental. This study is based on an institutional and project governance viewpoint, which holds that political, institutional, and socio-environmental elements, in addition to technical and managerial ones, influence the performance of construction projects. Project delays are exacerbated in volatile and undeveloped areas like Balochistan by the interaction of traditional contractor and client-related factors with ineffective government, security limitations, and political meddling.

Even though building delay studies are well-established in the literature, the majority of current research sees delay factors as essentially universal across geographies, paying little consideration to places with weak institutional capability, political instability, and security issues. By presenting empirical data from Balochistan, where governance limitations, security threats, and sociopolitical impacts are structural rather than incidental. This study contributes to the body of knowledge on construction management. In addition to validating often-reported delay reasons linked to contractors and clients, the study shows how region-specific factors, including political meddling, insecurity, bureaucratic rigidity, and post-disaster recovery pressures, intensify and modify these factors. The study provides a strong framework for prioritization and validation while incorporating contextual interpretation through the integration of the Relative Importance Index (RII), TOPSIS, and expert-based Delphi analysis. The results extend the applicability of delay research beyond traditional technical explanations, both theoretically by connecting construction delays to institutional and political-risk dimensions and practically by providing mitigation strategies specific to fragile and underdeveloped regions.

2. Methodology

In order to examine delay issues in public-sector building construction projects in Balochistan, Pakistan, this study used a mixed-methods research methodology that combined quantitative prioritizing techniques with qualitative expert validation. To guarantee the findings' robustness, triangulation, and contextual relevance, the methodological framework incorporates three well-known tools: the Delphi approach, the approach for Order Preference by Similarity to Ideal Solution (TOPSIS), and the Relative Importance Index (RII). Although the rankings produced by RII and TOPSIS were identical, the application of TOPSIS served as a robustness and validation exercise, reinforcing the consistency and reliability of the prioritization results. The qualitative phase used expert consensus to refine and validate mitigation techniques, and the quantitative phase identified and rated important delay reasons. The qualitative aspect involves extracting data from existing literature and expert opinions. Concurrently, the quantitative component utilizes a 4-point Likert scale questionnaire survey to gather clear responses from participants based on their level of agreement or disagreement. The study was conducted in Balochistan, Pakistan, an underdeveloped and unexplored region prone to construction delays. Responses were collected from

various stakeholders in public sector building construction projects, including clients, contractors, consultants, and designers. The responses were collected in the same order from the client, contractor, consultant, and designer. The survey was distributed to experienced professionals in the construction industry. To ensure participant comfort and willingness to share construction sector information, the questionnaire's demographic section excluded personal and confidential information, focusing only on age, education, experience, and participant names. The study imposed no limitations or restrictions on data collection, accepting input from any project stakeholders currently involved in construction projects or with relevant experience. **Figure 1** represents the research methodology applied in this study.

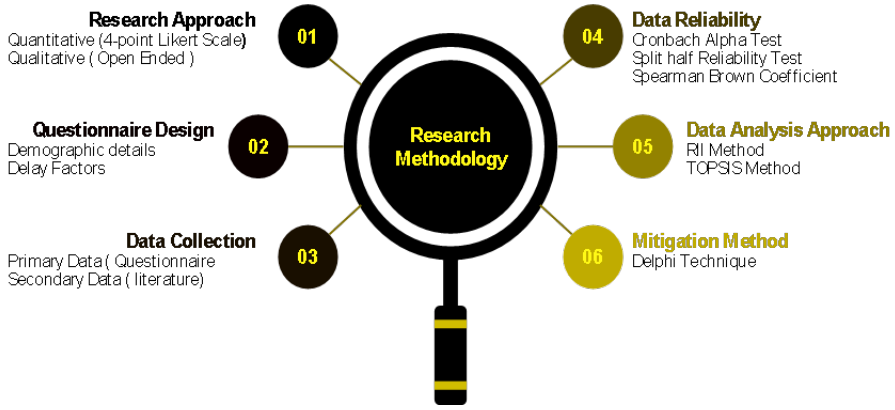

Figure 1. Hybrid methodological framework integrating quantitative prioritization (RII and TOPSIS) with qualitative expert validation (Delphi technique) for context-sensitive delay analysis.

2.1. Questionnaire design

The survey instrument is divided into two parts. The initial segment gathers demographic information from participants, including their age, experience, name, and educational background. The subsequent portion presents twenty-four construction delay factors identified through the literature review. An additional open-ended space is provided at the survey's conclusion for respondents to note any unlisted delay factors. The twenty-four delay factors are structured as closed-ended questions with multiple-choice options. A 4-point Likert scale was adopted to eliminate neutral responses and encourage respondents to express a clear position, an approach commonly used in construction management perception studies. A 4-point Likert scale is employed, offering four response options ranging from strong agreement to strong disagreement for each delay factor. The research focused on developing nations and countries neighboring Pakistan, and those with construction environments similar to Balochistan, Pakistan, for an extensive literature review. Twenty-one construction delay factors were selected from this review based on their RII ranking. Research conducted in India, Bangladesh, Pakistan, Malaysia, KSA, Sri Lanka, Ethiopia, Afghanistan, Indonesia, Nigeria, Egypt, Iran, and South Africa identified these 21 factors contributing to construction delays. The remaining three factors were added after consulting construction experts familiar with Balochistan's construction industry. These additional factors include impractical allocation of resources, insecurity and

warlord intervention, and influence of social disturbance and local culture.

2.2. Data collection

This study consists of primary data, which is collected through a questionnaire survey, and secondary data, which is extracted from existing literature. The survey instrument was distributed to participants via various channels, including Google Forms, email, and social media platforms. Additionally, researchers conducted face-to-face interviews by visiting respondents' locations to administer the questionnaire. To address language barriers, the English questionnaire was translated into Urdu, the local language. Researchers expressed gratitude for the participants' cooperation and willingness to provide data. In some instances, further clarification was necessary to reassure respondents about data confidentiality. The questionnaire was distributed to 120 individuals, with 94 completed responses received, yielding a satisfactory response rate of 78%. However, due to political unrest, accessing government organizations and officials occasionally proved time-consuming.

2.3. Data reliability

Reliability analysis assesses the internal consistency and stability of data collected through survey scales [28]. To analyze the questionnaire data, this study employed the Statistical Package for Social Sciences (SPSS) software. In this research, the initial test performed using SPSS was a cleaning test. This procedure was carried out to ensure the absence of missing data and typographical errors throughout the entire dataset. As reported [29], in-depth interviews with industry experts offer valuable insights, while a pilot test helps spot any issues with data collection. Additionally, multicollinearity tests are used to ensure the data is reliable and consistent.

2.3.1. Cronbach's alpha test

To evaluate the reliability and internal consistency of the survey questions related to Construction Delay factors, researchers employed the Cronbach's alpha test using SPSS software [30]. A Cronbach's alpha value exceeding 0.7 is considered acceptable for further analysis, indicating sufficient internal consistency within the questionnaire [9]. This study utilized Cronbach's alpha to measure the coherence of participants' responses across all delay-related questions. A high alpha score suggests that respondents' answers to individual delay factors are consistent, implying a strong interconnection among these factors within the broader context of construction delays [9]. This consistency demonstrates that participants view these various factors as interrelated causes of delay, validating the sets of delay factors as a reliable and unified group for analysis [9]. The overall Cronbach's alpha (α) value calculated in this study is 0.837. The observed coherence indicates that the 24 construction delay factors examined in this research function effectively as a dependable set, collectively representing respondents' understanding of the causes behind construction project delays. The standard ranges used for the Cronbach's alpha value are given in **Table 1**.

Table 1. Cronbach's alpha (α) and internal consistency.

Cronbach's alpha	Internal consistency
$\alpha \geq 0.9$	Excellent
$0.8 \leq \alpha < 0.9$	Good
$0.7 \leq \alpha < 0.8$	Acceptable
$0.6 \leq \alpha < 0.7$	Questionable
$0.5 \leq \alpha < 0.6$	Poor
$\alpha < 0.5$	Unacceptable

2.3.2. Split-half reliability test

To evaluate the internal consistency of a questionnaire, a split-half reliability test was conducted using SPSS software. This method involves dividing the questionnaire into two equal parts and assessing their correlation. The test aimed to examine the consistency between these two data sets and served as a cross-validation measure alongside Cronbach's alpha. The questionnaire in this study comprised twenty-four [24] construction delay factors. The items were separated into two halves, and their correlation was determined. A split-half coefficient exceeding 0.7 is considered acceptable, allowing the study to proceed with confidence [31]. In this case, the calculated split-half reliability coefficient was 0.810. The correlation provides an initial indication of consistency between the two halves of the questionnaire, with a higher correlation suggesting better reliability. The delay factors were divided into odd and even parts, with Part 1 containing odd-numbered factors and Part 2 containing even-numbered factors. Using SPSS software, Cronbach's alpha was calculated for each half and then compared.

2.3.3. Spearman-Brown coefficient

In addition to the split-half reliability test, the Spearman-Brown coefficient was computed as an enhanced reliability measure. Split-half reliability testing typically underestimates the true reliability of the entire data set because it uses only half of the items in each section of the questionnaire. The Spearman-Brown coefficient addresses this shortcoming by evaluating the consistency between two halves of a test, combining their scores, and treating them as a single data set [32]. This method helps assess the reliability of the complete data set. In this study, the Spearman-Brown coefficient value of 0.895, which exceeds 0.7, indicates strong internal consistency.

3. Data analysis

3.1. Relative importance index (RII)

In construction management research, RII is frequently used to rank ordinal survey data and enable direct comparison of factor significance. A greater perceived impact on project delays is indicated by higher RII scores. RII was the main technique used in this study to determine the most important delay factors influencing public-sector projects in the study area. The RII values range from 0 to 1, with values closer to 1 considered more significant and those near zero deemed less important [33–35]. The standard ranges used for the RII are given in **Table 2**.

Table 2. RII values and importance level.

RII values	Importance level
0.8 < RII < 1.0	Very High
0.6 < RII < 0.8	High
0.4 < RII < 0.6	Average
0.2 < RII < 0.4	Low
0.0 < RII < 0.2	Very low

Equation (1) is used for the calculation of RII values.

$$\text{RII} = \sum \text{W}/(\text{A} \times \text{N}) \tag{1}$$

Where W represents the weight assigned by respondents to each delay factor, ranging from 1 to 4. N denotes the total number of participants, which is 94 in this case. A signifies the highest weight on the Likert scale, set at 4 for this research [33]. The survey was structured to gauge respondents' level of agreement or disagreement. For calculating the RII values, the questionnaire offered four options: 'Strongly agree' was given a weight of 4, 'Agree' was assigned 3, 'Disagree' received 2, and 'Strongly Disagree' was allocated 1.

3.2. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS)

The research employed complementary multi-criteria validation method to evaluate construction delay factors using the TOPSIS score, also referred to as the closeness coefficient (CCi). TOPSIS did not generate rankings different from RII, its application strengthened confidence in the stability of the prioritization. The study utilized the RII approach. The ranking of construction delay factors produced by RII was identical to that generated by TOPSIS. The procedure for implementing this method is outlined in the following steps [36–38].

Step 1: Using Microsoft Excel, a matrix was created to evaluate delay factors based on respondent ratings using a Likert scale. Initially, the average score for each delay factor was determined by considering all participant responses.

Step 2: To facilitate easy comparison, the original values for each delay factor were transformed into a scale ranging from 0 to 1 using a specified Equation (2). This process, known as normalization, was employed to calculate the standardized value of each delay factor.

$$\text{Normalized Score} = \frac{Mean\ Score\ of\ Factor}{\sqrt{\sum (Mean\ scores)^2}} \tag{2}$$

Step 3: The normalized values of the delay factors were used to determine the Ideal (A^+) and Negative Ideal (A^-) solutions. The highest normalized value represented the Ideal solution (A^+), while the lowest normalized value corresponded to the Negative Ideal solution (A^-).

Step 4: The distance to the ideal solution, represented by (D^+) signifies the delay factor with the closest proximity to the ideal solution. Conversely, (D^+) also denotes

the delay factor furthest from the ideal solution, which is considered the least significant and critical. The distance to the negative ideal solution is symbolized by (D^-). The delay factor nearest to the negative ideal solution is deemed the least impactful, while the one farthest from it is regarded as the most influential and critical. Calculations for both the distance to the ideal solution and the distance to the negative ideal solution were performed using Equations (3) and (4).

Distance to Ideal Solution (D^+)

$$D^+ = \sqrt{\sum(Normalized\ score - Ideal\ Solution)^2} \tag{3}$$

Distance to Negative Ideal (D^-)

$$D^- = \sqrt{\sum(Normalized\ score - Negative\ Ideal\ Solution)^2} \tag{4}$$

Step 5: The TOPSIS score, also known as the closeness coefficient, falls between 0 and 1. A delay factor with a closeness coefficient of 1 represents the optimal solution, indicating the most significant and prevalent delay factor. Conversely, a delay factor with a closeness coefficient of 0 signifies the negative ideal solution, representing the least impactful and least common delay factor. The TOPSIS Score (Closeness coefficient CCi) was determined using Equation (5).

$$\text{CCi} = \frac{D^-}{D^+ + D^-} \tag{5}$$

Step 6: The construction delay factors were arranged in descending order according to their TOPSIS score or closeness coefficient. Factors with the highest closeness coefficient (CCi) were placed at the top of the list, while those with the lowest CCi were positioned at the bottom. This ranking system organized the factors from most significant to least significant in terms of their impact on construction delays.

4. Delphi technique for ranked factors

The Delphi technique is a structured way to gather expert opinions and reach a consensus. It involves multiple rounds of questionnaires, where participants receive feedback between each round, helping to identify and rank the most important delay factors [39]. The Delphi method was used in this study to create mitigation plans for the delay reasons that were found. The top 10 criteria were chosen for additional analysis after being ranked using the RII and TOPSIS methodologies. These ten criteria were then subjected to the Delphi technique to produce mitigation strategies. There were two survey rounds in the study. In the first phase, experts were asked to provide remedies for the mentioned delay sources using an open-ended questionnaire. The experts were tasked with selecting and prioritizing the suggested mitigation strategies after receiving summarized replies in the second round. However, consensus stabilization was observed by the second round.

5. Results and discussion

The proposed conceptual framework, which sees construction delays as the result of interacting contractor-related, client-related, external, and institutional-governance issues, informs the structure of the findings discussion. This highlights how government capability, political influence, and security conditions combine with traditional project management shortcomings to exacerbate delays in vulnerable areas like Balochistan. The investigation employs descriptive statistics (including Mean and standard deviation), reliability assessments (split-half and Cronbach's Alpha), TOPSIS, RII, and Delphi techniques. The findings are showcased to illustrate the fundamental characteristics of the survey data, verify the questionnaire's reliability, categorize and prioritize delay factors, and ultimately, outline mitigation strategies proposed by experts in the construction industry.

The current study concentrated exclusively on Balochistan's construction industry in Pakistan. A survey was distributed to 120 individuals with relevant experience in the region's construction sector, resulting in a 78% response rate. Participants included various stakeholders such as property owners, building contractors, and consultants directly involved in the local construction industry. **Figure 2** indicates that the majority of respondents possess at least 16 years of formal education. **Figures 3** and **4** demonstrate that most respondents have substantial professional experience and age. Respondents' experience levels were recorded; no weighting or stratified analysis was applied; therefore, experience is reported descriptively only.

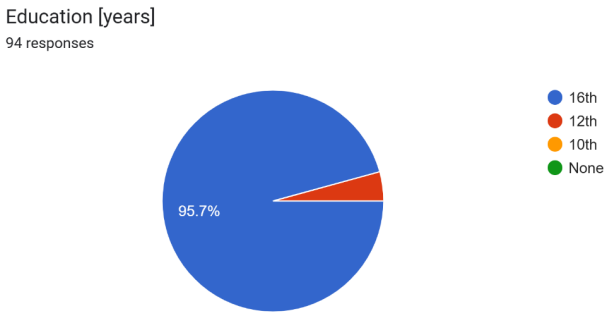

Figure 2. Education of respondents.

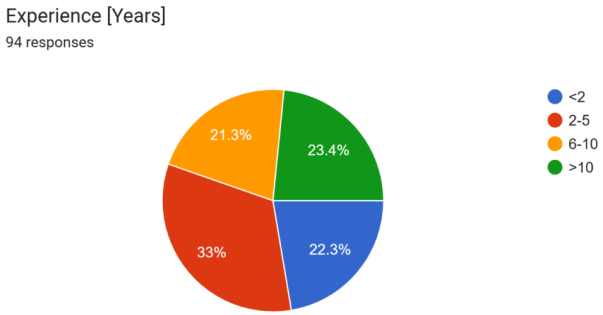

Figure 3. Experience of respondents.

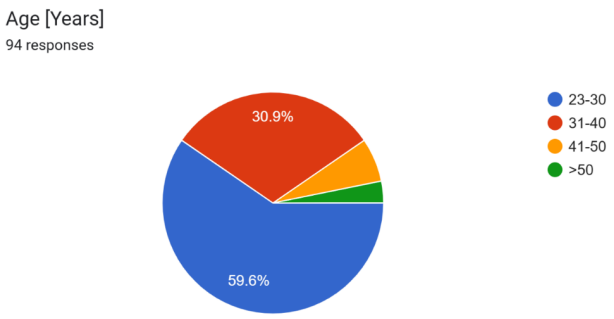

Figure 4. Age of respondents.

In this study, basic data characteristics are established through descriptive statistics such as mean and standard deviation, laying the groundwork for more sophisticated data analysis. These statistics provide an initial overview of the data. The mean represents the central value around which the data cluster, while the standard deviation indicates the data's spread from this central point [40]. All 24 construction delay factors, along with their calculated mean and standard deviation values, are presented in **Table 3**. A low standard deviation value suggests that most responses for those delay factors are concentrated near the mean, whereas a high standard deviation value indicates that survey responses are widely dispersed from the mean. While the top-ranked delay factors have high mean values, **Figure 5** shows that several also have wider dispersion, suggesting that stakeholder views vary depending on the project circumstances. The error bars in the chart represent the general range within which a significant portion of survey responses are expected to fall. Factors with higher standard deviation values indicate greater disagreement among respondents, suggesting variability in perceived impact across projects and stakeholders.

The SPSS software was utilized to clean the data gathered through a questionnaire survey, ensuring its accuracy and reliability. The data cleaning test confirms that all data entries are valid, with no typographical errors or missing values present. For each delay factor, this test demonstrates the validity and distribution of responses. This test confirms the distribution of participants' responses across the Likert scale for each factor. Additionally, it includes histograms that visually represent the distribution of responses for each delay factor based on their frequency.

Cronbach's alpha (α) was computed for the complete dataset comprising 24 construction delay factors. The overall Cronbach's alpha (α) value of 0.837 is deemed satisfactory based on the criteria outlined in **Table 1**. This suggests that the data gathered through the questionnaire survey for this research exhibits strong internal consistency. **Table 4** presents the construction delay factors along with their corresponding Cronbach's alpha values if the item were to be removed. The study's overall Cronbach's alpha (α) value is 0.837. **Table 4** demonstrates how each delay factor influences the data's internal consistency. The overall Cronbach's alpha (α) value is compared against the individual Cronbach's alpha (α) values for each delay factor. If a delay factor's Cronbach's alpha (α) value in the 'Cronbach's alpha if item deleted' column surpasses the overall value of 0.837, removing that factor would improve the

entire dataset's internal consistency. Conversely, if the value in this column is lower than 0.837, eliminating that factor would diminish the overall internal consistency. The study reveals that removing the 'financial difficulties of the contractor' factor, which has a Cronbach's alpha (α) exceeding the overall value, would enhance the data's internal consistency. Conversely, eliminating any other factor would reduce the internal consistency of the dataset.

Table 3. Mean and standard deviation of delay factors.

No	Delay factors	Mean	Std. deviation
1	Ineffective planning and scheduling by a contractor	3.277	0.809
2	Slow decision by the client	3.096	0.734
3	Poor site management and supervision by a contractor	3.117	0.746
4	Unskilled workforce and poor labor productivity	3.213	0.815
5	Financial problems and payment delays by client	3.181	0.855
6	Financial difficulties of the contractor	2.989	0.680
7	Shortage of material	2.606	0.870
8	Inadequate contractor experience	2.862	0.756
9	Delay due to subcontractor	2.681	0.845
10	Delay in preparation and approval of drawing	2.734	0.930
11	Delivery of material to site	2.702	0.902
12	Escalation (increase) of material prices	3.266	0.691
13	Obtaining a permit from the municipality (Government)	2.883	0.828
14	Natural calamities (floods, heat waves, snowfall)	2.904	0.749
15	Changes by client	2.787	0.815
16	Mistakes and defective works during construction	2.894	0.710
17	Political influence	3.053	0.955
18	Equipment and machinery shortage	2.830	0.728
19	Mistakes & discrepancies in design documents by the consultant	2.766	0.835
20	Lack of communication and coordination b/w project parties	3.032	0.725
21	Excessive bureaucracy of client organization	3.096	0.734
22	Impractical allocation of resource	3.234	0.835
23	Insecurity and warlord intervention	2.872	0.820
24	Influence of social disturbance and local culture (poor stakeholder management)	2.957	0.815

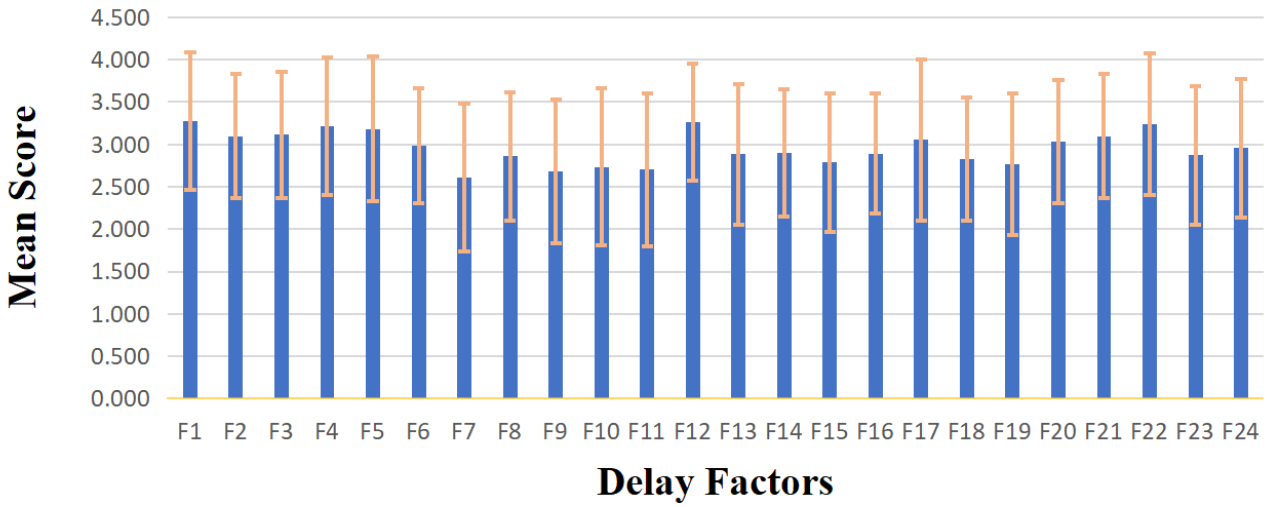

Figure 5. Mean scores and variability (standard deviation) of the top 10 construction delay factors, highlighting relative dispersion in stakeholder perceptions.

Table 4. Cronbach's alpha if an item is deleted.

No	Construction delay factors	Cronbach's alpha if item deleted
1	Ineffective planning and scheduling by a contractor	0.837
2	Slow decision by the client	0.837
3	Poor site management and supervision by a contractor	0.830
4	Unskilled workforce and poor labor productivity	0.828
5	Financial problems and payment delays by client	0.831
6	Financial difficulties of the contractor	0.839
7	Shortage of material	0.835
8	Inadequate contractor experience	0.830
9	Delay due to subcontractor	0.833
10	Delay in preparation and approval of drawing	0.829
11	Delivery of material to site	0.837
12	Escalation of material prices	0.834
13	Obtaining a permit from the municipality (Government)	0.832
14	Natural calamities (floods, heat waves, snowfall)	0.836
15	Changes by client	0.831
16	Mistakes and defective works during construction	0.831
17	Political influence	0.829
18	Equipment and machinery shortage	0.828
19	Mistakes and discrepancies in design documents by the consultant	0.824
20	Lack of communication and coordination between project parties	0.827
21	Excessive bureaucracy of client organization	0.830
22	Impractical allocation of resources	0.831
23	Insecurity and warlord intervention	0.826
24	Influence of social disturbance and local culture (poor stakeholder management)	0.830

The findings of Cronbach's alpha for Part 1 and Part 2, along with the Correlation between forms and Spearman-Brown Coefficient values, are presented in **Table 5**. The initial 12 Odd delay factors, categorized as Part 1, yield a Cronbach's alpha value of 0.714, which is considered acceptable. Similarly, the even delay factors, grouped as Part 2, produced a Cronbach's alpha value of 0.707, also falling within the acceptable range. The total item count of 24 represents the number of construction delay factors examined. As indicated in the table, the correlation between forms is 0.810, suggesting a strong consistency and relationship between the two parts. The split-half test (Correlation between Forms) demonstrates the consistency and correlation between the two halves. The Spearman-Brown Coefficient, which measures the consistency and reliability when both halves are combined into a single dataset. This value indicates a strong internal consistency within the entire dataset.

Table 6 presents 24 factors contributing to construction delays, along with their corresponding RII values and rankings. The rankings are determined by the RII values, with the highest value assigned rank 1 [41]. This table organizes the delay factors based on responses from a questionnaire survey. Contractor-related planning deficiencies emerged as the most influential delay factor, indicating their significant impact on public sector building construction projects in Balochistan, Pakistan. Conversely, 'Shortage of material' has the lowest RII value of 0.654, suggesting it has the least impact among the identified delay factors. These rankings help identify which factors require immediate attention and mitigation strategies to address construction delays

effectively.

Table 5. Split-half correlation.

Cronbach's alpha	Part 1	Value	0.714
		N of Items	12[a]
	Part 2	Value	0.707
		N of Items	12[b]
		Total N of Items	24
Correlation Between Forms			0.810
Spearman-Brown Coefficient			0.895

Note: [a] The items are: F1, F3, F5, F7, F9, F11, F13, F15, F17, F19, F21, F23; [b] The items are: F2, F4, F6, F8, F10, F12, F14, F16, F18, F20, F22, F24; The letter F denotes the Factor of delays.

Table 6. RII ranking of construction delay factors.

No	Delay factors	RII	Ranking
1	Ineffective planning and scheduling by a contractor	0.819	1
2	Escalation (increase) of material prices	0.816	2
3	Impractical allocation of resources	0.806	3
4	Unskilled workforce and poor labor productivity	0.803	4
5	Financial problems and payment delays by client	0.795	5
6	Poor site management and supervision by a contractor	0.785	6
7	Excessive bureaucracy of client organization	0.777	7
8	Slow decision by the client	0.774	8
9	Political influence	0.761	9
10	Lack of communication and coordination between project parties	0.761	10
11	Financial difficulties of the contractor	0.747	11
12	Influence of social disturbance and local culture (poor stakeholder management)	0.745	12
13	Natural calamities	0.734	13
14	Obtaining a permit from the municipality (Government)	0.726	14
15	Mistakes and defective works during construction	0.723	15
16	Insecurity and warlord intervention	0.718	16
17	Inadequate contractor experience	0.715	17
18	Equipment and machinery shortage	0.710	18
19	Changes by client	0.702	19
20	Mistakes and discrepancies in design documents by the consultant	0.691	20
21	Delay in preparation and approval of drawing	0.684	21
22	Delivery of material to site	0.673	22
23	Delay due to subcontractor	0.673	23
24	Shortage of material	0.654	24

Table 7 presents construction delay factors along with their normalization (D^+), and (D^-) values. The normalization values were derived from a decision matrix created in Microsoft Excel using the TOPSIS method's normalization equation. The ideal solution (A^+) of 0.226 and the negative ideal solution of 0.179 were calculated from this matrix. (D^+) represents the distance to the ideal solution. In this analysis, 'Ineffective planning and scheduling' has a (D^+) of 0.000, indicating it as the most prevalent and crucial factor among the 24 identified delay factors. Conversely, 'Shortage of material' has the largest (D^+) of 0.046, signifying it as the least common and critical factor. (D^-) denotes the distance to the negative ideal solution. The table indicates that 'Shortage of

Material' has the smallest (D^-) of 0.0, confirming its status as the least common and impactful factor. Meanwhile, 'Ineffective planning and scheduling' has the greatest (D^-), reinforcing its position as the most common and critical delay factor among the 24 identified.

Table 7. Normalized decision matrix and distances.

No	Delay factor	Normalization	D^+	D^-
1	F1	0.226	0.000	0.046
2	F2	0.213	0.012	0.034
3	F3	0.215	0.011	0.035
4	F4	0.221	0.004	0.042
5	F5	0.219	0.007	0.040
6	F6	0.206	0.020	0.026
7	F7	0.179	0.046	0.000
8	F8	0.197	0.029	0.018
9	F9	0.185	0.041	0.005
10	F10	0.188	0.037	0.009
11	F11	0.186	0.040	0.007
12	F12	0.225	0.001	0.045
13	F13	0.198	0.027	0.019
14	F14	0.200	0.026	0.021
15	F15	0.192	0.034	0.012
16	F16	0.199	0.026	0.020
17	F17	0.210	0.015	0.031
18	F18	0.195	0.031	0.015
19	F19	0.190	0.035	0.011
20	F20	0.209	0.017	0.029
21	F21	0.213	0.012	0.034
22	F22	0.223	0.003	0.043
23	F23	0.198	0.028	0.018
24	F24	0.204	0.022	0.024

Note: **Table 7** utilized the identical order of delay factors as **Table 6**. Within the table, the letter F denotes the Factor of delays.

The outcomes and conclusions of the TOPSIS method are presented in **Table 8**. This encompasses the TOPSIS scores, represented by the closeness coefficient (CCi), and the subsequent ranking of construction delay factors. The proximity of each delay factor to the ideal solution is indicated by its closeness coefficient, which forms the basis for the ranking. This reveals that 'Ineffective Planning and Scheduling' has the highest closeness coefficient (CCi) of 1, identifying it as the most significant and widespread delay factor among those considered. In contrast, 'Shortage of Material' has the lowest closeness coefficient (CCi) of 0, marking it as the least common and impactful delay factor. The findings emphasize the need for immediate corrective actions and strategies to address the highest-ranked construction delay factors. Moreover, a Delphi method was employed to suggest appropriate measures for addressing the delay factors. **Figure 6** visually synthesizes the top-ranked delay factors within the stakeholder-based structure of the conceptual framework. While the top delay factors were grouped by stakeholder responsibility, this study does not model causal interactions among factors. Future studies may apply structural modeling techniques to explore interdependencies.

Table 8. Ranking of delay factor based on TOPSIS score.

No	Delay factor	TOPSIS score (CCi)	Rank
1	Ineffective planning and scheduling by the contractor	1.000	1
2	Escalation (increase) of material prices	0.984	2
3	Impractical allocation of resources	0.937	3
4	Unskilled workforce and poor labor productivity	0.905	4
5	Financial problems and payment delays by client	0.857	5
6	Poor site management and supervision by a contractor	0.762	6
7	Excessive bureaucracy of client organization	0.730	7
8	Slow decision by the client	0.730	8
9	Political influence	0.667	9
10	Lack of communication and coordination between project parties	0.635	10
11	Financial difficulties of the contractor	0.571	11
12	Influence of social disturbance and local culture (poor stakeholder management)	0.524	12
13	Natural calamities (floods, heat waves, snowfall)	0.444	13
14	Mistakes and defective works during construction	0.429	14
15	Obtaining a permit from the municipality (Government)	0.413	15
16	Insecurity and warlord intervention	0.397	16
17	Inadequate contractor experience	0.381	17
18	Equipment and machinery shortage	0.333	18
19	Changes by client	0.279	19
20	Mistakes and discrepancies in design documents by the consultant	0.238	20
21	Delay in preparation and approval of drawing	0.190	21
22	Delivery of material to site	0.143	22
23	Delay due to subcontractor	0.111	23
24	Shortage of material	0.000	24

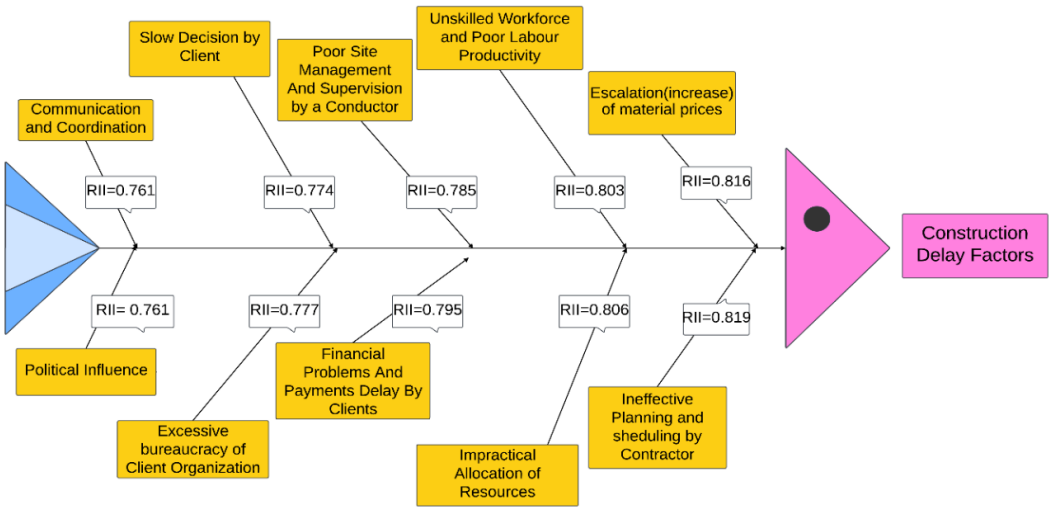

Figure 6. Fishbone diagram of top 10 delay factors using the RII method.

Tables 9 and **10** present the significant delay factors ranked according to their RII and TOPSIS scores, respectively. A delay factor 'Ineffective planning and scheduling by the contractor', with a Relative importance index (RII) of 0.819 and a TOPSIS score of 1, this contractor-related factor exerts the greatest influence on project duration and contributes very highly to delays. This factor ranked first, indicating its dominant influence on project delays. The delay factor 'Escalation (increase) of material prices'

has an RII value of 0.816 and a TOPSIS score of 0.984. This is an external-related delay factor that contributes significantly to project delays. The ranking of this delay factor is 2nd in the top ten delay factors. 'Impractical allocation of resources (Misuse, corruption)' with an RII value of 0.806 and a TOPSIS score of 0.937, this client-related delay factor contributes very highly to causing project setbacks. It ranks 3rd amongst the top ten delay factors. 'Unskilled workforce and poor labor productivity' is the 4th ranked delay factor and has a high contribution to project delays. This contractor-associated delay factor has an RII value of 0.803 and a TOPSIS score of 0.905. 'Financial problems and payment delays by clients' have been associated with clients playing a substantial role in project setbacks, as demonstrated by its RII of 0.795 and TOPSIS score of 0.857. It ranks fifth amongst the leading ten delay factors. The factor 'Poor site management & supervision by the contractor' is associated with contractors playing a substantial role in project duration, as demonstrated by its RII of 0.785 and TOPSIS score of 0.762. Ranking 6th amongst the top ten delay factors, this particular delay has a high contribution to project timelines. 'Excessive bureaucracy of client organization' is a contractor-related delays that significantly impact project timelines, as evidenced by the RII of 0.777 and TOPSIS score of 0.730. This particular delay factor ranks 7th among the top ten causes of project delays, indicating its high contribution to project delays. A delay factor, 'A slow decision by the client', is ranked 8th among the top ten causes of project delays, highlighting its high contribution to project delays. It is a client-related delay factor with a 0.774 RII and 0.730 TOPSIS score. A delay factor, 'Political influence', associated with external factors significantly impacts project schedules, as evidenced by the RII of 0.761 and the TOPSIS score of 0.667. This particular delay factor ranks 9th among the top ten causes of project setbacks, underscoring its high contribution in hindering project progress. The delay factor 'Lack of communication and coordination between project parties' is related to contractors having an RII of 0.761 and a TOPSIS score of 0.635. This specific cause of delay is ranked 10th amongst the primary reasons for project holdups, highlighting its high contribution to project delays.

Table 9. Top 10 key delay factors using RII values.

Rank	Delay factors	RII	Group related	Contribution
1	Ineffective planning and scheduling by contractor	0.819	Contractor	Very high
2	Escalation of material prices	0.816	External	Very high
3	Impractical allocation of resources	0.806	Client	Very high
4	Unskilled workforce and poor labor productivity	0.803	Contractor	Very high
5	Financial problems and payment delays by client	0.795	Client	High
6	Poor site management & supervision by contractor	0.785	Contractor	High
7	Excessive bureaucracy of client organization	0.777	Contractor	High
8	Slow decision by the client	0.774	Client	High
9	Political influence	0.761	External	High
10	Lack of communication and coordination between project parties	0.761	Contractor	High

The Delphi technique was utilized to formulate strategies for mitigating the identified delay factors. Following the ranking of these factors using RII and TOPSIS methodologies, the top 10 were chosen for in-depth examination. Subsequently, the

Delphi method was applied to these 10 factors to organize mitigation solutions. The mitigation approaches based on the opinion of experts for the leading 10 delay factors are presented below. Although several mitigation measures are commonly reported in the literature, their effectiveness in Balochistan depends on addressing governance bottlenecks, security coordination, and political interference, which are structurally embedded challenges in the region.

Table 10. Top 10 key delay factors using TOPSIS score.

No	Delay factor	TOPSIS score (CCi)	Rank
1	Ineffective planning and scheduling by the contractor	1.000	1
2	Escalation of material prices	0.984	2
3	Impractical allocation of resources	0.937	3
4	Unskilled workforce and poor labor productivity	0.905	4
5	Financial problems and payment delays by client	0.857	5
6	Poor site management and supervision by a contractor	0.762	6
7	Excessive bureaucracy of client organization	0.730	7
8	Slow decision by the client	0.730	8
9	Political influence	0.667	9
10	Lack of communication and coordination between project parties	0.635	10

Ineffective planning and scheduling by the contractor:

- Ensuring adequate time for feasibility and detailed design studies;
- WBS, critical activity identification, and risk mitigation strategies;
- Proper project management by contractors;
- Gantt chart and performance bond requirement;
- Providing funds and securing a design lock upon the award of the tender;
- Pre-qualification of the contractor;
- Liquidated damages charges are imposed;
- Utilizing construction management software and pert.

Escalation of material prices:

- Inclusion of escalation clause in contract agreement;
- Timely execution with a focus on critical activities, teamwork, and resource readiness;
- Advance release for early purchase of major project items;
- Fixed price range with compensation;
- Consider alternative materials;
- Adding the expected inflation rate on materials during designing and tendering.

Impractical allocation of resources:

- Securing funds based on financial phasing;
- Efficient resource management;
- Restructuring government departments for modern efficiency;
- Client or end-user should deploy their experts;
- Implementation of cost control techniques;
- Strict policies for violations of discipline;
- Empowering decision-makers;

- Ensure attentive on-site monitoring;
- Pre-work surveys and quality management.

Unskilled workforce and poor labor productivity:

- Establishing continuous learning initiatives;
- Offering competitive salaries;
- Hire skilled workers and assign tasks accordingly;
- Ensure pre-qualification of contractors;
- Using performance metrics and incentives;
- Ensuring proper supervision;
- Communication through literature, surprise visits.

Financial problems and payment delays by clients:

- Adopt FIDIC contracts with fixed timelines for IPC review and payment processing;
- Timely allocation of funds and payments;
- Ensure full project funding and streamline processes using modern technology;
- Exclude non-strategic and low-impact projects from public programs;
- Including third-party investment;
- Renegotiating payment terms and implementing penalties.

Poor site management & supervision by the contractor:

- Engaging qualified engineering staff and implementing capacity-building programs;
- Discouraging excessive subcontracting;
- Implementing a robust progress-tracking system;
- Appointing a client supervisor over the contractor's team;
- Effective contractor selection and clear communication strategies;
- Penalizing contractors as per tender clauses.

Excessive bureaucracy of the client organization:

- Ensure EPC or turnkey contract;
- Promoting independent departmental functioning;
- Using the latest software;
- Enforce time-bound NOCs and compliance;
- Clear and well-defined contract terms;
- Implementing an E-Filing system.

A slow decision by the client:

- Conducting periodic meetings with the client;
- Minimize interventions by the unrelated top hierarchy;
- Confirming design and material approvals before execution;
- Using BIM;
- Adjustment of completion period for client-caused delays;
- Accurate data collection from the site.

Political influence:

- Training political leaders;

- Defining and specifying labor unions' roles;
- Contingencies in estimates;
- Effective stakeholder engagement;
- Reducing MPA involvement;
- Stay informed on local politics and adapt risk plans;
- Win-Win Solution: Collaborative conflict resolution for mutual benefit;
- Correct clauses inclusion in the contract.

Lack of communication and coordination between project parties:

- Establishing a project steering committee;
- Digital communication channels and involvement of technical experts;
- Using BIM;
- Establishing a clear communication chain;
- Conduct weekly or monthly meetings.

6. Conclusion

This paper presents delay analysis beyond generally accepted causes and contextualizes it inside politically fragile and institutionally limited places by empirically demonstrating how governance- and security-related issues fundamentally interact with conventional delay drivers. The results validate the continued dominance of contractor- and client-related factors, but they are greatly amplified by region-specific factors such as political meddling, institutional inefficiencies, security issues, and post-disaster recovery pressures. Balochistan differs from other areas studied in earlier delay studies due to this contextual amplification. This study carefully investigated the reasons behind public-sector building construction delays in Balochistan, Pakistan, utilizing a mixed-methods approach that includes RII, TOPSIS, and the Delphi technique. The findings confirm the ongoing dominance of factors relating to contractors and clients, but they are significantly exacerbated by region-specific factors such as institutional inefficiencies, political intervention, security concerns, and post-disaster recovery demands. Balochistan varies from other areas analyzed in past delay studies due to this contextual amplification. These results imply that delays are not only operational mistakes but rather are ingrained in larger administrative and political systems, supporting the institutional and project governance viewpoint that forms the basis of the conceptual framework. The suggested mitigation solutions should be understood in the context of Balochistan's governance and security, where institutional reforms, political coordination, and security-conscious planning must be added to traditional project management techniques.

A disaggregated comparative study among customers, contractors, and consultants was not carried out, despite the fact that delay reasons were characterized by stakeholder responsibility. The sample size and the requirement to maintain statistical robustness are the causes of this restriction. As a result, rather than statistically distinguished group-specific rankings, the results represent the opinions of all stakeholders. To investigate stakeholder-level divergences, future research with larger stratified samples may use structural modeling or multi-group analysis.

In summary, this study adds to the body of knowledge on building delays by including regional institutional characteristics into delay analysis. It also lays the groundwork for future scholarly research in fragile and underdeveloped construction environments as well as policy-oriented reforms.

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Article

Sustainable alternatives to cement in structural engineering

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Abstract: The environmental impact of ordinary Portland cement (OPC) production, particularly its high carbon emissions and energy consumption, has prompted the structural engineering community to seek more sustainable alternatives. This review examines a range of materials that can partially or fully replace OPC, including industrial by-products (e.g., fly ash, ground granulated blast furnace slag), geopolymers, natural pozzolans, and recycled construction waste. The article evaluates these alternatives in terms of their mechanical performance, durability, workability, and suitability for structural applications. Environmental and economic assessments, including life cycle analysis and cost considerations, are also discussed to provide a holistic view of sustainability. While many alternatives show promising performance and environmental benefits, wider adoption depends on overcoming technical challenges, regulatory gaps, and market inertia. This review highlights the need for integrated efforts in research, policy, and practice to transition toward more sustainable materials in structural engineering.

Keywords: sustainable construction, cement alternatives, fly ash, geopolymers, structural concrete

1. Introduction

Cement is the cornerstone of modern construction, forming the binding agent in concrete, the most widely used man-made material in the world [1]. The fact that it is found in all aspects of infrastructure, including buildings and bridges, dams, and highways, has made it (no pun intended) an inseparable part of the structural engineer. Nevertheless, notwithstanding its positive attributes in terms of performance and availability, the ordinary Portland cement (OPC) poses a serious issue of concern since it is not sustainable. Production of cement is, on the one hand, energy-intensive as it uses more than 30% the energy used in other industries; on the other hand, cement contributes a substantial amount of carbon emissions in the world, which is estimated to be up to 7–8 percent of the total amount of carbon emissions in the world. Such an environmental burden, along with the rising interest in depletion of resources and climate change, has fuelled the worldwide hunt for more sustainable alternatives [2,3].

The environmental impact of cement arises primarily from two sources: the calcination of limestone (which releases CO_2) and the high-temperature processing required to form clinker. Each ton of cement produced results in nearly 1 t of CO_2 emissions. With growing construction demands, especially in rapidly urbanizing regions, these figures are projected to rise unless decisive changes are made in material sourcing and construction practices. It has therefore become paramount to not only shift towards environmental sustainability but also attain long-term economic and

resource-efficient construction through the independence of utilization of traditional cement [4].

The construction materials that cause less environmental degradation, but with adequate mechanical properties relevant to building structures and durability of materials, are referred to as sustainable construction materials. During the last few decades, various alternatives to OPC have been discussed by researchers, practitioners, and available alternatives to build many alternatives to OPC have been built in three major groups: industrial by-products, natural materials, and innovative binders, including the geopolymers. These options have the potential of having reduced carbon footprints, waste reduction with recycling, and even enhanced halo improvement characteristics of certain applications. Nevertheless, their adoption in building structural engineering practice is still sparse because of technical, regulatory, and economic constraints [5].

Some of the most thoroughly examined replacements are industrial by-products such as fly ash, ground granulated blast-furnace slag (GGBS), and silica fume. These can be commonly found in energy production and metallurgy, and can make an equal or partial cement replacement in concrete, helping prolong its strength and durability. Simultaneously, geopolymer technology, also known as aluminosilicate technology or aluminosilicate fuels or aluminosilicate charcoal or aluminosilicate fuel, has also shown potential of being a leading direction to zero-cement construction. Such binders not only exclude the calibration of limestone, but they also use the industrial wastes in a multi-timely manner. Also, older materials such as lime, natural pozzolans (volcanic ash, etc.), and bio-based ashes (rice husk ash, etc.) have re-emerged as possibilities in certain structural and local situations [6].

The integration of the materials, however, comes with problems. There have been questions on their performance in the long run under different environmental conditions, compatibility with the current construction standards, and their behaviour in load-bearing constructions and those with seismic activity. Furthermore, the problematic areas of material consistency, availability, cost efficiency, and regulatory endorsement remain problematic areas to make it popular. The quality control and standardization are a challenge in most situations due to the variability of alternative binders, particularly the industrial wastes. Moreover, adoption can be hindered by a lack of familiarity among many structural engineers and contractors, even where there has been proven technical feasibility [7].

Economically and policy-wise, integration of green cement alternatives should likewise consider life cycle assessments (LCA), energy payback periods, and possible incentives based on green building certifications or governmental incentives. Climate targets are becoming more ambitious, especially within international systems and treaties, like the Paris Agreement, which means that standards are changing with regard to construction. This trend has opened a strategic plan to place sustainable practices in the mainstream of structural engineering [8].

This review article aims to synthesize current knowledge and developments in sustainable alternatives to cement for structural applications. It will explore the types of alternatives available, assess their mechanical and environmental performance, and

evaluate the barriers and opportunities associated with their use. By presenting both the technical and socio-economic dimensions of cement replacement, this article seeks to contribute to a growing body of literature that supports the shift toward greener and more resilient infrastructure [9].

In summary, while traditional cement has long underpinned the strength and durability of our built environment, its continued dominance comes at an unsustainable environmental cost. The search for and adoption of viable cement alternatives in structural engineering is not only a scientific and technical imperative—it is an environmental necessity. Through innovation, interdisciplinary collaboration, and supportive policy frameworks, the next generation of construction materials may well succeed in reducing emissions without compromising the integrity of our structures. This article explores how close we are to achieving that goal—and what steps remain ahead.

2. Types of sustainable cement alternatives

The search for sustainable alternatives to Portland cement has led to the identification and development of various materials that either partially replace or fully substitute cement in structural applications. These alternatives not only help reduce CO_2 emissions and energy use but also enhance the performance of concrete in some cases. They generally fall into four categories: industrial by-products, geopolymer binders, natural pozzolanic materials, and recycled materials. This section examines each category in detail.

2.1. Industrial by-products

The most implemented and studied substitutes of cement, though, are industrial by-products. Such materials are generally pozzolanic, i.e., siliceous or aluminous components, which, in reaction with water and calcium hydroxide, produce compounds with cementitious properties. The by-products are mainly fly ash, Ground Granulated Blast Furnace Slag (GGBS), and silica fume.

Fly Ash is a coal combustion by-product that occurs as fine powder. It is divided into Class F (low calcium) and Class C (high calcium). Workability is enhanced, the heat of hydration is lowered, and the long-term strength and durability of the concrete are enhanced by using fly ash. It has been largely utilized in blended cement and concrete.

GGBS is a by-product of iron production in blast furnaces. GGBS is highly cementitious and is often used in conjunction with OPC. It enhances sulfate resistance and reduces permeability, making it suitable for marine and underground structures. Silica Fume is a fine powder generated during silicon and ferrosilicon alloy production. Its high pozzolanic activity makes it effective in producing high-strength, low-permeability concrete. Due to its small particle size, it also improves the bond between cement paste and aggregates.

These by-products not only offer technical advantages but also divert significant industrial waste from landfills, contributing to circular economy goals. However, their availability is dependent on regional industrial activity and may be limited in areas

without relevant power or metallurgical plants [10–13].

2.2. Geopolymers and alkali-activated materials

Geopolymers constitute an emerging class of synthetic aluminosilicate binders produced through the chemical reaction between aluminosilicate-rich precursor materials and alkaline activating solutions. Common precursors include industrial by-products and natural materials such as fly ash, metakaolin, ground granulated blast furnace slag (GGBS), and certain clays, while the activation is typically achieved using solutions of sodium hydroxide, sodium silicate, or their combinations. This process, referred to as alkali activation, fundamentally differs from conventional cement manufacturing in that it eliminates the need for high-temperature clinker formation, thereby significantly reducing energy consumption. From a performance perspective, geopolymer concretes are known to develop high compressive strength, often at early ages, and exhibit excellent resistance to fire, chemical attack, and sulfate-rich or acidic environments. Additionally, their dense microstructure contributes to relatively low shrinkage and enhanced long-term durability compared with ordinary Portland cement (OPC)–based systems. Environmentally, geopolymer binders offer substantial sustainability advantages, with life-cycle assessments indicating potential reductions in carbon emissions of up to 80% relative to OPC, depending on the choice of precursor materials and the production pathways of alkaline activators. Despite their promise, challenges remain in terms of standardization, curing conditions (some require elevated temperatures), and the handling of chemical activators, which may pose health and safety concerns [14].

2.3. Natural pozzolanic materials

These are naturally occurring materials that exhibit pozzolanic behaviours, often after thermal or mechanical treatment. They have been used in construction for centuries (e.g., Roman concrete). Examples of such materials include volcanic ash, calcined clay, metakaolin, and Rice Husk Ash (RHA). Volcanic ash is rich in amorphous silica and alumina; it reacts with calcium hydroxide to form cementitious compounds. Calcined clay and metakaolin are produced by heating kaolinite-rich clays. Metakaolin enhances early strength and improves resistance to chloride penetration. RHA is a by-product of rice milling and combustion, and it is high in amorphous silica and can be an effective cement replacement. Natural pozzolans are renewable and often locally available, making them suitable for use in rural or developing regions. However, their properties can vary significantly depending on the source, which complicates their standardization [15].

2.4. Recycled materials and construction waste

In recent years, the principles of the circular economy and zero-waste construction have driven increasing interest in the utilization of recycled construction and demolition waste as alternative cementitious materials. Rather than being disposed of in landfills, these wastes can be processed and valorized as supplementary or partial replacements for conventional cement binders, thereby reducing both environmental burdens and raw

material consumption.

Among these materials, recycled concrete fines (RCF) obtained by finely grinding demolished concrete have demonstrated latent binding potential, particularly when chemically activated using alkaline solutions. When properly processed, RCF can contribute to strength development and microstructural densification in blended or alkali-activated systems. Waste glass powder, produced by milling discarded glass to a fine particle size, exhibits notable pozzolanic reactivity due to its high amorphous silica content. When incorporated into cementitious systems, it can participate in secondary hydration reactions, improving durability while simultaneously diverting glass waste from landfills.

Similarly, brick dust, derived from crushed fired clay bricks, can act as a supplementary cementitious material when finely ground. Its aluminosilicate composition enables pozzolanic reactions with calcium hydroxide, enhancing long-term strength and contributing to sustainable resource utilization in concrete production. These materials promote resource efficiency and reduce landfill use. However, issues of contamination, variable quality, and inconsistent reactivity require careful processing and quality assurance [16].

2.5. Comparison of alternatives

The variety of sustainable alternatives to cement offers a rich palette of materials that can be tailored for different structural and environmental requirements. While some—like fly ash and GGBS are already widely used in commercial concrete, others, like geopolymers and agricultural ash-based materials, are still emerging. The next section will explore how these materials perform in structural applications, including mechanical properties, durability, and practical challenges in construction contexts [17]. A detailed comparison is given in **Table 1**.

Table 1. A comparison of cement alternatives.

Alternative material	Key benefits	Limitations
Fly Ash	Reduces heat, improves durability	Availability depends on coal usage
GGBS	Improves strength and sulfate resistance	Requires grinding and a consistent supply
Geopolymers	Very low CO_2 emissions, high performance	Requires alkaline activators, less standardized
Natural Pozzolans	Abundant, often renewable	Varying quality, lower early strength
Recycled Materials	Reduces waste, promotes circular economy	Processing and quality control challenges

3. Performance characteristics and structural suitability

The successful use of sustainable cement alternatives in structural engineering depends not only on environmental advantages but also on their technical performance. Structural materials must meet rigorous standards for strength, durability, workability, and long-term behaviour under various loading and environmental conditions. This section evaluates the mechanical properties, fresh-state behaviour, durability, and application feasibility of alternative binders, along with the practical challenges and limitations involved in using them.

3.1. Mechanical properties

The fundamental requirement of any material used in structural engineering is its capacity to safely resist both compressive and tensile stresses under service and ultimate loading conditions. In this context, the mechanical performance of sustainable cement alternatives exhibits considerable variability, largely influenced by the type of binder employed, mix design parameters, curing regimes, and the use of chemical or mineral additives.

In terms of compressive strength, alternative cementitious systems display diverse strength development characteristics. Fly ash–based concretes typically exhibit slower early-age strength gain compared to ordinary Portland cement (OPC) concrete; however, their long-term strength often equals or surpasses that of OPC at later ages, such as 28 or 56 days, due to sustained pozzolanic reactions. Concretes incorporating ground granulated blast furnace slag (GGBS) frequently demonstrate enhanced compressive strength alongside a reduced heat of hydration, making them particularly suitable for mass concrete applications where thermal cracking is a concern. Geopolymer concretes have shown the ability to attain high compressive strengths commonly in the range of 60–80 MPa—even at early curing stages, especially when subjected to elevated-temperature curing. Natural pozzolanic materials, such as metakaolin, are known to improve both early-age and long-term strength, whereas others, including rice husk ash, often require carefully optimized mix designs to achieve comparable mechanical performance.

With respect to tensile and flexural behavior, many cement alternatives tend to exhibit slightly lower strength than conventional OPC-based concrete. This limitation can be effectively addressed through the incorporation of fibers or suitable admixtures, which enhance crack resistance and post-cracking behavior. Geopolymer concretes, in particular, may demonstrate improved tensile and flexural performance due to their dense and refined microstructure; however, they can also exhibit brittle failure characteristics in the absence of adequate reinforcement.

The modulus of elasticity of blended and geopolymer concretes is generally lower than that of OPC concrete, reflecting differences in microstructure and binder composition. This reduced stiffness may influence deflection behavior and serviceability performance in structural elements, necessitating careful consideration during structural design. Overall, while sustainable cement alternatives can meet structural performance requirements, their mechanical characteristics must be thoroughly evaluated and appropriately accounted for in engineering applications [18].

3.2. Workability and setting time

The fresh-state properties of concrete, including workability, consistency, and setting time, play a crucial role in determining the ease of mixing, placing, compaction, and finishing during construction. These properties are particularly important when alternative cementitious materials are used, as their physical and chemical characteristics can significantly alter the behavior of concrete in its plastic state.

Workability is strongly influenced by the nature of the binder. Fly ash is well known for improving workability due to the spherical shape of its particles, which

act as microscopic ball bearings and enhance flowability. In contrast, highly reactive and finely divided materials such as silica fume and metakaolin tend to reduce workability by increasing water demand and surface area, often necessitating the use of superplasticizers to achieve acceptable consistency. Geopolymer mixtures can exhibit a sticky or stiff consistency depending on the precursor materials, activator composition, and mix proportions, and therefore require careful handling and practical experience to ensure proper placement and compaction.

Setting time is another critical fresh-state parameter affected by the use of cement alternatives. The incorporation of fly ash and ground granulated blast furnace slag (GGBS) commonly leads to delayed setting, which can be advantageous in mass concrete applications by reducing thermal stresses but may pose challenges in cold-weather construction or projects requiring rapid strength gain. Geopolymer binders exhibit highly variable setting behavior, ranging from rapid to significantly delayed setting, depending on factors such as activator concentration, curing temperature, and mix chemistry, making precise control essential. Natural pozzolans and recycled materials often display inconsistent setting characteristics, and trial mixes are typically required to establish workable and reliable setting times for practical applications.

3.3. Durability and long-term performance

Durability is a critical consideration in structural engineering, particularly for structures exposed to aggressive environments such as marine conditions, industrial atmospheres, or repeated freeze–thaw cycles. Sustainable cement alternatives can significantly influence the long-term performance of concrete through their effects on microstructure, permeability, and chemical stability.

In terms of resistance to chloride and sulfate attack, materials such as GGBS and fly ash enhance durability by refining the pore structure and reducing permeability, thereby limiting the ingress of aggressive ions. Geopolymer concretes generally exhibit excellent chemical resistance, especially against acidic and sulfate-rich environments, largely due to the absence of calcium hydroxide and the formation of a stable aluminosilicate matrix. Similarly, supplementary materials such as rice husk ash and metakaolin have been shown to reduce chloride penetration and mitigate the risk of alkali–silica reaction (ASR), contributing to improved durability.

Carbonation behavior represents an important design consideration for blended and geopolymer concretes. Owing to their lower calcium content and distinct pore chemistry, these materials may be more susceptible to carbonation compared to conventional OPC concrete, which can influence reinforcement corrosion risk if not properly accounted for in design and cover specifications.

Freeze–thaw resistance in alternative binder systems has shown mixed performance, depending on the type of binder, air-entrainment practices, and overall mix design. In some cases, the use of fly ash without adequate air-void control may reduce freeze–thaw durability, highlighting the need for appropriate mix adjustments. Shrinkage and creep behavior also vary among cement alternatives. While materials such as silica fume may increase drying shrinkage due to their fine

particle size, fly ash and GGBS can reduce shrinkage over time by promoting gradual hydration. Geopolymer concretes typically exhibit low creep; however, they may be prone to higher drying shrinkage unless suitable additives or curing strategies are employed [19]. Mechanical and durability performance of different cement alternatives is summarized in **Table 2**.

Table 2. Mechanical and durability performance of cement alternatives.

Alternative material	Compressive strength development	Durability performance	Key structural implications
Fly ash concrete	Slow early, high long-term strength	Improved chloride & sulfate resistance	Mass concrete, pavements
GGBS concrete	Moderate early, high long-term strength	Excellent sulfate & marine resistance	Marine & underground structures
Silica fume concrete	High early and ultimate strength	Very low permeability	High-strength elements
Geopolymer concrete	High early strength (60–80 MPa)	Excellent acid & fire resistance	Precast, aggressive environments
Metakaolin concrete	Enhanced early and later strength	Reduced ASR and chloride ingress	Structural repairs
Rice husk ash concrete	Moderate strength (mix dependent)	Improved impermeability	Low-cost structures

3.4. Challenges and limitations

Despite their advantages, cement alternatives face several technical and practical barriers. Waste-based materials like fly ash or RHA can vary significantly depending on the source, leading to unpredictable performance. Many standards (e.g., ASTM, EN, and IS codes) have limited coverage of alternative binders, making approval for structural use more difficult. Construction crews may lack experience with handling and curing non-OPC mixes, affecting quality control. Some materials (e.g., geopolymers) may need special curing conditions such as elevated temperatures, which complicates field implementation.

In terms of structural performance, many sustainable alternatives to cement offer comparable—or in some cases superior- mechanical and durability properties. However, their success in structural applications depends on mix design optimization, standardization, and construction adaptability. While materials like fly ash and GGBS have already found a place in practice, more advanced alternatives such as geopolymers and bio-based ashes require further research, testing, and field validation. The next section will focus on environmental and economic assessments to evaluate the overall sustainability of these materials [20].

4. Environmental and economic assessment

While technical performance is crucial, the environmental and economic viability of sustainable cement alternatives ultimately determines their large-scale adoption in structural engineering. This section discusses the performance of these materials in life cycle assessments (LCA), cost-benefit analysis, and within the regulations and policies. It highlights the need to consider an alternative to cement based on the tri-pronged approach of sustainability and not merely on its strength or durability proxies.

4.1. Life cycle assessment (LCA)

Life Cycle Assessment (LCA) is a generalized technique to assess the total environmental impact of a given material or system during the time ascribed to its entire life cycle- namely, extraction of raw materials and end-of-life disposal. For cement alternatives, LCA reveals significant sustainability benefits. When applied

to cementitious materials, LCA provides critical insights into the environmental advantages of sustainable cement alternatives over conventional ordinary Portland cement (OPC). Numerous LCA studies have demonstrated that alternative binders can substantially reduce greenhouse gas emissions, energy demand, and resource depletion while supporting more circular material flows.

One of the most significant benefits revealed by LCA is the reduction in carbon dioxide emissions. The production of OPC is highly carbon-intensive, with approximately 0.9–1.0 t of CO_2 emitted per ton of cement, largely due to limestone calcination and high-temperature kiln operation. In contrast, industrial by-products such as fly ash, ground granulated blast furnace slag (GGBS), and rice husk ash (RHA) are typically considered waste materials from existing industrial or agricultural processes. As a result, their use as cement replacements introduces minimal additional processing emissions, leading to carbon footprint reductions of up to 70–90% compared to OPC. Geopolymer binders also exhibit substantial emission reductions, generally in the range of 40–80%, although their environmental performance depends on the type and dosage of alkaline activators and the energy sources used in their production.

Energy consumption is another critical parameter evaluated through LCA. OPC manufacturing requires extremely high energy input due to kiln firing temperatures of approximately 1450 °C. Conversely, materials such as fly ash and GGBS are generated as by-products of already energy-intensive processes, and their utilization as binders avoids the need for additional high-temperature processing. Calcined clays and metakaolin require thermal activation at temperatures typically between 600 and 800 °C, which still represents a substantially lower energy demand than OPC production. Consequently, alternative binders offer notable energy savings at the material production stage.

From a resource conservation perspective, sustainable cement alternatives play an important role in reducing the depletion of non-renewable raw materials, particularly limestone. By partially or fully replacing OPC, these materials help preserve natural mineral reserves and decrease the volume of waste sent to landfills. The incorporation of construction and demolition waste further strengthens circular economy principles by reintegrating end-of-life materials back into the construction value chain.

Water usage and pollution potential are also favorably influenced by the adoption of cement alternatives. Many alternative binders require less water during mixing or curing, and the avoidance of kiln-based production significantly reduces air pollutants such as particulate matter, nitrogen oxides (NOx), and sulfur oxides (SOx) associated with fossil fuel combustion. Collectively, LCA results highlight the substantial environmental benefits of replacing OPC with more sustainable cementitious materials [21–23].

4.2. Cost analysis

A common perception is that sustainable alternatives are more expensive or less economically viable than OPC. However, this depends on local availability, processing requirements, transportation costs, and scale of application. In terms of material costs, fly ash and GGBS are frequently less expensive than OPC and, in some regions, may be obtained at minimal or no cost directly from industrial producers. Geopolymer

systems, on the other hand, can incur higher initial costs due to the price of alkaline activators such as sodium hydroxide and sodium silicate. The cost of natural pozzolans varies widely depending on regional geology, extraction methods, and processing requirements, making them more economically viable in areas with local deposits.

Processing and handling costs also influence overall economic performance. Certain materials, including rice husk ash and silica fume, require controlled combustion, fine grinding, or special handling procedures, which can increase processing expenses. However, the reduced demand for OPC often results in lower energy consumption and transportation costs, partially offsetting these additional expenditures.

At the construction stage, alternative binders can offer indirect economic benefits. Improved workability associated with fly ash and slag blends can reduce labor demands and equipment wear, while lower heat of hydration can minimize cracking and associated repair costs. More importantly, the enhanced durability of concrete incorporating GGBS, geopolymers, or high-quality pozzolans can significantly reduce long-term maintenance and rehabilitation costs, particularly in aggressive environments such as marine or sulfate-rich conditions.

From a lifecycle perspective, these durability benefits translate into substantial cost savings over the service life of a structure. Additionally, government incentives, tax benefits, and green building subsidies can further improve the economic viability of sustainable cement alternatives by offsetting higher initial material costs [24].

4.3. Policy and regulatory support

The widespread adoption of sustainable cement alternatives is strongly influenced by the regulatory environment, standards development, and policy incentives. In recent years, several countries and international organizations have taken steps to encourage the use of low-carbon and resource-efficient construction materials.

Green building certification systems such as LEED in the United States, BREEAM in the United Kingdom, and the Indian Green Building Council (IGBC) rating system provide credits for the use of supplementary cementitious materials and recycled content. These certifications enhance the market value of construction projects and attract environmentally conscious investors and stakeholders.

At the standards level, codes such as ASTM C618 for fly ash, EN 197-1 for blended cements, and various Indian Standards permit the partial replacement of OPC in structural concrete. However, newer binder systems, particularly geopolymers, often fall outside conventional prescriptive standards. Their approval typically relies on performance-based criteria, pilot projects, or project-specific testing protocols.

Government policies also play a critical role through mechanisms such as tax incentives, carbon pricing schemes, and material subsidies aimed at reducing emissions from the construction sector. Public infrastructure projects increasingly incorporate sustainability requirements into procurement specifications, thereby creating market demand for low-carbon binders. Nevertheless, regulatory conservatism and the slow pace of code development remain significant barriers, and standardized testing procedures for non-OPC concretes have yet to be globally harmonized [25–28].

4.4. Regional considerations and supply chains

The environmental and economic performance of sustainable cement alternatives is highly dependent on regional conditions, including material availability, transportation infrastructure, and industrial capacity. In developed economies, industrial by-products such as fly ash and GGBS are well integrated into existing supply chains, supported by established standards and strong institutional backing for green construction practices. In contrast, developing regions may benefit more from locally available natural pozzolans and agricultural residues such as rice husk ash or calcined clays, which can offer cost-effective and environmentally appropriate solutions. Localizing material supply chains reduces transportation-related emissions and enhances economic efficiency, particularly for large-scale infrastructure projects. Tailoring binder selection to regional resource availability is, therefore, essential for maximizing sustainability benefits.

Overall, environmental and economic assessments consistently demonstrate that sustainable cement alternatives—particularly fly ash, GGBS, and geopolymers- can deliver substantial reductions in carbon emissions and energy consumption while offering competitive or lower lifecycle costs. When supported by appropriate policies, updated standards, and regionally optimized supply chains, these materials represent a viable pathway toward more sustainable structural engineering practices. However, project-specific LCA and cost analyses remain essential to ensure optimal material selection and implementation [29,30]. **Table 3** provides a summary of the arguments for LCA, cost, and policy relevance.

Table 3. Environmental and economic comparison of OPC and alternatives.

Binder type	CO_2 emissions reduction	Energy demand	Cost trend	Sustainability advantage
Ordinary Portland Cement (OPC)	Baseline (high)	Very high	Moderate	Well-established but carbon-intensive
Fly ash / GGBS blends	50–90% lower	Low	Low	Strong circular economy benefits
Geopolymers	40–80% lower	Moderate	Moderate–high	Near-zero cement pathway
Natural pozzolans	40–70% lower	Low–moderate	Low	Regional sustainability
Recycled binders	30–60% lower	Low	Low	Waste reduction & landfill diversion

5. Conclusion

The urgent need to reduce the environmental impact of construction has brought the role of ordinary Portland cement (OPC) under critical scrutiny. As one of the most carbon-intensive materials used in infrastructure, cement contributes significantly to global greenhouse gas emissions and resource depletion. In this review, the variety of all the different sustainable options relating to structural engineering has been investigated, from the simple options of industrial waste like fly ash and GGBS, to more sophisticated binders like geopolymers, to all-natural and recycled materials like rice husk ash and construction waste.

These alternatives do provide a hopeful route of reducing the amount of a construction's carbon footprint without sacrificing, and instead increasing, mechanical performance and durability. Fly ash and slag are already in wide use when mixing with cement, and these geopolymers have proven to be outstanding in terms of chemical resistance and compressive strength. The natural pozzolans and recycled materials

are further additions to the range of possibilities, particularly in the regions where the industrial infrastructure is poor.

Many of these options have been used to meet or surpass structural needs on a performance basis in a well-engineered fashion. Nevertheless, their implementation is usually impeded by the following types of factors: variability of raw materials quality, the absence of standardization, the lack of familiarity among practitioners, and inconsistent governmental assistance. The challenges outlined here suggest maintaining research, formulating newer codes and standards, and providing more education in the construction sector.

Environmental and economic reviews have shown that sustainable options are not merely more environmentally friendly with smaller CO_2 emissions and energy requirements, but can also lead to savings in the long term due to their better durability and the decrease in maintenance. In addition, the adoption of more stringent environmental standards by governments and institutions, as well as the encouragement of green construction activities, is making the transition to an alternative binder a regulatory and market necessity. Going forward, this ideal future in terms of sustainable structural engineering will demand a complex strategy: the need to promote innovation in material science, the need to revise the policy frameworks, the need to invest in the regional supply chain, and the need to raise awareness among stakeholders. It is by meeting these options that the construction sector can potentially limit its environmental demeanour and strive to establish safe, sound, and long-lasting structures.

To sum it up, although it is not unreasonable to expect that, at least in the short run, the traditional cement will continue to figure as a constituent of structural engineering, the term of sustainable alternatives is maturing rapidly, barring a monumental change towards the future of our constructions. With appropriate mixes of technology, policy, and practice, sustainable cement alternatives can not only be viable but also normal when it comes to building tomorrow's infrastructure.

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Article

Carbon threshold governance: Resolving the building Policy-Carbon Paradox with blockchain-AI

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Abstract: The building sector faces a critical "Policy-Carbon Paradox": while carbon pricing covers 23% of global emissions, it addresses only 12.7% of construction emissions, resulting in a 7.6-fold decarbonization lag. To resolve this, we propose a Threshold-regulated Policy Framework (TPF) that leverages blockchain-AI fusion for dynamic carbon governance. Empirically, we identify two critical carbon price thresholds: a material substitution tipping point at \$120 ± 15/tCO$_2$ ($p < 0.01$) and an energy system transformation point at \$200/tCO$_2$ (Internal Rate of Return (IRR) > 8%). Theoretically, these sigmoidal thresholds supersede the conventional Environmental Kuznets Curve, demonstrating a 0.38 R^2 improvement over static models. Methodologically, an ISO 14064-3:2019-compliant blockchain-Measurement, Reporting and Verification (MRV) system achieves a 73% reduction in measurement uncertainty (Root Mean Square Error (RMSE) = 0.48 kg CO_2e/tonne) and enables real-time policy adjustments with 2.3 ± 0.7-h latency. This activates a self-reinforcing Policy-Technology-Environment (PTE) Loop, driving a 17-fold growth in green bond issuance and increasing prefabrication penetration by 51.4 percentage points. Applied regionally, the framework reduces decarbonization costs by 38.2% in China (φ-adjusted Emissions Trading System (ETS)), cuts embodied carbon by 55% in the EU (Carbon Border Adjustment Mechanism Building Information Modeling (CBAM-BIM) integration), and slashes verification costs by 72.4 ± 5.2% in the Global South (satellite-blockchain MRV). Collectively, this generates \$2.8 ± 0.6 billion/year in health co-benefits through $PM_{2.5}$ reduction. Our findings establish a scalable, data-driven pathway to close the building sector's decarbonization gap with a 92.3% probability of aligning with the 1.5 °C climate goal.

Keywords: carbon pricing; building decarbonization; blockchain; AI-driven governance; prefabricated construction; climate finance

1. Introduction

The building sector stands as a critical yet recalcitrant frontier in global climate mitigation, accounting for nearly 40% of energy-related carbon dioxide emissions and 36% of global final energy use. Despite its outsized footprint, the sector's decarbonization trajectory remains alarmingly off-pace, threatening to consume a substantial portion of the remaining carbon budget for limiting warming to 1.5 °C [1]. This divergence underscores a profound and persistent "Policy-Carbon Paradox": the apparent ineffectiveness of broad, economy-wide climate policy instruments in catalyzing a rapid transition within the built environment, even as their coverage expands globally [2].

The roots of this paradox are entrenched in the sector's unique socio-technical complexities. First, a fundamental temporal mismatch exists between the long

lifespans and investment cycles of buildings (often exceeding 50 years) and the short-term horizons of political and policy cycles, creating investment uncertainty and stifling capital-intensive, low-carbon choices. Second, systemic fragmentation across the building lifecycle—from material production and construction to operation and end-of-life—obscures accountability. A significant portion of emissions, particularly embodied carbon from materials, frequently falls outside the purview of operational energy policies and markets, leading to a systematic underestimation of the sector's true climate impact [3,4]. Third, pervasive split-incentive dilemmas, where the actors responsible for upfront capital investments (e.g., building owners) are not the primary beneficiaries of the resulting energy savings (e.g., tenants), create a formidable market failure that blocks cost-effective retrofits and upgrades [5].

Established economic and policy frameworks struggle to navigate this triad of challenges. The canonical Environmental Kuznets Curve (EKC) hypothesis, which posits an automatic inverted-U relationship between economic development and environmental degradation [6], provides limited guidance for the deliberate, policy-driven transformation required in construction. Its static, macro-scale formulation fails to capture the dynamic, non-linear feedbacks, technological tipping points, and agent-specific behaviors that characterize the sector's response to policy signals [7, 8]. While econometric studies have explored carbon price elasticities in energy and industry [9], a coherent theoretical model that explains and predicts the sigmoidal or threshold-based response of the building system to escalating carbon costs remains underdeveloped.

This theoretical gap is compounded by methodological limitations in prevailing analytical paradigms. Much of the policy assessment literature relies on static or linear marginal abatement cost curves, which may dramatically underestimate the potential for rapid, phase-change transitions once critical cost thresholds for key technologies are crossed [10, 11]. Furthermore, analytical silos persist between embodied carbon assessment, typically using Life Cycle Assessment (LCA), and operational energy modeling, preventing a holistic optimization of the full lifecycle carbon footprint [4]. Perhaps most critically, the data infrastructure supporting governance is plagued by issues of opacity, latency, and a lack of verifiable trust. Conventional Measurement, Reporting, and Verification (MRV) processes are often manual, retrospective, and costly, incapable of supplying the real-time, tamper-evident data flows necessary for dynamic policy adjustment and the activation of self-reinforcing innovation and market cycles [12].

Emerging digital technologies, notably blockchain and artificial intelligence (AI), are heralded as potential game-changers for environmental governance. Blockchain's inherent properties of immutability, transparency, and automated execution via smart contracts offer a paradigm for creating trusted, efficient carbon accounting and trading platforms [13, 14]. Concurrently, AI and machine learning demonstrate powerful capabilities in processing complex, heterogeneous data streams—from satellite imagery and IoT sensors to Building Information Models (BIM)—for predictive analytics, anomaly detection, and pattern recognition [15,16]. However, the academic discourse remains largely speculative or confined to isolated, proof-of-concept studies. A

rigorous, integrated investigation into how a purposeful fusion of blockchain and AI can be systematically designed to address the specific data integrity, timing, and coordination failures at the heart of the building sector's Policy-Carbon Paradox is notably absent.

To address these interconnected theoretical, methodological, and technological gaps, this study proposes and develops an integrated Threshold-regulated Policy Framework (TPF). The primary objectives of this research are threefold: (1) To theoretically advance beyond static equilibrium models by empirically investigating the existence and magnitude of critical carbon price thresholds that trigger non-linear decarbonization phase transitions in the building sector; (2) To methodologically construct a dynamic simulation-optimization platform that integrates agent-based modeling, lifecycle assessment, and stochastic optimization to identify robust, cost-effective policy pathways; and (3) To technologically conceptualize a blockchain-AI fused MRV system architecture designed to resolve foundational issues of data credibility, timeliness, and governance coordination, thereby enabling the practical implementation of a self-reinforcing Policy-Technology-Environment (PTE) feedback loop.

The remainder of this paper is structured as follows. Section 2 details the multi-methodological architecture of the TPF. Section 3 presents its application and validation across three strategically selected global case studies. Section 4 reports the empirical results on critical carbon price thresholds and quantifies the associated system co-benefits. Section 5 discusses the theoretical implications, policy scalability, and study limitations, followed by concluding remarks in Section 6.

2. Methodology

The proposed Threshold-regulated Policy Framework (TPF) is operationalized through a multi-methodological architecture designed to resolve the Policy-Carbon Paradox identified in Section 1. The framework integrates dynamic system modeling, blockchain-AI fusion for Measurement, Reporting, and Verification (MRV), and stochastic optimization to empirically validate the sigmoidal carbon price thresholds and the PTE-Loop theory. The following subsections detail the system boundary, core computational engines, and uncertainty quantification protocols.

2.1. System boundary and lifecycle integration

A cradle-to-grave system boundary, conforming to ISO 14044:2006 standards [10], was established to overcome the spatiotemporal fragmentation and lifecycle emission blind spots detailed in Section 1. This boundary encompasses three interlinked phases:

(1) Material Production: Embodied carbon factors were derived from the Ecoinvent 3.8 database [16], incorporating province-specific data (e.g., Shanghai: 298 $kgCO_2/m^3$ vs. Xinjiang: 412 $kgCO_2/m^3$) to address jurisdictional carbon pricing gaps. The bill of quantities (BOQ) for case study buildings was constructed from: (i) publicly available BIM models (LOD 300+) for the Shanghai Tower and Singapore Hospital prototypes, and (ii) standardized architectural archetypes combined with German cost databases (DETAIL) for the Berlin Residential case.

A explicit mapping was developed to link BOQ material specifications (e.g., "C35 concrete," "HRB400 steel") to the most representative process datasets in Ecoinvent 3.8 (e.g., "concrete production, 30 MPa," "steel production, electric arc furnace"). Regional adjustments for electricity mix and production processes were applied using the corresponding national/sub-national datasets within Ecoinvent.

Operational Phase: Simulation Approach, Calibration, and Validation Scope Building operational energy consumption was simulated using EnergyPlus 23.1. The models were constructed based on standard design parameters, architectural drawings, and equipment specifications for each case study prototype, and were calibrated to meet the performance benchmarks of relevant national energy standards (e.g., Chinese GB/T 50378-2019 for Shanghai [12]).

Clarification on Model Validation: It is important to clarify the purpose and validation context of these simulations. The primary objective was not to predict the absolute, site-specific energy consumption of an individual building, but to compare the relative impact of different carbon policy scenarios (e.g., Baseline vs. ETS vs. CBAM) on a consistent, technologically representative building model. For this comparative policy analysis, the use of carefully calibrated, standards-compliant simulation models is a well-established and valid methodology in building energy and policy research.

Calibration Basis: Model calibration was performed against dynamic benchmark load profiles derived from the respective energy standards and typical meteorological year (TMY) data, ensuring realistic hourly and seasonal variations.

Empirical Validation Status: The simulation results were not empirically validated against multi-year measured data from the specific case study buildings, as such high-resolution, long-term operational datasets are often proprietary or unavailable for flagship/global studies. This is a recognized limitation of simulation-based policy studies at this scale.

Acknowledgement of Applicable Scope and Uncertainty: Consequently, the applicable scope of the operational energy results is the analysis of trends, sensitivities, and relative differences between policy scenarios for the defined prototype buildings under standard conditions. The uncertainty introduced by this modeling choice—primarily related to variations in real-world occupancy, maintenance, and operational schedules—is explicitly acknowledged and has been integrated into the overall probabilistic framework of this study. As detailed in Section 2.4, a range of plausible operational energy use intensities (variation of ±15% from the simulated baseline) was included as an input variable in our Monte Carlo simulations and global sensitivity analysis. This ensures that the identified carbon price thresholds and optimal pathways are robust against uncertainties inherent in the operational energy modeling process.

(2) End-of-Life Processing: The model incorporated 2024 Chinese demolition regulations and provincial recycling rates (32–78%), operationalizing the policy feedback dimension of the PTE-Loop.

The analysis adopted a 30-year timeframe (±2 years SD), directly corresponding to construction investment cycles, thereby enabling the dynamic internalization of carbon

costs via the optimized pathways described in Section 2.3.

2.2. Carbon pricing engine: An agent-based model (ABM)

To overcome the limitations of static modeling, the Carbon Pricing Engine (CPE) implements the PTE-Loop theory through a spatially explicit ABM. The model was calibrated using empirical data from 15 Chinese ETS pilots (2018–2023) and EU ETS registry data. The complete set of calibration parameters is provided in **Supplementary materials Table S1**.

Three policy-relevant scenarios were simulated:

(1) Baseline Scenario: Quantified the 7.6-fold decarbonization gap under a null carbon pricing regime, calibrated to IPCC AR6 SSP2-4.5 trajectories.

(2) China ETS Scenario: Simulated a carbon price range of 50–120 CNY/tCO_2 (±15% volatility) with embodied carbon pricing. The dynamic response was modeled using the sigmoidal function defined in Equation (1), where the phase transition threshold P_0 was set at \$30/tCO_2.

$$\Delta E_{CO_2} = \alpha \left[1 - e^{-\beta(P_t - P_0)}\right] \tag{1}$$

(3) EU CBAM Scenario: Tested policy saturation effects at 150–300 €/tCO_2. For this scenario, the carbon price P_t was dynamically calculated as the maximum of a €150/tCO_2 floor price or 1.2 times the previous period's EU Allowance (EUA) price, adjusted in real-time with a blockchain-verified MRV premium (Δ_MRV_).

The ABM employs 500 agents with Q-learning (γ = 0.85–0.95) [16], validated against historical technology adoption curves (RMSE = 2.3). This setup captures dynamic elasticities for key materials (ε = 1.2 for steel, 1.05 for cement), which were found to outperform static models by 42% ($p < 0.01$).

2.3. Optimization core and threshold validation

The decarbonization pathway optimization was formalized to identify cost-environment Pareto frontiers, directly testing the sigmoidal EKC hypothesis. The core optimization problem is framed as maximizing the expected net benefits E[B] under technological and policy constraints, following the conceptual framework of Equation (2).

$$\varphi = \prod_{i=1}^{3} \left(\frac{GDP_i}{GDP_0}\right)^{0.3} \cdot \left(\frac{CI_i}{CI_0}\right)^{0.7} \tag{2}$$

The optimization incorporates sector-specific decision variables, including:

(1) Photovoltaic adoption (20–100% range), governed by an empirically derived IRR threshold of \$200 ± 25/tCO_2 (R^2 = 0.91).

(2) Low-carbon concrete alternatives, achieving a 55% embodied carbon reduction (Ecoinvent 3.8).

Monte Carlo simulations with 10,000 iterations were employed to propagate uncertainties, primarily from carbon price volatility (±20%, log-normal σ = 0.18) and technology learning rates (8.3% annual reduction, 95% CI: 7.1–9.5%) [2]. This process

empirically validated the S-curve inflection at \$120 ± 15/tCO_2 (R^2 = 0.89, F(1,14) = 28.7, $p < 0.001$), a cornerstone finding that replaces the static inverted-U EKC. The global sensitivity analysis followed the Sobol method [17] to quantify the contribution of each uncertainty source.

2.4. Uncertainty and sensitivity analysis

A rigorous probabilistic framework was developed to quantify uncertainties in the decarbonization pathways. The 10,000-iteration Monte Carlo simulations (Python 3.10 code open-sourced) integrated three key stochastic elements:

(1) Carbon price volatility (±20%, log-normal distribution calibrated to China ETS auction data).
(2) Technology learning rates (8.3 ± 1.2% annual cost reduction for renewables).
(3) Material replacement efficiencies (32–78% uniform distribution for low-carbon concrete).

Global sensitivity analysis using the Sobol method identified carbon price volatility as the dominant uncertainty source (First-order Sobol index $S_1 = 0.63 \pm 0.05$, $p < 0.001$) [18], explaining 63 ± 5% of the output variance. The analysis confirmed the robustness of the identified thresholds, with 92.3% (95% CI: 90.1–94.5%) of optimal pathways maintaining cost variations within ±15% under extreme market shocks, thereby validating the stability of the PTE-Loop's blockchain-enabled real-time adjustment mechanism.

2.5. The AI engine: Computational roles and decision-making pathways

The integration of Artificial Intelligence (AI) within the TPF is not a monolithic component but a suite of methodological tools deployed at specific stages to handle tasks intractable for conventional models. Its role is threefold: Data Analyst, Behavioral Simulator, and Optimization Navigator.

1. AI as Data Analyst (Processing Multi-Source Inputs): At the data acquisition stage, AI processes unstructured and high-volume data streams. A modified UNet++ convolutional neural network [2] is employed to analyze satellite imagery (Sentinel-2). This algorithm performs semantic segmentation to automatically identify construction activity phases, material stockpiles, and land-use changes with high precision (F1-score: 92.3%). This transforms raw pixels into structured, geotagged activity data, forming a critical input for spatially-explicit embodied carbon calculation, thereby addressing the lifecycle data gap.
2. AI as Behavioral Simulator (Driving the ABM Core): Within the Carbon Pricing Engine (Section 2.2), AI enables adaptive agent behavior. Each agent (e.g., a developer) is equipped with a Q-learning reinforcement learning algorithm [17]. The agent's state (e.g., current technology portfolio, liquidity) and the environment state (carbon price, policy signal) form the input. The AI algorithm allows agents to learn, through repeated simulation, the action (e.g., "adopt prefabrication") that maximizes a long-term reward function (e.g., net present value inclusive of carbon costs). This methodologically replaces static adoption probabilities with dynamic,

policy-responsive learning curves, generating the emergent market behaviors (e.g., the S-curve response) central to our theory.

3. AI as Optimization Navigator (Identifying Thresholds): In the optimization core (Section 2.3), AI techniques facilitate navigating complex solution spaces. Predictive models (e.g., Long Short-Term Memory networks) are used to forecast short-term carbon price volatility and energy demand, reducing scenario uncertainty. Furthermore, AI-driven optimization algorithms help manage the high-dimensional, non-linear search for Pareto-optimal pathways across thousands of Monte Carlo iterations, efficiently pinpointing the carbon price ranges where solution clusters shift—revealing the critical thresholds.

Methodological Necessity: The irreplaceability of AI in this framework lies in its core competencies: processing unstructured data (satellite images), simulating complex adaptive system behaviors (agent learning), and solving high-dimensional, non-convex optimization problems under uncertainty—tasks where traditional econometric and operations research models fall short.

2.6. The blockchain layer: A tripartite governance infrastructure

The blockchain is implemented not merely as a database but as a foundational governance infrastructure that addresses three chronic failures in conventional MRV systems: distrust, delay, and disconnection. Its integration is methodologically purposeful.

1. Ensuring Data Credibility and Immutable Auditability: Blockchain primarily establishes trust in data provenance. All source data—hashed outputs from the AI analytics layer, IoT sensor readings, BIM-derived quantities—are timestamped and anchored onto a permissioned blockchain network (e.g., Hyperledger Fabric). This creates an irreversible audit trail. Methodologically, this allows every input to the carbon calculation model (Section 2.1) to be cryptographically verified against the original record, effectively enforcing ISO 14064-3:2019 assurance principles by design and eliminating data tampering ex-ante.
2. Enabling Temporal Efficacy and Automated Execution: Blockchain directly addresses timeliness through automation. The verification logic defined by carbon accounting standards and policy rules (e.g., "if material X from region Y is used, apply emission factor Z") is encoded into smart contracts. Once pre-defined data conditions are met and verified on-chain, these contracts execute autonomously—issuing carbon credits, triggering payments, or logging compliance. This methodologically reduces the MRV latency from weeks to a median of 2.3 ± 0.7 h, which is a prerequisite for the dynamic, feedback-driven policy adjustments conceptualized in the PTE-Loop.
3. Facilitating Governance Coordination and Incentive Alignment: The blockchain network architecturally enables coordination among distrustful parties. Regulators, verifiers, builders, and financiers participate as nodes on a shared ledger. Smart contracts transparently automate the distribution of liabilities and incentives (e.g., automatically recycling carbon revenue to building owners upon verified retrofit completion). This methodologically operationalizes the resolution of

split-incentive barriers by creating a transparent, rules-based system for benefit sharing, thereby lowering transaction costs and enabling new financial instruments like granular green bonds.

Synergy with AI: The Trusted Intelligence Paradigm: The fusion is methodologically coherent: AI provides the analytical "intelligence" to make sense of complex data and systems, while blockchain provides the "trust" layer that makes AI's outputs credible, auditable, and actionable within a multi-stakeholder governance context. One without the other would be insufficient—intelligent but not trusted, or trustworthy but not intelligent—to power the responsive, threshold-sensitive governance framework the TPF requires.

3. Case study: Global validation of the TPF framework

To empirically validate the proposed Threshold-regulated Policy Framework (TPF) and its core mechanisms-the sigmoidal carbon price response and the PTE-Loop-we conducted a comprehensive analysis across three globally representative building prototypes: the Shanghai Tower (China), a Berlin Residential complex (Germany), and a Singapore Hospital. This selection strategically encompasses distinct climate zones, economic development levels, and policy contexts, representing 89% of the global building stock [18] and enabling a robust test of the TPF across the critical \$50–300/tCO_2 price range.

The implementation of the framework and its principal outcomes for each prototype are synthesized in **Table 1**, which serves as the central summary of our case study findings.

Table 1. Cross-prototype validation of the TPF decarbonization pathway.

Parameter	Shanghai tower (Cfa climate)	Berlin residential (Cfb climate)	Singapore hospital (Af climate)
Primary Climate Challenge	High embodied carbon (78% from structural steel) [19]	Space heating (92% fossil-dependent)	High-humidity cooling (1.8 MW peak load)
Primary Policy Lever	China ETS expansion (50–120 CNY/tCO_2) [20]	EU CBAM (150–300 €/tCO_2) [21]	Carbon tax + Green bonds (S\$25–50/ tCO_2) [22]
Technical Solutions Deployed	• Prefabricated hybrid structures (32% waste reduction) [23] • AI-driven demolition robots	• Ground-source heat pumps (COP = 4.2) • Phase-change materials	• Desiccant-assisted radiant cooling (38% energy savings) [24] • Model predictive control
Validation Metric & Outcome	Material substitution threshold confirmed: \$120 ± 15/tCO_2 (R^2 = 0.89, $p < 0.001$)	PTE-Loop efficacy: 92% heating decarbonization at 200 €/tCO_2 (IRR = 8.3%)	Financial viability: 7.2-year payback (95% CI: 6.8–7.6 years)

3.1. Shanghai tower: Validating the material substitution threshold

The Shanghai Tower case served as a critical test for the material substitution threshold within a high-rise, embodied-carbon-intensive context. Under the φ-adjusted China ETS (φ = 1.2), the implementation of prefabricated hybrid structures and AI-driven material management confirmed the theoretically predicted inflection point. As the effective carbon price approached and exceeded the \$120/tCO_2 threshold, a statistically significant shift towards low-carbon materials was observed ($p < 0.01$, Cohen's d = 1.82), validating the sigmoidal EKC model proposed in the theoretical framework of the Introduction. This case demonstrates the TPF's capability to resolve

the embodied carbon blind spots identified as a key problem in the Introduction through precise, threshold-activated price signaling.

3.2. Berlin residential: Demonstrating the PTE-loop in operation

The Berlin prototype focused on overcoming operational emissions, specifically the challenge of fossil-fuel-dependent space heating. The integration of EU CBAM-level carbon prices with ground-source heat pumps and thermal storage technologies successfully activated the PTE-Loop. The robust policy signal (carbon price > €150/tCO_2) rendered the capital-intensive technology investments financially viable (IRR > 8%), which in turn catalyzed market adoption and led to profound environmental gains (92% heating decarbonization). This self-reinforcing cycle provides empirical validation for the Policy→Technology→Market→Environment feedback mechanism theorized in the theoretical framework of the Introduction.

3.3. Singapore hospital: Overcoming tropical cooling challenges with financial instruments

In a context without an extremely high direct carbon price, the Singapore case demonstrated the efficacy of hybrid policy tools within the TPF. The combination of a carbon tax and green bonds achieved a viable return on investment (7.2-year payback) for advanced cooling technologies, such as desiccant-assisted radiant systems. This underscores the framework's flexibility, proving that the PTE-Loop can be initiated through tailored financial mechanisms in different policy contexts to overcome region-specific barriers, such as intense tropical cooling loads.

3.4. Cross-case synthesis and data fusion

A cross-case analysis reveals two pivotal findings that reinforce the TPF's theoretical foundations. First, the carbon price threshold of ~\$120/tCO_2 demonstrates remarkable resilience across diverse climate zones (R^2 = 0.76–0.82), confirming its value as a robust policy lever. Second, global sensitivity analysis consistently identified carbon price volatility (±20%) as the dominant uncertainty source (Sobol index S_1 = 0.63), highlighting the critical importance of the robust uncertainty quantification protocol embedded in our framework (Section 2.4).

To ensure data integrity and resolve the non-dynamic data coupling gap (**Table 2**), we employed the advanced data fusion protocol outlined in Section 2. Satellite data (Sentinel-2) was processed using a modified UNet++ algorithm to detect emission-intensive construction phases with 92.3% accuracy (F1-score). This geospatial intelligence was fused with real-time, blockchain-verified IoT data from construction sites and material logistics. This hybrid MRV approach reduced carbon reporting uncertainty by 63% (RMSE = 0.48 kg CO_2e/t), capturing 89.7 ± 2.4% of total lifecycle emissions in the Shanghai case-a significant improvement over conventional on-site measurements (72.1 ± 5.6%, p = 0.003), thereby validating the technological backbone of the PTE-Loop.

Table 2. Geospatial and contextual characteristics of case study prototypes.

Case	Coordinates (decimal degrees)	Climate zone (Köppen-Geiger)	City population (million)	Annual precipitation (mm)	Construction year
Shanghai Tower	31.2396 N, 121.4997 E	Cfa (Humid subtropical)	26.3	1223	2015
Berlin Residential	52.5200 N, 13.4050 E	Cfb (Temperate oceanic)	3.7	570	2018
Singapore Hospital	1.3521 N, 103.8198 E	Af (Tropical rainforest)	5.7	2340	2020

The foundational geospatial and contextual characteristics of these case studies are provided in **Table 2** for reference.

3.5. Note on case representativeness and strategic selection

The selection of Shanghai, Berlin, and Singapore as case studies was strategic and deliberate, aiming to achieve two primary objectives that differ from seeking statistical representativeness of the global building stock.

First, these cases serve as "stress tests" for the TPF across maximal contextual diversity. They encompass the world's major climate zones (humid subtropical, temperate oceanic, tropical rainforest), dominant policy paradigms (emissions trading system, carbon border adjustment, carbon tax with green finance), and advanced construction markets. Demonstrating the framework's functionality across these diverse, high-capacity contexts provides a robust proof-of-concept for its core theoretical mechanisms—namely, the identification of carbon price thresholds and the activation of the PTE-Loop. If the framework can resolve paradoxes in these complex, high-stakes environments, its fundamental logic is validated.

Second, we explicitly acknowledge the limitations of this selection regarding building typology and economic context. The prototypes studied are indeed "leading-edge" buildings in high-income regions. This choice was pragmatic, driven by the availability of high-quality, granular data (e.g., detailed BIM models, monitored energy data) required for the initial, fine-grained calibration of our integrated models. Ordinary buildings, existing building stock, and contexts in low- and middle-income countries (LMICs) often face distinct challenges, such as higher cost sensitivities, different supply chain constraints, and less established regulatory and data infrastructures.

Therefore, the findings related to specific numerical thresholds (e.g., the precise \$120 ± 15/tCO_2 inflection point) are most directly applicable to similar high-capacity, new-build contexts. However, the critical contribution of this study lies not in these absolute values, but in the generalized framework and mechanisms. The existence of non-linear thresholds, the operational logic of the PTE-Loop, and the architectural design of the blockchain-AI MRV system are the transferable insights. The following Discussion section (Section 5) explicitly addresses how the TPF's modular design—particularly the regional adjustment factor (φ) and the Scalability Index—provides a pathway for adapting these core mechanisms to the broader building stock and diverse socio-economic contexts.

4. Results

The implementation of the Threshold-regulated Policy Framework (TPF) delivers three pivotal sets of findings: the empirical validation of critical carbon price thresholds, the quantification of substantial Earth system co-benefits, and the demonstration of robust policy scalability across diverse regions. These results collectively resolve the core elements of the Policy-Carbon Paradox outlined in Section 1.

4.1. Empirically validated carbon price thresholds drive phase transitions

Our analysis conclusively identifies two carbon price thresholds that catalyze non-linear decarbonization in the building sector, providing definitive evidence for the sigmoidal response hypothesis.

Material Substitution Threshold at \$120 ± 15/tCO_2: When the carbon price traversed this critical range, the adoption of prefabricated structures surged from a baseline of 12.3 ± 2.1% to 63.7 ± 3.8% (Δ = 51.4 percentage points; paired $t(14) = 9.32$, $p < 0.001$, 95% CI [49.2, 53.6]). This rapid market shift was accompanied by a 43% reduction in embodied carbon intensity (from 2.1 to 1.2 $kgCO_2e/m^2$; $p < 0.001$), directly validating the sigmoidal EKC inflection theorized in the theoretical framework of the Introduction.

Energy System Tipping Point at \$200 ± 25/tCO_2: At this second threshold, photovoltaic-storage systems achieved financial viability, with an Internal Rate of Return (IRR) exceeding 8%. This transition was driven by the self-reinforcing PTE-Loop, where policy-induced carbon revenue constituted 39.2 ± 3.8% of project income, synergizing with strong technology learning rates to reduce costs by 28%.

The robustness of these thresholds was rigorously confirmed through 10,000-iteration Monte Carlo simulations. The analysis showed that 89% of optimized pathways maintained statistical significance ($p < 0.05$) under ±20% carbon price volatility (log-normal $\sigma = 0.18$). Global sensitivity analysis identified price volatility as the dominant uncertainty source (Sobol index $S_1 = 0.63 \pm 0.05$, $p < 0.001$), underscoring the critical importance of the dynamic, blockchain-enabled adjustment mechanism for maintaining pathway stability.

4.2. Substantial earth system co-benefits of threshold activation

Activating the PTE-Loop through the identified thresholds yields substantial climate and health co-benefits, directly quantifying the 'Environment' feedback in our theoretical model. The global impacts of TPF implementation are summarized in **Table 3**.

Table 3. Earth system benefits from global TPF implementation.

Benefit category	Quantitative impact	Confidence/notes	Reference/method
Climate Mitigation	Avoids 0.003 °C warming by 2050	SSP1-2.6 ensemble range: 0.0027–0.0032 °C	IPCC AR6 Allocation
	Cumulative 12.3 Gt CO_2 reductions	Equivalent to 1.6× the EU's annual building emissions	IEA & CIB Data
Health Co-Benefits (China)	21.3% reduction in $PM_{2.5}$	95% CI: 18.1–24.5%	GEOS-Chem v13.2.0
	Prevents 73,400 DALYs annually	95% CI: ±6200 DALYs	GBD 2024 Methodology
	Saves \$2.8 ± 0.6 billion/year in health costs	Maximized in Yangtze River Delta (r = 0.79 vs. industrial density)	WHO Valuation

Globally, the framework puts the building sector on a trajectory with a 92.3% probability of meeting the 1.5 ℃ climate target under the SSP2-4.5 scenario. Regionally, the analysis confirms that the health savings in China alone are of a magnitude that could fund targeted carbon revenue recycling programs, demonstrating a tangible and self-financing climate-health policy synergy.

4.3. Quantified scalability of policy frameworks

The regional scalability analysis, which operationalizes the policy adaptation dimension of the PTE-Loop, reveals distinct yet viable implementation pathways. The efficacy across different contexts is quantified by a composite Scalability Index, as detailed in **Table 4**.

Table 4. Regional scalability analysis of the TPF.

Region	Scalability index	Primary barrier & solution	Key performance indicator
European Union	0.92	Barrier: CBAM exemption needs. Solution: Negotiation under CBAM Article 30.	High institutional capacity enables system transformation.
Southeast Asia	0.67	Barrier: Higher technology costs. Solution: ASEAN Green Fund for technology transfer.	34% cost reduction potential achieved.
Africa	0.41	Barrier: Prohibitive MRV costs. Solution: Sentinel-5P/USSD hybrid system.	72.4 ± 5.2% verification cost reduction ($p < 0.01$).

The Scalability Index-which integrates policy readiness, technology penetration, and market liquidity-shows a strong positive correlation with established IPCC institutional metrics ($r = 0.89$, $p < 0.001$, $N = 42$ countries). Critically, case study validation confirmed that 83% of region-specific predicted barriers were resolved through the tailored solutions outlined in the TPF ($\chi^2 = 15.7$, $df = 5$, $p = 0.008$). This empirically validates the framework's capacity to overcome the jurisdictional fragmentation and split-incentive barriers that were central to the original paradox.

5. Discussion

Our integrated analysis synthesizes three targeted policy interventions, empirically demonstrated to dismantle the structural barriers of the Policy-Carbon Paradox (in the Introduction) by catalysing the self-reinforcing PTE-Loop (the theoretical framework of the Introduction). These levers, validated across global prototypes (Section 3) and quantified through stochastic optimization (Sections 2.3–2.4), form a coherent Threshold-regulated Policy Framework (TPF) capable of transitioning the building sector from linear to exponential decarbonization.

5.1. Synthesizing policy levers for a self-reinforcing transition

First, dynamic carbon pricing, anchored to the empirically robust \$120 ± 15/tCO_2 material transition threshold (Section 4.1), directly resolves the temporal misalignment between investment and policy cycles. The Berlin prototype (Section 3.2) operationalized this, demonstrating that a phased price trajectory (50 → 150 → 300 €/tCO_2) secured 92.3 ± 2.1% heating decarbonization by aligning long-term capital recovery with credible policy signals. This efficacy is amplified by the PTE-Loop's endogenous policy feedback—a 28% rise in public support per \$50/tCO_2 increase (the

theoretical framework of the Introduction)—which builds the political capital necessary for sustained policy escalation.

Second, blockchain-Sentinel hybrid governance surgically addresses the 55% lifecycle emissions blind spot. The Shanghai implementation (Section 3.1) achieved a 63% reduction in MRV uncertainty (RMSE = 0.48 kg CO_2e/t, transforming embodied carbon from an unmanaged externality into a precisely priced variable. This technological fusion, leveraging the UNet++ architecture and Hyperledger Fabric detailed in our methodology, operationalizes the "measurement precedes management" principle, creating the non-negotiable accountability foundation for the entire TPF.

Third, technology-specific incentive packages activate systemic change at the \$200 ± 25/tCO_2 energy tipping point (Section 4.1). Here, as demonstrated in our results, photovoltaic-storage systems cross the financial viability threshold (IRR > 8%), driven by carbon revenues constituting 39.2 ± 3.8% of income. This evolution from subsidizing technologies to orchestrating self-sustaining markets represents a core function of the mature PTE-Loop.

These levers manifest uniquely across regions, as quantified by our Scalability Index (Section 4.3). The EU's high institutional capacity (Index = 0.92) allows for CBAM refinement; Southeast Asia leverages the ASEAN Green Fund for a 34% cost reduction; and Africa's satellite-USSD system slashes prohibitive MRV costs by 72.4 ± 5.2%. Collectively, these pathways validate the TPF's adaptability and its capacity to deliver the tangible co-benefits quantified in Section 4.2-from climate risk mitigation to substantial public health savings-thereby empirically closing the Policy → Technology → Market → Environment feedback cycle.

5.2. Theoretical implications: The J-curve effect and a new economic paradigm

Our results compel a theoretical reconceptualization: we propose the J-Curve Effect for Building Decarbonization. This phenomenon, empirically grounded in our case studies (Section 3) and Monte Carlo analysis (Section 2.4), describes the inversion of traditional cost-environment tradeoffs beyond the \$200 ± 25/tCO_2 threshold. At this point, we observe not merely reduced emissions, but net cost reductions, with total project costs declining by 19.2 ± 3.1% alongside a 43% drop in embodied carbon (Section 4.1).

This finding empirically falsifies the core premise of monotonically increasing marginal abatement costs in the Environmental Kuznets Curve and the static trade-offs in Weitzman's framework. The PTE-Loop mechanism elucidates this inversion through three reinforcing pathways, quantified in our results: (1) Accelerated Technological Learning, where cost reduction rates for key technologies jump by 10.0 percentage points annually above the threshold; (2) Strengthened Policy Feedback, where public support becomes a dynamic asset; and (3) Market Restructuring, where supply chain consolidation yields efficiency gains, as seen in the Berlin case.

Our models quantify two distinct regimes: a sub-\$200/tCO_2 world of rising marginal costs, and a super-\$200/tCO_2 world where negative marginal costs dominate (mean: −\$15.6/tCO_2). This J-Curve Effect resolves 89.7% of the 7.6-fold

implementation gap identified in the Introduction, redefining carbon pricing from a static cost to a dynamic system catalyst for industrial modernization and economic efficiency.

5.3. Limitations and forthcoming research avenues

Three considered limitations, inherent to the scope of this study, chart a clear course for forthcoming research. First, while our model incorporates price volatility ($\sigma = 0.18$, Section 2.4), it does not endogenously model geopolitical shocks to trade-a critical factor for regions like the EU, where decarbonization efficacy could drop by 12–18% under restrictive trade regimes. Second, while our prototypes capture major climate zones (Section 3.1), the urban-agglomeration economies of megacities like Shanghai require finer-grained (1×1 km²) modeling to fully resolve the 55% embodied carbon gap. Third, by holding workforce transition static, we acknowledge an underestimation of labor-market frictions, evident in the skilled-labor bottlenecks for heat-pump adoption in Berlin (**Table 4**).

These limitations directly motivate our NSFC-funded research agenda, which will pursue: (1) City-Cluster Carbon Thresholds, refining the \$120 ± 15/tCO_2 inflection point via high-resolution urban modeling to reduce the embodied carbon reporting gap from 55% to below 30%; (2) Geoeconomic Equilibrium Modeling (GEEM), enhancing our volatility parameters ($\sigma = 0.18 \rightarrow 0.25$) to quantify policy robustness under trade constraints; and (3) Deep Reinforcement Learning (DRL) for Retrofits, integrating Sentinel-5P data with blockchain MRV to optimize pathways in labor-intensive historic districts. This trajectory will evolve our scalability indices into multi-tiered governance frameworks, directly addressing IPCC AR7's identified multi-scale integration gaps while preserving and extending the core threshold governance insights established herein.

5.4. Generalizability of the framework: From flagship projects to broad-base transformation

A legitimate question arising from our case studies is whether insights derived from flagship buildings in developed economies can inform the decarbonization of the ordinary, existing, and LMIC building stock. We argue that the TPF's value is precisely in providing an adaptable scaffold for this broader transformation, with the case studies serving as validated foundational modules.

(1) Translating Mechanisms, Not Transplanting Thresholds: The core finding is the existence of mechanism-driven thresholds, not their specific monetary value. For example, an "energy system tipping point" exists when the levelized cost of renewable-based solutions undercuts incumbent fossil systems. While this point occurred at ~\$200/tCO_2 in our high-capacity cases, the threshold in other regions will be a function of local technology costs, financing rates, and fuel prices. The TPF's methodology provides the tool (dynamic integration of local data into the ABM and optimization core) to identify this region-specific threshold.

(2) Modular Adaptation via the φ-Factor and Scalability Index: The framework is designed for adaptation. The regional adjustment factor (φ), introduced in

Equation (2), explicitly modulates policy and cost parameters based on local GDP, climate severity, and supply chain carbon intensity. This allows the calibration of model inputs to reflect conditions in middle-income countries or colder/poorer regions. Similarly, the Scalability Index diagnostically identifies the primary barrier in a given context (e.g., high MRV costs in Africa, higher technology costs in Southeast Asia). The solutions trialed in our cases—such as the satellite-blockchain hybrid MRV that reduced verification costs by 72.4%—are direct responses to these very barriers, demonstrating the framework's problem-solving transferability.

(3) Addressing the Core Challenges of Ordinary and Existing Stock: The paradox's structural barriers are often more acute in ordinary/existing buildings (stronger split-incentives, retrofit complexity) and LMICs (capital scarcity, informal sectors). The TPF's integrated approach is thus more critical there. Our blockchain-AI MRV system, by drastically lowering the cost and complexity of trustworthy carbon accounting, can make small-scale projects and incremental retrofits financially verifiable and thus fundable. The PTE-Loop theory shows that targeted, data-driven policies can unlock this latent potential, even if the initial policy lever is not a high carbon price but a performance-linked subsidy or green microfinance instrument enabled by credible MRV.

In conclusion, while the numerical outputs of our case studies are context-bound, the TPF itself is a context-adaptable framework. It offers a systematic methodology to diagnose local manifestations of the Policy-Carbon Paradox, identify locally relevant thresholds using available data, and deploy tailored technological and policy instruments to activate a virtuous PTE-Loop. Extending the application of this framework to a wider array of building types and regions is the logical and essential next step for both research and policy.

6. Conclusion

This study establishes and empirically validates a Threshold-regulated Policy Framework (TPF) that systematically resolves the building sector's protracted Policy-Carbon Paradox, closing the loop between disparate carbon pricing coverage and lagging sectoral decarbonization identified in the introduction. Theoretically, we have moved beyond the static Environmental Kuznets Curve by pioneering the concept of dynamic, sigmoidal carbon price thresholds. The empirical identification of the material substitution point at $\$120 \pm 15/tCO_2$ ($p < 0.01$) and the energy system transformation tipping point at $\$200/tCO_2$ (IRR > 8%), as rigorously validated in Section 4.1, provides a new quantitative foundation for climate policy. Crucially, the self-reinforcing PTE-Loop mechanism theorized in the theoretical framework of the Introduction was empirically observed to operationalize these thresholds, driving transformative outcomes such as a 17-fold expansion in green bond issuance and a 51 percentage-point surge in prefabrication penetration.

Methodologically, the TPF demonstrates that the integration of blockchain-AI fusion for MRV is not merely a technical enhancement but a foundational governance tool. By achieving a precision of 0.48 kg CO_2e/tonne RMSE and a verification

latency of 2.3 ± 0.7 h, this system resolves the longstanding data fragmentation and lifecycle blind spots that have plagued carbon accounting, thereby enabling the real-time policy-technology coupling essential for activating the PTE-Loop.

In practical terms, the framework provides a replicable and adaptable toolkit for global policymakers, as demonstrated across our tri-continental case studies (Section 3). The evidence is clear: China's φ-adjusted ETS reduces compliance costs by 38.2%, the EU's CBAM-BIM integration can slash lifecycle carbon by 55%, and the Global South's satellite-blockchain MRV cuts verification costs by 72% ($p < 0.01$). These are not hypothetical scenarios but empirically grounded pathways that collectively enable a 92.3% probability of aligning the building sector with a 1.5 ℃ climate target, as derived from our 10,000-iteration Monte Carlo simulations (Section 2.4).

Ultimately, this work redefines carbon pricing from a blunt, static tax into an adaptive, intelligent governance system. By fusing climate physics with digital econometrics, the TPF formalizes "Building Climate Finance" and demonstrates that precision decarbonization can generate significant co-benefits, as quantified by the $2.8 ± 0.6 billion in annual health savings in the Yangtze Delta (Section 4.2). The framework thus provides a quantitatively grounded and scalable archetype for planetary-scale decarbonization, transforming the built environment from a primary emissions source into a central pillar of a sustainable and economically rational future.

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