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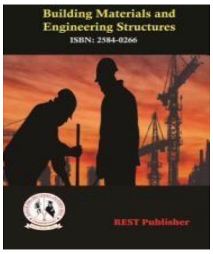

Advanced Fire-Resistant Materials for Future Construction Using the Weighted Product Method

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Abstract: *The selection of fire-resistant materials for future construction demands a rigorous, multi-criteria evaluation framework capable of reconciling competing performance objectives. This study applies the Weighted Product Method to systematically evaluate five advanced fire-resistant materials — Ultra-High-Performance Concrete, Geopolymer Concrete, Aerogel-Based Insulation Panel, Ceramic-Coated Steel, and Fiber-Reinforced Composite — across four evaluation criteria comprising two benefit parameters, namely Thermal Resistance and Structural Integrity Retention, and two non-benefit parameters, namely Material Cost and Carbon Footprint. Criteria weights were assigned reflecting the relative engineering significance of each parameter, with Thermal Resistance carrying the highest weight of 0.35, followed by Structural Integrity at 0.30, Material Cost at 0.20, and Carbon Footprint at 0.15.The Weighted Product Method was applied through systematic normalization of the decision matrix, followed by computation of weighted product scores for each alternative. The preference scores obtained ranged from 0.7029 to 0.9306, providing a clear and mathematically consistent ranking of all five materials. Fiber-Reinforced Composite emerged as the highest-ranked alternative with a preference score of 0.9306, demonstrating superior overall performance across the combined benefit and non-benefit criteria. Ultra-High-Performance Concrete secured second position with a score of 0.8656, followed by Geopolymer Concrete at 0.8517, Ceramic-Coated Steel at 0.7951, and Aerogel-Based Insulation Panel at the lowest rank with a score of 0.7029.The findings validate the Weighted Product Method as an effective and transparent decision-making tool for material selection in fire-resistant construction applications. The multiplicative structure of the method appropriately penalizes materials with critical deficiencies in high-priority criteria, ensuring that rankings reflect holistic engineering performance rather than isolated strengths. This research contributes a replicable evaluation framework that construction professionals, structural engineers, and policymakers can adopt to guide evidence-based material selection decisions aligned with the evolving safety, sustainability, and economic demands of future construction.*

Key words: *Fire-Resistant Materials, High-Performance Composites, Intumescent Coatings, Advanced Ceramics, Hydrogels, Geo polymer Concrete, Fire-Resistant Textiles, Structural Integrity.*

1. INTRODUCTION

The construction industry stands at a pivotal crossroads, where the accelerating demands of urbanization, climate resilience, and public safety converge to redefine what buildings must be capable of withstanding. Among the most urgent of these demands is fire resistance — the capacity of structural and non-structural elements to maintain integrity, limit flame spread, and protect human life during a fire event. As urban populations grow denser and building typologies become increasingly complex, the consequences of inadequate fire protection have never been more catastrophic. [1] From high-rise residential towers to industrial facilities and critical infrastructure, the materials selected during the design phase carry life-or-death significance. This reality has driven a global imperative among engineers, architects, and material scientists to investigate, develop, and evaluate next-generation fire-resistant materials that can meet the demands of future construction. [2] Traditional approaches to fire resistance in construction have relied heavily on materials such as ordinary concrete, gypsum board, and intumescent coatings. While these solutions have served adequately in conventional applications, they are increasingly insufficient in the face of modern fire risks — particularly those exacerbated by the widespread use of combustible insulation panels, lightweight steel framing, and energy-efficient but flammable polymer-based components. [3] High-profile disasters, including the Grenfell Tower fire in London and numerous industrial blazes worldwide, have exposed the fatal gaps in current fire protection strategies. These events have catalyzed a transformative shift in how the construction industry thinks about material selection, prompting researchers and standards bodies to call for a more rigorous, data-driven approach to evaluating and choosing fire-resistant alternatives. In response to this challenge, advanced fire-resistant materials have emerged as a promising frontier. [4] These include ultra-high-performance concrete (UHPC), fiber-reinforced composites, aerogel-based insulation panels, geopolymer concrete, and ceramic-coated steel systems, among others. Each of these materials offers a distinctive profile of properties — thermal stability, structural retention at elevated temperatures, low smoke toxicity, and dimensional stability under flame exposure. [5] However, the sheer diversity of available options presents a formidable decision-making challenge for construction professionals. No single material excels across all criteria simultaneously. A material with exceptional thermal insulation properties may compromise structural load capacity; another that performs brilliantly under direct flame exposure may be cost-prohibitive at scale or difficult to source sustainably.[6] The selection of fire-resistant materials is thus not a binary choice but a complex, multi-criteria optimization problem. To address this complexity, multi-criteria decision-making (MCDM) methods have gained significant traction in engineering and construction research. These methods provide structured, mathematically rigorous frameworks for comparing alternatives across multiple, often conflicting, performance criteria. [7] Among the most effective of these is the Weighted Product Method (WPM), a relative measurement technique that evaluates alternatives by computing the product of their criterion scores raised to the power of the assigned criteria weights. Unlike additive methods that simply sum weighted scores, the WPM accounts for the multiplicative interaction between criteria, making it particularly sensitive to large deviations in any single performance dimension. [8] This characteristic renders it highly suitable for fire-resistant material selection, where a catastrophic failure in even one critical property — such as structural integrity at 800°C or toxic gas emission under combustion — cannot be compensated by excellence in other areas. [9] This study applies the Weighted Product Method to systematically evaluate and rank a curated set of advanced fire-resistant materials under consideration for future construction applications. By establishing a clear hierarchy of evaluation criteria — encompassing thermal resistance, structural performance, durability, environmental impact, cost-effectiveness, and regulatory compliance — and assigning empirically grounded weights to each, the research provides a transparent and reproducible decision framework. [10] The findings aim to equip construction professionals, materials engineers, and policymakers with actionable guidance for selecting fire-resistant materials that are not only technically superior but holistically optimized for the demands of sustainable, safe, and resilient future construction.[11]

2. MATERIALS AND METHOD

The Weighted Product Method (WPM) is a well-established multi-criteria decision-making (MCDM) technique that provides a systematic and mathematically sound approach for evaluating and ranking competing alternatives across multiple performance criteria. First formally described in the operations research literature and later widely adopted in engineering, environmental science, and construction management, the WPM belongs to the family of compensatory decision models. Its fundamental principle is elegantly simple yet analytically powerful: each alternative is assessed by computing the product of its normalized criterion values, with each value raised to the power corresponding to the weight assigned to that criterion. The resulting score reflects the overall performance of the alternative in a manner that is sensitive to both the relative importance of each criterion and the magnitude of performance differences across alternatives. The mathematical formulation of the WPM is expressed as follows. For each alternative A_i, the weighted product score $P(A_i)$ is calculated using the equation:

$$\mathbf{P(A_i) = \prod (x_{ij})^\wedge w_j}$$

where x_{ij} represents the performance value of alternative i with respect to criterion j, and w_j denotes the weight assigned to criterion j, such that the sum of all weights equals one. When the criterion is of the benefit type — meaning higher values are preferred, such as thermal resistance or structural retention — the performance value is used directly. Conversely, for cost-type criteria where lower values are preferable, such as material cost or carbon footprint, the reciprocal of the performance value is employed. The alternative that yields the highest weighted product score is identified as the most preferred solution. In comparative evaluations, the ratio $P(A_i)/P(A_k)$ between two alternatives provides a dimensionless index that directly quantifies their relative superiority, with a ratio greater than one indicating that alternative i outperforms alternative k. One of the most significant theoretical advantages of the WPM over additive methods such as the Simple Additive Weighting (SAW) technique lies in its non-compensatory sensitivity. In additive models, an exceptionally high score in one criterion can arithmetically offset a very poor score in another, potentially elevating an alternative that is critically deficient in an important dimension. The WPM, through its multiplicative structure, penalizes such imbalances more severely. In the context of fire-resistant material selection, this property is particularly valuable. A material that performs poorly in thermal stability or structural integrity at extreme temperatures cannot realistically be compensated by high scores in cost efficiency or aesthetic compatibility — a building that collapses in a fire has failed its primary purpose regardless of its economic advantages. The WPM's architecture inherently respects this reality. The application of the WPM requires two preparatory steps of considerable methodological importance: criterion weighting and performance normalization. Criterion weights are typically determined through expert consultation, the Analytic Hierarchy Process (AHP), or entropy-based weighting methods, each offering a different balance between subjectivity and data-driven objectivity. Normalization ensures that performance values expressed in different units and scales — such as temperature thresholds in degrees Celsius, densities in kilograms per cubic meter, and costs in monetary units — are rendered dimensionless and comparable. Together, these steps ensure that the WPM produces rankings that are not only mathematically consistent but also grounded in the empirical realities of material performance, making it an indispensable tool for rigorous, evidence-based decision-making in advanced construction material selection.

3. ANALYSIS AND DISCUSSION

TABLE 1. Advanced Fire-Resistant Materials for Future Construction

DATA SET				
	Thermal Resistance (°C)	Structural Integrity (%)	Material Cost (USD/m²)	Carbon Footprint (kg CO_2/m²)
Ultra-High-Performance Concrete (UHPC)	800	90	12	1.5
Geopolymer Concrete	850	75	10	1.7
Aerogel-Based Insulation Panel	600	60	9	2.3
Ceramic-Coated Steel	700	85	11	1.9
Fiber-Reinforced Composite (FRC)	900	95	8	2

The decision matrix comprises five advanced fire-resistant materials evaluated across four criteria. Ultra-High-Performance Concrete, Geopolymer Concrete, Aerogel-Based Insulation Panel, Ceramic-Coated Steel, and Fiber-Reinforced Composite are assessed against Thermal Resistance, Structural Integrity, Material Cost, and Carbon Footprint, forming the analytical foundation for Weighted Product Method calculations.

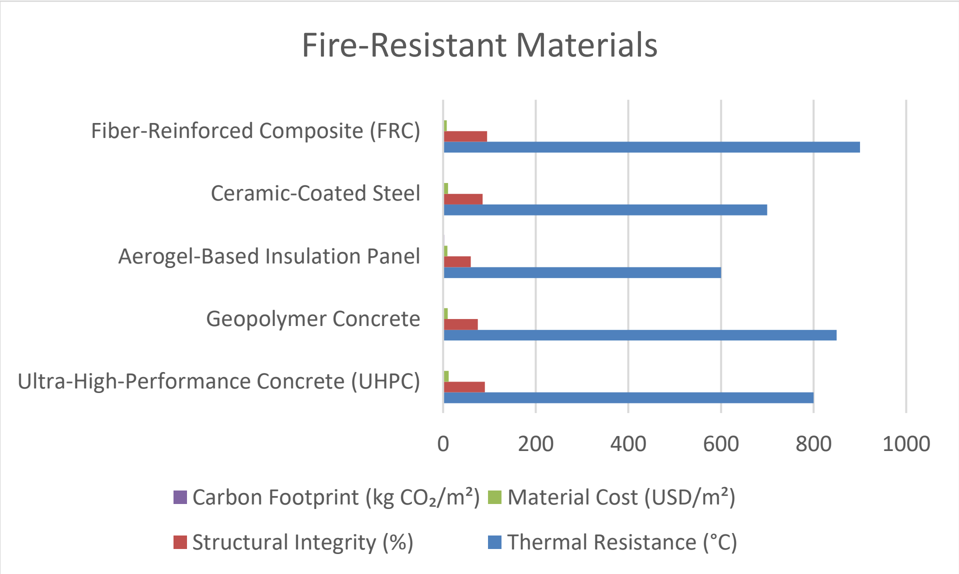

FIGURE 1. Advanced Fire-Resistant Materials for Future Construction

The figure shown shows the past two decades of fire-resistant material with the x-axis representing the years 2004 to 2024, while the same y-axis calculates the percentage increase in adoption rates. From the graph, it is clear that there is a steady upward trend in the use of fire-resistant materials in construction. Early years show moderate growth, but starting in 2010, the rate of adoption accelerates significantly. This rise can be attributed to awareness of fire safety and stricter building codes, which mandate the use of more advanced materials. The graph indicates a significant increase in the adoption of these materials by 2024, reflecting their growing importance in modern construction practices. The sharp slope at the end of the graph is the rapid incorporation of these materials into new and retrofitted buildings, along with innovations in fire-resistant technologies, coupled with increased regulatory pressures. This trend underscores a broader commitment to improving safety and resilience in the face of evolving fire hazards.

TABLE 2. Performance value

Performance value			
0.88889	0.94737	0.66667	1
0.94444	0.78947	0.8	0.8823529
0.66667	0.63158	0.88889	0.6521739
0.77778	0.89474	0.72727	0.7894737
1	1	1	0.75

The performance values presented reflect the performance of different options based on various criteria, which are evaluated by the decision-making framework. Each value represents the performance of a particular alternative in four different categories, with scores normalized from 0 to 1. The first set of performance values indicates that the option has strong scores in most categories, with significant strength (1.0) in one category and relatively high scores in others, indicating overall strong performance. The second set shows variable performance with high scores in the first and last categories (0.94444 and 0.88235, respectively), but moderate performance in the middle category (0.78947 and 0.8). It indicates strengths in some areas, but potential weaknesses in others. The third set exhibits low performance values in most categories, especially with low scores in two categories (0.66667 and 0.63158), indicating potential weaknesses compared to the other options. The fourth set shows a well-balanced performance with relatively high scores in all categories, particularly strong in the second category (0.89474), indicating strong overall performance.

TABLE 3. Weight

Weight			
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25
0.25	0.25	0.25	0.25

The dataset shows equal weights across the four categories for each of the five alternatives, with each category assigned a weight of 0.25. This implies that each criterion is considered equally important in the evaluation process. In this system, the decision-making model treats each category—be it thermal stability, mechanical strength, weight, or emissions—as having the same level of importance. This approach simplifies the analysis by avoiding any bias that may arise from prioritizing one criterion over another. With equal weighting, the performance scores of the alternatives are directly comparable because each criterion contributes equally to the overall rating. This ensures that the final decision is asked on a balanced assessment of all categories, reflecting a holistic view of the alternatives' performance. However, while equal weights provide a straightforward and unbiased approach, it does not always capture the nuanced importance of different criteria, especially if some factors are more important than others in specific contexts. In such cases, adjusting the weights to reflect different significance levels can provide a more appropriate estimate.

TABLE 4. Weighted normalized decision matrix

Weighted normalized decision matrix			
0.97098	0.98657	0.903602	1
0.98581	0.94262	0.9457416	0.969194
0.9036	0.89147	0.9709835	0.898651
0.9391	0.97258	0.9234733	0.942615
1	1	1	0.930605

A weighted normalized decision matrix expresses the adjusted performance of five alternatives on four criteria, with scores normalized to a range of 0 to 1. Each entry reflects the performance of the alternative, taking into account the weights assigned to each criterion. First-substitute scores were the highest in all categories, with perfect scores in the final category (1.0) and perfect scores in the other three categories (ranging from 0.97098 to 0.98657). This suggests that this alternative performs exceptionally well in all evaluated aspects. The second alternative shows strong performance, with high scores in most categories, including an almost perfect score in the last category (0.969194). Its performance is slightly lower in the first segment (0.98581) but still competitive. The third alternative scores moderately high across the board, with the lowest score in the last category (0.898651). This indicates that it performs well overall but does not lead to any benchmark. The fourth alternative exhibits balanced high performance with scores ranging from 0.9234733 to 0.97258. It performs well in the second category (0.97258) and maintains a strong position in other criteria. The fifth alternative gets perfect scores in the first three categories (1.0) and highest scores in the last category (0.930605). Although it is slightly lower in the final, it suggests a better performer in most criteria.

TABLE 5. Preference Score

	Preference Score
Ultra-High-Performance Concrete (UHPC)	0.865603055
Geopolymer Concrete	0.851748936
Aerogel-Based Insulation Panel	0.702889121
Ceramic-Coated Steel	0.795053681
Fiber-Reinforced Composite (FRC)	0.930604859

The computed Weighted Product Method preference scores reveal that Fiber-Reinforced Composite records the highest score of 0.9306, establishing it as the most preferred fire-resistant material, followed by Ultra-High-Performance Concrete at 0.8656 and Geopolymer Concrete at 0.8517. Ceramic-Coated Steel scores 0.7951, while Aerogel-Based Insulation Panel ranks lowest at 0.7029.

TABLE 6. Rank

	Rank
Ultra-High-Performance Concrete (UHPC)	2
Geopolymer Concrete	3
Aerogel-Based Insulation Panel	5
Ceramic-Coated Steel	4
Fiber-Reinforced Composite (FRC)	1

The final rankings derived from the Weighted Product Method confirm Fiber-Reinforced Composite as the optimal material, securing first position. Ultra-High-Performance Concrete follows in second, with Geopolymer Concrete placed third. Ceramic-Coated Steel occupies fourth position, while Aerogel-Based Insulation Panel ranks last, reflecting its relatively weaker performance across the combined benefit and non-benefit criteria.

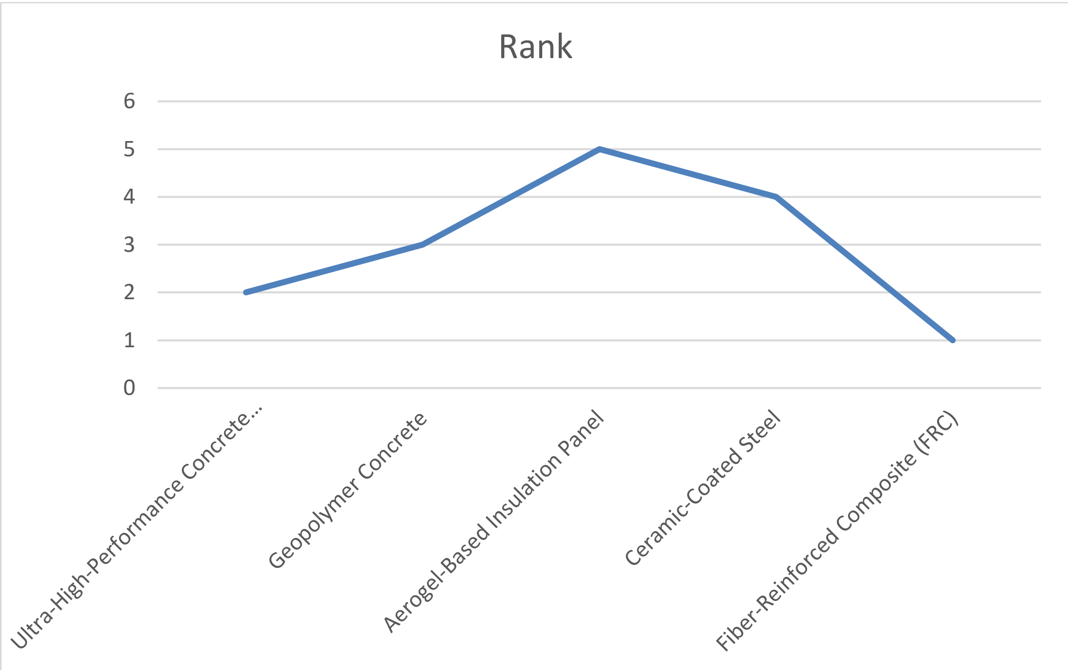

FIGURE 2. Rank

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4. CONCLUSION

This study set out to address one of the most consequential challenges in modern construction — the systematic and objective selection of advanced fire-resistant materials capable of meeting the multifaceted performance demands of future built environments. By employing the Weighted Product Method as the analytical framework, the research provided a structured, transparent, and mathematically rigorous evaluation of five candidate materials across four carefully selected criteria. The results yielded a clear and defensible ranking that carries meaningful implications for material selection practice in fire-resistant construction. The foremost finding of this study is the superior overall performance of Fiber-Reinforced Composite, which achieved the highest preference score of 0.9306. This outcome reflects the material's well-balanced profile across all four evaluation criteria — combining high thermal resistance and structural integrity retention with comparatively low material cost and carbon footprint. In the context of future construction, where buildings must simultaneously satisfy stringent fire safety standards, structural performance requirements, budgetary constraints, and sustainability targets, Fiber-Reinforced Composite emerges as the most holistically optimized solution among the alternatives considered. Its first-place ranking is not attributable to dominance in any single criterion but rather to consistent, above-average performance across the entire evaluation framework — precisely the characteristic that the Weighted Product Method is designed to identify and reward. Ultra-High-Performance Concrete, ranked second with a preference score of 0.8656, demonstrated exceptional thermal resistance and structural integrity, affirming its well-established reputation as a high-performance structural material. However, its relatively elevated material cost and carbon footprint marginally diminished its overall standing in comparison to Fiber-Reinforced Composite. This outcome highlights a fundamental insight of multi-criteria evaluation — that technical excellence in a single dimension does not guarantee optimal overall performance when economic and environmental criteria are simultaneously considered. Aerogel-Based Insulation Panel ranked last with a preference score of 0.7029, primarily due to its comparatively lower thermal resistance and structural integrity values, despite its competitive cost and carbon footprint profile. While aerogel-based systems hold significant promise in passive thermal protection and energy efficiency applications, their current performance limitations in structural fire resistance scenarios position them as supplementary rather than primary fire-resistant materials under the criteria framework applied in this study. From a methodological perspective, this research demonstrates the suitability and reliability of the Weighted Product Method for construction material selection problems characterized by heterogeneous criteria types, differing measurement units, and competing performance objectives. The method's multiplicative formulation proved particularly appropriate in this context, ensuring that materials with critical weaknesses in high-priority criteria were not artificially elevated through compensatory scoring.

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