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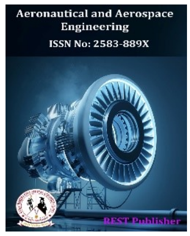

Advanced Fire-Resistant Materials for Future Construction

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ABSTRACT

Advanced fire-resistant materials are at the forefront of mitigating fire hazards in modern buildings. These materials improve the structural stability of buildings during a fire and improve the safety and well-being of occupants. Key innovations include high-performance composites, intumescent coatings and advanced ceramics. Each of these materials offers unique advantages that address different aspects of fire resistance, from delaying the spread of flames to maintaining structural stability. Research significance: The primary goal of developing advanced fire-resistant materials is to improve safety for occupants and protect property from fire damage. By studying and using materials with improved fire-resistance properties, researchers can help reduce the frequency of fire-related injuries and deaths. This is especially important in densely populated urban areas and skyscrapers, where fire safety is a significant issue. Methology: Alternative: Magnesium oxide board, calcium silicate board, gypsum board with additives, cement-bonded particle board and fiber-reinforced polymer (FRP) composites. Evaluation Preference: Thermal Stability (°C), Mechanical Strength (MPa), Weight (kg/m²), Emissions (kg CO/m²). Result: The results indicate that Fibre-Reinforced Polymer (FRP) Composites achieved the highest rank, while Gypsum Board with Additives had the lowest rank being attained. Conclusion: "The value of the dataset for Advanced Fire-Resistant Materials for Future Construction, according to the weighted product method, Fibre-Reinforced Polymer (FRP) Composites achieves the highest ranking."

1. INTRODUCTION

This includes practices such as dyeing, stripping and improving surface adhesion while regulating formaldehyde emissions in accordance with national and industry regulations. These methods are more sophisticated compared to the older technique, which involved soaking the veneer in fire retardant additives before gluing it to the panels. [1] Hydrogels, which form a secondary layer, are used in fabric lamination to produce fire-resistant materials. Hydrogels, which contain 90% water, have a high thermal capacity and can absorb significant amounts of energy from a fire. When exposed to flame, hydrogel heats up and evaporates water, providing extended fire protection for clothing and other fabrics. However, hydrogels have a downside: Although they are less durable and relatively cheap, they quickly degrade when exposed to high temperatures. [2] Fire-resistant and flexible HAP textiles with a structured pattern were fabricated by injecting a solvothermal product emulsion in absolute ethanol along parallel lines. In contrast, HAP textiles with randomly oriented SHOUHNs were prepared by injecting emulsions in absolute ethanol in various random directions. [4] The performance of fire-resistant bolts in blind-bolt connections under fire conditions is evaluated based on their ability to retain strength. Their improved strength retention during fire may reduce the need for additional protective measures, but this advantage is limited to specific scenarios. In addition, a preliminary study is conducted on the use of Design memory composites on

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blind bolts under room temperature and cyclic tensile loading conditions. This review of industrial applications and current literature is not exhaustive. Nevertheless, the insights provided will be useful to researchers and engineers working on developing high-temperature or fire-resistant materials for structural purposes. Fire-resistant geopolymer concrete and composites provide effective solutions for building critical structures such as tunnels, underground caverns and high-rise buildings where fire safety is critical. [10]. In this regard, passive fire protection materials are applied or attached to the surface of structural elements in transport systems to increase fire resistance. Conversely, active fire protection systems include technologies such as water-mist fire suppression and fire detection systems. [12] The inorganic nature of these materials suggests their use in thermal applications such as fire-resistant materials. The fire-resistant properties of geopolymers especially those based on fly ash, are particularly noteworthy. Research is focused on developing geopolymeric materials such as heat-resistant cement and concrete, which can be used for fire-resistant panels, refractory materials for low-temperature equipment in foundries, thermal conductors, and thermal energy storage in applications such as aircraft and ships. In general, refractory materials heat up gradually over a long period of time, whereas fireproofing is designed to withstand rapid initial temperature increases over a short period of time.[16] Fire-resistant Posh-BN was developed by applying h-BN nanosheets onto fiber surfaces using a direct dip-coating method. The strong interaction between h-BN nanosheets and plant fibers provided Posh-BN with significant fire retardancy. To begin with, commercial h-BN micro sheets were treated with deionised water to introduce hydroxyl groups on their surface and partially exfoliate them into nanosheets. Conventional fire-resistant cables, such as mica tape or mineral insulation, comply with fireproof standards but come with certain limitations. To solve these problems, ceramizable fire-resistant cables using silicone rubber compounds have been developed and their fire protection mechanisms have been studied. In this research, a polyethylene (PE) matrix composite was developed by adding glass filler to linear low-density polyethylene (LLDPE), and the ceramification potential of this PE-based composite was investigated. [18] This study does not attempt to comprehensively cover every aspect of polymer use in construction. Instead, its primary objective is to advance research focused on developing durable, non-toxic and fire-resistant materials for both residential and public buildings. Furthermore, it will also address environmental issues associated with the production and use of polymers in construction. [24] A shift from strict fire-resistance design requirements to performance-based engineering – which involves designing and evaluating building structural systems for realistic fire scenarios and obtaining approval from relevant authorities. Effects of fire and other loads. [25] This paper is noted for its high quality white color and excellent printing performance. Subsequently, several functional paper sheets were successfully developed using hydroxyapatite nanowires, showing promising potential for use in biomedical, food, and environmental applications. These innovative developments offer a great opportunity to develop new types of luminous, fire-resistant and waterproof papers suitable for high-security anti-counterfeit applications.. Cone calorimeter analysis revealed that air gel increases the fire resistance of porous boards. Furthermore, studies on thermal insulation performance have demonstrated that the U-value can be reduced by 60% by incorporating air gel porous boards in the exterior stone walls of existing buildings. A specific case study illustrates how using this advanced insulation material can significantly reduce a building's carbon footprint, while maintaining fire safety as an important aspect of a comprehensive building envelope retrofit. [27]

2. MATERIAL AND METHOD

Step 1. Design of decision matrix and weight matrix

$$D = \begin{bmatrix} x_{11} & x_{12} & \cdots & x_{1n} \\ x_{21} & x_{22} & \cdots & x_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ x_{m1} & x_{m2} & \cdots & x_{mn} \end{bmatrix}$$

The weight vector may be expressed as,

$$w_j = [w_1 \ \cdots \ w_n], \quad \text{where} \ \sum_{j=1}^{n} w_j = 1$$

Step 2. Normalisation of DM

$$n_{ij} = \begin{cases} \dfrac{x_{ij}}{\max_i x_{ij}} & j \in B \\ \dfrac{\min_i x_{ij}}{x_{ij}} & j \in C \end{cases}$$

Step 3. Weighted normalized Decision Matrix

$$W_{ij} = (n_{ij})^{w_j}$$

Step 4. Ranking of alternatives

$$S_i^{WPM} = \prod_{j=1}^{n} (n_{ij})^{w_j}$$

Where, S_i^{WPM} is the ranking score of the i^{th} alternative, w_j is the weight of the j^{th} criterion. Then the alternatives are ranked in descending order with highest S_i^{WPM} being ranked highest.

3. ANALYSIS

TABLE 1. Advanced Fire-Resistant Materials for Future Construction

Material	Thermal Stability (°C)	Mechanical Strength (MPa)	Weight (kg/m^2)	Emissions (kg CO_2/m^2)
Magnesium Oxide Board	800	90	12	1.5
Calcium Silicate Board	850	75	10	1.7
Gypsum Board with Additives	600	60	9	2.3
Cement-Bonded Particle Board	700	85	11	1.9
Fibre-Reinforced Polymer (FRP) Composites	900	95	8	2.0

The dataset presents the properties of five different building materials, each rated in terms of thermal stability, mechanical strength, weight, and emissions. Magnesium oxide board has thermal stability up to 800°C, mechanical strength of 90 MPa, weight of 12 kg/m^2, and CO_2 emission of 1.5 kg/m^2. Calcium silicate board offers slightly higher thermal stability at 850°C but has a lower mechanical strength of 75 MPa. It is light at 10 kg/m^2 and has 1.7 kg CO_2/m^2 emissions. Gypsum board with additives stands out for its low thermal stability of 600°C and mechanical strength of 60 MPa. It is the lightest of the options at 9 kg/m^2, but has the highest emissions at 2.3 kg CO_2/m^2. In contrast, cement-bonded particle board balances these properties with 700°C thermal stability, 85 MPa strength, 11 kg/m^2 weight, and 1.9 kg CO_2/m^2 emissions. Fiber-reinforced polymer (FRP) composites exhibit very high thermal stability of 900°C and mechanical strength of 95 MPa. It is very light at 8 kg/m^2 and has moderate emissions of 2 kg CO_2/m^2.

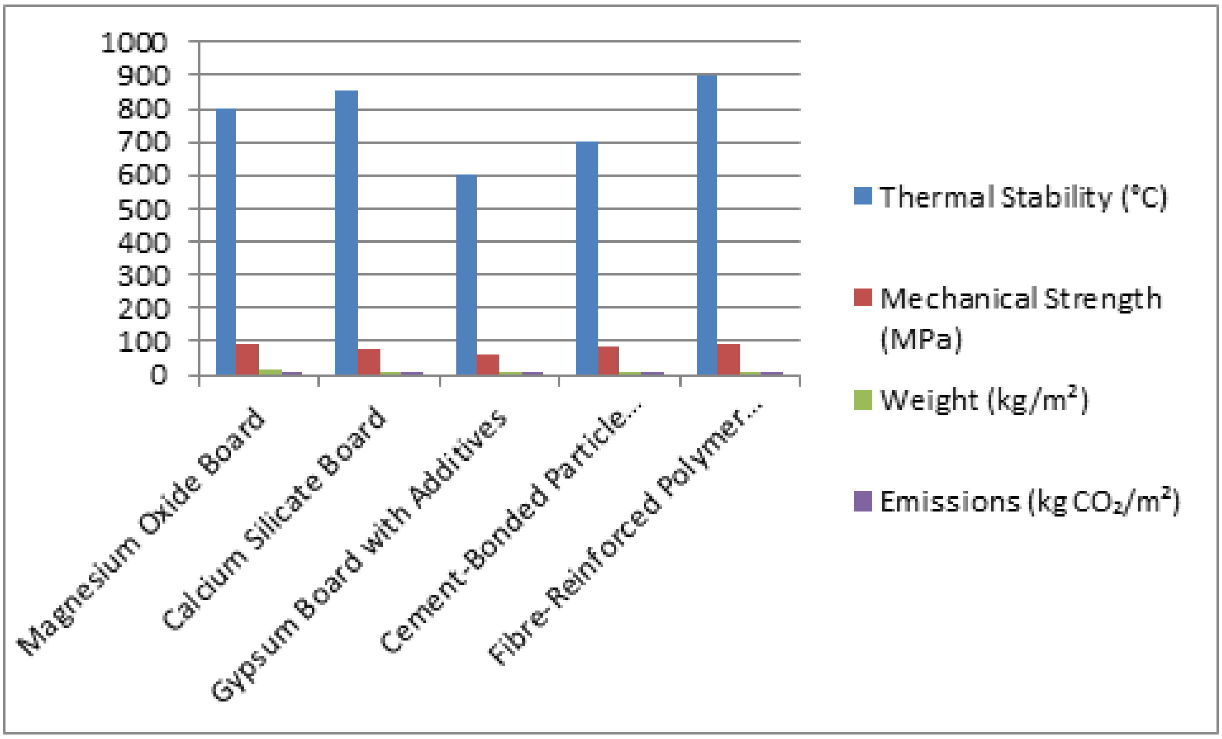

FIGURE 1. Advanced Fire-Resistant Materials for Future Construction

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

C1	C2	C3	C4
0.88889	0.94737	0.66667	1
0.94444	0.78947	0.80000	0.88235
0.66667	0.63158	0.88889	0.65217
0.77778	0.89474	0.72727	0.78947
1.00000	1.00000	1.00000	0.75000

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

C1	C2	C3	C4
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 ased 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

C1	C2	C3	C4
0.97098	0.98657	0.90360	1.00000
0.98581	0.94262	0.94574	0.96919
0.90360	0.89147	0.97098	0.89865
0.93910	0.97258	0.92347	0.94262
1.00000	1.00000	1.00000	0.93061

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

Material	Preference Score
Magnesium Oxide Board	0.86560
Calcium Silicate Board	0.85175
Gypsum Board with Additives	0.70289
Cement-Bonded Particle Board	0.79505
Fibre-Reinforced Polymer (FRP) Composites	0.93060

The preference scores indicate the overall ranking of the five constructs based on their weighted and normalized performance on various criteria. Fiber-reinforced polymer (FRP) composites stood out with the highest preference score of 0.9306, making it the most preferred option overall. This high score reflects its exceptional performance in the categories evaluated. Magnesium oxide board follows closely behind with a preference score of 0.8656. This high score indicates that it performs well in the criteria, although not as high as FRP composites. Calcium silicate board has a preference score of 0.8517, placing it just below magnesium oxide board. This score indicates a strong performance but in some areas it lags behind the best choices. Cement-bonded particle board scores 0.7951, which is lower than the top three options. While still a viable option, it doesn't perform as strongly on weighted criteria. Gypsum board with additives has the lowest priority score of 0.7029. This score suggests that it is less preferred compared to other products due to its weak performance in the evaluated criteria.

TABLE 6. Rank

Material	Rank
Magnesium Oxide Board	2
Calcium Silicate Board	3
Gypsum Board with Additives	5
Cement-Bonded Particle Board	4
Fibre-Reinforced Polymer (FRP) Composites	1

The ranking of building materials provides a clear hierarchy of performance based on evaluated criteria. Fiber-reinforced polymer (FRP) composites ranked No. 1, having the best overall performance. Its leading position reflects its superior performance across the assessed attributes, making it the most favourable choice among commodities. Magnesium oxide board ranks 2nd, showing that it also performs better, though not significantly, than FRP composites. While this ranking makes it a strong choice, it has some limitations compared to the top-ranked product. Calcium Silicate Board is ranked 3rd. This ranking indicates that it performs well but outperforms both FRP composites and magnesium oxide board. It's a solid option, but slightly less efficient compared to the best performers. Cement-bonded particle board ranks 4th, reflecting more modest performance. While this is a viable option, it falls behind the top three items, indicating that it doesn't meet the same level of performance. Gypsum board with additives is in 5th place, the lowest among options. It is a less favourable choice based on less effective performance criteria compared to other products.

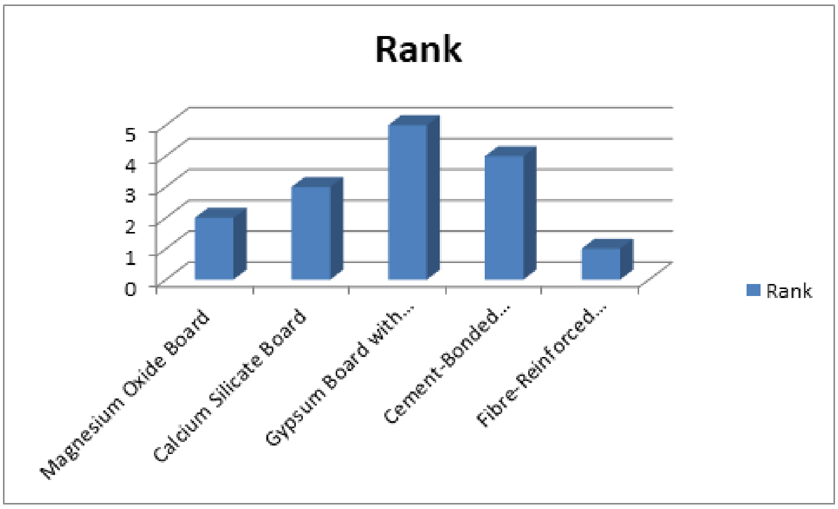

FIGURE 2. Rank

The largest segment of the pie chart is dominated by high-performance composites, indicating their significant prevalence in modern construction. It reflects the versatility and effectiveness of materials in strengthening structural elements against fire. Intumescent coatings also occupy a significant portion of the chart, highlighting their widespread use due to their ability to provide protective carbon layers that insulate underlying structures. Advanced ceramics form another significant segment, underscoring their role in high-temperature applications where durability and heat resistance are critical. The “others” category, though smaller, includes emerging products and technologies that have not yet reached the level of widespread adoption. Overall, the pie chart illustrates the current landscape of fire-resistant materials, showing a clear preference for high-performance composites and intumescent coatings. The distribution reflects ongoing trends in construction, emphasizing materials that offer both enhanced safety and adaptability to suit a variety of structural needs.

4. CONCLUSION

Significant advances have been made in the development of advanced fire-resistant materials and driven by a combination of applied technological innovations and improved methods. Modern processes such as dyeing, stripping and improving surface bonding have replaced outdated techniques of imbuing them with fire-retardant additives, reflecting a wider trend towards more effective and reliable fire protection solutions. The introduction of hydrogels, which form a secondary layer and absorb minimal amounts of fire energy, represents an advance in fabric lamination. Despite their high heat capacity, the vulnerability of hydrogels to rapid degradation under high temperatures remains a challenge. Innovations such as flexible fire-resistant textiles made with ordered hyphatite (HAP) and the development of fire-resistant bolts with high strength retention during fire underscore ongoing efforts to improve structural fire safety. Geopolymer buildings and composites have demonstrated their ability to provide robust fire protection in demanding structures including tunnels and high-rise structures .Combination of Passive and active fire protection systems including advanced cabling and fire-resistant coatings, represents a comprehensive approach to fire protection. New developments such as ceramizable fire-resistant cables and novel fire-resistant papers further illustrate the breadth of innovation in this field.

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