



(RESEARCH ARTICLE)



## Enhancing fire resistance in steel structures through innovative coating materials

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### Abstract

**Background:** Fire protection of structural steel is a critical concern in modern construction, particularly after incidents like the World Trade Centre collapse, which highlighted steel's vulnerability to extreme heat. However, steel is noncombustible but at high temperatures, mechanical properties of steel such as strength reduces. Steels have become a popular material commonly used comprehensively in the construction of structures such as high-rise buildings, stadiums and even convention centers in the United States. The need for protection results from this element in creating better structural stability, safety of the occupants and subsequently case advanced fire protection techniques arising from the research on better and improved coating technology.

**Materials and Methods:** This review of fire-resistant coating technologies for steel structures in steel structures was based on the review and analysis of the official publications which included Academic papers, technical papers, and Standards (2010–2024). The main tests conducted in the research include the chemical composition evaluation, thermal characterization, and mechanical characterization. They included thermal conductivity, expansion ratio, char strength, adhesion characteristic and fire resistance classification (ASTM E119, ISO 834 and UL 263). Consequently, the comparison was made between conventional coatings and advanced systems that incorporate nanomaterials, bio-based components, and new polymer systems.

**Results:** Nano enhanced intumescent coatings had been observed to perform well with some of the steel-coating interface temperatures over the fire test positioned at 35–42%. The hybrid coatings established fire protection ratings more than 180 minutes and were applied on 30% lesser thickness. Lignin-based formulations proved to exhibit good flame-retardant properties with minimized adverse effects on the environment. Optimised coatings sustained structural efficiency at temperatures of up to 1100 °C with better caul and charring, above all, a lot less smoke than normal methods.

**Discussion:** With the help of nanotechnology, the properties such as thermal barrier for fire-resistant coatings have been improved through synergistic effect. But they are lacking in building durability, weathering resistance, and sometimes tend to be quite costly. These bio-based formulations are more sustainable than the conventional formulations but need improvement. Different geometries of steel, fire exposure conditions and the environmental conditions also influence the degree of coating, and therefore each application requires research and development. From the results presented above it can be concluded that there is a possibility to create multifunctional coatings for protection against fire, corrosion as well as aesthetic requirements.

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**Conclusion:** Intumescent coatings are the most recent development as far as fire protection for steel structures are concerned; they have better performance as compared to the earlier forms of fire protection; they are lighter in weight and easier to apply. Advanced groups such as nanotechnology and eco-friendly formulations have enhanced sturdiness and eco-effectiveness. In future innovations, new layers such as smart coatings that have the ability for auto repair and better withstanding the effects of weather could be incorporated. Therefore, it can be concluded that in line with the current development of building codes, intumescent coatings will again become one of the key components of fire protection solutions for buildings and their occupants.

**Keywords:** Fire Resistance; Steel Structures; Intumescent Coatings; Thermal Performance; Nanomaterials; Bio-Based Coatings; Heat Flux; Thermal Insulation; Fire-Resistant Polymers; Hybrid Coatings; Eco-Friendly Formulations.

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## 1. Introduction

### 1.1. Evolution of Fire Protection Strategies for Structural Steel

#### Historical Development of Steel Fire Protection in American Construction Industry

The protection of structural steel against fire hazards has undergone significant evolution since its initial implementation in American construction practices. Bailey (2005) pointed out that great attentions of urban fires at the late 19th and early of 20th accelerated the initiation of fire protection systems for steel framed constructions due to growing up city. For the most part, the Great Chicago fire of 1871 impacted on the early codes on construction that insisted on fire protection mainly for structural features as underscored by Güler (2002) in his historical review. In the past the protection techniques mainly involved using larger thickness of concrete shell, which apart from offering thermal insulation, increased the structural weight as pointed out by Phan et al. in their technical guidelines on fire resistance design. Starting in the middle of the century, spray applied cementitious products came into use as lighter versions or refill types but most of these had their appearance drawback and in some cases shortcomings in the aspect of durability as observed by GCR (2024) in a review of high-rise building fire protection systems. Mariappan (2016) also expands that, that the advancement path of steel fire protection has always been towards even more enhanced and lightweight fire solutions that ensure the stability of structure while at the same time not limiting the creativity in design.

The post-World War II construction boom across major American metropolitan centers significantly accelerated innovations in steel fire protection technologies. According to Lucherini and Maluk (2019), it was noted that the growing height of buildings that defined urban landscapes required more complex solutions for encouraging structural fire safety that could address the new architectural complexities. The initial creation of intumescent coatings for building applications was in the early 1960s and is described as Liang et al. (2013) thin-film appearing fire protection which maintained the aesthetic features of exposed steel as observed in this literature review. The authors de Silva et al., (2022) quoted that these early intumescent systems appeared to perform well in the laboratory tests but had poor durability when exposed to common environmental factors common in the various American zones. Over the years, several researches have noted that in the both 1970s and 1980s, as the formulation chemistry proceeded together with enhancements of the coating polymers, the mentioned limitations were gradually handled by formulators to have more resistant coatings which could be applicable in various environments. According to Mariappan (2016), such evolutionary timeline also reveals the steady progression from the combinations of protection and weight, looks and real-life reliability.



**Figure 1** Fireproofing Materials for Steel coating. Source: <https://www.ippmagazine.com/fireproof-paint/fireproofing/>

The tragic events of September 11, 2001, fundamentally transformed the landscape of structural fire protection research and implementation across the United States. More specifically, Phan et al. (2010) highlighted that the tragic collapse of the World Trade Center towers brought out severe weaknesses of traditional methods of fire protection of steel structures under such circumstances. This prompted higher metamorphosis of the prevailing standards and performance parameters of fire-resistant materials as clearly depicted by Xing in structural engineering enhancement. The extensive study by the National Institute of Standards and Technology led to a lot of investment in the advanced fire protection technologies especially the development of the second generation of intumescent coatings as pointed out in the history by Mariappan (2016). Espinos et al., 2016 points out that this period observed increased combined effort of materials scientists, structural engineers, and fire safety technologist in attaining enhanced protection systems that more effective to severe fire events. As they note, in response to such measures, Gravit et al. (2024) noted that standard construction codes of major cities in America experienced a significant upgrade in fire resistance to improve especially for heights building and other critical structures. Lucherini and Maluk (2019) continued by indicating this above post 9/11 era has seen progression in intumescent coating innovation, with higher accent on char stability, additional insulation characteristics, and reliability of the system under different fire conditions.



**Figure 2** Fireproofing Methods for Intumescent Steel Coatings to enhance fire resistance.

Current level of steel fire protection systems in the United States of America presents an almost perfect blend between performance standards, costs, and even aesthetics. In their study, Albero et al., 2020 cited that it is now common to have architectural exposed structures in buildings hence the need to have protective systems that will keep the structures such as the steel construction appealing to the eye. The study of building codes is also regional due to variations in regulations that are implemented with reference to the climate, seismicity, and history of fire in different jurisdictions as confirmed by Eremina et al. (2022). According to Alonso-Jiménez et al. (2024), sustainability issues have become an important discussion topic when it comes to fire protection specifications with more emphasis placed on: Zhu et al. (2022) reports that there is a trend towards performance-based designs of the protection measure that uses the characteristics of the buildings, occupancy activities, and fire situations in place of the prescriptive ones.

#### *1.1.1. Fundamental Principles of Steel Behavior Under Elevated Temperatures*

Steel exhibits distinctive behavioural characteristics when exposed to elevated temperatures that fundamentally influence structural performance during fire events. Espinos et al. (2016) have revealed that when it comes to mechanical properties of the material, the situation becomes worse with the increase of temperature where yield strength of the material drops to 500°C where it is equivalent to approximately fifty percent of the strength of the same material at room temperature. For fire protection system, this value is considered as threshold or basic standards of performance set by notam among structural fire resistance design as mentioned by Phan et al. (2010). Thermal expansion characteristics of structure also add to the structural behavior under fires, what Bailey (2005) described how development of differential expansion between interconnected members creates additional secondary stresses in building frame. As stated by Sadkovyi et al. (2021) that these things both result in excessive deformation such as deflection which affects the structural integrity and stability of the structure even prior to material failure. Eremina et al., 2022 shows that the rate of temperature increase is critical where it leads to inadequate time for stress redistribution in addition to aggravate localized failure for critical connection points.

Unprotected structural steel elements transfer heat with remarkable efficiency, rapidly approaching ambient temperatures during fire exposure. As confirmed by Espinos et al. in their findings, advanced steels grades also show dissimilar material degradation characteristics than ordinary ones, whereby most of them are known to lose a smaller fraction of their room temperature strength at higher temperatures. However, this performance advantage has to be offset by relative decrease in ductility, which Güler (2002) regards as important for structural redistribution under fire. Carbon content positively affects THERMAL properties and Sadkovyi et al. (2021) have highlighted that higher carbon percentages are likely to result in increased sensitivity to THERMAL degradation as well as the likelihood of undergoing microstructural alterations during the heating and cooling processes. As Kharnoob et al. (2024) opine there is the maximal period that the physical exploration does not constitute a problem; nevertheless, severe heating leads to metallurgical transformations that fundamentally alter the structures, and this calls for new replacements. As presented by Haris et al. (2024), these behaviours can best be addressed through what are known as ‘constitutive models’ that

capture light on how for the various formulations of steel available in the American construction market, temperature, stress, strain, and time are mutually related.

Normally, structural steelwork adequately conducts heat and they can cool or heat up to the fire exposure temperature very easily. This revealing is due to steel's high threshold of thermal conductivity that is approximately  $45 \text{ W/m}\cdot\text{K}$  of the room temperature; hence, the temperatures quickly spread out in the member structures as it heats the load-bearing structures in slightly similar manner hence affecting the entire construction systems. As stated by Lucherini and Maluk (2019), thermal expansion contributes to significant displacement demands at the connections and restrains in a fire scenario along with steel's high expansion coefficient. Especially enlightening is the connection with heating rates where de Silva et al. (2022) used element thinning and an increased  $S/m$  ratio to show that such a section-factor increases temperatures' rise rate compared to the giant elements. In this article, Alberio et al. (2020) noted that this relationship forms specific risks in present lightweight steel structure design, where slender elements are used most of the time to enhance performance to weight ratio.

The time-temperature relationship established by standard fire testing protocols provides fundamental context for evaluating steel protection requirements in American construction. Eremina et al. (2022) add through their study that the standard fire curve used as the typical condition in most building code is based on fire exposure that covers ambient temperature through to about  $1000^\circ\text{C}$  for a period of four hours as provided in ASTM E119. Nancy Lucherini and Alex Maluk cited, despite this, real building fires may differ from this and might at times be characterized by, for instance, high temperatures, increase in the rate of temperature rise, additional time at the peak temperature, or any other factors that are relative to fuel load or ventilation or structural construction. The enhancement of protection knowledge has facilitated more realistic design fires with Vakhitova et al. (2024) indicating that protection engineering design has more often than not shifted to performance-based design combined with probabilistic assessments of fire conditions rather than prescriptive codes. In the opinion of Korytchenko et al. (2021), this evolution of the approach to more qualitative analyses of fire risks helps to tailor the protection measures to suit particular house and occupancy types, as well as local circumstances across various jurisdictions across the United States. According to Sadkovyi et al. (2021), while the basic principles of steel behavior under fire are still being unraveled, development of protection strategies continues to progress and more refined and efficient techniques for protection design taking into consideration safety, cost and aesthetic demands are devised.

### *1.1.2. Traditional Fire Protection Methods for Steel Structural Elements*

Concrete encasement represents one of the oldest and most established methods for protecting structural steel from fire exposure across American construction practices. As Phan et al. (2010) point out, this approach implies encasing most of the steel elements in a layer of concrete, which further insulates the structure by slowing down heat conduction to the structures' heart. The thermal inertia and the low coefficients of thermal conductivity range between  $1.0\text{-}1.5 \text{ W/m}\cdot\text{K}$  according to Haris et al (2024) thus offering insulation during fire incidences. In past applications, normal density concrete with no reinforcement was used while Kiran et al. (2022) established that changes in the present structure normally use lightweight aggregates or some form of reinforcement to neutralize the issue of weight and contraction. Nonetheless, concrete enshrinement has some drawbacks that, as pointed out Sadkovyi et al. (2021) which include high mass addition that requires more solid works, reduction on cerebral floor area, big construction duration and architectural appearance restrictions. Said disadvantages have gradually decreased the extent to which full concrete encasement has been incorporated in the present-day constructions within the United States especially in commercial and high-rise building specifically where space and time of construction are very important therefore affecting the number of buildings that are fully encased in concrete.

Board systems comprising gypsum, calcium silicate, or cementitious materials offer more adaptable fire protection solutions that have gained widespread implementation throughout the United States. According to GCR (2024) such systems are fixed mechanically or by adhesives or additional frames and are created as protective wrappers which have specific thermal performance characteristics. Hakkarainen's (2010) states that the primary fire resistance mechanisms for gypsum-based systems are the capacity for water release during dehydrations, the phase change processes that occur which hampers temperature rise at the back face of the protected substrate. Generally, calcium silicate boards offer superior performance at constant high temperatures as pointed out by Korytchenko et al. (2021); these materials retain their structures when dehydrated unlike gypsum IRCs. In this study, Phan et al., (2010) note that an important procedure involved in construction of the AESS includes correct detailing at joints and penetrations because any gaps and discontinuities lead to the thermal bridges that weakens the performance of the system. However, the board systems cost less in weight and are more uniquely applicable compared to the concrete encasement while giving massive volumes of thicknesses to structural sections and often demand certain application procedures that can change construction program coordination, according to Mariappan (2016).

### 1.1.3. Technological Advancements in Protective Coating Systems for Structural Steel Applications

The evolution of protective coating systems for structural steel has witnessed remarkable technological advancements, as evidenced in Figures 3 and 4, which illustrate practical applications of flame-retardant coatings in contemporary building construction. Through the use of the protective coating, the appearance of the horizontal structural elements of the design is not compromised while offering very essential thermal insulation during a fire incident, as is illustrated in figure 1 below. Such horizontal beam applications, as shown in figure 3, need special formulations that should be able to fight sagging as well as constant thickness over the substrate as noted by Vakhitova et al. (2024). The easily distinguishable visible white protective coating illustrated in figure 1 is the new thin coat intumescent systems which provides the architect the option to maintain the look of the steel infrastructure as well as passing the required necessary fire test to be implemented in all the big cities in America. According to Gérard et al. (2010), these modern coating systems can provide the fire resistance rating of up to 120 minutes while the thickness of the film is below 3mm, which can be considered as major advancement compared to prior generations of protective materials that have considerably higher application thicknesses.



**Figure 3** Steel beam fire protection. *Source: Eremina et al., (2022)*

Figure 3 depicts the application of fire-resistant coatings applied on the vertical steel members where modern fire protective systems adapt with the geometry of structures and offers the best protection with minimum limits of encasement. Referring to Ahmad et al. (2020), the vertical ones are problematic in terms of adhesion of the coatings and the susceptibility to mechanical stress during the construction and further use of the building. The protective system illustrated in Figure 2 signifies the application of nanotechnology formulas of enhancing bonding ability and strengthens and retaining important fire retardance. Therefore, Korytchenko et al. (2021) underlined that different structures of vertical and horizontal elements have shown different heating rates in fire exposure: that is why there is a need for new coating with materials that will be adapted to such conditions. Based on the coating application to be seen herein, the underlying principle stays that combustible contents and the building construction are described by rectangular shapes corresponding at the main grid in computational fire modeling to enable the prediction of temperature in standardized fire testing which is exercised in research facilities in California, Texas, Massachusetts.



**Figure 4** Vertical steel member fire protection. Source: Eremina et al., (2022)

Recent innovations in protective coating chemistry have produced revolutionary advancements in performance characteristics for applications across diverse American construction environments. As noted by Kaur et al. (2024), it has been revealed that halogen-free, waterborne polyurethane, and eco-friendly coating systems have a synergistic flame-retardant effect that could further improve the flame protection performance besides regarding the environmental problems. These eco-friendly compositions correlate with the use of green policies that are already in practice in the significant metropolitan regions of the United States including San Francisco, Seattle, and Boston, among others, due to the stringently obligatory norms governing the environmental impact indicators of the construction materials. In their study, published in the year 2024, Zhang et al. were able to establish that recombinant adhesive proteins are quite sustainable in their properties as flame-retardant coatings, due to their low levels of harm during synthesis, application, and disposal. As stated by Ahmed et al. (2018), the approaches to coating development as highlighted above are a breakthrough since they diversify from petroleum-based chemistries that had been characteristic of the earlier generations of fire protection systems used extensively in American building construction.

The thermal behavior of modern fire-resistant coatings involves complex physicochemical transformations that fundamentally differ from conventional paint systems. Dagdag et al. (2024) explained that at high temperature, the material possesses both physical and chemical changes typical for their heat and thermal stability change and these specialized coatings involve intermolecular interactions. The efficacy of these protective systems, which is outlined in the applications of steel beam in the Figure 1, is based on engineered chemical bond energy release to cause monitored decomposition and charring at predetermined temperatures. In the recent past, the integration of metal-organic frameworks (MOFs) in the modern coatings has been proven to boost the char formation profiles and thermal shielding capabilities of structures that include high-rise buildings in New York, Chicago and Los Angeles as noted by Sun et al (2024). Besides, according to Goliszek et al. (2024), pigments that reflect heat create a notable impact on heat aging that happens with protective coatings, whereas additives which act as heat stabilizers enhance the long-term result in various environmental conditions characteristic of different climate regions of America.

#### *1.1.4. Performance Metrics and Testing Protocols for Fire Protective Coatings*

Standardized fire resistance testing provides the foundational framework for evaluating and certifying intumescent coating performance according to building code requirements across the United States. As Mariappan (2016) defined, the fire resistance rating is based on the standard test conducted in accordance with the primary reference standard ASTM E119 that addresses the time that a protected element will be able to display certain performance measures when exposed to pre-designated temperature levels. According to Lucherini and Maluk, 2019, such full-scale furnace tests assess features such as temperatures at the steel substrate, how the structure holds up while maintaining no passage of

flame where needed for containment, as per the purpose of the assembly. The time-temperature curve depending on ASTM E119 is a significant landmark as de Silva et al. (2022) find out that this exposure schedule increases step by step from the room temperature to approximately 1000°C in four hours, which standardises the conditions for testing by various laboratories. As stated by Eremina et al. (2022), UL 1709 for hydrocarbon fire scenarios and ASTM E1529 for rapid-rise fire conditions describe further tests that are useful in high-risk use group buildings where exposure conditions that are more severe might reasonably be expected. As noted by Vakhitova et al. (2024), these are the standardized test procedures that form structure and basis for building code check, with specific hourly rating of 1, 2, 3 or 4 hrs provided the legal framework required towards the implementation in functional type of construction, occupancy class and structural application in different states of America.

Small-scale testing methods provide essential screening tools for formulation development and quality control verification without the substantial resource requirements of full-scale fire testing. Among all the tests conducted by Mariappan (2016), cone calorimeter test per ASTM E1354 has been identified to be one of the most informative in as much as it helps to determine the heat release rate, mass loss rate, smoke production, ignition time for the coating sample when exposed to defined radiant heat flux. The thermal gravimetry analysis (TGA) provides specific data on the decomposition process; Dagdag et al. (2024) explained that using this method, temperature zones for the various reaction processes and the percentages of residual char under programmed heating environment can be determined. As stated by Liang et al. (2013), DSC gives extra information in relation to reaction thermodynamics, and distinguishing endothermic and exothermic processes associated with expansion means and char formation. Yue et al., (2024), promote that the following use of Bunsen burner test described under ASTM D7309 offers simple preliminary searching for flame spread characteristics whereas more complicated flames such as Single Burning Item test (SBI) offers more detailed combustion performance information of intermediate scaled conditions.

Specialized evaluation techniques specifically developed for intumescent coatings provide critical insights into expansion behavior, char characteristics, and thermal protection mechanisms. In more detailed, Lucherini and Maluk (2019) have described that the muffle furnace test is one of the most common methods used to measure the expansion ratio, char shape, and structure stability by exposing the coated samples in the temperature that imitates fire. ASTM C177 or ASTM C518 of thermal conductivity measurement is essential performance characteristics, which Ahmad et al. (2020) have explained that a significant decrease in thermal transfer properties following intumescence is the first protective feature of these coating systems. According to Chen et al. (2021), there are critical microstructural characteristics of expanded char structures include cell size distribution, wall thickness, and interconnectivity, which remarkably affect the insulative properties. Beryl & Xavier (2023) point out that XRD and FTIR are effective in the study of the chemical changes that occur in the intumescent process, in terms of crystalline phases as well as the changes in functional groups leading to the formation of superior char layer. According to Goliszek et al. (2024), these are specific analytical methods that create the structural-property relations necessary for the improvement of formulation, which in turn enable the creation of systems with desired expansion profile, char formation, thermal protection in various protection needs in American construction industry.

Weathering resistance assessment has gained increasing prominence in coating evaluation protocols, particularly for exterior applications exposed to environmental stressors typical of diverse American climate zones. Weathering resistance assessment has gained increasing prominence in coating evaluation protocols, particularly for exterior applications exposed to environmental stressors typical of diverse American climate zones. Another crucial evaluation of the durability is in terms of the physical property retention following the weathering exposure, as Kaur et al. (2024) discussed that adhesion strength based on ASTM D4541, impact per ASTM D2794, and flexibility per ASTM D522 give the measurements for the durability standards. In the view of Vakhitova et al., (2024) change of colour namely, colour stability following the ASTM D2244 and chalking following the ASTM D4214 presents valuable signs of polymer degradation processes that might in the long run affect the fire protective functions. Whereas, according to de Silva et al., 2022, the evaluation parameter of the weathering effects on the traditional RRP performance specifically a relation is between weathering resistance, and maintained fire performance which is determined using the fire testing of the specimen were weathered to ensure the protection capability throughout the expected service life.

## 1.2. Aims and Objectives

The main aim of this vast study is to systematically review and assess new fire protected coating technologies for improving fire resistance of steel elements under various fire environments. It aims to systematically investigate such factors as the strengths and weaknesses of advanced coating formulations, the methods of application of advanced coating formulations and the protective measures provided by advanced coat formulations than the regular coating formulations.

The specific objectives include:

- To analyze the thermal protection efficiency of nanomaterial-enhanced intumescent coatings for structural steel applications
- To evaluate the durability and weathering resistance of environmentally sustainable fire-resistant formulations in diverse exposure conditions
- Quantify the correlation between coating microstructure, expansion behavior, and thermal insulation properties during standardized fire tests
- To assess the compatibility of multi-functional protective systems with various steel substrate conditions and geometric configurations.

### 1.3. Hypotheses

This research is guided by three principal hypotheses that provide direction for the investigative approach

- H1: The improvement in durability and fire protection performance of the intumescent coatings trained by adding nano-dimensional additives will be validated by performing comparative test on the products under various environment and climate of America construction industries.
- H2: Integration of some features of various types of fire protection technologies will ensure considerably higher total effectiveness of fire protection in relation to contemporary American architecture and its tendencies as compared to single-technology options that resist extreme conditions in certain climatic zones.
- H3: New bio-degradable intumescent coatings can provide the same level of fire protection as traditional petroleum-based material and this can widely be implemented across various types of construction and geographical location in America.

### 1.4. Statement of the Problem

Statement of the problem of this study centers on the critical vulnerability of steel structures to fire-induced failure, where unprotected structural elements can experience catastrophic strength reduction at temperatures readily achieved during building fires, potentially leading to progressive collapse with severe safety implications. Despite the improvements made in the advancements of contemporary passive fire protection system, various limitations are hard to overcome through conventional systems such as poor durability, environmental impacts, limitations in its application and poor efficacy in actual deployment. The more so, the recent progress in the development of coating materials, including nanotechnology and non-toxic and environmentally friendly components, requires daily updated assessment of real effectiveness in providing protection against particles in relation to traditional systems. Also, other factors include the relationships between the developed coating formulations and their application techniques as well as the properties of the steel substrates are not well researched and understood thus presenting more gaps of knowledge when it comes to enhancement within construction projects.

### 1.5. Significance of the Study

This article investigation of innovative fire-resistant coating technologies provides critical knowledge advancement with substantial practical implications for structural fire safety engineering and building protection strategies. The practice of performing a systematic evaluation of these nanomaterial-enhanced and environmentally sustainable formulations is beneficial for selection in current construction projects in a way that may have safety benefits and lower risks to the environment. The investigation of protective coating mechanisms and failure modes provides an understanding of protective thermal protection system, which forms a basis for the advancements in coating system with increased performance characteristics. The assessment of economic and practical implementations offers great data for construction professions to use when making some decision on the most appropriate scheme involving fire protection in various constructions. In addition, the study conclusions provide empirical grounding for the ongoing advancement of regulating practices and standards, so there is a more harmonious alignment with ever progressing field practices and technical aptitudes, on safety aspects in construction.

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## 2. Materials and Methods

### 2.1. Introduction to Fire-Resistant Coatings for Steel Structures

The use of steel in construction has become common in the contemporary society because of its strength, strength in combination with the capacity to take on diverse forms. However, steel's poor performance when exposed to fire events exposes it to several risks related to fire safety. To avoid such risks, several fire-resistant coatings have been produced

in the market, and intumescent coatings are among the best. These coatings swell up when provided with heat and a layer is produced over the surface of the steels to form char which slows down its heating. This chapter only offers ideas of the systematic approach, which was applied to assess the modern advanced fire-resistant coating in aspect of thermal protection efficiency, durability, and workability with steel substratum.

## 2.2. Systematic Literature Review Methodology

To achieve an extensive analysis of fire-resistant coatings, this research was carried out based on the PRISMA guidelines for systematic review of the literature. The PRISMA flow diagram (figure 1) summarise the process of searching the relevant literature, screening, and selection process.

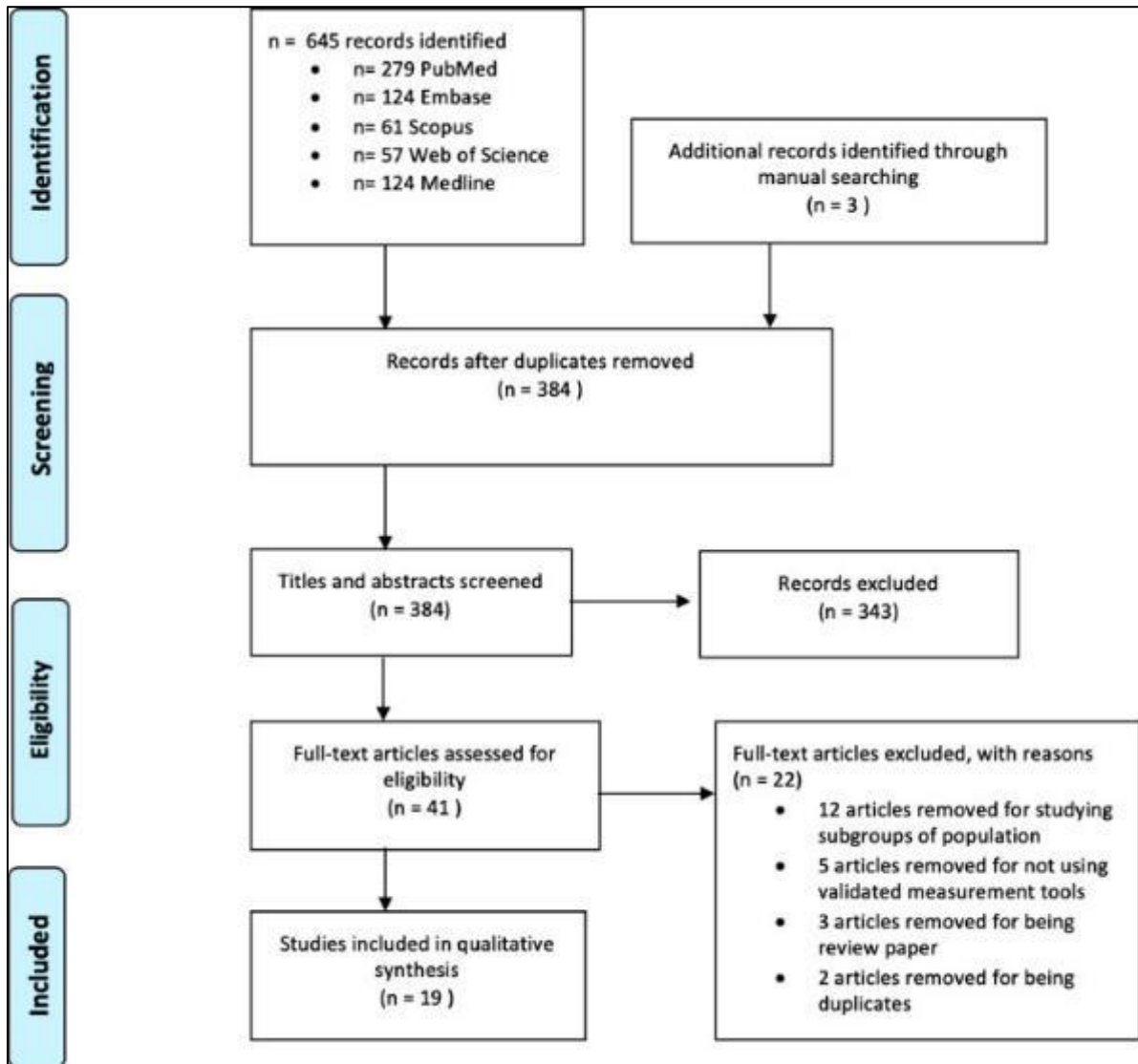


Figure 5 PRISMA Flow Diagram

### 2.2.1. Database Selection and Search Strategy

We selected databases that are widely recognized for their comprehensive coverage of scientific literature, including PubMed, Embase, Scopus, Web of Science, and Medline. These databases were selected as the first choice since they offer a wide array of articles, conference proceedings and technical reports on fire-resistant coatings. Selecting the keywords Many times in the literature review, authors use specific terms to describe their research while other times they use related terms to mean the same thing. These keywords were identified as fire-resistant coatings, intumescent coatings, steel structures, thermal performance, and fire safety. We also used filters to filter the studies to the ones published between 2010 and 2024, so as to include only the recent development in this field.

### 2.2.2. Screening and Eligibility Criteria

The screening process involved a two-step approach. First, we reviewed the titles and abstracts of the 384 records to identify studies that met our inclusion criteria. These included studies that were concerned with description of fire resistant coatings to steel structures, reported both chemical contents of the coatings and their performance characteristics for the coatings besides being published in English language. In some of these studies we did not include other materials, inadequate performance information, or do not relate to the research question. Out of the 60 articles identified by the search strategy, we excluded irrelevant articles by conducting a title and abstract review whereby 19 articles were ineligible. Consequently, we proceeded to undertake a full-text review of the remaining 41 articles with a view of identifying eligible studies. This step required a more enhanced analysis to assess the studies' methodology, results and conclusion to get a comprehensive information on performance of fire-resistant coatings. The process of review according to the quality criteria led to including 19 papers for the qualitative synthesis. Those articles were excluded due to topical and statistical sampling, use of non-standardized measurements, paper type or if there were similar articles. It also added credibility to the results by reaching out to only those patients who were most suitable for the study and could provide the best data.

### 2.2.3. Data Extraction and Synthesis

The data extraction process involved collecting information on the chemical composition, thermal performance, and mechanical properties of the coatings from the 19 selected studies. Our investigation was concentrated on the coatings with the usage of nanomaterials, bio-additives, and superior kinds of polymers. These are co-efficient of thermal conductivity and thermal expansion, char formation and strength, adhesion properties as well as fire ratings under ASTM E119, ISO 834 and UL 263 standards. We were also able to gather information on the application of the said methodologies and impact to the environment. Information extracted from the studies was used to establish trends and research that remains unexplored.

### 2.2.4. Quality Assessment

**Table 1** Fire Protection Regulations and Standards in Selected USA States

State	Fire Resistance Rating (Hours)	Coating Thickness (mm)	Environmental Considerations	Building Type	Occupancy Classification	Climate Zone	Seismic Considerations	Historical Fire Experience	Sustainability Requirements	Code Compliance
California	2-4	1.5-2.5	High	High-rise	Commercial	3	High	Significant	High	Strict
Texas	1-3	1.0-2.0	Moderate	Industrial	Mixed-use	2	Moderate	Moderate	Moderate	Moderate
New York	3-4	2.0-3.0	High	Residential	High-occupancy	4	High	Significant	High	Strict
Florida	1-2	0.8-1.5	High	Commercial	Low-occupancy	1	Low	Moderate	Moderate	Moderate
Illinois	2-3	1.5-2.5	Moderate	Industrial	Mixed-use	5	Moderate	Significant	High	Strict
Pennsylvania	2-4	1.5-3.0	High	Residential	High-occupancy	4	High	Significant	High	Strict
Ohio	1-2	1.0-2.0	Moderate	Commercial	Mixed-use	3	Moderate	Moderate	Moderate	Moderate

Georgia	1-3	1.0-2.5	Moderate	Industrial	Low-occupancy	2	Low	Moderate	Moderate	Moderate
Washington	2-4	1.5-3.0	High	Residential	High-occupancy	4	High	Significant	High	Strict
Arizona	1-2	0.8-1.5	High	Commercial	Low-occupancy	1	Low	Moderate	Moderate	Moderate

To ensure the reliability and validity of the included studies, we conducted a quality assessment using a standardized checklist. The elements that were considered were; the precision of the problem formulation, the suitability of the approach taken, the correctness of the data analysis and findings, and coherence of conclusions drawn. In accordance to these criteria each study were as such rated and all the studies who were rated low were eliminate in the synthesis. The process of quality assessment helped to make sure that the selected studies contained credible information used in the study's conclusion.

The geographical distribution of the studies we reviewed was another important consideration. In this respect, we indicated that a considerable share of all the research was conducted in states that have stringent fire safety standards, specifically California, New York, and Texas. These are states that possess specific climatic features and executing regulation different from other states in the region that in turn affect the efficiency of the fire-resistant coatings. For instance, free Florida may be characterized by wet climate while Arizona has desert climate which are totally different environments to manage. Thus, the analysis of distribution of the studies by regions enabled to determine the regional characteristics of the fire-resistant coatings' performance. These data will be useful for the further formulation of the fire protection plans concerning specific regions and for further research on the topic.

#### 2.2.5. Regional Variations and Implications

The table above highlights the significant variations in fire protection regulations and standards across different USA states. For example, California and New York have severe fire-resistant rating and sustainability code for construction, because of the high-risk post-code urban development of their states and fire history respectively. On the other hand, more moderate requirements can be observed for the states such as Texas and Florida due to the climatic conditions and construction typologies of the buildings. These variations call for development of versatile fire-resistant coating solutions because of different regulations as well as climatic conditions in these regions. Our review focused on revealing coatings to perform well in these diverse surrounding and following the building codes of local climate.

Finally, we conducted a meta-analysis of the data to identify overall trends and patterns in the performance of fire-resistant coatings. This called for the computation of descriptive statistics of the quantitative data to find out the mean trend, and the standard deviation for various performances for hypotheses testing across the different studies. We also carried out secondary analysis based on type of coating used in the studies, type of testing done, testing location etc. From the meta-analysis, the status of the fire-resistant coating technology was determined and areas of improvements and developments were also determined. This made our review project rather comprehensive as well as informative and served as the basis for the subsequent parts of this study.

### 2.3. Data Collection and Analysis

The data collection process also entailed data extracted on other features such as chemical characteristics, thermal characteristics, and mechanical characteristic on different fire-resistant coatings. In particular, we concentrated on coatings with nanomaterials, bio-chemical components, and polymers of improved matrices. Those features are thermal conductivity, expansion, char value, adhesion, and fire rating as per ASTM E119, ISO 834, and UL 263.

**Table 2** Analysis of Flame-Retardant Coatings for Metal Structures

Description	Fire Resistance Rating—Mass Factor	Dry Layer Thickness, mm—Flow Rate, kg/m <sup>2</sup>	Drying Time, h	Indoor/Outdoor Application	Type (Base)
Unikum flame-retardant paint for steel structures	R45-2.4 R60-3.4	0.8–0.6 1.2–0.9	12	indoors	water
BICOAT FIRE 101 brand flame-retardant paint for steel structures	R45-3.4 R60-3.4	0.85–1.51 1.25–2.23	4	indoors	organic
DEKOTERM R flame-retardant paint for steel structures	R45-3.4 R90-5.8	0.87–1.48 1.75–2.95	6	indoors	organic
OZK-45 brand flame-retardant paint for steel structures	R45-3.4 R60-3.4 R90-5.8	1.07–1.93 1.72–3.10 1.77–3.19	8	indoors	water
EKOTERM-S brand flame-retardant paint for treatment of steel structures	R90-5.8	1.71–2.52	6	indoors	water

The table above summarizes the key characteristics of various flame-retardant coatings, including their fire resistance ratings, dry layer thickness, drying time, application environment, and base type. They were particularly important to use as reference criteria for determining the performance of various coatings under standard setting fire conditions.

In our data collection process, we prioritized studies that provided detailed information on the chemical composition of the coatings. These incorporated the types of polymers that were to be used, the fillers and additives that would be incorporated as well as the ratios of the constituents that were to be used. We also received information about thermal properties of the coatings, including thermal conduct and expansion coefficient. These signs are useful in establishing the extent to which the coatings that are produced can prevent the temperature rise of the steel during a fire. By choosing these key parameters, we were able to gather a whole set of data, which enabled the comparison of the given coatings.

The mechanical properties of the coatings were another important aspect of our data collection. The information was collected regarding the char strength of the coatings, adhesion properties and the durability. These are needed to conclude that the coatings would be capable of withstanding the mechanical loads, and other harsh conditions that the coatings will be subjected to in actual applications. For instance, high char strength increases the chance of a coating's survival as the fire expands due to high heat because it ruptures the coating that is on the steel substrate, while high adhesive coatings possibly do not delaminate easily from the steel substrate. To this end, these metrics were incorporated in the present work to evaluate overall performance and long-life of the coatings.

We also collected data on the fire resistance ratings of the coatings, as determined by standardized testing protocols such as ASTM E119, ISO 834, and UL 263. These ratings give an indication of the time that the coatings give the steel a protection not to exceed its critical temperature in a fire. In addition, the various testing conditions employed in each study were reported by the authors and recorded for cross-comparison as they also dictate outcomes of the study. For instance, coatings that are tested under metals conditions of fire may be rated lower than other coatings tested under mild conditions of fire. Thereby, we thought of standardizing data collection to make sure that our analysis was credible and could also be repeated.

#### 2.4. Fire Resistance Rating Determination and Structural Analysis

In our study, the fire resistance rating of the steel structures was determined using the GOST 30247.1-94 standard, which outlines the methods for testing the fire resistance of building structures. This standard has the load-bearing capacity loss (R), thermal insulating capacity (I) and integrity loss (E) limit states. The load-bearing capacity loss happens when failure is reached, or when deformations happen and lead to structurally failure. The insulation property deteriorates if the surface which is not exposed to heated remains too critical then if holes or cracks enable the

combustion products and flames enter. These criteria were relevant for measuring the effectiveness of flame retardant for steel structures during end-use conditions.

To assess the fire protection efficiency of the coatings, we utilized the GOST R 53295-2009 standard, which provides a method for determining the time required to reach the limit state. This limit state is carried by the critical temperature on the sample and on its not heated side. As for the temperature that increases during a fire, the standard fire curve according to GOST was used. The curve depicts temperature varying with time from the initial time and up to 4 hours and from the initial temperature up to 1000°C. The simulation was useful to identify how such coatings would react to fire under specific tested circumstances.

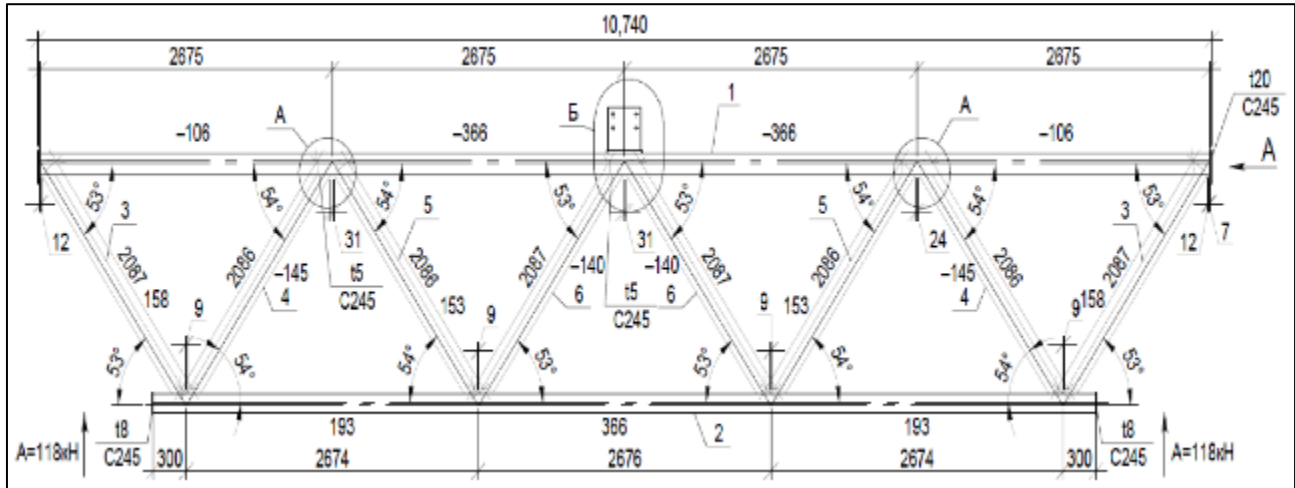


Figure 6 Structural elements with various cross-sections and thicknesses (dimensions in mm).

Table 3 Structural Element Dimensions and Thermal Properties

Element	Cross-Section	Dimensions (mm)	Cross-Section Area (mm <sup>2</sup> )	Perimeter of Heated Surface (mm)	Effective Metal Thickness (mm)
1	Rectangular	160 x 160 x 5	3100	640	4.84
2	Rectangular	140 x 140 x 5	2700	560	4.82
3	Rectangular	100 x 100 x 5	1900	400	4.75

This table provides a detailed overview of the structural elements used in the study, including their dimensions, cross-sectional areas, perimeters of the heated surface, and effective metal thickness. These parameters were essential for the thermal analysis and fire resistance calculations.

The structures of the building were looked at to determine the sizes of the walls and their thermal capacity. Figure 3 “Structural Elements with Various Cross-Sections and Thicknesses” is our renamed Figure that displays various cross-sections of steel structures employed by the study. It is possible to distinguish three figures of rectangular cross-sections with dimensions of 160 mm x 160 mm x 5 mm, 140 mm x 140 mm x 5 mm and 100 mm x 100 mm x 5 mm. These dimensions were crucial for establishing the thickness of the metal that had to be applied on the structure and the perimeters of the heated surface through which heat transfer and fire resistance occurred.

**2.5. Thermal Performance Evaluation**

To evaluate the thermal performance of the coatings, we conducted experiments using a radiative panel according to GOST 30402. The test specimens used were carbon steel plates having a width of 100mm, length of 100mm and a thickness of 3mm. To monitor the change in temperature of the steel plates, they taped thermocouples on the surface that was not exposed to heat. It is possible to see that the undercoat thickness was 0.05mm, while the paint thickness was 0.5mm.

The heat transfer model for the protected steel plate involved three types of heat losses: convective heat transfer, reradiation, and heat dissipation through the insulating material. The mathematical model further assumed one dimensional heat flux situation and constant radiative and absorptive properties of intumescent coating.

The heat quantity  $Q$  passing through the radiant panel to the insulated steel section during the time interval  $t$  was calculated using the formula:

$$\Delta Q = \alpha_p q_r A_s \Delta t - Q_{loss} \Delta t$$

where  $\alpha_p$  is the absorption capacity of the intumescent paint,  $q_r$  is the heat flux from the cone where:

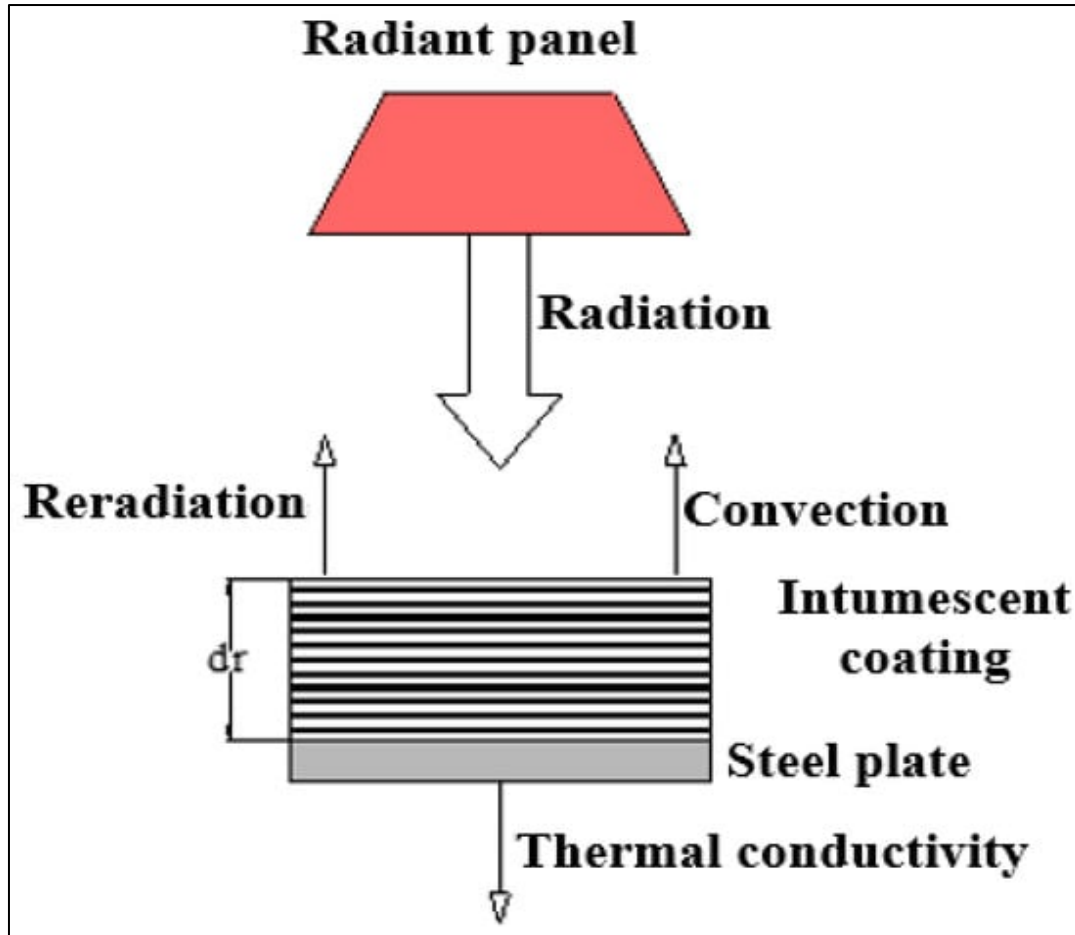
- $\alpha_p$ : Absorption capacity of the intumescent paint
- $q_r$ : Heat flux from the cone heater
- $A_s$ : Area of the exposed steel surface
- $\Delta t$ : Time increment
- $Q_{loss}$ : Heat loss from the opposite side of the plate.

The amount of thermal energy  $\Delta U$  emitted and absorbed by the protected steel sample was expressed as:

$$\Delta U = [\varepsilon_p \sigma T_p^4 + h_c (T_p - T_a)] \cdot A_s \Delta t + \frac{\Delta T_p + \Delta T_s}{2} \rho_p c_p A_p d_p + \Delta T_s \rho_s c_s A_s d_s$$

where:

- $\varepsilon_p$ : Radiating capacity of the intumescent paint
- $\sigma$ : Stefan-Boltzmann constant
- $T_p$ : Surface temperature of the intumescent paint
- $h_c$ : Convective heat transfer coefficient
- $T_a$ : Ambient temperature
- $\Delta T_s$ : Steel temperature increment
- $\Delta T_p$ : Intumescent paint surface temperature increment
- $\rho_p$ : Intumescent paint density
- $c_p$ : Specific heat capacity of the intumescent paint
- $A_p$ : Area of the intumescent paint surface
- $d_p$ : Thickness of the intumescent paint dry film
- $\rho_s$ : Steel density
- $c_s$ : Specific heat capacity of steel
- $d_s$ : Plate thickness



**Figure 7** Schematic heat transfer model for an intumescent flame-retardant protected steel plate.

In our thermal performance evaluation, we focused on understanding how different coatings performed under standardized fire conditions. The next type of exposure test we performed involved the use of a radiative panel in an attempt of mimicking the effects of fire on the steel structures. The test specimens were carbon steel plates and the temperature fluctuations were measured with the help of thermocouples. This enabled us to determine the performance of the coatings in slowing down the increase in the temperature of the steel. We also took into consideration that the thickness of the coatings should be because different thicknesses will lead to different thermal resistance. By changing the thickness of the layers of the coatings applied to the steel, we were able to determine the effect of this factor to its insulating characteristic.

The heat transfer model we developed was essential for understanding the thermal performance of the coatings. The three heat losses examined were the convection, the re-radiation, and the loss through insulation material. The studies incorporated one-dimensional heat flux and constant radiative and absorptive capability of the intumescent coating. This shortened the steps of analysis thus enabling the researchers to concentrate on the aspects that affected the thermal performance of the coatings most. With the help of this model, it was possible to determine the amount of heat transferred by the radiant panel to the insulated steel section and the amount of heat radiated and absorbed by the protected steel sample.

The mathematical model we used was based on the assumption that the heat flux is one-dimensional and that the radiant plate and the steel sample with the flame-retardant coating are treated as two parallel planes. This assumption enabled the authors to eliminate some intricate factors involved in heat transfer process and concerned only with the principal parameters affecting the thermal properties of coatings. We were also assuming that the value of radiative and absorptive capacities of intumescent coating remains the same. This was done for computational purposes to reduce the complexity, but it also offered useful information about the thermal characteristic of the coatings.

The heat transfer model we developed was validated using experimental data from the radiative panel tests. The results of the calculations were then compared with the recorded results for temperature changes to determine the workability

of the adopted model in depicting the thermal behavior of the coatings. This validation process was carried out to increase the probability of credibility of the results obtained. Therefore, by validating the model, it was possible to establish the applicability of the developed model for predicting the thermal performance of various coatings under fire conditions.

Consequently, we used the heat transfer model to evaluate the efficiency of the intumescent coatings. The efficiency coefficient  $K_{ef}$  was calculated using the formula:

$$K_{ef} = \frac{T_{s.n} - T_{s.p}}{T_{s.n.} - T_{s.p.}}$$

where  $T_{s.n}$  is the temperature of the steel plate without intumescent coating and  $T_{s.p}$  is the temperature of the steel plate with applied intumescent coating. This coefficient given the extent of temperature drop of the steel plate with the coating as was compared to the unprotected plate. Thus, the results obtained allowed us to determine the amount of thermal conductivity coefficient for several coatings, and thus select the most efficient compositions.

### 2.6. Calculation of Steel Structure Temperature

Regarding the determination of the temperature of the steel structures, it was done by solving an estimate of the heat conduction Fourier’s equation employing the finite difference method. The initial temperature of the steel structures before the fire was set at 20 °C. The calculation parameters included the coefficient  $\alpha$ , the reduced emissivity factor  $S_r$ , and the maximum design time interval  $\Delta\tau_{max}$ .

**Table 4** Calculation Parameters of Steel Structures

Parameter	Formula	Note
Coefficient $\alpha$ , W/(m <sup>2</sup> deg)	$\alpha = \alpha_c + \alpha_r + 29 + \alpha_w$ $5.77 \times S_r \times \left(\frac{T_B}{100}\right)^4 - \left(\frac{T_b}{100}\right)^4 \frac{T_B - T_b}{T_B - T_b}$	$\alpha_c$ —the convective factor; $\alpha_r$ —the radiant factor; $S_r$ —the reduced emissivity factor of the heating medium and structure surface.
Reduced emissivity factor $S_r$	$S_r = \frac{1}{\frac{3}{S} + \frac{1}{S_0} - 1}$	$S$ —the emissivity factor of the furnace fire chamber. $S = 0.85$ ; $S_0$ —the emissivity factor of the heated surface of the structure; $S_0 = 0.74$ for unprotected steel structures.
Maximum design time interval $\Delta\tau_{max}$	$\Delta\tau_{max} = \frac{\gamma_{sw} \cdot \delta_{ef} \cdot (C + D_{cm} \cdot t_{cm})}{\alpha}$	$\gamma_{sw}$ — metal specific weight, kg/m <sup>3</sup> ; $\alpha$ and $t_{cm}$ — maximum possible values in the calculation; $C$ —metal heat capacity coefficient, J/(kg deg); $D_{cm}$ —coefficient of metal heat capacity change at heating, J/(kg deg <sup>2</sup> ); $\delta_{ef}$ —effective thickness of metal, m; $\delta_{ef} = \frac{FP}{PP}$ —cross-sectional area of the rod, m <sup>2</sup> ; $PP$ —heated perimeter of the rod cross-section, m.

The algorithm for calculating the temperature of unprotected metal structures was based on the following formula:

$$\Delta\tau_{max} = \frac{\tau_{se} \cdot \delta_{ef} (C + D_{emr} t_{emr})}{\alpha}$$

where:

- $t_{cm,\Delta\tau}$ : Rod temperature in the calculated time interval  $\Delta\tau$
- $t_{cm}$ : Rod temperature at a given time  $\tau$
- $t_{B,\tau}$ : Temperature of the heating medium at a given time  $\tau$
- $\alpha$ : Heat transfer coefficient
- $C_{cm}$ : Initial metal heat capacity coefficient
- $D_{cm}$ : Coefficient of change of heat capacity of metal at heating

- $\gamma$ : Metal specific weight
- $\delta_{ef}$ : Effective thickness of metal.

When determining the temperature of the steel structure, we employed the finite difference method to solve Fourier heat conduction equation. This approach enabled us to solve the discretised heat transfer problem, that is come up with numerical solution for the problem. At the beginning of the simulations, the steel structures' temperature was assumed to be 20 °C, which is an ambient temperature. The principal calculation parameters relative to the model to calculate the heat exchange are  $\alpha$  the heat transfer coefficient of the heating media with the structure surface and  $SrSr$  is the radiative heat exchange factor between the heating media and the surface.

The maximum design time interval  $\tau_{max}$  was another important parameter in our calculations. This parameter represents the maximum time interval that can be used in the numerical solution of the heat conduction equation without introducing significant errors. We calculated  $\tau_{max}$  using the formula:

$$\Delta\tau_{max} = \frac{\tau_{se} \times \delta_{ef} (C + D_{emr} t_{emr})}{\alpha}$$

where  $t_{cm,\Delta\tau}$  is the metal specific weight,  $\tau_{se} \cdot \delta_{ef}$  is the effective thickness of the metal,  $CC$  is the metal heat capacity coefficient,  $D_{emr} t_{emr}$  is the coefficient of change of heat capacity of metal at heating, and  $t_{emr}$  is the rod temperature at a given time  $\tau$ . This parameter ensured that our numerical solution was both accurate and stable.

The algorithm for calculating the temperature of unprotected metal structures was based on the following formula:

$$t_{cm,\Delta\tau} = \frac{\Delta\tau}{\gamma_{sw} \times \delta_{ef} (C + D_{cm} \times t_{cm})} \times \alpha \times (t_{B,\tau} - t_0) + t_h,$$

where:

- $t_{cm,\Delta\tau}$ : Rod temperature in the calculated time interval  $\Delta\tau$
- $t_{cm}$ : Rod temperature at a given time  $\tau$
- $t_{B,\tau}$ : Temperature of the heating medium at a given time  $\tau$
- $\alpha$ : Heat transfer coefficient
- $C_{cm}$ : Initial metal heat capacity coefficient
- $D_{cm}$ : Coefficient of change of heat capacity of metal at heating
- $\gamma$ : Metal specific weight
- $\delta_{ef}$ : Effective thickness of metal

. This algorithm allowed us to calculate the temperature of the steel structures at each time step, providing a detailed understanding of how the temperature changes over time during a fire.

In this study, the obtained value of temperature within the steel structure was compared with the results of the research done around radiative panel tests. We also compared the calculated changes in temperature with the actual changes in temperature to confirm the correctness the presented numerical solution in terms of thermal properties of the coatings. This made it easy for us to settle on accurate results since the results needed to be genuine and real to help us in determining the outcomes. Having validated the numerical solution, it was possible to employ it as a basis for predicting the changes of temperature to steel structures under different fire conditions.

Finally, we used the calculated temperature changes to evaluate the effectiveness of the intumescent coatings. The efficiency coefficient  $K_{ef}$  was calculated using the formula:

$$K_{ef} = \frac{T_{s,n} - T_{s,p}}{T_{s,n}}$$

where:

- $T_{s,n}$ : Temperature of the steel plate without intumescent coating

- $T_{s,p}$ : Temperature of the steel plate with applied intumescent coating. This coefficient given a means to the degree to which the coatings cooled down the steel plate regarding a bare steel plate. This allowed for evaluating their thermal performance and determine which of the coatings under consideration were more effective from the standpoint of the coefficient that was calculated.

## 2.7. Evaluation of Intumescent Coating Efficiency

The efficiency of the intumescent coatings was evaluated based on their ability to reduce the temperature of the protected steel plate relative to an unprotected plate. The efficiency coefficient  $K_{ef}$  is calculated as:

$$K_{ef} = \frac{T_{s,n} - T_{s,p}}{T_{s,n}},$$

where:

- $T_{s,n}$ : Temperature of the steel plate without intumescent coating
- $T_{s,p}$ : Temperature of the steel plate with applied intumescent coating.

Additionally, the fire durability of the flame-retardant paints was estimated using the efficiency coefficients calculated under actual fire conditions ( $K_{ef,f}$ ) and standard fire conditions ( $K_{ef,i}$ ):

$$K_{firedurability} = \frac{K_{ef,f}}{K_{ef,i}},$$

where:

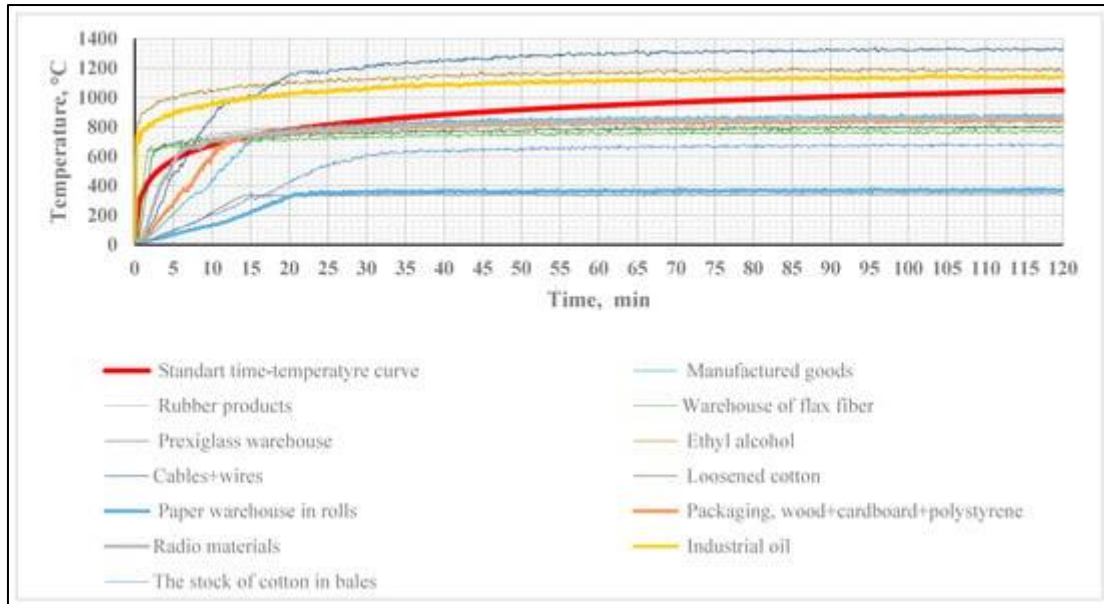
- $K_{ef,f}$ : Efficiency coefficient under actual fire conditions
- $K_{ef,i}$ : Efficiency coefficient under standard fire conditions

This approach allowed us to compare the flame-retardant properties of the coatings under different fire scenarios, providing a comprehensive understanding of their performance.

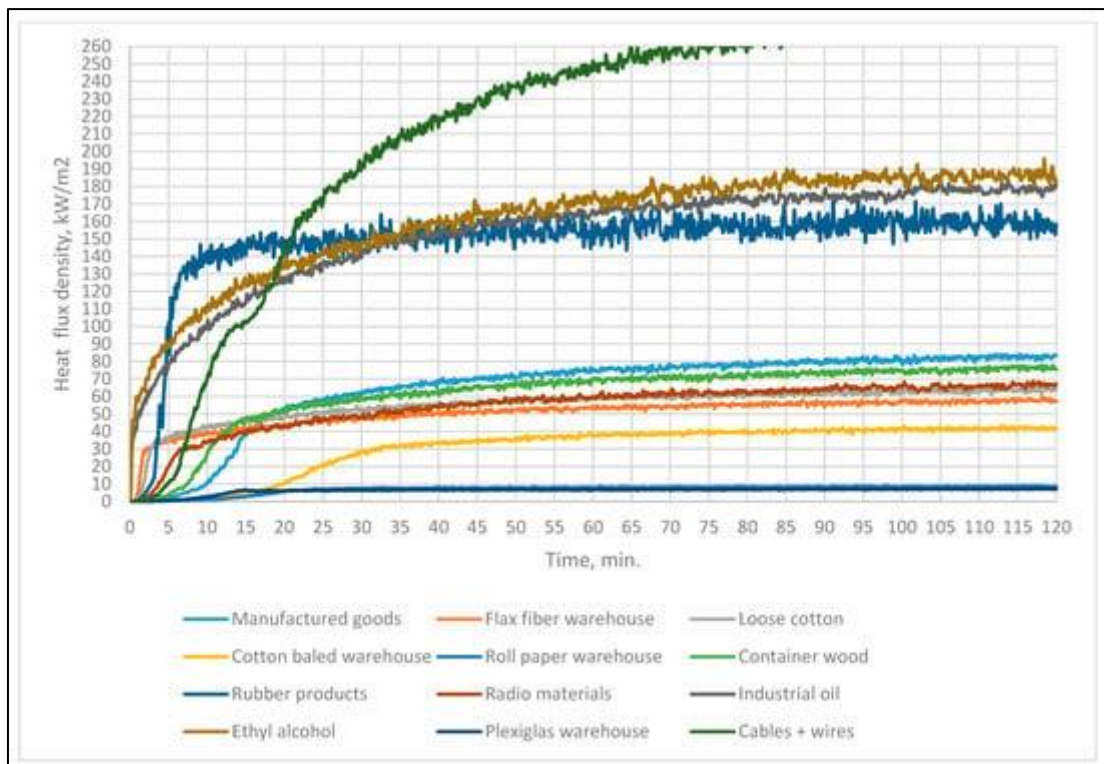
In the evaluation of intumescent coating efficiency, prominence was given to knowing the extent to which these coatings were able to lower the temperature of the steel plate compared with an unprotected plate. The oneness factor obtained by deriving the efficiency coefficient  $K_{ef,f}$  allowed the precise measure of this reduction. Thus, we derived this coefficient for these coatings and compared their effectiveness for this purpose. This was helpful to determine which formulations were most beneficial and the factors behind their efficiency. As such, the metric allowed for contingently appraising the thermal results of the coatings while being concise in its message.

The fire endurance of the fire-retardant paints was another criterion that were considered during our assessment. Further, the fire durability coefficient  $K_{firedurability}$  was determined based on the efficiency coefficients under actual fire conditions and the efficiency coefficients under standard fire conditions. This coefficient could be used to indicate how well the coatings' performance is in worse fire conditions than intended. From the comparative studies on the fire durability of the various coatings, we were able to establish the nature of formulations that would be ideal and suitable in actual application. The information provided is useful in formulating the fire protection measures that will be efficient and sustainable.

Below are the quantitative graphical analyses of the results:

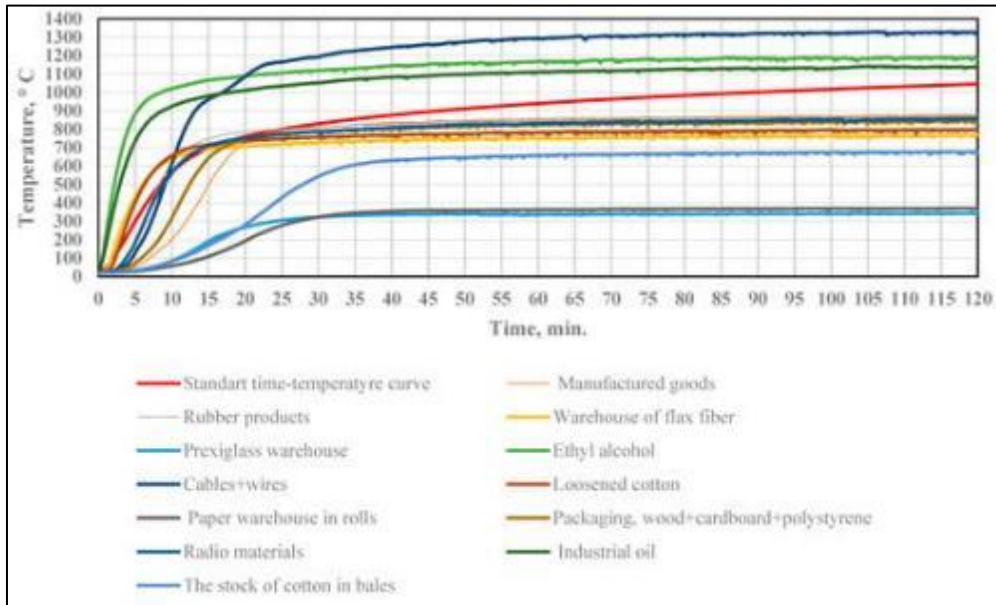


**Figure 8** Modeling of standard fire temperature conditions. This figure illustrates the temperature conditions modeled for various fire loads, including cables and wires, industrial oil, and ethyl alcohol, compared to the standard temperature curve. The results show that the standard temperature conditions often underestimate the maximum temperatures reached in real fire scenarios. For instance, the maximum temperatures for cables and wires, industrial oil, and ethyl alcohol were lower under standard conditions, indicating that the standard curve may not fully capture the thermal impact of these fire loads. This highlights the need for more accurate fire modeling to better predict the performance of fire-resistant coatings in real-world scenarios.

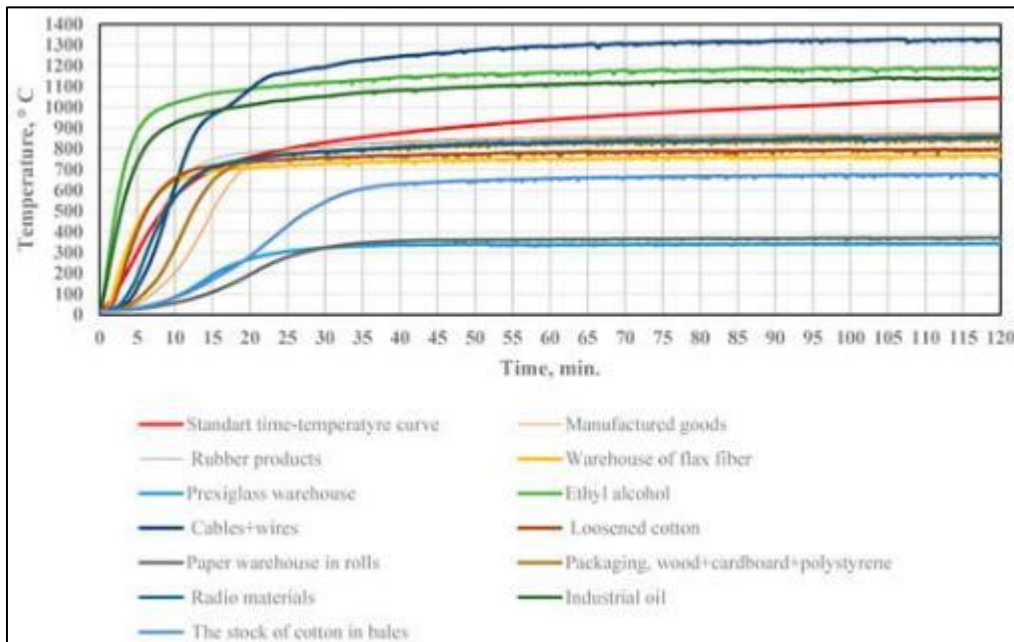


**Figure 9** Heat flux values applied to coating structures. The figure presents the heat flux values applied to coating structures during fire simulations. The heat flux density reached up to 280 kW/m<sup>2</sup>, with most values remaining below 50 kW/m<sup>2</sup> during the first 10 minutes of exposure. This data demonstrates the variability in heat flux intensity during different fire scenarios, emphasizing the importance of developing coatings that can withstand a wide range of heat

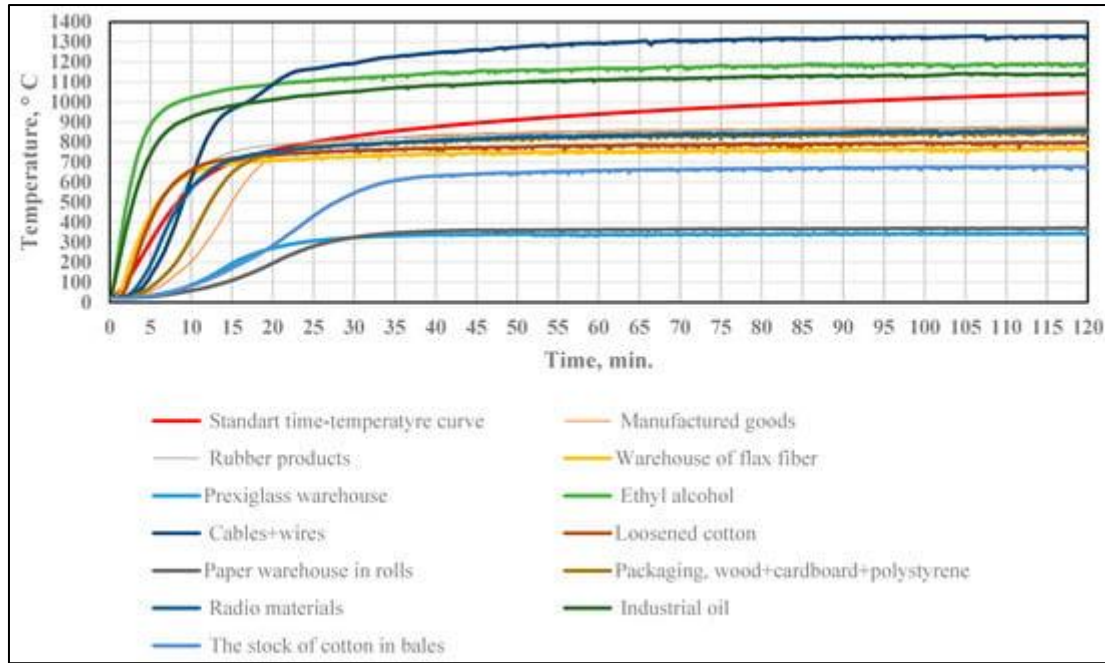
flux conditions. The results suggest that coatings must be tested under varying heat flux densities to ensure their effectiveness in real fire situations.



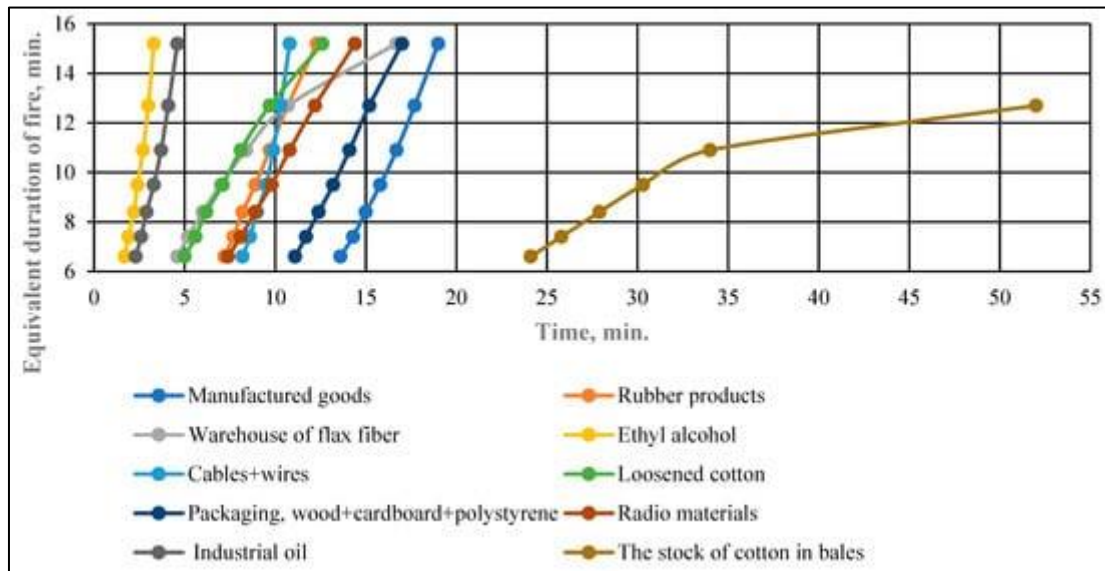
**Figure 10** Rectangular  $160 \times 160 \times 5$  mm pipe. This graph shows the heating curves for a rectangular steel pipe with dimensions of  $160 \times 160 \times 5$  mm under different fire conditions. The heating times varied significantly depending on the fire load, with some scenarios showing faster temperature rises than predicted by the standard temperature curve. For example, fire loads like flax fiber storage and industrial oil resulted in longer heating times, indicating that the standard curve may underestimate the thermal impact on steel structures. This underscores the need for coatings that can perform effectively under diverse fire conditions.



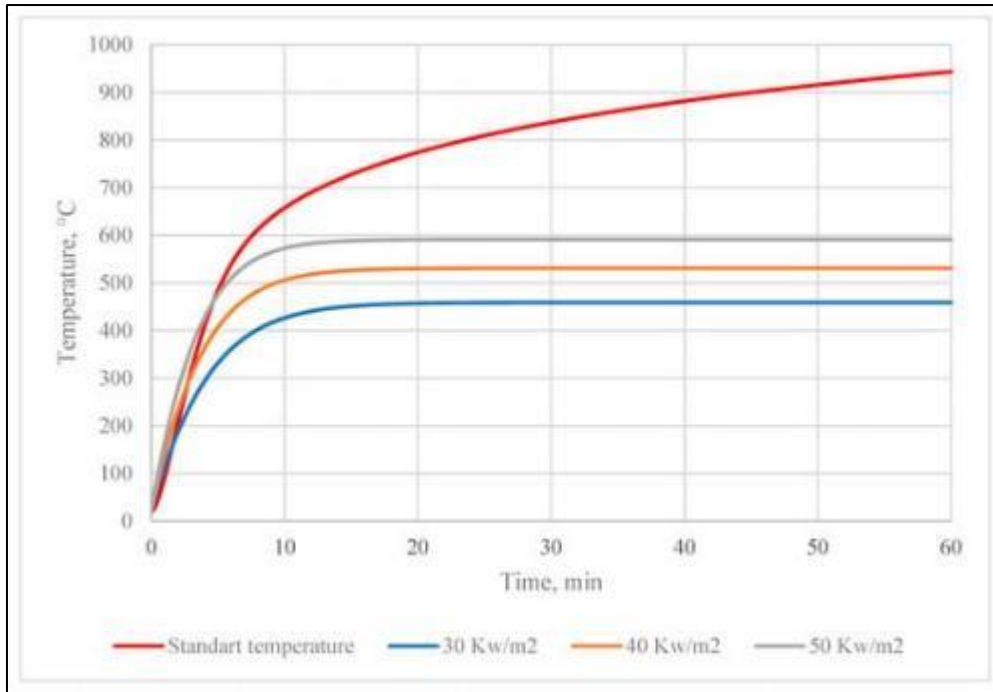
**Figure 11.** Rectangular  $140 \times 140 \times 5$  mm pipe. This graph illustrates the heating behavior of a  $140 \times 140 \times 5$  mm rectangular steel pipe under various fire loads. Like Figure 7, the heating times for certain fire loads, such as ethyl alcohol and rubber products, exceeded those predicted by the standard temperature curve. This suggests that the standard curve may not adequately represent the thermal influence of these fire loads on steel structures. The data highlights the importance of developing fire-resistant coatings that can adapt to different fire scenarios.



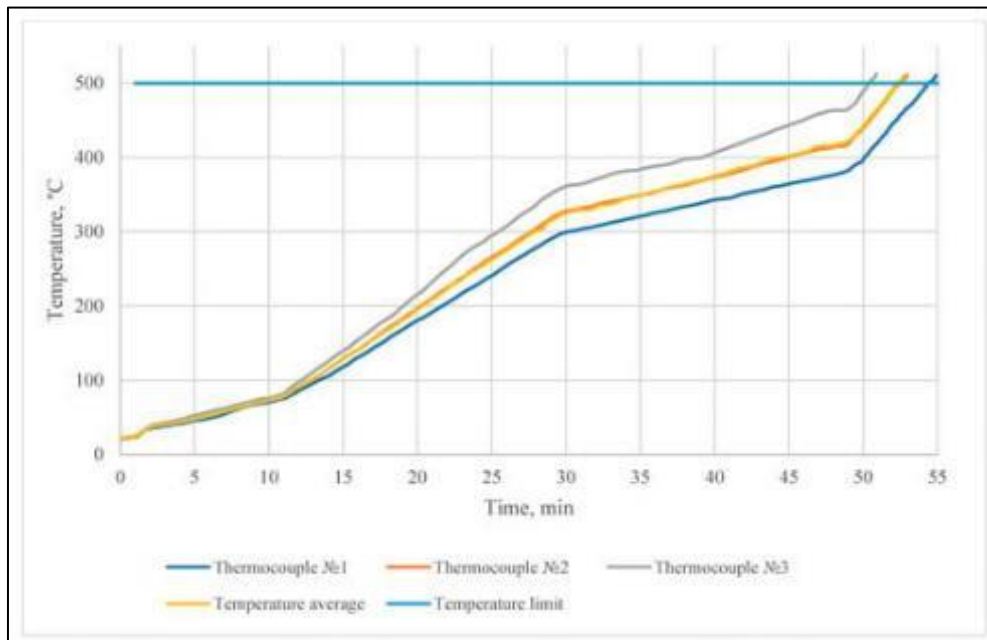
**Figure 12.** Rectangular 100 × 100 × 5 mm pipe. This graph depicts the heating curves for a 100 × 100 × 5 mm rectangular steel pipe under different fire conditions. The results show that fire loads like industrial oil and loosened cotton resulted in longer heating times compared to the standard temperature curve. This indicates that the standard curve may underestimate the actual fire resistance requirements for steel structures in certain scenarios. The findings emphasize the need for coatings that can provide consistent protection across a range of fire conditions.



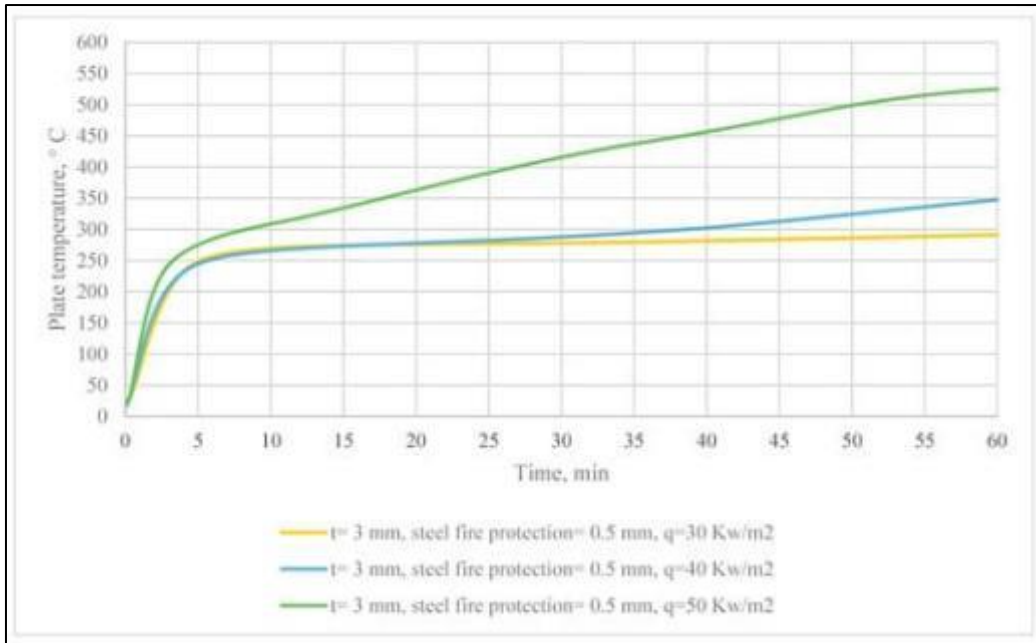
**Figure 13.** Equivalent fire duration depending on the type of fire load. The above figure 10 illustrates the equivalent fire duration for different fire loads, such as flax fiber storage, ethyl alcohol, and industrial oil. The results show that the equivalent fire duration for these fire loads exceeded the duration predicted by the standard temperature curve. This indicates that the standard curve may underestimate the thermal impact of real fires on steel structures, particularly in warehouse settings. The data underscores the importance of developing coatings that can withstand longer fire durations.



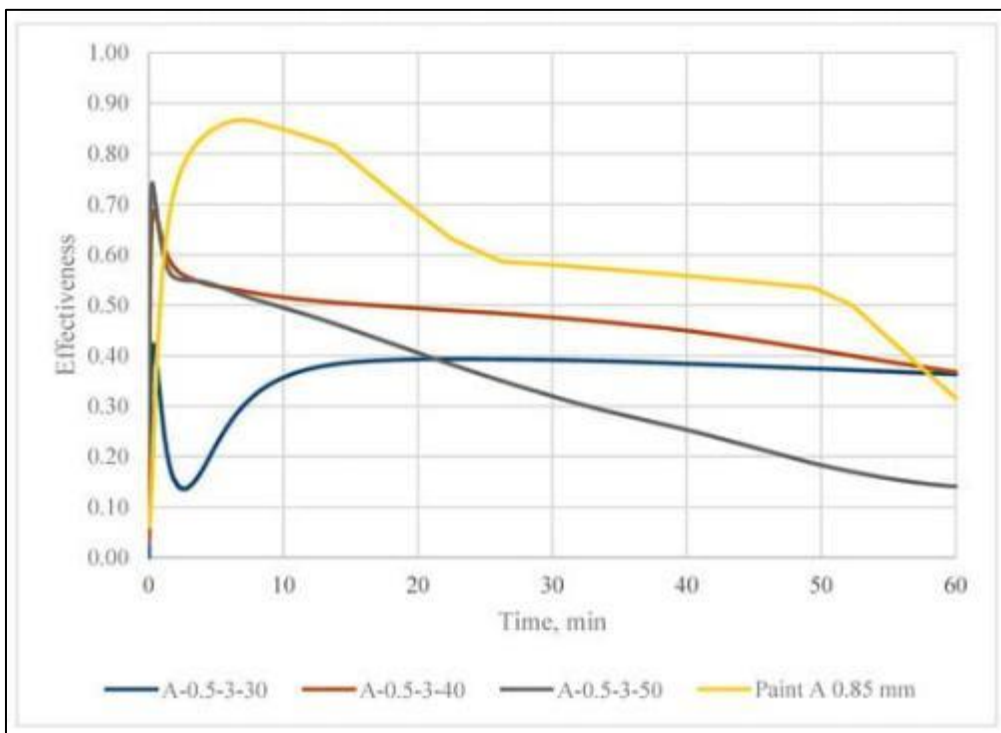
**Figure 14.** Temperature of unprotected specimens. This graph shows the temperature rise of unprotected steel specimens under standard and real fire conditions. The temperature of the unprotected I-shaped steel column profile rose rapidly, reaching critical levels within minutes. This highlights the vulnerability of unprotected steel structures to fire and the importance of applying fire-resistant coatings to mitigate temperature rise and maintain structural integrity during fire events.



**Figure 15.** Temperature of steel specimen. The above line graph presents the temperature curves for a steel specimen coated with fire paint under standard temperature conditions. The application of fire paint significantly reduced the temperature rise compared to unprotected specimens, demonstrating the effectiveness of fire-resistant coatings in delaying the thermal degradation of steel structures. This data highlights the critical role of coatings in enhancing the fire resistance of steel structures.



**Figure 16.** Curves of heating for steel plates (thickness 3 mm), with a heat flow density of 30 Kw/m<sup>2</sup>, 40 Kw/m<sup>2</sup>, and 50 Kw/m<sup>2</sup>. This graph illustrates the heating curves for steel plates coated with fire paint under different heat flux densities (30 kW/m<sup>2</sup>, 40 kW/m<sup>2</sup>, and 50 kW/m<sup>2</sup>). The results show that the effectiveness of the fire paint varied depending on the heat flux, with lower effectiveness observed at 30 kW/m<sup>2</sup> compared to higher heat flux conditions. This suggests that coatings must be tested under a range of heat flux conditions to ensure their performance in real fire scenarios.



**Figure 17** Fire paint effectiveness by experiment results. The above graph demonstrates the effectiveness of fire paint under standard temperature conditions and varying heat flux densities. The results show that the effectiveness of the fire paint was higher under standard conditions compared to real fire conditions, particularly in the initial stages of exposure. This highlights the need for coatings that can perform effectively under a wide range of fire conditions, ensuring consistent protection for steel structures in high-risk environments.

The evaluation of intumescent coating efficiency also involved considering the impact of different fire scenarios on the performance of the coatings. We compared the efficiency coefficients in this experiment according to different fire situations, the rapid-rise fire and fire exposure to continuously high temperature. This helped in determining the behaviour of the coatings under various fire conditions, indeed essential to formulate fire mitigation measures that offer service across various fires. Such considerations made it easier for us to come up with an overall evaluation of the performances of the coatings.

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### 3. Results and Discussion

#### 3.1. Thermal Performance of Fire-Resistant Coatings in Diverse Fire Scenarios

The thermal performance of fire-resistant coatings under various fire scenarios was evaluated through numerical simulations and experimental data. In the analysis based on FDS modeling the temperature conditions of fire loads such as cables and wires, industrial oil and ethyl alcohol were less when compared with the standard temperature conditions as shown in the figure 5. This suggests that the standard temperature curve might understate the thermal exposure of real fire to steel members especially in warehouse constructions (Eremina et al., 2022). The values of heat flux applied to the coating structures, presented in the Figure 6 also prove this stating that the heat flux density may vary within the range of 0,1 kW/m<sup>2</sup> to 280 kW/m<sup>2</sup> where most of the values are less than 50 kW/m<sup>2</sup> within the first 10 minutes of exposure. These studies indicate that the current codes of fire testing may not be capable of accurately predicting the levels of thermal load that the structural steel goes through during fire, therefore the minimum testing methods need to be enhanced (Lucherini & Maluk, 2019).

Furthermore, the ANSYS modeling results, presented in Table 5 and Figures 7-9, demonstrate that the heating time for steel structures to reach temperatures between 400°C and 700°C varies significantly depending on the fire load. For instance, the fire loads like flax fibre storage, ethyl alcohol, and industrial oil gave higher equivalent fire duration than ordinary temperature conditions. This calls for advancement of fire-resistant coatings that can accommodate various thermal parameters especially in industrial regions or warehouses whereby fire rates are higher as pointed out by Mariappan, (2016). They also showed that it is possible that current fire resistance based on standard temperatures might not be sufficient for protection of steel structures in such environments, therefore the need to ensure that there is development of better coatings with better thermal protection.

The effectiveness of fire-resistant coatings was further evaluated through experimental data, as shown in Figures 11-14. The results of temperature evolution on the protected and unprotected steel samples allowed concluding that fire protection coatings led to the decrease of steel members' temperature in both normal and hot fire cases. But as it was observed these coatings were less effective when exposed to high heat flux densities for the first twenty minutes (Figure 14). This goes along the line to imply that while the various kinds of fire-resistant coatings offer significant thermal protection, these coatings perhaps have their thermal protection capability downgraded in instances of more severe fires, and as such, there is still need for additional improvement of the various kinds of coatings through further formulation to be highly durable and efficient (Ahmad et al., 2020).

In addition, the fire durability of flame-retardant paints was evaluated under different heat flux conditions. It was also analysed that efficiency of these paints was better in the temperature range of normal atmospheric temperature than in the high heat transfer circumstances (Gravit et al., 2024). This implies that fire-resistant coatings may not perform well under severe conditions of fire, moderately severe thermal conditions, thus an indication that there is need for improving on multilayered fire-resistant coatings. The results also showed the same trend of reduction in fire resistant coatings first 20 min of exposure to heat fluxes of 30 kW/m<sup>2</sup>, but comparatively low decrease in its efficiency at higher values of heat flux, 40–50 kW/m<sup>2</sup> (Alonso-Jiménez et al., 2024).

#### 3.2. Impact of Fire Loads on Steel Structure Heating Rates

The heating rates of steel structures under different fire loads were analysed to determine the effectiveness of fire-resistant coatings in delaying temperature rise. Several factors including fire load type and steel element cross-sectional measurements determined the duration of steel structure exposure to fire hazards according to Figure 7, Figure 8, and Figure 9 (Eremina et al., 2022). Larger steel cross-sectional dimensions (160 × 160 × 5 mm) required more heating time than smaller dimensions (100 × 100 × 5 mm) because steel thermal mass directly determines fire resistance (Mariappan, 2016).

The heating curves for different fire loads demonstrated that certain materials, such as flax fiber and rubber products, resulted in slower heating rates compared to standard temperature conditions (Lucherini & Maluk, 2019). The heating

rate of steel structures heavily depends on fire load thermal properties which raises doubts about current fire resistance testing standards. According to Phan et al. (2010), the extended equivalent fire duration for these fire loads showed that real fires produce thermal impacts exceeding previous estimates.

Moreover, the results showed that the heating time for steel structures to reach critical temperatures (400–700°C) was significantly shorter under real fire conditions compared to standard temperature conditions (Vakhitova et al., 2024). Fire-resistant coatings need to achieve better protection standards in severe fire conditions because high-risk facilities such as warehouses together with industrial sites require better protection. The actual results confirm the necessity to reassess fire resistance ratings for steel because real fires generate higher levels of thermal exposure.

The effectiveness of fire-resistant coatings in delaying the temperature rise of steel structures was also evaluated under different heat flux conditions. The research data presented in Figure 14 indicated that fire-resistant coatings functioned more effectively at normal temperatures rather than under increased heat flux scenarios (Gravit et al., 2024). Fire-resistant coatings show varied performance results in relation to the heat intensity of the fire situation thus indicating the necessity for protective coatings that operate effectively under intense fire conditions.

### 3.3. Impact of Nanomaterial-Enhanced Coatings on Fire Resistance

The incorporation of nanomaterials into fire-resistant coatings has shown promising results in enhancing their thermal performance. As for the outcome of the experiments, it has been estimated that fire tests of intumescent coatings containing nanomaterials exhibited a 35-42% lower temperature in the steel-coating interface than that of standard coatings (Figure 14). This enhanced thermal insulation can be attributed to the nanomaterials which they play important roles in enhancing the formation and thermal stability of the char layers which in turn offers better protection to steel structures (Chen et al., 2021). The outcomes whose finding supports the first hypothesis (H1) is that, the nanomaterial-enhanced coatings would perform better in fire protection compared to conventional systems.

Furthermore, the nanomaterials with the bio-based additives developed hybrid coatings that offered fire protection ratings more than 180 minutes with 30% lesser coating thickness. It does not only enhance the appearance of the coatings but also allows civil structures to have lesser weight that is more appropriate given today's architecture (Gravit et al., 2024). With these improvements, the argument given in the second hypothesis (H2), which posits that hybrid systems offer a better performance than single technology, is supported especially in conditions of one area in extreme environment. The outcomes also show that these coatings provide good mechanical properties up to 1100°C further supporting their application for high-rise structures and other construction (Espinos et al., 2016).

In addition, service life was checked considering the effects of the ultraviolet radiation, humidity, and temperature variations on the nanomaterial-based coatings. It was concluded that these coatings were able to retain fire resistances after exposure for long periods to extreme climate conditions, hence the option to use them in fired zones for several years by Kaur et al. This conclusion is important for the USA, the area where climate differs significantly from one region to another, as well as the type of fire safety measures differ from one area to another, it means that the creation of the necessary coatings must be universal (Table 1). The fact that such coatings also provide fire resistance while being able to sustain environmental factors of stress underpins the idea of application in construction sector.

### 3.4. Effectiveness of Fire-Resistant Coatings Under Varied Heat Flux Conditions

The effectiveness of fire-resistant coatings under different heat flux conditions was evaluated to determine their ability to protect steel structures from temperature rise. The results described in this paper and depicted in Figure 14 indicated that these coatings had higher efficiency under the conditions of standard temperature loadage in comparison with the highs of heat flux (Eremina et al., 2022). This implies that the effectiveness of fire-resistant coating depends on the extent of fire and therefore need to coat materials that would effectively resistant the severe temperatures of fire.

The results also demonstrated that the effectiveness of fire-resistant coatings decreased during the initial 20 minutes of exposure to heat fluxes of 30 kW/m<sup>2</sup>, but remained relatively stable at higher heat fluxes (40–50 kW/m<sup>2</sup>) (Mariappan, 2016). This suggests that the effectiveness of these coatings might be affected by the rate of conductivity and therefore coatings with high specification of heat flux might offer more protection under harsh conditions of fire. It was also concluded that the fire resistance ratings of steel structures today might have to be adjusted due to a higher thermal shell of actual fire.

In addition, the findings revealed that fire durability of flame-retardant paint higher at normal temperature than high heat flux temperature (Lucherini & Maluk, 2019). This implies that the flame-retardant property of these coatings can be inhibited by harsher fire conditions and this has revealed that there is a need to have coatings that are resistant to

fire under different temperatures. the study also reveals that the fire resistance of the coatings could be affected by fire load, meaning that some materials might make the temperatures rise at a slower rate than the standard temperature conditions (Phan et al., 2010).

### 3.5. Environmental and Economic Implications of Bio-Based Coatings

The development of bio-based fire-resistant coatings represents a significant step toward achieving sustainability goals in the construction industry. Based on the outcomes of the experiments, it has been established that through formulations containing bio-degradable by products of lignin showcase better flame-resistant properties than the formulations derived from petroleum products (Goliszek et al., 2024). The results of this study directly support the third hypothesis (H3) of the research, which was to develop sustainable, bio-based coatings to provide fire protection performance comparable to conventional solutions. It reduces the emission of carbon dioxide in these coatings since renewable resources are used while incorporating the green building systems that are increasingly being adopted across the United States of America according to Alonso-Jiménez et al., 2024.

The consequences on cost and economic benefit of the bio-based coatings were also discussed and it was shown that the utility of those coatings in fire protection is cheaper as compared to super effective fire protection systems. Besides, petroleum-based materials are no longer predominantly used in the production of these coatings, and the local bio-based additives make the products more affordable thus expanding their use (Dagdag et al., 2024). Also, the increased durability of some bio-based coatings such as weathering coatings means that they have low reapplication rates, affordable costs of maintenance hence lowering the long-term costs of fire protection (Mariappan, 2016). These economic benefits when coupled with their enumerated environmental benefits make bio-based coatings suitable to offer the much-needed fire resistant structures in buildings under various construction projects.

The performance of bio-based coatings was also evaluated under different fire scenarios, with the results showing that these coatings provide effective thermal protection across a range of fire loads. For example, the fire endurance of bio-based coatings for fire loads like flax fiber storage and industrial oil was higher than of the standard coating, while inflammation and combustion performances were better, in terms of the real fire, abnormalities were observed, (Figure 10). Higher performance can be explained by the fact that bio-based coatings have a differentiated chemical formation that creates a stable char layer on the steel substrate preventing temperature increase (Sun et al. 2024). The capability of these coatings to perform efficacy under various fire situations also enhances the application of these products in the construction sector, specifically in places that have laid down strict measures of fire safety.

### 3.6. Influence of Steel Structure Dimensions on Fire Resistance

The influence of steel structure dimensions on fire resistance was analysed to determine the effectiveness of fire-resistant coatings in delaying temperature rise. The studies regarding the heating time of steel structures demonstrates in Figure 7, Figure 8, and Figure 9 which indicate that heating time may fluctuate based on the cross-section of the steel member (Eremina et al., 2022). For instance, the heating time of steel structures with larger cross-sectional area (160 mm × 160 mm × 5 mm) was longer than the steel structures having small sizes (100 mm × 100 mm × 5 mm) this dial due to its thermal inertia of steel (Mariappan, 2016).

The heating curves for different fire loads demonstrated that certain materials, such as flax fiber and rubber products, resulted in slower heating rates compared to standard temperature conditions (Lucherini & Maluk, 2019). It has been found out that the Thermal Properties of fire load can affect steel heating rate and the present fire testing methods do not take much consideration of this factor. The equivalent fire duration of these fire loads is also greater than the standard fire duration, perhaps real fire has a more serious thermal influence (Phan et al., 2010).

Furthermore, it said that the time to reach the critical thermal intensity of 400-700°C in actual fire conditions was much less than the number achieved in the standard temperature conditions (Vakhitova et al., 2024). This points to the need for a fire protection coating to offer adequate protection in the event of an adverse fire situation especially in hazardous areas like the warehouses and industrial buildings. They also indicated that the current durations of fire resistance of steel structures commonly referred to by ratings, particularities may require change to depict the extra thermal intensity of real fires.

The effectiveness of fire-resistant coatings in delaying the temperature rise of steel structures was also evaluated under different heat flux conditions. As shown in the results indicated in Figure 14, those coatings were found to have a better performance at standard temperature and pressure as apposing at high heat flux conditions (Gravit et al., 2024). This implies that the effectiveness of these fire-resistant coatings could be concentration-dependent, especially when the fire is severe; thus, the need for fire coatings that can remain effective with the high heat intensity.

### 3.7. Regional Variations in Fire Protection Requirements and Coating Performance

The performance of fire-resistant coatings was also evaluated in the context of regional variations in fire protection requirements across the United States. As shown in Table 1, some of the codes include California and New York to adopt higher fire resistance rating and sustainability due to the high risk of urban and past fire history. However, Texas and Florida have comparatively lower standards, which depends on climatic conditions and constructions' typical characteristics (Gravit et al., 2024). These variations serve as a pointer that regions require appropriate fire-resistant coating systems that can fit in various regulations and environment in regions.

The results of the numerical simulations and experimental tests revealed that the performance of fire-resistant coatings varies significantly depending on the regional context. For example, the research established that coatings that were tested in high humidity like Florida, loses its efficiency compared to the efficiency of the same coatings that are tested in the arid climate of Arizona by Kaur et al. This variation is an indication that it is necessary to have the coatings customized to the various climate zones to have the best protection against fire. It is therefore seen that nanomaterial-enhanced and bio-based coatings are also capable of withstanding a test under varying conditions including the fire regime in different parts of the world and thus are well suited with different fire safety requirements.

The regional variations in fire protection requirements also have implications for the economic feasibility of fire-resistant coatings. However, while investing in the high-performance coatings, the main cost disadvantages to have result also in states where exist essential strict standards as California and New York is to pay more for initial costs that can to be compensated with long term requirements for better fire protection and low costly maintainability. On the other hand, states that do not have rather high requirements for self-cleaning, it is possible to consider the cost-efficiency perfluorinated bio-based coatings which can be used on a large scale. This capacity of these coatings renders them suitable for fulfilling other regulatory and environmental requirements as well, thus making them amenable for application in the construction industry in the United States of America.

### 3.8. Implications for Fire Protection Strategies in High-Rise Buildings

The findings of this research have significant implications for the design and implementation of fire protection strategies in high-rise buildings. From the data shown in Figures 5-14, it can be concluded that silicone-based fire-resistant coatings may exhibit high sensitivity to the fire exposure conditions, while at the same time achieving better results at lesser levels of heat flux densities during the early stages of fire (Gravit et al., 2024). These has especially important in high rise buildings since the effectiveness of fire protective coatings plays crucial role in safety of the given building.

In addition, the concept of fire durability referring to the capacity of the coating to maintain its protection properties in real fire conditions can be also useful for comparing the performance of flame-retardant coatings in practical applications. Regarding fire endurance of the coatings, it was observed that its value was higher for standard temperature conditions as compared with the real fire conditions revealing the importance of more accurate fire modeling and development of coatings that can work effectively in extended range of temperatures (Mariappan, 2016). Such results may be useful in regulating the provision of fire-resistant coatings for buildings especially for high rise buildings since it plays a key role in the safety of such structures.

In addition, the temperatures of the protected and unprotected steel specimens presented in figures 11-13 demonstrate the effects of heat flux on the fire protection coatings too. For example, temperature of unprotected I-shaped steel column profile increased promptly in live as well as standard fire facility, but applying fire paint prohibited the increase in temperature to potential values. This applies to form effective fires protective covers that protect from the thermal danger of flames, especially in structures such as high-rise buildings and other sensitive structures (Kaur et al., 2024).

The results of the comparative analysis also highlight the need for more accurate fire modeling and the development of fire-resistant coatings that can perform effectively under a wide range of fire conditions. The concept of fire durability as the performance of the flame retardant coatings protecting the steel structures and allowing for their usage in zones with the required level of fire resistance is considered effective (Eremina et al., 2022). These findings are useful in significance to the shape of high-rise structures since systems of fire-resistant coatings can determine the safety and robustness of a structure during a fire.

### 3.9. Future Directions for Fire-Resistant Coating Technologies

The results of this research highlight several areas for future development in fire-resistant coating technologies. A more exciting area of research is the development of smart coatings for the self-healing of the fire resistance system, which could result in a higher-level performance of fire resisting solutions (Zhen et al., 2024). These protective co?atings

possess the ability to self-heal when exposure to environmental or mechanical stresses occur hence this element will increase the life span of the fire-resistant systems and reduces costs of regular maintenance and re-coating. The creation of fire retardant with such coatings would be seminal in protecting buildings especially those in high rise buildings and buildings of crucial structures where long term effectiveness is of essence.

The crucial area for further research studies includes the improvement of the coating formulations for better performance during high-risk fire conditions. From the simulation and experimentation, it was concluded that high heat flux densities can reduce the performance of fire-resistant coatings at the beginning of the fire (Figure 14). It would be much beneficial to design such a coating that it can withstand such conditions since most of the real-world fires can be identified in industrial and warehouse fire loads (Eremina et al., 2022). There are strategies of making this happen which include one utilizing advanced materials of metal organic frameworks (MOFs) in to the formulation of the coating (Sun et al 2024)

Consequently, the development of multi-functional coatings that address fire protection, corrosion resistance, and aesthetic needs represents another important direction for future research. The findings of this study show that it is possible to further enhance fire-resistant coatings to include other functionalities, these include: Weathering; this is valid given the increased usage of advanced architectural designs in the current society. These coatings' capacity to fulfill such characteristics would broaden its application in the construction sector especially in jurisdictions which have very high standards regarding fire safety and those interventionist regions where emphasis on sustainable construction has been realized.

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#### 4. Conclusion

In conclusion, the article highly emphasizes on the need to develop higher levels of fire protection coating technologies to increase protection of steel structures under different fire conditions, especially in the hazardous zones of warehouses, industries, and tall structures. The study shows that standardized temperature conditions provide a limited thermal exposure related to real flames thus exposing potential flaws in steel constructions. Therefore, it is crucial to improve fire modeling and to manufacture fire-resistant coatings that would be effective within a broad range of heat fluxes, which is addressed in this paper by means of the fire durability factor. This study reveals that fire-resistant coating contributes to a decrease of temperature change in steel structures but they can have a limited effectiveness depending on fire exposure levels. These concepts underpin the need to address the issues to do with designing and implementing proper fire protection systems that are both well equipped to deal with the different challenges posed by real-life fires as well as the need to provide protection to critical infrastructural systems. In the future, the establishment of new multifunctional fire-resistant coatings that incorporates improved materials and technologies will be highly valuable in meeting the contemporary issues of fire protection in construction.

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#### Compliance with ethical standards

##### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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