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Evaluating the fire-reaction properties of building materials used in informal settlements in Dhaka, Bangladesh

Swagata Dutta[1], Farid Ahmad[1], Rashadul Islam[2] and Mohammad Salim Kaiser[3,*]

[1]Institute of Appropriate Technology, Bangladesh University of Engineering and Technology, Bangladesh
[2]Directorate of Continuing Education, Bangladesh University of Engineering and Technology, Bangladesh
[3]Innovation Centre, International University of Business Agriculture and Technology, Bangladesh
[*]Corresponding author: dkaiser.res@iubat.edu

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Abstract

In Bangladesh, the alarming rise of fire incidents in informal settlements is becoming a growing concern for the government and citizens. Informal settlements, also known as slums, ghettos, etc., are unplanned developments often not in compliance with planning and building regulations, overcrowded, lacking basic infrastructure, and constructed of flammable materials highly vulnerable to fire outbreaks are unplanned areas illegally where housing is not in compliance with planning and building regulations. Overcrowded and lack basic infrastructure and are highly vulnerable to fire outbreaks. The lack of proper firefighting equipment and inadequate access to clean water make it difficult to control the spread of fire in these areas, further exacerbating the situation. Consequently, hundreds of families are losing their homes and livelihoods, and many lives are being lost in devastating fires. A comprehensive numerical analysis for understanding the fire-reaction properties of construction materials used in informal settlements and Cone Calorimeter simulation according to ASTM E1354: Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products were conducted. An Oxygen Consumption Calorimeter was used to characterize the fire-reaction properties of construction materials under varying heat flux values. Additionally, an advanced numerical model based on the finite volume method was developed using Fire Dynamics Simulator (FDS) and PyroSim. Wood, polyurethane foam, and cardboard were chosen for rapid fire development. Simulation results have been compared against analytical and experimental data with reasonable accuracy. This paper extends the understanding of the behavior of construction materials that are directly responsible for rapid-fire growth.

Keywords: Building materials, Fire dynamics simulator, Fire-reaction properties, Fire safety

1. Introduction

Informal settlements, such as slums, shacks, and favelas, are usually constructed with highly flammable and locally available materials. Due to the combustible nature of these building materials, the high flammability of the interior trims/claddings, and the close proximity between dwellings, fire is most likely to initiate, grow and spread to adjacent structures under appropriate conditions [1]. Generally, materials found within the settlements vary in type and nature and are often difficult to characterize, thereby making it challenging to create a database of the fire properties of the materials. Fire properties are needed to understand and predict the mechanisms of fire growth and spread. In order to characterize the material fire-reaction properties, the measurement and/or robust prediction of critical parameters, such as ignitability, which includes time to ignition (t_{ig}) and ignition temperature (T_{ig}), rate of heat release (HRR), peak heat release rate (PHRR), time to PHRR (t_{PHRR}), and total burn time (t_b). Individual materials have unique contributions to fire initiation, growth, propagation, and severity. A recent study [2] reports that polyurethane (PU) foam, cardboard, wood, carpet, and clothing are mostly responsible for fire development inside an informal settlement, while materials such as clothing, shade netting, and tire, contribute to the spread of fire between dwellings. Tire, PU foam, carpet, and wood were found to contribute the most to the severity of a fire scenario.

Fire hazard in Dhaka, Bangladesh is a common occurrence. It was reported that nearly all slum dwellers witnessed a fire hazard in their lifetime [3]. It was also observed that about 70 % of slum dwellers have lost their assets and livelihood due to fire events. Firefighting and evacuation are extremely difficult in slums due to high population density, narrow streets, and unplanned and irregular dwelling structures [4-7]. According to the Organisation for Economic Co-operation and Development (OECD) Glossary of Statistical Terms [8], informal settlements are unplanned settlements and areas where housing is not in compliance with planning and building regulations. In addition, the inhabitants often occupy the areas illegally. The poor quality of housing, lack of access to adequate water, overcrowding, and insecure utility services of these settlements pose heavy fire hazards. Recent statistics [2-9] show that more than 110000 people die worldwide every year due to fire accidents. In Bangladesh, the number of fire incidents has increased alarmingly. According to the Bangladesh Fire Service and Civil Defence (BFSCD) [10], the number of fire accidents, victims, and death toll in the country have risen respectively from 9310, 1412, and 233 to 22283, 14932 and 2138 during 2008-2019. In 2019, Bangladesh incurred an asset loss of BDT 400 crore due to havoc caused by fire [10]. This precarious situation suggests the imperativeness of taking necessary measures for proactive and reactive risk management to reduce the number of fire accidents, casualties, and economic losses.

Several studies [11-16] have shown that fire performance characterization can be valuable for fire accident prevention and risk management as they correspond to materials' burning greatly. Cone calorimetry is a widely employed and adaptable experimental method utilized to assess the fire behavior characteristics of materials. It is recognized for its versatility and is commonly employed as a bench-scale technique. In this technique, material response to external irradiance is characterized by the oxygen consumption method (ASTM E1354). In particular, the calorimeter utilizes a conical heater and has acceptable repeatability to define a controlled fire situation. The cone can be placed in horizontal or vertical positions depending on fire conditions. The test generally offers a useful understanding of how various materials decompose and burn. Of all the fire-reaction properties, it was reported that HRR is the single most important fire-reaction property as materials with high HRR can supply extra thermal energy needed for fire growth and spread and for establishing the fire feedback cycle [17]. Due to the significant expenses associated with conducting extensive fire tests on a large scale, it becomes crucial to develop reliable computer models that can predict how materials will behave when they catch fire. This process begins with understanding how materials behave in smaller, more manageable tests and then gradually expanding our predictions to larger, real-world scenarios. This approach helps save costs and allows us to better grasp and foresee how materials will react to fires of different scales. Fire Dynamics Simulator (FDS)® is a computational fluid dynamics (CFD) tool of fire-driven fluid flow developed by the National Institute of Standards and Testing (NIST), USA. With a focus on smoke and heat transfer from fires, FDS numerically solves a variant of the Navier-Stokes equations suitable for low-speed, thermally driven flow. FDS has been designed to provide a tool for studying fundamental fire dynamics and combustion while also providing a solution to real-world fire challenges in fire protection engineering [18]. In this study, we conducted a comprehensive numerical analysis for understanding the fire-reaction properties of construction materials used in informal settlements

2. Materials and methods

A comprehensive survey was conducted to identify the most commonly used construction materials in the informal settlements of Dhaka, the capital city of Bangladesh. This study incorporates both primary and secondary data sources for its research. Primary data collection methods employed were field observations, building inventory assessments, land use surveys, and interviews. The field survey was conducted in 2022-2023 to gather primary data and to select the appropriate materials for characterizing their fire-reaction properties. In parallel, secondary data was gathered from a variety of published and unpublished sources, including governmental and non-governmental organizations. An open-ended questionnaire was used during the interviews. The questionnaire included questions on the types of building materials commonly used in the area, the frequency of their use, and any fire safety concerns related to these materials. 95% of participants (total 100 participants) completed the survey. Participants were selected based on their experience in the construction industry, either as workers or supervisors, and their familiarity with the types of building materials commonly used in informal settlements. It was found from the survey that dwellings are built very close to each other and a large number of combustible materials are distributed between the settlements (Figure 1(A) and 1(B)). It was also observed that various types of materials with different characteristics were used in informal settlements. Inside the houses, several layers of floor covering made of different materials were used. During our inspection in the settlements, wood was found to be widely used to construct doors and window framings. Housing structures in slum areas were constructed using more affordable materials such as straw, leaves, polythene sheets, wood, bamboo, and coarse papers. These constructions offer the advantage of easy relocation with minimal notice and can be erected swiftly. Typically, slum residents reside in cost-effective housing structures, with a majority residing in Kutcha/Tin/wood-built houses.

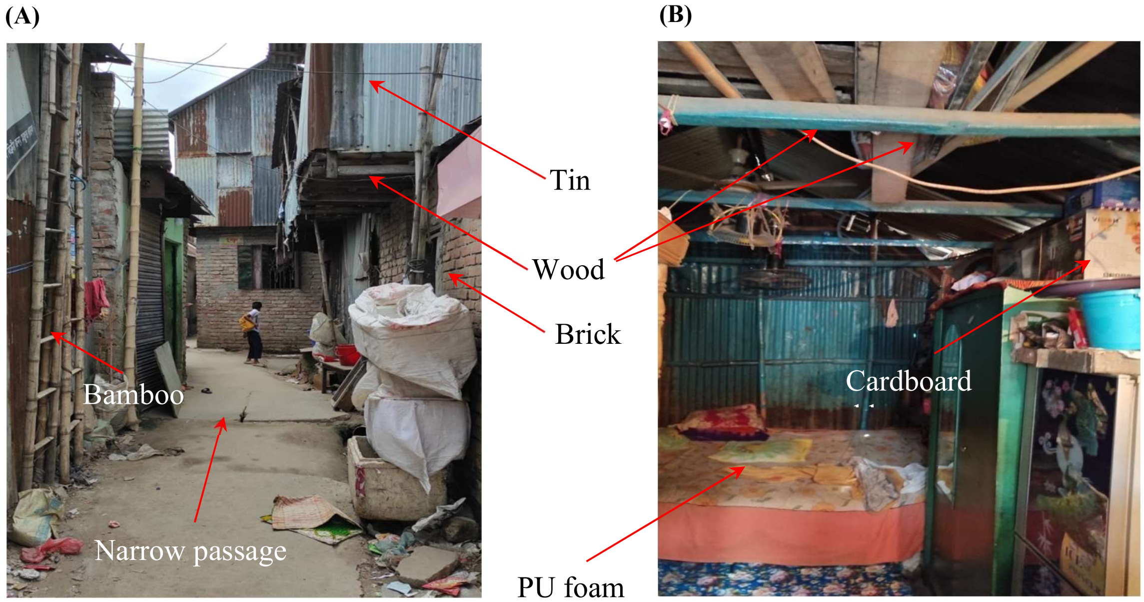

Figure 1 Informal settlements in Bhashantek Bazar, Dhaka (A) outside view and (B) inside view.

The objective was to comprehensively understand the characteristics of informal settlements in Bangladesh, including housing types, materials used, and population density. Moreover, another objective was to collect information on the housing and household facilities of slum dwellers. The survey was conducted through on-site visits and interviews with residents of informal settlements in selected areas. Data was collected from 35 informal settlements during the period from April 2022-January 2023 in Bhashantek Bazar, Dhaka, which has a cluster of informal settlements. Table 1 lists the typical housing type of the informal settlements.

Table 1 Types of housing structures.

Housing type	Description
Single-room Shanty	Simple one-room structures made of mud, wood, bricks, tin, steel
Semi-permanent	Houses with more substantial materials like bamboo or wood
Tin-roofed Shanty	Shacks with tin roofs constructed from makeshift materials
Multi-story Shanty	Multi-level structures made of various materials

The predominant materials used in construction within the studied context are bamboo, corrugated tin sheets, wood, and cardboard. Wood serves a dual purpose, both structural and finishing, making up 85% of construction materials. Corrugated tin sheets, vital for roofing and walls, are prevalent at 50% usage. Additionally, cardboard is traditionally used for wall cladding, accounting for 88% of the materials employed in construction. These materials collectively form the cornerstone of construction practices within this context. The most widely used materials are listed in Table 2.

Table 2 Major materials used for construction and household items.

Major materials	Description	Usage (%)
Bamboo	Natural material, often used for structural support	45
Corrugated Tin Sheets	Frequently used for roofing and walls	50
Tarpaulin	Lightweight material used for temporary shelters	10
Wood	Used for both structural and finishing purposes	85
Cardboard	Traditional materials for wall claddings	88

Table 3 provides an overview of three distinct settlements: Benaroshi Palli, Jahangir's Slum, and Bashbari Slum. Benaroshi Palli comprises approximately 2,200 dwellings with an average of 5 to 6 occupants per dwelling, resulting in an estimated total population ranging from 11,000 to 13,200. Meanwhile, Jahangir's Slum encompasses around 500 dwellings with an average of 6 to 7 occupants per dwelling, or an estimated total population between 30,000 and 35,000. Bashbari Slum consists of approximately 400 dwellings with an average of 4 to 5 occupants per dwelling, totaling an estimated population of 16,000 to 20,000 residents.

Table 3 Population density in different settlements.

Settlement	Total number of dwellings (approx.)	Average number of occupants per dwelling (approx.)	Estimated total population (approx.)
Benaroshi Palli	2,200	5 - 6	11,000 - 13,200
Jahangir's Slum	500	6 - 7	30,000 - 35,000
Bashbari Slum	400	4 - 5	16,000 - 20,000

In Benaroshi Palli, dwellings, 92% of the houses were constructed entirely of wood, tin, cardboard claddings, and with concrete floors. The number of rooms in a house varied, with 30% having one room, 23% having two rooms, and 40% having more than two rooms. The typical room dimensions were 3 m in length, 3 m in width, and 2.8 m in height. Moreover, all doors in the surveyed houses were constructed using tin, with dimensions typically measuring 0.76 m in width and 1.76 m in height. In addition, only 8% of the houses had windows, which were typically made of wood and tin and measured 0.61*0.61 m. In contrast, 85% of the houses lacked windows. The primary water source for 90% of the households was a tube well, while the remaining 10% relied on tap water. Approximately 90% of the houses were directly attached to adjacent structures, emphasizing the high population density and close proximity of dwellings. In 14% of the structures, there was a distance of less than 1 meter between neighboring houses. PU foam emerged as a ubiquitous material within the informal settlements, finding extensive utility in various upholstery and multifarious applications. Remarkably, a significant proportion (45%) of household items within these communities incorporated PU foam in some form, underscoring its pivotal role as a versatile and prevalent material in this context. Based on the survey, the three most widely used materials in informal settlement construction (wood, PU foam and cardboard) were selected for further analysis.

The majority of households (85%) used wood and paper as cooking fuels, while the remaining 15% relied on gas. In terms of the width of the road in front of the houses, 52% of houses had a road width of 1.06 m and 32% had a road width of 0.91 m. In terms of the width of the road in front of the houses, 60% had a road width of 1.22 m, and 33% had a road width of 0.91 m. A significant proportion (87%) of households reported cooking at night, while a smaller fraction (3%) did not. Multiple reports of fire hazards were found in the past few years. For Jahangir's slum, 100% of the houses were constructed entirely of wood, tin, and had concrete floors. Dwellings in Jahangir's slum were similar to the dwellings of Benaroshi palli. The distribution of the number of rooms in a house remained similar to the previous slum, with 23% having one room, 27% having two rooms, and 50% having more than two rooms. The room dimensions remained unchanged at 3 m in length, 3 m in width, and 2.89 m in height. There was a slight change in the cooking fuel distribution, with 80% of households using wood and paper and an increased reliance on gas (20%). A high percentage (90%) of houses remained directly attached to adjacent structures, indicating both structural and population density. In 7% of cases, houses had a distance of less than 1 meter to neighboring structures as before.

Ensuring adequate spacing between structures is crucial for safeguarding buildings from the potential spread of fire from neighboring ones. The government of Bangladesh made amendments to construction regulations in 1996, which included provisions related to setbacks, site coverage, and plot usage, all aimed at enhancing building safety during various hazards. Setbacks establish the minimum separation distance that a building should adhere to concerning nearby roads and other buildings. For Dhaka city, these regulations mandate a minimum space of 1.5 m in the front, 1 m at the back, and 0.8 m on both sides for plots sized at 134 m^2 or smaller (GOB, 2008). This study's findings indicate that a significant majority, specifically 91% of the structures, lack adequate spacing between them. Furthermore, having appropriately wide staircases is crucial for ensuring swift and efficient evacuation in the event of fire. Field assessments revealed there are no emergency exits present in any of the structures. Moreover, the coexistence of various functions within a single structure, known as mixed-use (in which a building can serve multiple purposes such as residential, commercial, or restaurant use), significantly heightens the potential fire risk. In mixed-use buildings, the ground floor often serves as a storage area for items such as waste paper, discarded plastic and tin containers, obsolete electronic components, and plastic bags. These materials are highly susceptible to fire. Certain roads in the area are exceptionally narrow. Our survey of Bhashantek dwellings did not reveal the presence of any emergency exit within those structures. Furthermore, none of those buildings were equipped with fire protection measures or equipment. Additionally, there were no provisions for conducting fire drills in this locality. It is worth noting that in the past, several buildings were employed as depots for combustible materials; however, our field survey did not identify any depots in the area.

The majority of access roads in the Bhashantek area are characterized by their narrowness. In accordance with the Dhaka Metropolitan Building Construction Rules of 2008, it is mandated that each site should be accessible via roads with a minimum width of 6 m (GOB, 2008). This prescribed minimum width serves the dual purpose of facilitating convenient access for both people and vehicles. Additionally, a minimum road width of 3.05 m is deemed necessary to adequately accommodate firefighting efforts, particularly in the case of smaller-sized fires. These findings provide valuable insights into the living conditions and characteristics of informal settlements in Bangladesh, highlighting the predominant use of wood, tin for construction, use of unrated upholstery in the rooms, limited access to windows, reliance on tube wells for water, and the challenges posed by high population density and narrow roads. Therefore, investigating the fire properties of the construction as well as the household materials typically used in the informal settlements is of prime importance. In terms of fire safety, the Bhashantek area remains vulnerable to fire incidents due to various factors. The mixed-use of structures and the handling of waste materials need to be better regulated to mitigate the risk of fires in this study area. Additionally, it is imperative to consider relocating electricity lines underground to reduce the risk of electrical fires. Strict enforcement of building codes by government authorities is also crucial. Both building owners and residents should actively ensure the implementation of fire safety measures and conduct regular fire drills to enhance preparedness and reduce fire risks in Bhashantek. structurally risky and fire-vulnerable buildings should be identified and warning should be issued.

2.1 Numerical Model

We developed a numerical model based on the finite volume (FV) method in Fire Dynamics Simulator (FDS) ® aided by the Graphical User Interface (GUI) interface developed by PyroSim. FDS serves as a tool for conducting numerical simulations in the realm of fluid dynamics. Its primary focus lies in modeling thermally induced, low-speed flows, with a specific emphasis on factors, such as smoke behavior and the transfer of heat arising from fire events. Notably, FDS is renowned for its computational efficiency and speed when calculating time-dependent flow scenarios [9,10]. In its computations, FDS employs a second-order accurate finite element approach, both spatially and temporally. To update variables like temperature and heat flux over time, the software utilizes an explicit second-order Runge-Kutta scheme. Within the governing equations, spatial derivatives are computed through second-order accurate finite differences, implemented on a rectilinear mesh [1]. Scalar attributes, such as density, find their assignment at the center of each computational cell, while vector characteristics, like velocity, are designated at cell surfaces [11]. FDS grants users the capability to define and assess simulation conditions within a specified domain. Typically, the outcomes produced by FDS are examined and interpreted with the assistance of Smokeview, a companion software.

The large eddy simulation (LES) scheme was utilized to simulate the Cone Calorimeter (CC) experimental results. The simulations were conducted under different heat flux values to characterize the fire-reaction properties of the various construction materials used in informal settlements. For each simulation, the critical fire-reaction properties, such as the t_{ig}, t_b, HRR, etc., were predicted. To adhere to the specifications outlined in the ASTM E-1354 standard, the computational domain was established to match the physical layout of the cone calorimeter in all instances. To perform the FDS simulation, a cubic domain measuring 400 mm was utilized, as depicted in Figure 2. Boundary conditions were applied, with the domain consisting of walls made of glass. The lower part of the domain was given open boundary conditions to allow unobstructed airflow into the burning region. A vent for exhaust air flow with a prescribed volume flow rate was given according to the authors' earlier work in [16]. Details of the numerical model and the governing equations can be found in [16] and [18], respectively.

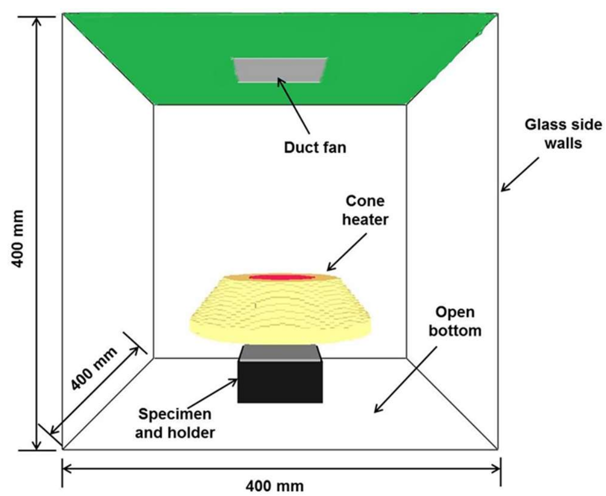

Figure 2 Cone calorimeter: FDS model setup.

Several heat fluxes (30-75 kW/m^2) were chosen to simulate various fire scenarios at different stages: initial, growing, and fire at flashover. The igniter was modeled using a surface burner type application on the inner surface of the cone with prescribed temperatures for different heat fluxes. These heat fluxes were achieved by specifying temperatures on the cone heater surface, namely 700°C, 750°C, and 950°C for heat fluxes of 35, 50, and 75 kW/m^2, respectively. The model was developed based on the previous work of the corresponding author, as described in references [12-17]. The gaps between the lower segment of the cone heater and the test specimen, as well as the upper portion of the cone heater and the ventilation fan, were maintained at distances of 25 mm and 270 mm, respectively. Concerning the boundary conditions, the four lateral walls enclosing the domain were sealed glass surfaces, while the base was left unobstructed to facilitate air intake. A gas or flame flow rate of 24 liters per second was designated for the duct fan to direct the flow toward a vent situated at the domain's zenith. The primary component of the cone calorimeter responsible for emitting heat onto the specimen is the cone heater. replicating the design of the cone heater involved transforming a 3D heater model into FDS input code, with the objective of closely emulating the configuration depicted in Figure 3(A). The crimson sections on the model were employed to signify the heating elements, thereby enabling precise specification of surface temperatures as suitable boundary conditions. it is worth noting that in all instances, single-layer materials were employed with a volume fraction set at 1.0. the rear surface of the specimen was insulated, effectively inhibiting any heat dissipation from the rear. The simulation was repeated several times, and the average values were used for data analysis in FDS and with other statistical analysis tools. The results were compared with the values obtained from literature [2,18,28,29] of similar materials to evaluate the accuracy of the simulation.

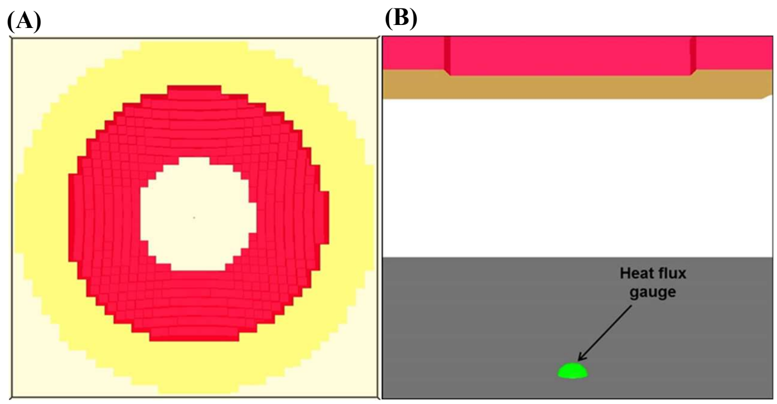

Figure 3 (A) The lower section of the cone heater and (B) the heat flux sensor placed on the surface of the specimen.

The temperature configuration for the cone heater in the simulation was established using an iterative approach. In the cone calorimeter experiment, a specific heat flux of 50 kW/m² was employed. Throughout the simulation, a heat flux sensor was strategically kept at the center point of the test specimen, shown in Figure 3(B), to monitor the heat flux generated by the specimen in response to the temperature input provided within the FDS. Figure 4 depicts the heat flux patterns of the material under different cone heater temperatures in the FDS simulations. It is worth noting that an input temperature of 850°C was found to correspond to a heat flux of 50 kW/m², with sharp increases in the heat flux curves, signaling the ignition of the material. Consequently, elevating the temperature led to earlier ignition of the material.

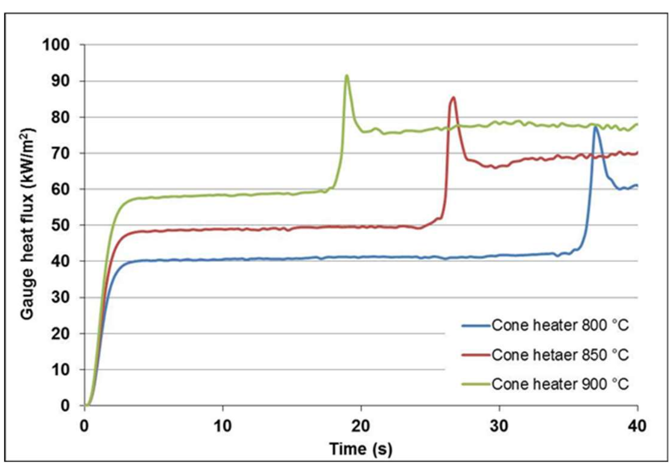

Figure 4 Heat flux on specimen surface at different temperature.

Physical and thermal properties of wood, PU foam, and cardboard were employed as input parameters to simulate the cone calorimeter test and obtained from [19-27] are shown in Table 4.

Table 4 Critical thermal and physical properties of construction materials [19-27].

Property	Value		
	Wood	PU Foam	Cardboard
Heat of Combustion (kJ/g)	12	25	30
Soot Yield (g/g)	0.001	0.13	0.050
CO_2 Yield (g/g)	1.27	1.5	0.013
H_20 Yield (g/g)	0.442	1.6	0.422
Emissivity	0.9	0.88	0.87
Density (kg/m^3)	550	118	130
Thermal Conductivity (W/m-K)	0.168	0.02	0.10
Specific heat (kJ/kg-K)	2.3	1.30	2.07

To incorporate the combustion reaction rate of a solid material into the FDS simulation, it necessitates obtaining kinetic parameters like activation energy and pre-exponential factor. FDS employs a combination of the Arrhenius function and power function to ascertain these kinetic parameters and reaction rates for diverse materials. We scrutinized the Thermogravimetric (TG) curves [19-28] of the materials to extract critical data, specifically the reference temperature and reference reaction rate. These parameters are pivotal in characterizing the kinetics within the simulation. For each of the tested samples, a single-step Arrhenius-type reaction was defined. The reference temperature was characterized as the temperature at which the material undergoes its maximum rate of mass fraction reduction, as observed in the TG curves. Conversely, the reference reaction rate corresponds to the highest decomposition rate witnessed in the same TG curves. Both of these crucial parameters were deduced from the Derivative Thermogravimetric (DTG) curves and subsequently utilized as input data for the simulation.

An appropriate grid dimension was selected through a systematic refinement process until the PHRR exhibited independence from the grid size. The procedure for identifying the optimal grid configuration for the computational domain was carried out according to reference [2]. Initially, in the first phase, various grid sizes were exclusively applied along the vertical axis, denoted as Z. Subsequently, in the second phase, the horizontal axes, referred to as X and Y, were partitioned into distinct grid sizes based on the dimensions determined in the first phase along the Z axis. The outcomes of the grid analysis, particularly concerning the output parameter recorded at the moment of PHRR during combustion, are provided in Table 5.

Table 5 Grid analysis results.

Grid resolution (mm)		At time to PHRR	Grid resolution (mm)		At time to PHRR
X / Y axis	Z axis	PHRR (kW/m^2)	X / Y axis	Z axis	PHRR (kW/m^2)
10	5	1380	10	3	1580
	3	1520	5		1710
	2	1570	4		1530
	1.3	1640	3		1580

The assessment brings to light a noticeable disparity in the calculated PHRR between a vertical grid resolution of 5 mm and 3 mm, whereas the distinction between grid sizes of 3 mm and 2 mm is less pronounced. Additionally, the variation between the 3 mm and 2 mm grid dimensions closely mirrors what was observed between the 2 mm and 1.3 mm grid sizes. Consequently, we selected a vertical grid resolution of 3 mm for subsequent grid analysis. Delving further into the evaluation of horizontal grid resolution at the 3 mm vertical grid setting, it became apparent that the difference in simulated PHRR values at the time of PHRR between a 5 mm and 4 mm grid size was relatively substantial, whereas the differentiation between grid sizes of 4 mm and 3 mm was less conspicuous. For this study, a grid size of 4 mm was deemed suitable for both the X and Y axes. as a result of the grid sensitivity assessment, the horizontal and vertical grid dimensions were set at 4 mm and 3 mm, respectively, for the FDS simulation.

3. Results and discussion

3.1 Wood

The heat release rates (HRRs) of the building materials were predicted using a cone calorimeter simulation model developed in FDS. The simulation gave insightful information about the materials' fire performance, enabling comparison of their HRRs. This comparison made it easier to identify the materials with faster rates of heat release, which will induce larger fire growth, in vulnerable structures. In general, we observed the cone calorimeter simulation model was a useful tool in assessing the fire performance of various building materials used in informal settlements. The HRR curves at different heat flux values, i.e. 30, 50 and 75 kW/m^2, for wood are shown in Figure 5(A)-5(C). It can be clearly seen that the four generic phases of burning such as ignition, stable combustion, growth, and decline are clearly discernible in the figures. The simulated HRRs were compared with the HRR values that Janssens [28] and Brohez [29] reported in their studies. We observed that the FDS predicted HRR curves at different heat fluxes reasonably well with both analytical models.

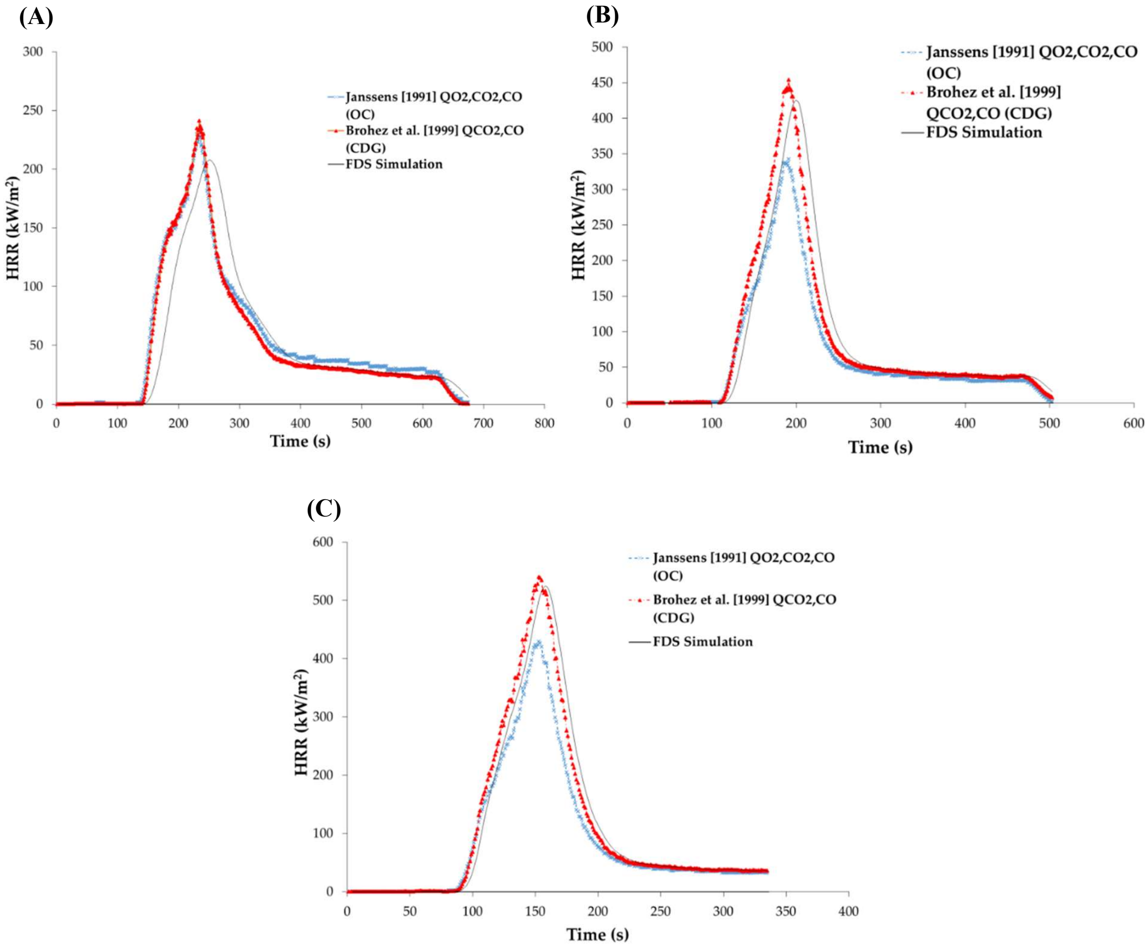

Figure 5 FDS-predicted heat release rate (HRR) curves for wood at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

For all the heat flux values, the HRR curves for wood display a particular pattern (sharp peak) that corresponds to the material's dynamic combustion behavior. The PHRR value is produced when the wood ignites and remains in the stable combustion phase, causing a quick release of heat. The HRR finally drops quickly in the second phase, causing the curve to eventually flatten out at longer burning times. The peak HRR and t_{ig} for wood under different heat fluxes are depicted in Figure 6 and Figure 7, respectively. From Figure 3, it can be found that for 30 and 75 kW/m^2, the predicted t_{ig} for wood were 120 s and 80 s, respectively, which is significantly shorter (~ 40 s), and the PHRR increased from 2.2 kW to 5.3 kW. As a result of its rapid burning and high heat release rates, wooden materials pose a significant fire risk at higher heat fluxes, as shown in Figure 6 (~ 5.3 kW at 75 kW/m^2). In general, we observed that FDS-predicted PHRRs for all the incident heat flux values were slightly lower than that calculated from [28,29]. In contrast, t_{ig} (Figure 7) and t_b (Figure 5) were predicted almost accurately. The difference in the PHRR values may be due to the type of wood used to determine the fire-reaction properties and to the inadequacy of accurate thermal and physical properties. It is also seen that t_b reduced significantly (690 s and 340 s for 30 and 75 kW/m^2, respectively) with increases in incident heat flux. It is noteworthy that the critical heat flux (HF_c) and average t_{ig} of the materials are contributing factors to the fire growth inside informal structures and exposes adjacent dwellings to the risk of spreading flames ; smaller values of HF_c and t_{ig} will increase the speed and risk of fire growth and propagation.

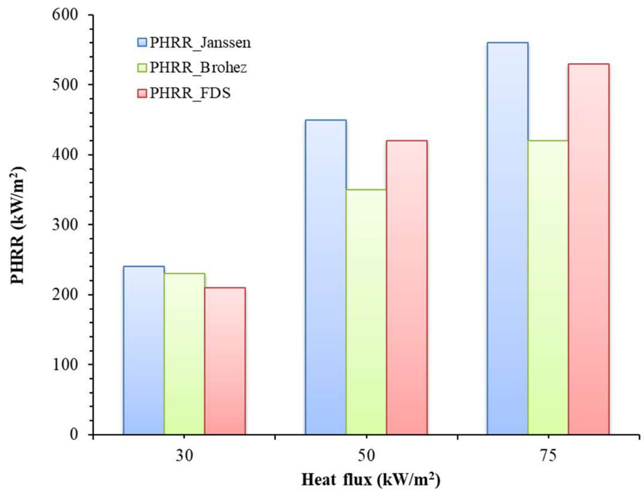

Figure 6 FDS-predicted peak heat release rate (PHRR) curve for wood at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

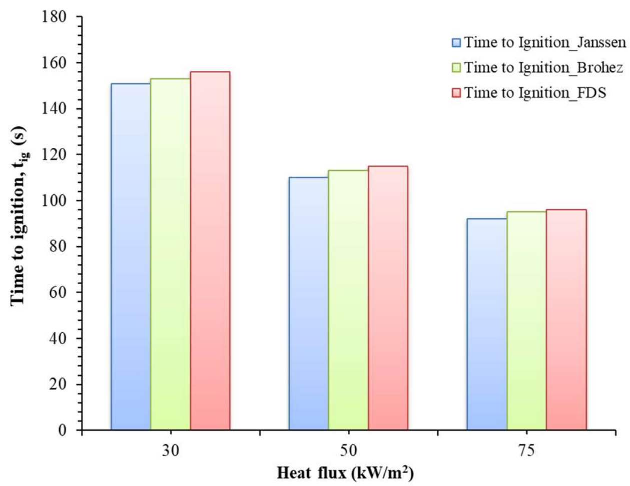

Figure 7 FDS-predicted ignition time (t_{ig}) for wood at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

3.2 PU Foam

The necessity of using fire-resistant materials in structures is highlighted by the HRR curves, which offer insights on the material's dynamic combustion behavior and potential for fire hazard. The HRR curves at different heat flux values, i.e. 30, 50, and 75 kW/m^2, for PU foam are shown in Figure 8(A)-8(C). The simulated HRRs were compared with the HRR values that Janssens [28] and Brohez [29] found from their analytical models. It is clearly observed that the predicted HRR curves at different heat flux values, when superimposed with both previously developed analytical models, match with considerable accuracy. The HRR curves can be characterized by an ignition phase, growth, and final decline phase. It is noted that similar to wood, the t_{ig} and t_b for 30, 50, and 75 kW/m^2, respectively, reduced significantly (Figure 9 and Figure 8 respectively). However, as can be seen in Figure 9, the PHRR increased considerably (2.8 to 5.8 kW). The PHRR for wood and PU foam showed similar values at a given heat flux value. For example, at 30 kW/m^2, the PHRR values for wood and PU foam were 2.2 and 2.9 kW, respectively. However, for PU foam, the PHRR values were better predicted than that of wood. In contrast to PU foam (~50-80 s), the PHRR for wood samples was obtained within a very short period of time (~15 s). Moreover, the time to PHRR (t_{PHRR}) for both materials under different heat fluxes was ~ 150-250 s. Therefore, it implies that the incident heat flux did not affect the t_{PHRR} significantly. This indicates that the t_{PHRR} is more sensitive to a material's inherent property rather than incident heat flux. the t_{ig} at all the incident heat fluxes was also accurately predicted. The wood samples burned longer than the PU foam. For instance, at 75 kW/m^2, the t_b for wood was ~ 340 s, whereas for PU foam, it was ~ 270 s. Therefore, it can be concluded that wood and PU foam have effectively the same impact for fire development; however, for flame spread and severity of fire between adjacent dwellings, wood may have more influence. For the design of fire safety measures, such as fire detection and suppression systems, as well as the creation of flame retardants for wood materials, the curves offer crucial information.

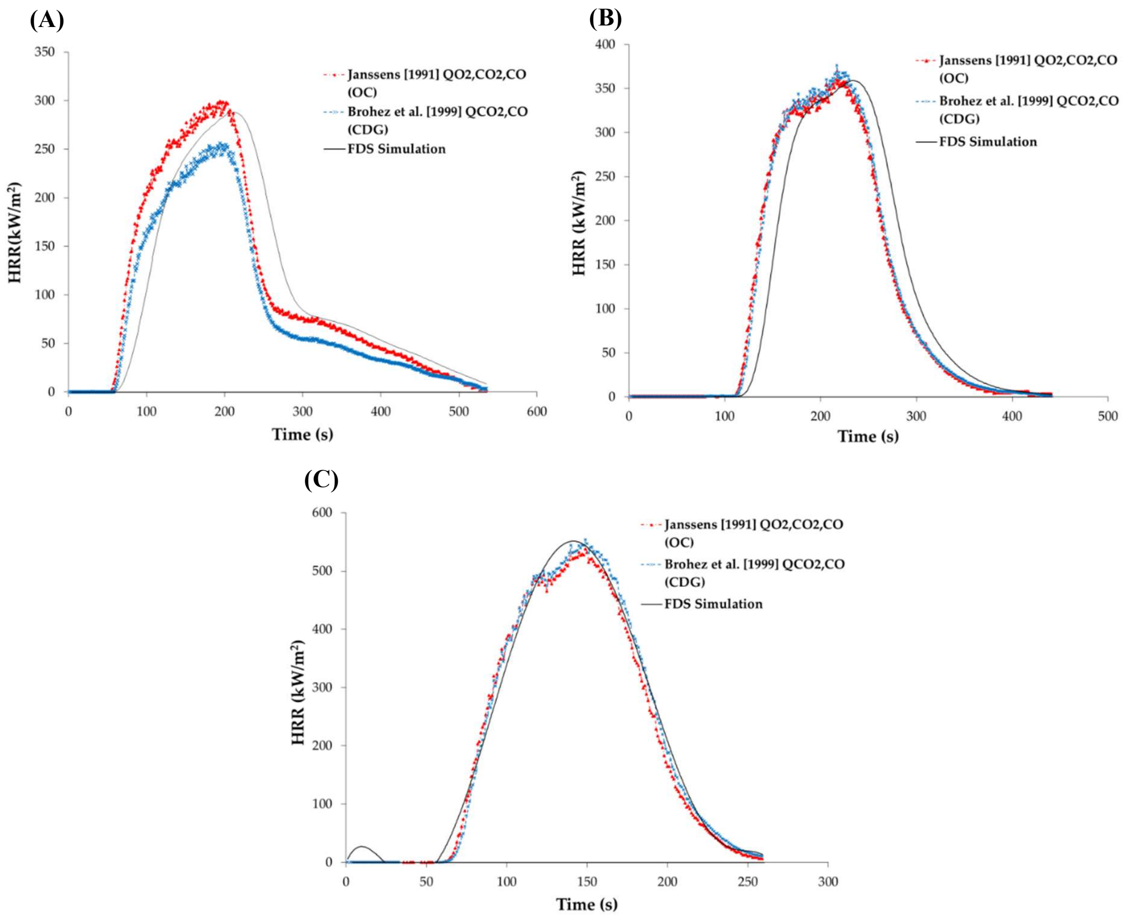

Figure 8 FDS-predicted heat release rate (HRR) curves for PU foam at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

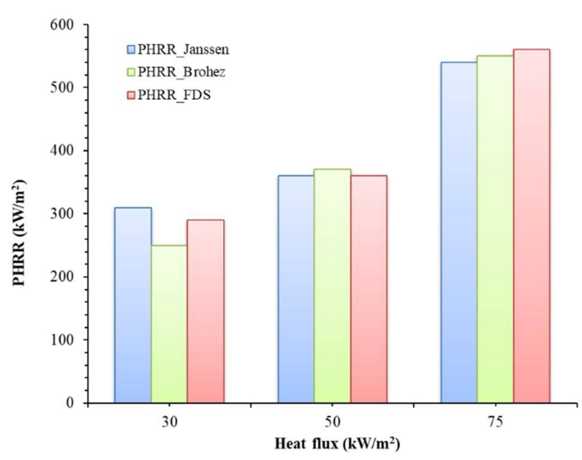

Figure 9 FDS-predicted peak heat release rate (PHRR) curve for PU foam at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

3.3 Cardboard

Similarly, the HRR curves at different heat flux values, i.e. 30, 50, and 75 kW/m^2, for cardboard are shown in Figure 10(A)-10(C). In general, the cardboard samples ignited earlier (lower t_{ig}) with significantly lower PHRR and t_b values under different heat fluxes. For example, at 30 kW/m^2, the t_{ig}, t_b, and PHRR for the cardboard samples were ~60 s, ~380 s, and ~0.9 kW, respectively. The simulated HRRs were compared with the HRR values that Janssens [28] and Brohez [29] found in their studies. It was observed that the FDS-predicted HRR curves at different heat fluxes merge reasonably well with both the analytical models. It is interesting to note that the cardboard samples showed two distinct peaks at 30 and 50 kW/m^2. The predicted curves from FDS simulation were also able to accurately capture these peaks. As can be seen in Figure 10(A), the HRR curve showed an initial peak (~ 0.94 kW) at ~ 110 s, then steeply declined until 190 s. At 190 s, the second peak (~ 0.6 kW) was observed followed by a gradual descent to 0 kW at 380 s.

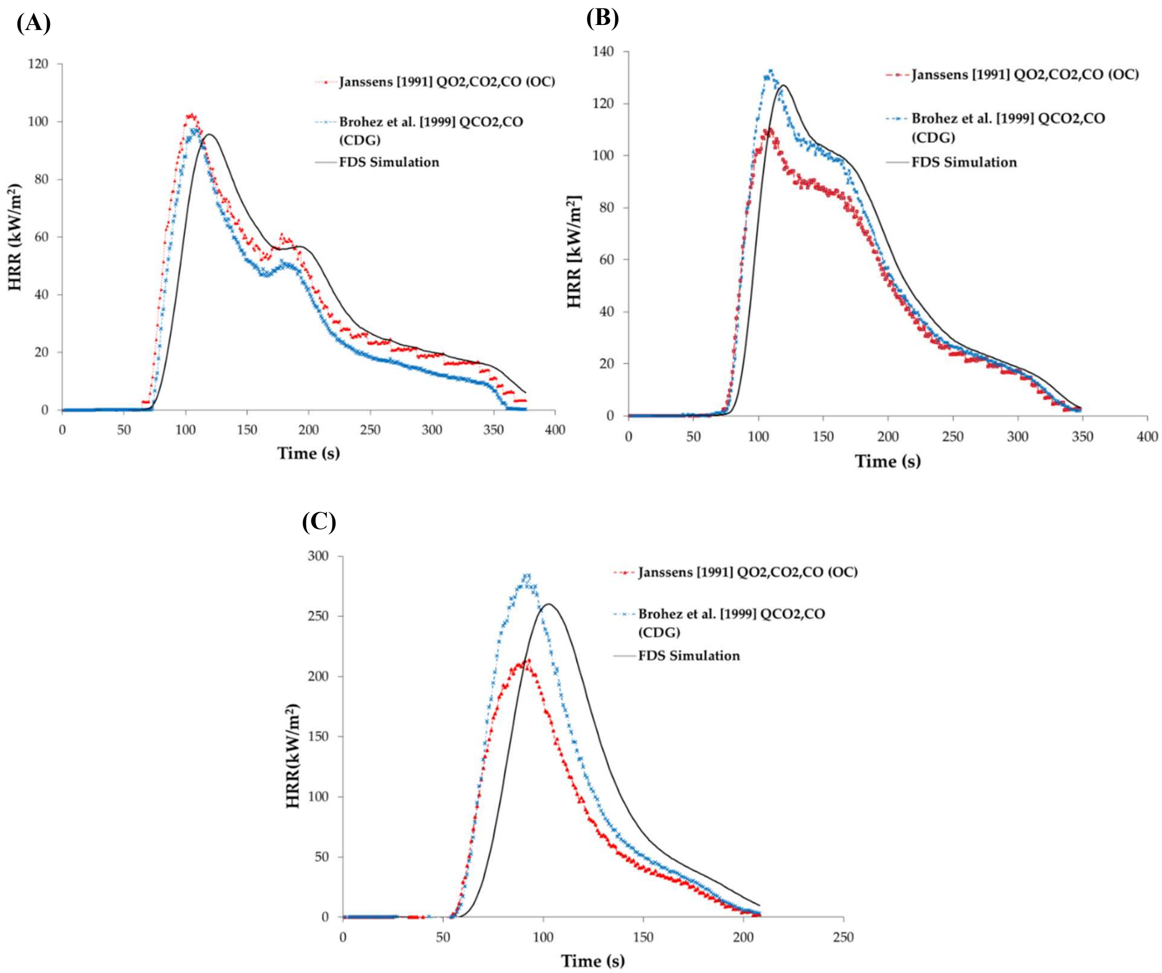

Figure 10 FDS-predicted heat release rate (HRR) curves for cardboard at (A) 30, (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

At 50 kW/m^2, the curve shows a similar trend, first peaking at ~ 100 s (1.25 kW) and with a diffused second peak at 165 s (1.1 kW) (Figure 11) with t_{ig} ~75 s. The peak heat release rate values of materials are crucial for comprehending fire growth inside houses. from the results, it can be envisioned that a second peak may contribute to a feedback cycle in an otherwise declining fire scenario. This may be due to some smothering effect during initial burning. at higher incident heat flux values, the second peak was not observed. This may be due to the complete burning of the samples at higher heat fluxes leaving no residue to start the feedback cycle. In contrast to other parameters, t_{ig} was found to be massively responsive to the incident heat flux values. We found for all the materials, incident heat flux has a similar effect on t_{ig}, PHRR, and t_b. In all cases, higher incident heat flux caused lower t_{ig}, higher PHRR, and lower t_b.

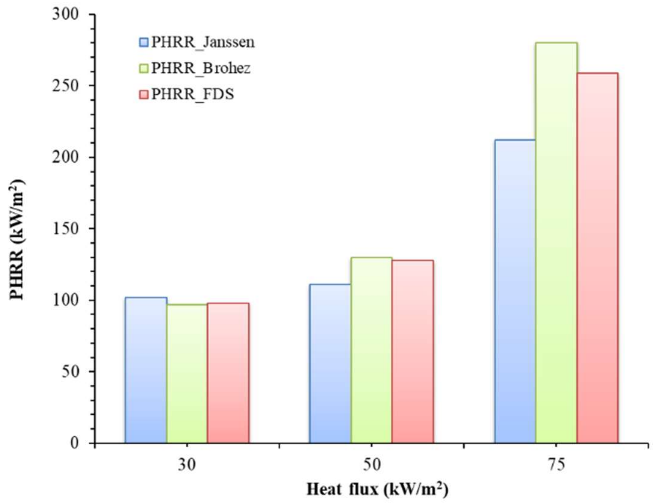

Figure 11 FDS-predicted peak heat release rate (PHRR) curves for cardboard at (A) 30 (B) 50, and (C) 75 kW/m^2 compared against results from models proposed by Janssens [28] and Brohez [29].

A comparative analysis of wood, PU foam, and cardboard based on their response to varying heat flux levels is shown in Table 6. It is evident from the results in Table 6 that wood exhibited the highest PHRR values across all heat flux levels, with a maximum of 530 kW/m^2. This suggests that wood is the most flammable material among the three. In terms of ignition time, PU foam exhibited the quickest ignition, with an average ignition time of approximately 56 seconds, followed by cardboard and wood. PU foam also showed the longest burn time, indicating its capacity to sustain combustion. Cardboard demonstrated an intermediate behavior in most aspects, showcasing a balance between ignition time and burn time. Interestingly, wood required the least time to reach its PHRR, suggesting rapid heat release in case of a fire. Overall, the results highlight the importance of material selection in fire safety considerations, with PU foam showing the fastest ignition and longest burn time, wood exhibiting the highest PHRR, and cardboard occupying an intermediate position in the context of fire safety. Further research into the fire resistance and safety of these materials is warranted to inform practical applications and safety measures.

Table 6 Comparison of properties at different heat fluxes

Heat Flux	30 kW/m^2			50 kW/m^2			75 kW/m^2		
Properties	Wood	PU Foam	Cardboard	Wood	PU Foam	Cardboard	Wood	PU Foam	Cardboard
PHRR (kW/m^2)	210	290	98	420	360	128	530	560	259
Ignition time, t_{ig} (s)	156	62	65	115	56	59	96	43	53
Burn time, (t_b) (s)	681	526	374	502	438	344	339	259	206
Time to PHRR (s)	245	208	119	195	180	115	156	140	103

3.1 Model Validation

A cone calorimeter simulation was performed and the predicted reaction-to-fire properties of different construction materials (wood, PU foam, and cardboard) were compared against two well-known analytical models proposed in [2]. In addition, the HRR of PU foam at three different heat fluxes was simulated to validate experimental data published in [2] (Figure 12). From Figure 12, it can be seen that the predicted HRR curves for PU foam at different heat fluxes show reasonable accuracy with the experimental results. For example, at 75 kW/m^2, the simulated PHRR (~ 578 kW/m^2) was very close to the experimentally determined PHRR (~ 580 kW/m^2). The t_{ig} (~ 56 s) and t_b (~ 400 s) were slightly over predicted than that of experimentally determined values, 50 s and 290 s, respectively. However, for lower heat fluxes (30 and 50 kW/m^2), the predicted time to ignition and burn time were predicted with higher accuracy. The model was able to capture the trends and nature of the HRR curves. Therefore, we conclude that the model predicted the fire-reaction properties and the burning behaviors of the construction materials reasonably well.

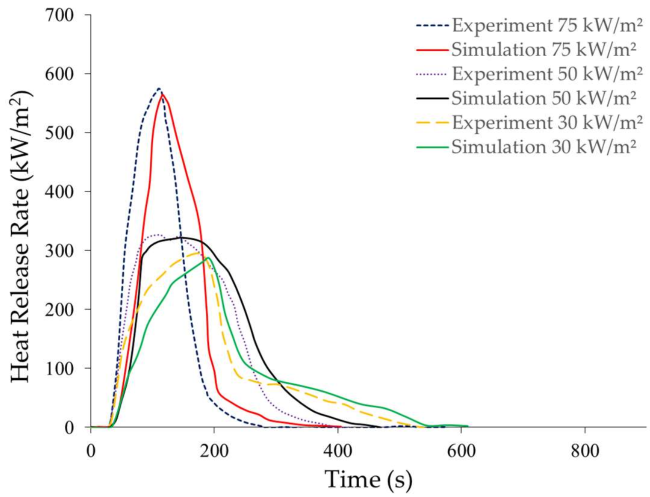

Figure 12 FDS-predicted heat release rate (HRR) curves for PU foam at (A) 30, (B) 50, and (C) 75 kW/m^2 validated against experimental data in [2].

4. Conclusion

A thorough and encompassing field survey was diligently undertaken with the primary objective of identifying the prevailing construction materials typically employed within informal settlements. This investigation sought, to assess the potential fire hazards inherently associated with these habitation structures. The survey of informal settlements in Dhaka, Bangladesh, including Benaroshi Palli and Jahangir's slum, revealed common characteristics, such as the predominant use of low-cost construction materials, narrow access roads, and limited fire safety measures within these densely populated areas. These findings underscore the urgent need for enhanced fire safety awareness, stricter enforcement of building codes, and regulatory measures to address the high-risk factors prevalent in informal settlements, such as mixed-use structures and the storage of combustible materials. Moreover, to mitigate fire hazards and enhance the safety of residents in areas like Bhashantek, a comprehensive approach that considers both construction materials and household items, coupled with improved urban planning and infrastructure development, is essential to protect lives and property from fire incidents. An advanced numerical predictive model based on the finite volume method in FDS was developed to simulate materials' fire behaviors in a cone calorimeter environment. For boundary conditions, a single layer of specimens was utilized for simulating the fire behavior of construction materials. Through grid refinement analysis, it was determined that the suitable mesh sizes were 4 mm for both the X and Y axes and 3 mm for the Z axis, particularly for assessing the heat release rate in various directions. The simulated HRR curves for the construction materials exhibited a reasonably similar trend to earlier studies. The HRR values generated in the FDS model for the materials were obtained through consideration of specific chemical species and calculated reaction rate for combustion and pyrolysis models. These results demonstrate the potential capability of the FDS model for further research in the context of construction materials. Additionally, other parameters related to construction and household materials, such as mass flux and surface temperature, can be quantified and incorporated alongside HRR data to provide a more accurate prediction of the materials' combustion behavior. We observed that wood was the most susceptible to combustion among the three materials. Regarding ignition time, PU foam displayed the shortest ignition delay, averaging around 56 seconds, surpassing both cardboard and wood. Additionally, PU foam demonstrated an extended burn time, suggesting its ability to sustain combustion for a longer duration. Cardboard, on the other hand, exhibited an intermediary behavior across various parameters, striking a balance between ignition time and burn time. Of particular interest is the fact that wood reached its PHRR in the shortest time, indicating a rapid release of heat in the event of a fire. In summary, these results underscore the critical role of material choice in fire safety considerations: with PU foam showing the swiftest ignition and longest burn duration, wood displaying the highest PHRR, and cardboard occupying an intermediate position i. Further investigations into the fire resistance and safety attributes of these materials are imperative to guide practical applications and safety protocols.

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