Towards a Fire Safety Framework in Informal Settlements in Costa Rica

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Abstract

This investigation develops a provisional understanding of fires in informal settlements in Costa Rica. This is achieved by analyzing previous fires and observing how the population behaved. One of the case studies is the El Pochote informal settlement fire, where it was possible to analyze the fire dynamics, the reaction of the inhabitants against the fire, how the first responders faced the fire and the working relationship between inhabitants and first responders. Then, a comparison between four informal settlements of different sizes will be performed in order to characterize their physical features and understand if the differences result in different behaviours of the population when facing fire events. The research includes a comparison on how Costa Rica and Canada manage their housing issues and analyzes what both countries can learn from each other. The thesis concludes with a test methodology for assessing materials that may be proposed in these settlements.

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Statement of Co-Authorship

The work presented herein has been inspired by previous and recently submitted publications for peer review, made by the author with the help of colleagues and co-authors. The chapters of this thesis have been modified to be written in manuscript format, where most of the chapters are based on journal or conference articles that have been published or submitted to journals or conferences. For all of these publications, the author helped in the conception and design of the topic, the coordination of the information gathering, the collection of the field data, the analytical research and drafted the majority of the documents. The co-authors helped with the copy edit and their knowledge input enhanced the document in general.

Chapter 3 offers an extension in analysis from the Author's previous undergraduate study "Analysis of the existing information of La Carpio informal settlement, Roble Norte sector, to create the basis for future research in fire safety." For which the inclusion of interviews of firefighters is reviewed. A novel analysis of a real fire video allowed studying fire dynamics and human behaviour which formed a new journal contribution for which Chapter 3 is based upon:

> Guevara, S., Jeanneret, C., Gales, J., Antonellis, D., and Vaiciulyte, S. (2021). "Human behaviour in informal settlement fires in Costa Rica." Safety Science, Elsevier Ltd, 142.

Chapter 4 is based on the conference paper:

> Guevara, S., Carton, H., Gales, J. (2022). "Fire building codes in developed and developing countries: a case study of Canada and Costa Rica". Canadian Society for Civil Engineering (CSCE) 2022, 270, v3.

Chapter 5 is based on the submitted paper:

> Guevara, S., Gales, J. (2023). "A provisional fire risk characterization of informal settlements of different scales in San Jose, Costa Rica". Fire, (Submitted).

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Acronyms

ASCE: American Society of Civil Engineers

ASTM: American Society for Testing and Materials

CEN: European Committee for Standardization

CNFL: National Company of Force and Light (Costa Rica)

CODECA: La Carpio Community Development Council

CSA: Canadian Standards Association

INEC: National Institute of Statistics and Censuses of Costa Rica

MIVAH: Ministry of Housing and Human Settlements of Costa Rica

NFPA: National Fire Protection Association

NGO: Non-Governmental Organization

OCDE: Organization for Economic Co-operation and Development (OECD)

OCO: Strategic Communication Office of the Costa Rican Fire Corps

SEI: Structures Engineering Institute of the American Society of Civil Engineers

UN: United Nations

USFA: United States Fire Administration

WUI: Wildland Urban Interface

Chapter 1: Introduction

1.1. General

In November 2022 the global population reached eight billion people. It is estimated that it will increase by approximately two billion by 2050, and it might reach around 10.4 billion by 2085 (United Nations, 2022). Currently, nearly one billion people worldwide live in informal settlements, most of which are located in the global south countries (UN-Habitat, 2015). This means that population growth happens unequally, being the most affected people residing in low- to middle-income countries (United Nations, 2018). As the overall population grows it is expected a similar growth pattern in the informal communities, in fact, if the current growth trend prevails it is projected that two billion people will be living in informal settlements by 2030 and three billion by 2050 (Agyabeng et al., 2022). Informal settlements can be defined as places where several dwelling units have been built on property that the residents do not legally own or are occupying unlawfully, where housing does not comply with the current planning and building regulations (OECD, 2001), where residents might also experience a lack or be completely cut off from city infrastructure and basic services (UN-Habitat, 2015). As the population grows so does the lack of property and lands where people can settle, consequently, new informal settlements are expected to appear, and existing ones to grow and evolve.

One of the biggest concerns regarding informal settlements is their susceptibility to fires and their magnified outcomes including property, goods, and life losses. Short distances between dwellings, high density of houses, lack of compliance with building regulations, the use of combustible materials for construction, the presence of rubbish throughout their alleys, amongst others increase the likelihood of a fire, and in case of one, they foster a faster fire spread within the community. Walls et al., found that for flaming fires in fragile dwellings, flashover can occur in approximately one minute (Walls et al., 2017a).

Past studies in the United States have related fire rates to a variety of social variables, including poverty, concluding that fire rates and fire deaths are higher in poor communities. (Fahy & Maheshwari, 2021). It is estimated that 300,000 people die in fire-related accidents yearly, where 95% of the deaths and burn injuries occur in low- to middle- income countries

(Twigg et al., 2017). Besides, not only the higher probability of fires or the faster fire spread are matters of concern, but the long-lasting damage and the difficulty in recovering informal settlement dwellers have. Even though poverty has been linked with higher probabilities of fire; it also has a strong influence on the ability to recover. Although after a fire, the reconstruction of the houses occurs almost immediately, the recovery of their belongings would take longer, which also results in a more unstable economy than what they already have.

Most of the investigation performed regarding informal settlement upgrading and fire safety has been performed in African and Asian countries, while little research has been carried out in American countries. This tendency is probably due to the number of people living in informal settlements in these regions. By 2018 Eastern and South-Eastern Asia allocated 35.8% (370 million), Sub-Saharan Africa 23% (238 million), Central and Southern Asia 22% (227 million), and the rest of the regions hosted 19% (199 million) (United Nations, 2019). By 2016, in Latin America and the Caribbean, roughly 16% of the urban population lived in informal settlements (The World Bank, 2020). For this region, little attention has been paid to research on informal settlements, and if done most of them has being concentrated in North and South Latin American countries such as Mexico, Colombia, and Brazil. Countries located in Central America have even less research done; therefore, this document will focus on Costa Rica.

Costa Rica was chosen due to the availability of the author to perform visits to four informal settlements within San Jose (the capital of the country), escorted by diverse public institutions (detailed further). Having the capacity to perform visits with public institutions can be a difficult endeavour since their time availability can be limited. For this study, the visits were performed during on-field inspections scheduled by these institutions, avoiding extensive coordination processes between them and the author. Another reason was to have the opportunity to create ties with the Engineering Unit of the Costa Rican Fire Corps, the unit in charge of fire investigation (Engineering Unit from now on), allowing to gather unpublished information on fires from a reliable source.

This research has the intention to contribute to the Sustainable Development Goals (SDG) set by the United Nations, specifically SDG goal 11: Make cities and human settlements inclusive, safe, resilient, and sustainable (United Nations, n.d.). Mainly focused on two targets 1) ensure access for all to adequate, safe, and affordable housing and basic services, and upgrade slums, and 2) significantly reduce the number of deaths and the number of people affected and substantially decrease the direct economic losses relative to the global gross domestic product caused by disasters, including water-related disasters, with a focus on protecting the poor and people in vulnerable situations (United Nations, n.d.).

This study has the main intention of 1) performing exploratory research and qualitative analysis of several Costa Rican informal settlements, to set the foundations for further studies. 2) propose straightforward and economical material testing procedures, that can be easily used to test proposed materials for informal housing construction and protection. The overarching goal is to collect information which allows starting to generate the basis towards a fire safety framework which includes suitable safety plans for informal communities.

1.2. Motivation

The main motivation for this research is to provide knowledge in areas where the population is most vulnerable and where not too much attention has been paid in the past. Informal settlement fires are a societal problem that is shaped by government priorities and efficacy in terms of resource distribution, tenure rights, and infrastructure delivery. (Spinardi et al., 2020). The author, for their part, considers that one of the main duties of the engineer is to ensure the safety of life of different people regardless of their socio-economic condition, religion, and political factors, among others.

Recent investigations have highlighted the scarcity of research and the need for a greater effort in addressing and developing means for enhancing fire safety for people living in informal settlements (Walls et al., 2017a) (Cicione et al., 2019), as well as the necessity for more quantitative analysis to be carried out to be able to perform more accurate fire risk assessment (Wang et al., 2020).

In recent years, there has been an increasing interest in investigating fire risk and reduction inside informal settlements (Spinardi et al., 2020). It is crucial to understand that fire risk in informal settlements is a multifaceted issue. Which is framed by several underlying socio-cultural, economic, and political elements (Antonellis et al., 2018).

From the mentioned above, a first exploration of the subject was carried out by the author, which collected the available information regarding informal settlements and their fire safety. The lack of reliable information regarding informal settlements, and the urgency to raise awareness and solutions on the matter, called the author's attention thus expanding the research and including other topics, such as the study of informal settlements within the legislation, the characterization of informal settlements of different sizes and the proposal of some testing methods for housing construction materials.

Although there are still many areas of research that need to be explored within this subject, this thesis helps to close the knowledge gap on fire safety in informal settlements in San Jose Costa Rica, in addition to creating the basis for future research to be carried out in the country.

1.3. Scope

Previous investigations have highlighted that informal settlement fire safety is globally understudied and have encouraged other researchers to join in the effort to minimize the existing information gap, as knowledge needs to be gathered across several different jurisdictions to build a more comprehensive understanding of the subject (Wang et al., 2020). The basis of this thesis is therefore focused on exploring and gathering available information on Costa Rican informal settlements, mainly the ones located inside San Jose. The research presented in this thesis explores four interrelated themes:

1. The study of the observed behaviours during fires of a population within an informal settlement,
2. The inclusion of informal settlements in the country's legislature and how it differs from a developed country,
3. The characterization of informal settlements of different scales and the comparison of the differences and similarities, and
4. The procedure for rapid evaluation of materials proposed for the construction or protection of housing in informal settlements.

The first theme is addressed by the analysis of available video footage of a real fire in an informal settlement of San Jose, which allows observing the behaviour of the population towards the fire and the first responders. It also allows for determining the different roles the members of the community can adopt and how these roles are observed in several moments of the fire, in different locations within the settlement, and by different people. Inside this first theme, it is also possible to observe the evolution of the fire throughout the event. The second theme arises from the necessity of obtaining knowledge of the existing regulations in the country related to informal settlements, and in turn the importance of comparing it with a developed country to analyze how the issue is approached from different points of view. The third theme includes the exploration of four informal settlements of different sizes within San Jose. The main objective is to determine the differences or similarities between these settlements and to compare them with each other. In addition, from these observations, the author was able to determine which actions performed by the inhabitants increase the risk of fires. The last theme proposes two different materials testing methods, which will allow a quick evaluation of the feasibility of implementing a new material in the construction or protection of housing in informal settlements.

1.4. Objectives

The general objective of this project is to develop a provisional understanding and exploratory research of fires in informal settlements in Costa Rica, aiming to create the basis towards a Fire Safety Framework tailored for these informal communities. The novelty of this thesis lies in delving into human behaviour in informal settlements fires and fire evolution from observations of a real fire. It includes a comparison between developed and developing countries when addressing housing informality, and also provides a comparison of informal settlements of different scales and their implication regarding fire risk. Finally, it provides a material testing procedure using non-standard fires that can be applied to new materials that can be used further in the construction or protection of informal settlement dwellings.

Therefore, the research objectives of this thesis include:

1. Analyze the human behaviour during an informal settlement fire among community members and with first responders, and simultaneously observing and understanding the fire evolution throughout the settlement and what features affected it.
2. Study the approach differences in informal housing regulations between developed and developing countries and governmental efforts to ameliorate the matter.

3. Identify the differences in physical features of informal settlements of different scales and determine which can mostly affect fire safety and fire risk inside the settlement.
4. Develop a test methodology that allows for quickly assessing new materials that may be proposed to be further used in housing construction and protection in informal settlements.

1.5. Thesis outline

The chapters of this thesis are based on journal or conference articles that have been published or submitted to journals or conferences. The thesis chapters have been modified to be written in manuscript style format, to be read as a narrative. The author of this thesis was the first author of journal papers used to create this document, thus fulfilling the role of authorship. In this context, authorship is defined as sufficiently participating in the manuscript's conception, design, analysis, writing, and/or revision.

The following paragraphs give a brief description of each of the sections contained in this manuscript.

Chapter 2: Background gives a general overview of research performed globally in informal settlements, although it mostly refers to fire investigations that have been conducted in South African informal settlements. It also evidences the gaps in knowledge on this subject. This chapter also describes the informal settlement situation in Costa Rica, it briefly refers to the statistics and research performed, as well as shows that there is very little research on fire safety in Costa Rican informal settlements. The last section presents to the reader some important definitions to wholly understand the following parts of the manuscript.

Chapter 3: Human behaviour in Costa Rican informal settlement fires analyses a video of the El Pochote informal settlement fire that happened back in 2019 in San Jose, Costa Rica. Here it is studied the human behaviour of the population amongst the members of the community and with the first responders. The video also allows to observe the advance of the fire throughout the settlement and to document the evolution of it. The first part of the chapter gives an overview of the point of view of firefighters towards fires in informal settlement communities, and how they attend fires of that type. Timestamps were used to represent events in a more organized manner and to facilitate the reader's understanding. At the end of the chapter, a summary of the behaviours observed in the population during the fire is shown and discussed.

Chapter 4: Legislation for informal settlements contrasts how developed (Canada) and developing (Costa Rica) countries include informal housing in their legislations, it also presents the code advancement processes and refers to current politics concerning informal housing. It delves into housing and fire statistics and addresses solutions proposed by different actors. A comparison between the informal settlements of both countries is performed, to find out their differences of similarities. The last section refers to lessons learnt from one country to the other.

Chapter 5: Characterization and fire risk of informal settlements of different scales present a comparison of the physical features of informal settlements of different scales within San Jose, Costa Rica. It contrasts differences and similarities related to the cleanliness, the free space between alleys, the ease of entering the settlement, the number of entrances, and if there were certain communication or emergency plans within the different informal settlements. This chapter also highlights actions that inhabitants do which can increase the risk of fire. Finally, this section discusses the current challenges when modelling informal settlements, and the incapability of using existent software.

Chapter 6: Material testing procedures propose a practical procedure to quickly evaluate new materials proposed for the building or protection of informal settlement houses. It helps to quickly determine if the material needs to be investigated further or if it should be discarded due to non-compliance with current standards. The procedures are focused on pool fire tests and cone calorimeter tests, which allow for testing samples of different scales. In the end, the pool fire is tested together with the chosen fuel to check the temperatures reached and their stability during the test.

Chapter 7: Conclusions and Recommendations provides the major conclusions and recommendations found in the investigation and highlights the novelty of the thesis presented. Future research considerations on the topic of fire safety in informal settlements are proposed.

Chapter 2: Background

2.1. Research around the world

The first step towards a fire safety framework for informal settlements in Costa Rica is to perform a literature review on what research has been done globally towards the improvement of fire safety in these communities. The scope of this literature review consists in delving through previous research done and collecting information that will be valuable for the Costa Rican situation. Furthermore, this literature review provides an overview of the fire risk in informal settlements and the efforts to improve fire safety.

Fire safety in informal settlements can be considered understudied, with the majority of the research efforts in recent years concentrated in South Africa. Most of them are related to fire dynamics and fire behaviour such as the research conducted by Cicione, et al., regarding the determination of ignition time, time-temperature, and time-heat flux in informal settlement fires; which also includes first-step analysis on how leakages or ventilation can affect fires in these type of dwellings (Cicione et al., 2021). Another input of this kind was developed by Walls et al., in which a series of large-scale fire tests were conducted, giving preliminary information on flame spread, fire growth, compartment fires, and times for flashover. These tests were conducted over three different scenarios: a smouldering setup; a timber fuel load test; and a "Representative" fire test (Walls et al., 2017a). Cicione et al., have also conducted research focused on potential causes and hazards associated with informal settlement fires, determination of peak temperatures reached in fires, and critical separation distances between dwellings to avoid fire spread (Cicione et al., 2019). Regarding small-scale test Yu Wang, et al., carried out 345 cone calorimeter tests to build a database with 32 combustible materials usually found in South African informal settlements dwelling (Wang et al., 2020). These are only to mention some of the recent developments from a robust list of research focused mainly on solving fire issues in African countries.

Asian countries have shown to have different approaches, for example, research performed in China, tends to address the political and economic context of informal settlements (Zhang, 2011) (Wang et al., 2009), also called "urban villages", as well as redevelopment policies intended to recover or eliminate informal Chinese communities (Wu et al., 2013). But few research has been done concerning fire safety in informal settlements in China (Wang et al., 2022), Bangladesh (Rahman et al., 2022), India and the Philippines (Westwell, 2011), just to mention some Asian countries.

Although fire safety research is scarce in Asian countries, recently several research has been published in order to contribute to filling this knowledge gap. A recent study in China has focused on looking into the characteristics of informal settlements and a thorough knowledge of historic ethnic minority settlement fires (Wang et al., 2022). In Bangladesh, a study related to measuring an individual's overall degree of fire preparedness in Dhaka was recently performed (Rahman et al., 2022). These recent publications allow suggesting that fire safety awareness in informal communities has been gaining momentum in the research field.

It must be acknowledged that South Africa has been leading fire safety in informal settlements, serving as a guide for countries that have developed less research on this subject. Several of these investigations, include details about the dwelling structures, fuel loads, materials configuration, construction details, recommended separations for dwellings, and so forth (Cicione et al., 2019), allowing to understand their construction techniques and compare them with the ones found in other countries informal communities such as Costa Rican informal settlements for example.

In Latin America, informal settlements have been approached from the regularization side (Fernandes, 2011) (Costa & Hernández, 2010), and their upgrading perspective (Magalhães, 2016). Recent studies have addressed the challenges for sustainable development in these settlements (Bonilla Ortiz-Arrieta & Silva, 2019), and some research has been done on risk and urban resilience in informal settlements (Sandoval & Sarmiento, 2018). Even though, there is scarce research related to fires in informal settlements for the whole region, efforts done by other parties can help to understand and address the matter. For instance, the framework for fire safety in informal settlements published by ARUP, which has the intention to be the first step in the development of tools to assess fire risk in informal settlements and target effective and efficient investments in fire risk reduction (Antonellis et al., 2018). All of these contributions set the foundations of the subject discussed throughout the chapters of this thesis.

2.2. Costa Rican informal settlements and fire research

From the Central American countries, Costa Rica is considered the country with the smallest percentage of urban population living in informal settlements with 4%, in contrast with Belize 16%, Guatemala 38%, Honduras 32%, El Salvador 17%, Nicaragua 67% and Panama 16% (The World Bank, 2020). During the past decades, Costa Rican governments have strived for the reduction of poverty and housing informality. According to The World Bank, the percentage of the urban population living in Costa Rican slums has linearly decreased since 2000 when the country hosted 13% until now with 4% of people living in informal settlements.

Consulting a database generated with ArcGIS using the data gathered by the INEC and MIVAH, the country has an estimated of 192,000 people living in 63,140 dwellings distributed in 418 informal settlements (INEC & MIVAH, 2011). This data, although the most recent, it can be considered out of date. Of these settlements around 112 are located inside San Jose the Capital city of the country (MIVAH, 2013), but these numbers can vary depending on the institution consulted, being similar or completely different, which makes it difficult to precisely quantify them.

Some efforts have been done in the country in order to gain knowledge about informal settlements or create visibility of the issues they face daily, some of them will be mentioned as follow:

- In Costa Rica, fire safety in informal settlements is understudied, from previous discussions with members of the Engineering Unit, it was revealed that there was a serious concern in this regard. Therefore, there was an attempt to create a document addressing fire safety in informal settlements, but it was never published. The author attempted to get the draft of the document, but the attempt was unsuccessful.
- Some actions have been made in order to give visibility and increase population awareness of the fire safety issue within informal communities, for instance, television broadcasts such as *"Precarious: potential bonfires"* (Naranjo, 2019), and documentaries such as *"Informal Settlements: A time bomb for fires?"* (Chacón, 2019), have addressed the fire risks of the people inhabiting informal settlements.

- Research on disaster risk assessment has been performed recently, where the disaster risk of every informal settlement of the Greater Metropolitan Area (GAM) was determined (Quesada Román, 2022). The study concluded that the majority of the disasters in informal settlements are related to hydrometeorological events, provoking subsequent disasters such as landslides and floods as a result of inefficient sewerage and stormwater management.
- From the governmental side, most of the approaches related to informal settlements are from the eradication and sustainable development context (MIVAH, 2022), and the upgrading and regularization perspective (MIVAH, 2018) (Campos Gómez, 2018). In 2020 a new bill proposed the involvement of the communities in the development of urban renewal programs, from their planning to their implementation, creating a participatory model for decision-making and project management (*Ley de Transformación y Titulación de Asentamientos Humanos Informales e Irregulares*, 2020).
- TECHO, an NGO that builds emergency housing in poor communities and develops different projects to overcome poverty in Latin America. TECHO also performs research on vulnerable communities, in their latest study they stated that 90% of the Costa Rican informal settlements, maintain some kind of community organization (TECHO, 2016), which aligns with the ethos of the law proposed.

Even though several efforts have been made by different researchers or institutions, which have also followed different approaches, the information is still scattered, incomplete and non-standardized, which is one of the main limitations when performing research in Costa Rican informal settlements. This information allowed the author to determine that an exploratory approach should be followed, and it was understood since the beginning that the information gathered will be provisional as informal settlements evolve (change) quickly in a short time.

2.3. Relevant definitions

Before digging into this thesis, it is necessary to define some concepts that are crucial to wholly understanding the informal settlement and fire safety subject discussed herein.

Following some definitions will be briefly explained in order to contribute to the reader's comprehension.

2.3.1. Fire Dynamics

Fire Dynamics is the study of how chemistry, fire science, material science and the mechanical engineering disciplines of fluid mechanics and heat transfer interact to influence fire behavior. In summary, Fire Dynamics is the study of how fires start, spread, and develop (NIST, 2021). In turn, Fire, according to the NFPA, is defined as a rapid oxidation process, which is a chemical reaction resulting in the evolution of light and heat in varying intensities (NFPA, 2021). Fires can be measured by Temperature, Heat Release Rate (HRR), Heat Energy and Heat Flux, which are defined as:

Temperature: is a measure of the average kinetic energy of translation of the gas molecules. It is mainly measured using the Celsius scale (freezing point of pure water = 0 °C, boiling point of pure water = 100 °C) and the Fahrenheit scale (freezing point of pure water = 32 °F, boiling point of pure water = 212 °F) (NASA, 2021), although Kelvin scale is also used for calculations.

Heat Release Rate: provides information about the intensity at which the fire releases the heat energy. It is measured in Watts units, commonly in Kilowatts or Megawatts depending on the size of the fire (Tübke & Vogt, 2019).

Heat Energy: is a type of energy characterized by molecular vibration and capable of starting and supporting chemical and state changes. Heat energy is the amount of energy required to change the temperature of an object and it is typically measured in Joules (J) (NIST, 2021).

Heat Flux: it can be defined as the rate of heat energy transferred through a given surface (Wm^2) (ScienceDirect, n.d.).

Another relevant concept when studying fire dynamics is the heat transfer. According to the American Society of Civil Engineers, heat transfer is defined as the exchange of thermal energy due to a temperature difference. There are three forms of heat transfer:

- Convective: heat transfer due to the bulk motion of a fluid to a solid surface,
- Conductive: transfer of heat through a solid body due to a spatial thermal gradient,

- Radiative: transfer of heat through electromagnetic waves.

All of them are measured in kilowatts per square meter (kW/m^2) (ASCE, 2018).

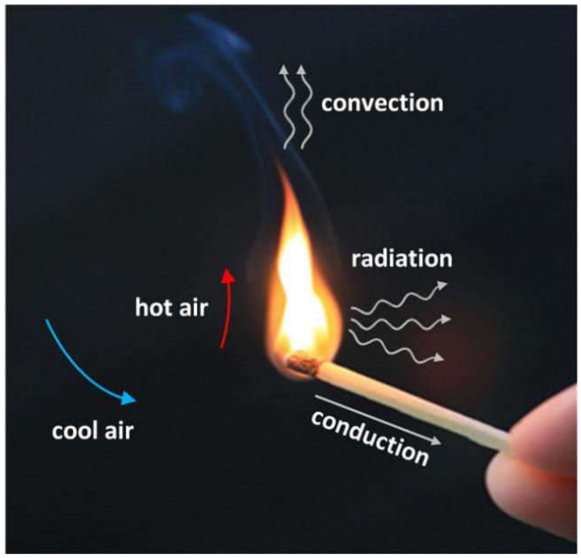


Figure 2.1. *Heat transfer forms* (Zeinali, 2019)

When studying fires in houses or confined places (compartment fires), flashover is a phenomenon commonly mentioned. Flashovers refer to the thermally driven event in which all combustible surfaces exposed to thermal radiation in an enclosed area, or a compartment ignites quickly and simultaneously (U.S. Fire Administration, 2020).

To determine fire dynamics in certain materials, several test procedures can be conducted. They can be roughly divided into outer and inner (laboratory-based) fires. Forrest et al., stated that fire dynamics in large, open, atrium-like spaces are poorly understood and pose many challenges for fire safety practitioners. Real structures suitable for experimental fire research are difficult to procure, and due to burning restrictions outer large-scale tests have been forced to use decaying infrastructures (Chorlton et al., 2021). To improve their understanding of them, Forrest et al., performed a fire test on a barn-style (exposed timber) structure, to examine the fire dynamics of a well-ventilated exposed timber structure (Chorlton & Gales, 2019a). On the other hand, indoor fire tests, know also as laboratory-based tests, are more frequently carried out as they involve the use of smaller-scale samples, and the main requirement is to have a facility and the equipment that allows the tests to perform the material assessment safely.

Figure 2.2. Cone Calorimeter test performed in the University of Waterloo. (Photo by Hannah Carton, with permission)

Laboratory-based tests are well studied, they also have standards that regulate them such as the Eurocode 1, ISO 834, CAN/ULC-S101, and ASTM E119, amongst others. These standards detail how to perform the test methods to measure and detail the response of materials, products, and assemblies to heat and flame under controlled conditions (ASTM International, 2020); the acceptance criterion for materials being tested is also provided. For instance, the ASTM E119 states that the procedures described in the standard apply to assemblies of masonry units and composite assemblies of structural materials for buildings, including loadbearing and other walls and partitions, columns, girders, beams, slabs, and composite slab and beam assemblies for floors and roofs (ASTM International, 2020), but each norm will provide basic information about the use of the procedure.

For Chapter 6: of this thesis, pool fire tests were conducted at York University High Bay laboratory, meanwhile, Cone Calorimeter tests were carried out in the Fire Safety Engineering Laboratory of the University of Waterloo.

2.3.2. Human behaviour

Generally described as the physical, mental, and social capacity to respond when facing internal or external stimuli during the different phases of human life (Lerner et al., 1999). Several theories of human behaviour have been developed throughout history, but these are not fully applicable when studying human behaviour during emergencies, as unexpected behaviours have been found when studying this type of events.

Kobes et al., commented that human characteristics related to individual, social, and situational features affect the fire response performance of a person. To expand on this, individual features relate to the personality traits of the people in a building, their knowledge, experience, powers of observation and judgment, and their mobility. Social features include the interactions amongst the people present, the degree of task commitment, and the roles or responsibilities of those in the building. Finally, the situational features refer to awareness (alertness), physical position (passive or in motion) and familiarity with the layout of a building (Kobes et al., 2010).

Human behaviour in fire combines the knowledge of engineers and psychologists; this multidisciplinary collaboration has become critical for understanding and planning for the uncertainty that exists in real-life scenarios (Mazur et al., 2019). According to Kuligowski, studies from community evacuations during disasters and building fire evacuations have demonstrated that before individuals executed an action, they observed particular cues, assessed the situation and risk based on those cues, and then made a decision about what to do based on their interpretations. Some examples of actions taken during an evacuation can include information seeking, milling (moving around in a confused mass), preparing for evacuation, and informing others (Kuligowski, 2009).

Regularly, it is observed that humans do not always behave as planned, for example, when an alarm activates, it is expected that people begin to egress, but in reality, these expected reaction is often delayed due to several factors, such as assuming a false alarm which leads to believe that they are not in danger, taking time to collect their belongings, finding a family member or friend, and so on (Chorlton & Gales, 2019b).

Incident assessment has shown that in an emergency, people are more likely to collaborate rather than act individually (Sime, 1995). Crowd behaviour is often observed in fire evacuations, previous studies have worked on the difference between physical crowds: where members are in the same place at the same time; and psychological crowds: groups that are aware of having a personal connection to others in the group (Templeton et al., 2018). Aucoin et al., commented on how previous experimental studies have demonstrated that when people identify with a group or have a psychological connection to other group members, they behave differently; they tend to have more coordinated and constructed movements and were incited to stay closer to other members of their group regardless of the overall number of persons in the area (Aucoin et al., 2019).

Figure 2.3. *Crowd behaviour of the numbered groups* (Templeton et al., 2018)

Personal behavioural factors such as the personality of a person in the evacuation can also affect the egress time, for instance, highly motivated individuals move faster, and the more highly motivated they are, the more the crowd around them will follow their lead (Mazur et al., 2019). Other factors that affect human behavior and the egress time during evacuation include, the relative homogeneity of the demographic in space, the affectivity amongst group members, the ages of the members in the social group, if a group member is assumed to have authority or experience with evacuation protocols, among others (Mazur et al., 2019).

The culture of the group studied is another crucial feature to look at when studying human behaviour in fires, as risk perceptions vary depending on the population observed. Under comparable conditions, various cultural groups tend to behave differently. According to a study related to the impact of culture on evacuation response behaviour in a public arena, different cultures have distinct behavioural norms, beliefs, and attitudes concerning physical contact, personal space, the feeling of community, and response to authority (Galea et al., 2015). This is also due to risk perception being influenced by psychological, social, physical, political (regulatory and normative) and cultural factors that are different for each person or group (Tancogne-Dejean & Laclémence, 2016). Unsafe practices are commonly observed in evacuation assessment as well, people's beliefs and assumptions about how fast fire and smoke grow are often incorrect, which means that people often put themselves in danger when there is no need to do so (Kobes et al., 2010).

Figure 2.4. *Human behaviour observed in El Pochote Fire. (Photo by OCO, with permission)*

It is certainly a challenge to describe precisely human behaviour in evacuation scenarios, as empirical data is difficult to gather, time-consuming, expensive, and will always have a certain degree of subjectivity attached, which will depend on the interpretation of the individual reviewing the data (Gales et al., 2022).

2.3.3. Material response

The wide range of technologies and materials available in the market have posed during history the necessity to study their performance within structures. The knowledge of these materials, including their origin, formation, physical and mechanical properties, and decay behaviour, among others, is fundamental for selecting, processing, using, maintaining, and recycling materials. The selection of proper materials for a project is the main factor for feasibility, stability, safety, economy, production, services, maintenance, and aesthetics (Rashad, 2020).

Material testing procedures look for controlled and repeatable tests, allowing the evaluation of the mechanical properties and characteristics of a certain material. These properties include but are not limited to finding out the strength, resistance, durability, strains, and deformations. These assessments also allow for determining weaknesses or inconsistencies in the materials that can result in compromising the structural integrity of a structure. It is crucial as well to understand how materials behave during emergencies such as fires. Fire tests provide information on material behaviour and resilience under fires, they allow the collection of data on how the mechanical properties of a specific material are affected under a certain time and temperature. These tests allow correlating the time and temperature with the decay of the mechanical properties, allowing the establishment of percentages of losses in a given characteristic of a material throughout the time and temperature tested. To this end, cone calorimeter and pool fire tests were chosen as the main test procedures for this thesis.

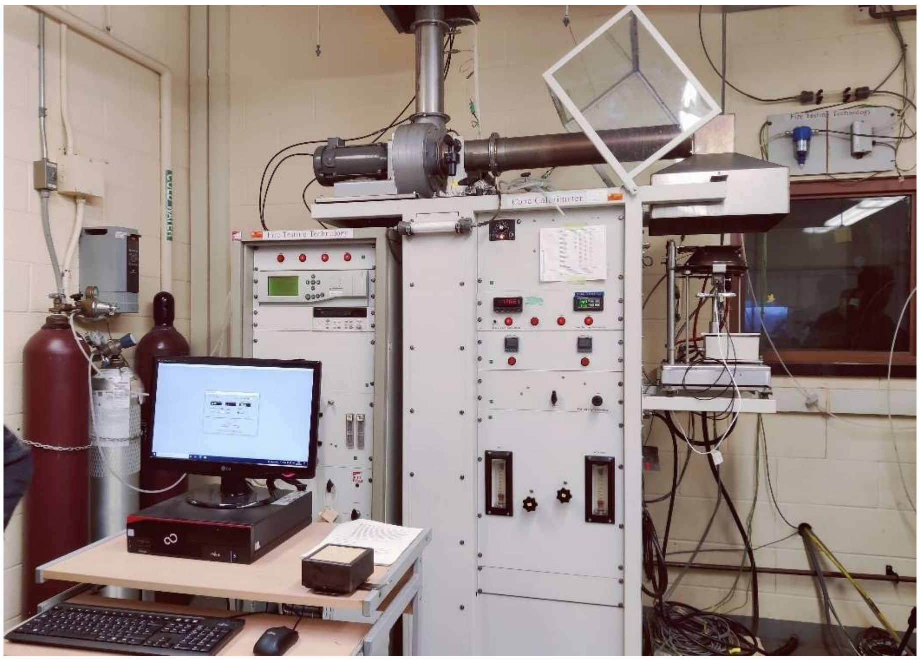


Figure 2.5. *Cone calorimeter at Waterloo University*

The cone calorimeter is an apparatus that uses a coiled radiant heater to expose a test sample to the desired heat flux (Chorlton & Gales, 2020), it can be calibrated to the desired heat flux by the user, ASTM E1354 standard is followed to perform this test (ASTM International, 2022). Cone calorimeter tests provide information on oxygen consumption, mass loss, and heat release rate, among others, it is used to assess the fire hazard and determine the combustibility of a material.

Pool fires, by their side, are meant to subject elements to severe thermal stresses, they allow observing the heat transfer throughout the material and its behaviour under harsh conditions. This test also allows to observe fuel evaporation (combustion process), radiative heat transfer and soot formation. Pool fires also permit testing the applicability of narrow-spectrum illumination technology along with DIC for larger-scale fires. Narrow-spectrum illumination allows for optical measurement methods like digital image correlation (DIC) to be applied during the fire scenario (Nicoletta et al., 2021).

Figure 2.6. *Pool fire with narrow-spectrum illumination. (Photo by Chloe Jeanneret, with permission)*

When looking for fire behaviour on different materials, the aim is to collect relevant and quantifiable information that allows to check if the material fulfills the required fire performance specifications (standards). Depending on the material tested, there are significant observations, such as assessing how wood specimens respond when exposed to a fire, for example, timber begins to pyrolyze and char, and in the case of engineered timber, adhesive degradation also begins to occur (Chorlton et al., 2018). For steel, it has been observed that local behaviour may control the response of steel structures under fire exposure, while for reinforced and prestressed concrete, spalling and moisture loss are some of the main features to observe when testing (ASCE, 2018).

The main aim when testing materials is to determine characteristics such as local and global behaviour in the entire material or element since the goal is to develop in the future an appropriate local and global behaviour acceptance criterion for different materials (ASCE, 2018).

Chapter 3: Human behaviour in Costa Rican informal settlement fires

The Interviews conducted as part of this chapter are reviewed from the author's undergraduate thesis "Analysis of the existing information of La Carpio informal settlement, Roble Norte sector, to create the basis for future research in fire safety." The interviews were approved for ethics compliance per their Instituto Tecnológico de Costa Rica, Escuela de Ingeniería en Construcción procedures by the author program director. This data is only referenced as part of the literature review in this chapter.

3.1. Introduction and Motivation

There is currently a global trend of population growth, and it is expected that the world population will rise by 13% by 2050 (United Nations, 2018). This growth will be unequally distributed geographically, driving a continuous and faster urbanization in low to middle income countries (United Nations, 2018). This can be observed in San Jose, Costa Rica, where the employment opportunities presented to the population in the Great Metropolitan Area are greater than in the countryside. This is leading to the migration of the population from rural to urban areas. However, a lack of affordable housing in cities has resulted in the creation of new informal settlements in and around San Jose and increasing densities of existing informal settlements in the area. UN-Habitat defines 'informal settlements' as "residential areas where inhabitants have:

- No security of tenure vis-à-vis the land or dwellings they inhabit;
- Neighbourhoods usually lack, or are cut off from, basic services and city infrastructure;
- Housing may not comply with current planning and building regulations, and is often situated in geographically and environmentally hazardous areas." (UN-Habitat, 2015)

Considering the extensive degrees of spatial, social, economic, and political marginalization people living in informal settlements often experience, it is critical to acknowledge that 'informal' does not mean illegitimate or temporary. The lack of formality associated with informal housing is generally the result of historic prejudices or conflicts, governance failures, and failures in socioeconomic and political systems. Regardless of the root causes, people living in informal settlements bear the burden, often with increased exposure to hazards and substantial vulnerabilities – potentially leading to additional consequences. Poor people are nearly twice as likely to live in fragile dwellings, and while not all people living in informal settlements are poor, there are positive correlations between poverty and informality (Hallegatte et al., 2017). Spinardi et al. (Spinardi et al., 2017) stated that it is widely believed that the fire problem is greater in the poorer economies of the world, and particularly in informal settlements, and better data collection and statistical analysis would be an important step towards addressing this problem.

Fire risk in informal settlements is a function of complex interactions between the built environment, the natural environment, and people. The high density of dwellings is one factor. The use of combustible construction materials, like timber, plastic, cardboard, and steel sheets, in close proximity is another. Open cooking, issues with lighting and poor electrical connections present ignition sources. Research from South Africa found flashover inside local informal settlement dwellings can happen in less than a minute, and there's little time before it spreads to adjacent dwellings (Walls et al., 2017a). Fires in informal settlements often spread between dwellings and can quickly evolve into large conflagrations, influenced by wind and other environmental factors. Fire services response to informal settlement fires is often hampered by delayed notification, challenges finding the location of the fire, poor access due to a lack of road infrastructure and low hanging electrical wires, limited water infrastructure to support firefighting efforts, and in some cases, social tension with residents, where the fire services response is perceived to be too slow by residents, for example.

Many people living in informal settlements incrementally upgrade and expand their dwellings over time. In Costa Rica, some houses are several stories high, which can increase fire risks when compared to the single-story houses due to factors such as increased ignition risks (linked with population density), higher fuel load densities, and higher likelihood and consequences of structural collapse during a fire. Multi-story dwellings also pose direct risks to life, due to potential delays or complications with evacuation or search and rescue activities. **Figure 3.1** depicts the construction of houses with several stories in La Carpio, an informal settlement in San Jose.

Figure 3.1. *Multi-story houses in La Carpio (source: author's photo. May 7th, 2019).*

According to the census carried out in 2011 by the Costa Rican National Institute of Statistics and Censuses, there are around 418 informal settlements in the country, which house more than 220,000 inhabitants. Costa Rica has a population of 5 million at the time of writing, meaning more than 4 percent of the country's population live in informal settlements. The metropolitan city of San Jose hosts approximately 104 informal settlements, making it the city with the most informal settlements in the country (TECHO, 2014).

According to fire reports from the Engineering Unit of the Costa Rican Fire Corps, the number of fires in Costa Rican informal settlements has been fluctuating over the last five years (Costa Rican Fire Corps, 2019), though information is sparse to the accuracy of this reporting (fires may be underreported or handled internally without reporting). In 2018, the Engineering Unit reported a total of 1126 structural fires, of which 50 fires occurred in informal settlements (Costa Rican Fire Corps, 2019) (Engineering Unit (Costa Rican Fire Corps), 2019a). Within all of the structural fires, it was reported that a total of 30 people perished due to fire-related incidents (Engineering Unit (Costa Rican Fire Corps), 2019a), which is the highest number observed in the previous nine years (Engineering Unit (Costa Rican Fire Corps), 2018).

In 2019, two large-scale fire tragedies occurred in informal settlements in San Jose. The first fire occurred in a leased dwelling located inside the informal settlement called La Carpio on April 13th. Seven people died in this isolated house fire (Engineering Unit (Costa Rican Fire Corps), 2019b). **Figure 3.2** is an image of this dwelling after the fire, which was constructed of masonry and concrete, and bound on all sides. The other fire occurred on September 16th in El Pochote, an informal settlement located in the Barrio Cuba region. This fire spread through forty dwellings and left 219 people homeless (Engineering Unit (Costa Rican Fire Corps), 2019c). Video footage of the development and responses to this fire, as well as post-fire damage, was obtained by the author for analysis through the Costa Rican Fire Corps.

Figure 3.2. *Post-fire in La Carpio, Costa Rica (source: author's photo. May 7th, 2019).*

Over the past 5 years, there has been an emerging field of research into fires in informal settlements. While this is not a new problem or the first research in this area, recent efforts have been at a much larger scale and with stronger dissemination and communications than previous decentralized efforts. Globally, there is growing recognition of the importance of addressing fire challenges in these contexts. For example, Arup developed a framework that proposes a holistic sociotechnical approach to fire safety in informal settlements (Antonellis et al., 2018). Referencing the widely used disaster cycle, the framework aims to establish an accessible common language to promote collaboration among diverse stakeholders. It provides a conceptual framing for fire safety challenges and opportunities in these complex environments and introduces a resilience-based approach to fire safety. The framework specifically addresses cultural differences and beliefs that may present challenges in considering fire safety or evacuation strategies (Antonellis et al., 2018).

Another example is a research project known as IRIS-FIRE, developed by engineers and social scientists, which is looking to improve the resilience of informal settlements to fire(IRIS-Fire, n.d.). Conducted by the University of Edinburgh (United Kingdom) and Stellenbosch University (South Africa), IRIS-FIRE focuses on informal settlements primarily located in the Western Cape province of South Africa (IRIS-Fire, n.d.). At the time of writing, a literature review of the work completed by IRIS-FIRE shows their research efforts were concentrated on two categories: technology/modelling and full-scale experiments for understanding fire dynamics, structural and material response. For example, Gibson et al. (L. L. Gibson et al., 2018) published a paper which outlines a new approach to mapping historic and ongoing fires in informal settlements using Sentinel satellite imagery. Others focused on modelling fires and predicting their spread in informal settlements by using B-RISK technology (Cicione, Collen, et al., 2020) and Fire Dynamics Simulator (Cicione & Walls, 2019). IRIS-FIRE conducted several outdoor full-scale fire tests on representative informal settlement dwellings to analyse compartment fire behaviour and fire spread between dwellings. Informal settlement fires in the Western Cape often spread between dwellings and through communities due to high densities and proximities of dwellings (Koker et al., 2020). Factors such as heat release rates (HRR), heat fluxes, time of ignition, and the effect of fuel load were studied through experimentation. Based on this research, methods have been proposed to limit fire spread and reduce fire risk generally. Recently, these researchers have begun collating videos of real fires in South African settlements and are beginning to consider human behaviour (Flores Quiroz, Walls, Cicione, et al., 2021).

Even though there has been some seminal research, there are still significant gaps in informal settlement fire safety research. Scientific research of human behavioural responses to fires in informal settlements is severely lacking. There is no study, to the author awareness, which links current behavioural theories to informal settlement fire scenarios. This is despite recent advancements in the development of modern behavioural theory frameworks for fire generally.

For example, Kinsey et al. (Kinsey et al., 2019) have studied the role of cognitive biases in behaviour during fires and provided short statements to help practitioners contextualize a person's decision-making process during a fire. Cognitive biases, however, have been associated with inaccurate judgements, as shortcuts used for decision-making can sometimes lead to important information or actions being overlooked (Tversky & Kahneman, 1974). Another theory is the Protective Action Decision Model (PADM) (Lindell & Perry, 2012). PADM is a provisional multistage decision-making model based on the research of people's responses to environmental hazards and disasters – it attempts to describe the pre-decisional and decisional sequence of action making. PADM integrates the processing of information derived from social and environmental cues with the messages transmitted through communication channels (Lindell & Perry, 2012). In previous research, PADM has been adapted to households' response to bushfire threat. For instance, research conducted by Folk et al. (Folk et al., 2019) aimed to create a survey to collect further information about the factors influencing protective action decision making during wildfires. As well, Strahan and Watson's study addresses the question of how PADM can be applied to the analysis of behaviour in Australian bushfires and North American wildfires (Strahan & Watson, 2018). More recently in the context of mass gatherings, social identity and influence theories have also been proposed to help describe decision making within a group (Drury, 2018). That research implies that during a fire or emergency, a collective (shared) approach to decision making can occur, though this is still emerging with more research attention in the context of evacuation or fighting of fires. These frameworks are only a few of the many behavioural frameworks currently being developed and explored by researchers in fire safety.

While these behavioural theories provide insights to the way people process information in emergency scenarios in general, their relevance to the way people behave during fires in informal settlements is not yet known. Applying these theories (and others) in this study could generate inaccurate outcomes since there is insufficient data for validation, resulting in bounding the behaviours observed in frameworks which may not necessarily be appropriate. Empirical evidence from several informal settlement fires in similar contexts is needed to enable observations of common behaviours and to better understand the interactions between people, their environment, and fire. Current knowledge gaps around fire behaviour in informal settlements compounds uncertainties associated with linking human responses to environmental cues for example. While it is premature to apply existing behavioural theories to informal settlement fires, and it is possible entirely new frameworks may need to be developed, studies as herein can contribute behavioural observations from real fire incidents.

Using the obtained video footage of an informal settlement fire, this first stage research attempts to consider four principal goals that begin to address the identified research needs: (1) to collect human behaviour and fire evolution data in an informal settlement, (2) to illustrate some of the key variables that make informal settlements fires difficult to study, (3) to consider the challenges faced when extending observations beyond a specific fire, and (4) to propose a methodology for collection of behavioural data in informal settlements for post fire analysis of other informal settlement fires in the future. By compiling a body of evidence of human and fire behaviour in an informal settlement fire, this study aims to support future research efforts and to enable the eventual development of a fire response framework for informal settlements in Costa Rica.

3.2. Firefighting and emergency response procedures

3.2.1. Methodology

To holistically understand informal settlement fires, it is important to seek the perspectives of key stakeholders, namely residents, firefighters, and others who support communities in times of crises such as during or after a fire. Due to ethical concerns, it was not possible for the author to engage directly with the residents involved in informal settlement fires. Also, when permission was requested to conduct interviews amongst the residents, it was rejected by the author's previous institution (Instituto Tecnológico de Costa Rica, Escuela de Ingeniería en Construcción) due to safety concerns related to the residents and author welfare. Further explanation on this will be done in section 3.3. However, the author was able to engage with firefighters in San Jose, who offered valuable insights about fire responses in informal settlements. To conduct these interviews, ethics clearance was made through the program director of the Escuela de Ingeniería en Construcción (Construction Engineering School) of the Instituto Tecnológico de Costa Rica. For the approval a series of meetings with the Program Director were carried out where the action plan was described and explained. After those meetings the permission was approved.

For this project, the interviews performed by the author in its previous thesis were reviewed. The interviews were performed in two sessions of informal and semi-structured oral interviews in two fire stations in San Jose (four sessions total), with a total of 20 firefighters (Guevara Arce, 2020). These interviews were undertaken over two working days per station, to allow information to be obtained from different firefighters due to shift work. The first interviews were carried out at the Barrio México station, where the interviews were carried out with individual firefighters. The second set of interviews were performed at the Pavas station, where the interviews were performed in groups (as per the station's preference). These two stations were selected due to the relatively large number of informal settlements they are responsible for in the case of fire, with Pavas being the station that handles the most informal settlement fire cases in the country (Guevara Arce, 2020).

The interviews were carried out in Spanish and audio-recorded, after which they were transcribed and translated to English. The questions were formulated to be semi-structured and open-ended. The questions prompted firefighters to share details from their past experiences responding to informal settlement fires, with particular attention on firefighting challenges, similarities/differences between fighting fires in the suburbs in contrast with informal settlements, and their observations and perceptions relating to human behaviour during these fires (Guevara Arce, 2020).

Table 3.1 shows a summary of the themes selected to formulate the questions and their relevance to the study. The following questions were then formulated and posed to the interviewed firefighters. These questions were chosen to inform the author understanding of pre-decisional and decisional behavioural responses of residents as well as the interacting actions of the firefighters:

- What are the main causes that start fires in informal settlements?
- What is the process and duration between fire detection and when the station is informed?
- What is the approximate response time it takes to service a fire in this area?
- Which factors influence the time it takes to put out a fire?
- What difficulties do you face in extinguishing a fire in an informal settlement as opposed to in the suburbs?
- How do you extinguish fires, what equipment, techniques or products are used?
- What preventive measures or recommendations are offered to the population inhabiting informal settlements?
- What would you propose to reduce fires in this type of settlement?
- Could you tell me about your experience with fires in this type of settlement?

Table 3.1

Fire Fighter Survey Themes and Relevance.

Themes	Relevance
Causes of the fires	The main issues that cause fires in informal settlements
Fire detection and warning	Identifying systems that are used for fire detection and warning, and their effectiveness.
Response time	Identifying factors that affect firefighter response time to a fire incident in an informal settlement.
Fire containment and extinguishment	Identifying factors that affect firefighting efforts to contain and extinguish the fire, including comparison of attendance to fires in these regions versus fires in the suburbs.
Strategies and equipment used to fight fires	Identifying tools, techniques and products used for firefighting, considering possible differences in fire behaviour and access compared to fires in the suburbs.
Advice for communities	Determining how the Fire Corps engage with communities for fire prevention, including what type of advice or preventive measures they provide.
Experience in past events	Feedback of past experiences could help to better address the problem.

3.2.2. Results

The questions were formulated under specific themes as described in **Table 3.1**, therefore, the results are discussed herein under the same theme headings.

3.2.2.1. Causes of the fires

While some fires in San Jose informal settlements had unique causes, all of the firefighters interviewed indicated that many fires had causes related to the following:

- Electrical connections in disrepair and short circuits;
- Cooking with open flame (including irregular ground causing stoves to fall);
- Poorly maintained and manipulated gas cylinders;
- Arson;
- Dwellers performing welding tasks near combustible materials (e.g., mattresses);
- Attempted controlled burns of wires (for the collection of metal);
- Self-ignition of dry grass;
- Lit cigarette butts;
- Candles or wood-burning cookers left on without surveillance; and
- Children playing with matches, candles or left alone in their houses.

Firefighters also noted some informal settlement residents store hazardous items like buckets with sodium hypochlorite or pool chlorine. The interviewed firefighters have attended emergencies involving chemical reactions that can cause injuries (e.g., irritation to respiratory tract) or lead to fires.

Firefighters indicated there is a relationship between seasonality (time of year) and the occurrence of certain fire causes. They noted, for example, that most fires are related to non-controlled (self-ignition due to heat or sparked from other sources) grass burns which affect the surrounding structures in the dry season (December to April, low humidity). Similarly, in the rainy season (May to November), the most common cause of fire is short circuits in electrical connections presumably due to higher humidity. However, the frequency of fires in informal settlements and their causes are not recorded in a consistent systematic way, so these insights are based on firefighters' perceptions.

At the time of writing, only fires which meet the following criteria are recorded and investigated in Costa Rica: accidents that involve deaths; fires in hospital, penitentiary, public meeting, state buildings or educative centres; fires that burn more than 100 m^2; fires where the time required to control them surpass 30 min after the dispatch of units; and fires in structures with an insurance policy. Fire investigators try to identify fire origin, cause, and other relevant information. This data is then processed with the Judicial Investigation Corps to verify it. The produced report is not typically shared with the public, unless a request is approved.

3.2.2.2. Fire detection and warning

At the time of writing, the only emergency alert system in use in Costa Rica is phone dialling 9-1-1. This service is managed by Emergencias 9-1-1 Costa Rica and the dispatch of the fire units is managed by the Operational Communications Office (OCO) which belongs to the Costa Rican Fire Corps. When the 9-1-1 service receives a call, they either verify it by calling back the person who reported the incident or consider it to be verified if they receive several calls from different people regarding the same incident. Once verified, the information is transmitted to the OCO, which communicates to the corresponding station via radio to dispatch the units. For informal settlement fires, the only difference in the emergency alert process is the verification of the call. When the call is received, the 9-1-1 service immediately communicates to the OCO and they make the dispatch. The verification process is carried out while the units are on their way. This procedure has been streamlined by firefighters because they acknowledge fire spreads in informal settlements faster than in other areas, such as in the 'formal' residential areas.

No information is available regarding informal settlement residents' awareness or willingness to use the 9-1-1 service. This is a research gap that could be explored in future studies including community engagement.

3.2.2.3. Response time

The firefighters interviewed estimated that five minutes elapses from the time a 9-1-1 call is received until units are dispatched via radio communication. The travel response time for units to reach the incident varies based on factors such as traffic, weather conditions, and the availability of the units. Access to the location of the fire can be a significant issue because the streets in informal settlements are often too narrow to allow fire truck access. Firefighters are therefore required to access the fire incident by foot, resulting with delays in the initial response and challenges with subsequent firefighting efforts.

The El Pochote settlement (described in Section 3.3.3), for example, can only permit the use of fire trucks along the exterior of the settlement. Alleyways that lead to the centre of the community can be as small as approximately 1 m in width (based on video observation). Around 75% of the firefighters interviewed commented that the people living in informal settlements often guide them to the fire through paths which are unknown to the fire brigades, helping them to get to the site.

The firefighters interviewed did not indicate any issues regarding delays in response due to tension with the residents upon arrival. However, they did indicate it is common procedure to involve the police when responding to informal settlement fires, whose responsibilities include crowd control.

3.2.2.4. Fire containment and extinguishment

Firstly, it should be acknowledged that there is a complex relationship between the specific fire scenario, detection and alarm time, fire growth and spread, resident response and fire services' response. In other words, informal settlement fires, and all fires for that matter, are highly situational. This section provides an overview of technical aspects of fire response from the perspectives of firefighters. While it was not possible for the author to engage directly with residents for this study, it is important to recognize their role in fire response, including before and after the firefighters arrive. Residents are the first responders in a fire event and their capacity (or lack of capacity) for communications, evacuation and firefighting will impact everything, from the development of the fire to their decision if/when to contact the fire services, and more.

It is also important to acknowledge how physical and socioeconomic vulnerabilities of informal settlement dwellers may influence behaviour before, during, and after a fire. For example, persons with disabilities, elderly persons, children`, and others who may require assistance to escape may be more likely to evacuate away from the incident than to assist with firefighting.

Recovery from fire can be a long and difficult process, which can be exacerbated in informal settlements where financial insecurity, insecure tenure, and a lack of insurance are common. People may lose all their possessions, their home, and their livelihoods can be impacted. These factors can affect how people behave during fire incidents. In South Africa, for instance, it is common for residents to re-enter their dwellings to retrieve their most valuable belongings and to fight the fire without protective equipment or sufficient water resources (Kahanji et al., 2019). The impact of retrieval of belongings on evacuation is a topic area which has been recognized as needing more research within the Human Behaviour in Fire research community (Kobes et al., 2010) (D'Orazio & Bernardini, 2014) (Bode & Codling, 2019).

The firefighters interviewed highlighted several factors that often make their response to informal settlement fires difficult and affect the time it takes to contain and extinguish fires.

Location. The dwellings in informal settlements are not always located near the streets, and if they are, the streets often do not have adequate dimensions for the fire units to access them. Therefore, attacking a fire entails creating long combinations of hoses. Sometimes the only entrance available to reach the fire are through narrow streets, which often have steep slopes and steps made of soil or wood. Firefighters use a range of technologies including aerial drones to plan access during incidents.

Structure characteristics. The materials and methods of construction, dimensions, and the resulting structural stability can influence fire behaviour. Most of the houses in San Jose informal settlements have been constructed with flammable materials, as shown in **Figure 3.3**, such as wood, cardboard, plastic, or materials that may enable heat transfer like corrugated steel sheets (uncoated).

Figure 3.3. *Typical Dwelling Configuration at La Carpio (Author' photo. May 7th, 2019).*

Other fuel loads within houses and settlements. Residents' belongings both inside and outside of their homes can act as fuel for the fire and contribute to fire behaviour and fire spread. Considering the small compartment size of many informal settlement dwellings, a mattress and basic furniture can be more than enough fuel to cause severe fires, with very short time to flashover, perhaps even less than 1 min. Furthermore, walls are often thermally thin with significant leakage. Fire may spread to adjacent dwellings in just a few minutes. Combustible garbage and vegetation surrounding dwellings can also help to increase the severity of the fire and act as a bridge for fire spread between dwellings. If several dwellings become involved in a fire, fire behaviour sometimes appears to be akin to wildfire behaviour, with a fire line of several dwellings spreading through a settlement (Walls et al., 2017a).

Access to water supply resources. Informal settlements usually lack basic services and city infrastructure, including access to fire hydrants with reliable water supplies. It is common for firefighters to respond to informal settlement fire incidents in locations without nearby fire hydrants, or where available hydrants do not have reliable water supplies. When firefighters have insufficient water, they depend on cistern trucks, which usually take more time to arrive at the fire scene. Multiple cistern trucks may be required for larger fires and delays in additional trucks being dispatched and arriving on scene may hinder firefighting efforts.

Topography and weather conditions. Some informal settlements in Costa Rica are on river edges, mountain slopes, or in places with rugged topography. Thus, some of the properties are on steep slopes and experience high wind speeds, which along with other weather conditions, can intensify fire spread.

Floor plans and lack of structural integrity. There are several differences between fighting a fire in informal settlements and in the suburbs. According to the firefighters interviewed, emergencies in suburbs are easier to manage since those dwellings are normally constructed following the country's construction codes and standards, thus, having stable housing construction and safer communities. The informal settlements are more difficult regions to attend to due to complexities associated with access and the features of the houses built.

The houses located in suburbs are divided by masonry walls, meanwhile, the informal settlement houses are commonly divided by thin corrugated metal sheets, which intensifies the likelihood of fire spread and collapse. However, a benefit of the metal sheet walls is that residents can sometimes deconstruct them during a fire to escape, whereby masonry walls can more easily trap residents attempting to evacuate during a fire. In suburbs, it is easier for the firefighters to rescue people trapped in the property on fire since these houses have more standard floor plans and are therefore easier to navigate compared to informal settlements dwellings. Firefighters interviewed noted they can usually clearly identify the number of people living in dwellings in the suburbs and therefore quickly figure out if search and rescue support is needed (and for how many people). In contrast, overcrowding is common in informal settlements and the number of people living in a dwelling is often unknown to firefighters, so thorough searches are needed. Despite these significant search and rescue challenges, firefighters need to work quickly because the poor structural integrity of dwellings in informal settlements presents a serious collapse hazard to firefighters and residents.

Interactions with residents. In both formal and informal settlements, it is reported by the firefighters that people's behaviour is very group oriented and collaborative in response to fire. Firefighters interviewed said that upon their arrival to a fire in an informal settlement, residents will most likely be attempting to control the fire themselves. They noted that residents usually want to support their firefighting efforts as well. Firefighters generally appreciate their willingness to help, and therefore give them orders so they can support fire response in a coordinated way. For example, residents may form bucket brigades to transport water to the fire and firefighters may direct them. However, the firefighters also commented that even when the action was helpful, these people sometimes risk their own lives and hinder firefighting efforts. Also, residents often take their belongings out of their houses and place them in the alleys or the streets, which further limits the space available to move and respond to the fire.

The firefighters interviewed noted they have observed aggressive behaviour more often in responding to fires in informal settlements compared to fires in the suburbs. These firefighters said they have received insults and threats, been stolen from, forced out of their fire truck upon arrival on site, and in some cases, physically harassed. Of the firefighters interviewed, 25% of them perceived that children partook in stealing equipment when this happened. While the firefighters interviewed did not provide insights to the potential triggers of this behaviour, one firefighter did note that residents sometimes seem frustrated that firefighters do not do what residents ask them to do. The Fire Corps response plans to informal settlement fires now include the support of the police on site due to these concerns.

3.2.2.5. Strategies and equipment used to fight fires

The main resource used to extinguish fires is the application of water, but on some occasions, firefighters use a combination of water and pressurized air to respond to the fire. The pressurized air is mixed with various quantities of water to produce different mist densities. Firefighters interviewed shared that the predetermined vehicular response for informal settlements is two fire trucks (each with a thousand gallons of water) and a paramedic unit. In cases where the fire cannot be controlled, reinforcements are then requested which include the dispatch of cistern trucks with more water if necessary.

Upon arrival, firefighters first observe the fire behaviour to identify which techniques should be used to control the fire. In Costa Rican informal settlement fires, firefighters mostly try to create fire advance control lines, which means they destroy the houses near the fire to make space and eliminate the surrounding fuel (i.e. fire breaks). This is performed to control the growth and spread of the fire. There was no indication from the firefighters to whether community members in Costa Rican informal settlements support this strategy, or not. Note, this technique has been observed in other countries – e.g., it is referred to as ‘flattening’ in

South Africa and as the creation of ‘spontaneous fire breaks’ in Syrian refugee camps in Lebanon (Antonellis et al., 2018).

3.2.2.6. Support to communities

Once the fire is extinguished, firefighters have observed residents helping their neighbours who suffered losses by sharing their belongings and providing comfort.

Immediately after the Costa Rican Fire Corps extinguishes a fire in an informal settlement, they engage with the affected community to share fire safety good practices. The information they share is mainly related to improving electrical connections, however other recommendations are given regarding behaviours and physical changes to their living spaces, such as:

- avoiding storing chemical products or fuels;
- avoiding having dry grass surrounding the walls;
- not leaving candles or open flames stoves unattended;
- improving gas connections;
- when performing welding jobs, informing their neighbours and having a fire extinguisher nearby;
- avoid leaving children alone; and
- implement the usage of flashlights instead of candles.

The firefighters, however, indicated that these recommendations are not usually implemented. They believed this is predominantly because residents do not have the budget to improve their condition.

To promote these preventative measures, the Fire Corps create campaigns, children’s camps, prevention speeches, etc, with the main objective being to encourage prevention and raise awareness within these communities. Electrical companies also provide information, training, and recommendations regarding safety for electrical connections.

Following a fire, several governmental institutions such as the National Commission of Emergencies (CNE), Aqueducts and Sewers (AyA), the Municipal Committee of Emergency (CME), the Ministry of Housing and Human Settlements (MIVAH) and the Mixed Institute for Social Aid (IMAS) join with other non-governmental organizations like Obras del Espíritu Santo (Works of the Holy Spirit) to activate their humanitarian response protocols for affected families, providing them shelter, food, potable water, clothes, personal hygiene supplies, and subsidies, which may include payment of rent in a formal leased apartment for three months.

It should be noted that this information was shared from the point of view of the firefighters and related organizations. As there was no interaction with informal settlement residents in this study, it is unsure if they are aware of these resources, or their ability to access them.

3.3. El Pochote Case-Study

To meet the objectives and aims previously described, the author examined a case study fire that occurred on September 16th, 2019 at 4:19 pm, in the El Pochote informal settlement, located in Barrio Cuba, Hospital district, San Jose Province. The reported cause of the fire was a failure in the electrical system (not identified specifically to the powerlines, connection system nor a dwelling itself). For this fire, seven fire stations dispatched firefighters and equipment in order to achieve fire containment and extinguishment. Six of the stations were from San Jose and the other station was from the Alajuela province. Once the fire was extinguished, the Fire Corps reported a burned area of 2400 m^2, with 40 houses and 219 individuals directly affected, among which there were 70 children (Engineering Unit (Costa Rican Fire Corps), 2019c). **Figure 3.4** show the totality of the informal settlement, the blue lines show the boundaries which encompass an extension of 0.16 km^2 and the red hatch represents the burned area.

Figure 3.4. *El Pochote informal settlement and the representation of the burned region (shown in red)* (INEC, 2020).

Through the Costa Rican Fire Corps, the author obtained 71 min of real time video footage of the fire, as well as five aerial drone videos (10 min each) taken by a journalist from the San Jose Municipality showing the damage post-fire (provided to the author upon request for publication). The author received written permission to use the videos for research purposes from the owners (the Fire Corps and the journalist) and university ethics clearances were then performed where needed and appropriate. The films were blurred to remove possible identification of individuals for publication.

The raw videos were analysed in order to better understand the behavioural actions during this fire by residents and emergency response crews, as well as their interactions. The author attempted to objectively appraise the behaviours of firefighters and inhabitants observed in the videos, while avoiding subjective comments that can mislead the reader's interpretation. Section 3.4 will provide further discussion. The interviews presented above also enabled comparative analysis of firefighter perceptions with observed actions from the videos.

Surveys and interviews with the population inhabiting the informal settlements were not conducted mainly due to ethical and safety concerns relating to a lack of existing relationships and appropriate resources to support the engagement. Furthermore, the author institutions did not grant safety and ethics clearance to enter the settlement, as the fire was perceived to potentially be criminal before the fire investigation was completed (Engineering Unit (Costa Rican Fire Corps), 2019b) and it was not permissible to take an investigative approach post-fire in the site for researcher safety consideration. It is also possible that residents of the El Pochote settlement may not have wanted to contribute information, considering the then ongoing investigation into the fire′s potentially criminal nature. If they did share and it was of a criminal nature, sharing their opinions and information could leave them exposed to retaliation and fear for their welfare. For all the reasons described above, interviews with residents were not carried out. The author recommend engagement with residents should be included in future studies if safety and ethics can be ensured.

To provide context for the behavioural study described in subsequent sections and the discussion to follow, it is first necessary to describe the settlement′s socio-economic background and the fire severity seen in the settlement. Despite the efforts of the author to holistically undertake the study of this community and this fire, it must be recognized that there is only limited information available regarding the background, sociodemographic data, and physical features of this community.

3.3.1. Settlement characterization

The socio-economic and political context of the El Pochote settlement is critical to understand the fire incident studied. Each settlement is unique, and researchers must seek to understand how specific contextual factors, such as regional cultural factors, influence decision making and behaviour (both daily and during a fire incident). The most recently available sociodemographic data of the population inhabiting El Pochote informal settlement was from the last National Census undertaken in 2011 (INEC, 2013). A more contemporary survey is needed to draw demographic-specific conclusions, although the earlier census is still useful in gauging a general understanding of demographics within informal settlements in Costa Rica.

The census indicates that overall, there are approximately 2000 people living in El Pochote, with an average of around 3.8 dwellers per household. Of the whole population, approximately 21% have at least one disability documented (the type of disability is not described in the census). Furthermore, there are an average of 2.5 children per family. The population consists of 8% seniors (65 years or older). Among other socio-demographic indicators, 41% of the population are unemployed, and only 59% of the population have high school education. Half of the population has internet access via a computer, and approximately 75% have cell phones. All dwellings have water and electrical access (which cannot be said for all informal settlements in Costa-Rica), however only half are documented to have sewage access.

The census (INEC, 2013) also provides information to the condition of the dwelling structures: 20% of the homes are considered to be in a state of disrepair; 42% are considered to be in regular state; and 38% are considered to be in good condition. The condition statements are subjective though as the census does not provide information to what qualifies each condition state. Due to the inconsistent nature of the structures, the ventilation conditions, construction materials and building geometries of each unit are highly variable, resulting in varying fire loads and leading to significant difficulty in estimating the potential fire dynamics. Of the dwellings themselves, 35% are rented, 7% are borrowed, and the remainder are owned by the residents (INEC, 2013). The census does not give indication if ownership of the dwelling implies land tenure as well.

There is no specific information regarding on the possessions present within each dwelling, which could provide a better understanding of a typical fire load in a settlement. However, it was observed in the video footage described later that an abundance of furniture and technology (TV and computers) exists within the settlement.

3.3.2. Fire characterization

The fire within the El Pochote settlement started due to a short circuit within the south-western corner of the burned area. The author hypothesize that this fire could have been more severe without the previous day's rainy weather which pre-wetted the exterior of the buildings and reduced the likelihood of ember-induced fire spread. The wind also directed the fire towards a main transportation road (potentially serving as a fire break). On the day of the fire, the wind was blowing with a maximum speed of 12 km/h in the southwest direction, carrying the fire to the front road and the entrance of the settlement. Wind speed and direction can influence the spread of the fire, via transport of flaming (pre-heated) materials (embers from combustible materials) and by the fire plume orientation itself. If the wind had blown in the north direction, it likely would have spread the fire in that direction due to the number of houses with overlapping proximity to each other (exact measurements are not available).

To describe the size and severity of the fire from different angles, drone footage was referenced. These pictures and videos show the fire damage footprint, and some of the activities performed post-fire by the inhabitants of the settlement. One of these videos provides a view from above, with the drone beginning near the ground and increasing in height until the full fire footprint can be observed. **Figure 3.5** shows the damaged footprint in detail.

Figure 3.5. *Post-fire footprint with a burned area of 2400 m^2. (Drone footage photo by Jason Fernández, September 17th, 2019, with permission)*

Examining these videos enabled the author to analyse the materials left after the fire, including construction materials, and the general condition of the settlement. The videos show the following building materials which are typical to informal settlements in San Jose: masonry, rusted metal sheets, wood, steel tubes and steel hangers. Alleyways and pathways in the settlements are mud with protruding stones.

3.3.3. Methodology

The Costa Rican Fire Corps captured cell-phone camera footage (71:40 min) during the fire, recorded by a member of the Strategic Communication Office. It showed the arrival to the site of the fire units and continued until the situation was considered to be controlled by firefighters. The video shows both firefighters′ actions, settlement dwellers′ actions, and the interaction among them.

To contextualize the video that was analysed, **Figure 3.6** illustrates the informal settlement in this study. It illustrates the road names that have been established by the author for descriptive purposes. **Figure 3.6** also locates an area described by the firefighters as 'Sector 3', which is composed of a roofed alley created by surrounding houses. The video is in Spanish and required translation by the author post-filming.

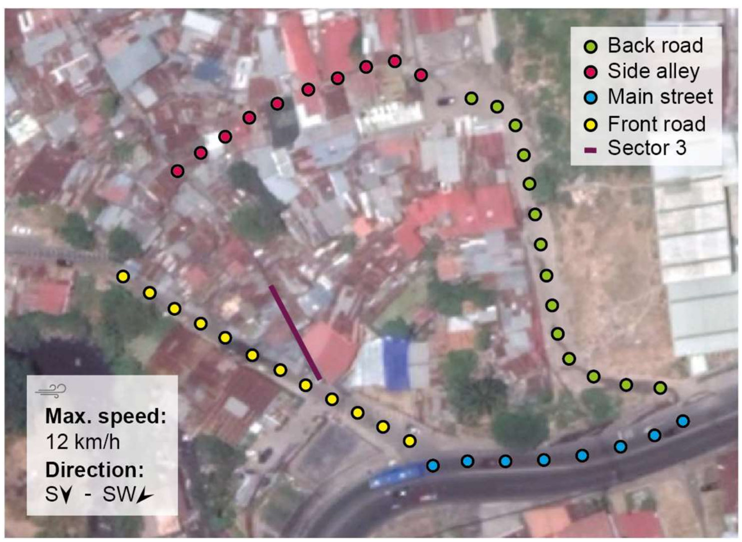


Figure 3.6. *Wind speed and author given names of the roads of the El Pochote informal settlement fire* (Weather Underground, 2019).

In the video, the cameraperson moves into several points of the settlement at different timestamps, allowing the author to observe and describe the magnitude of the fire at determined moments and places. It should be highlighted that the start of the video occurs when firefighters are on route to the scene and does not coincide with the time of ignition of the fire. It was not possible to incorporate any insights to the fire′s timeline before the arrival of the firefighters.

3.3.4. Results - fire behaviour

A brief description of the development of the fire will be made using images within this section followed by descriptions of behavioural and management observations in Section 3.3.5. Fire development is critical context that can influence behavioural actions of residents and firefighters. Screenshots are provided herein to help the reader understand fire development, but many of the observations described are not clear in only screenshots so description of the video footage is provided to allow much deeper insights.

Figure 3.7 to **Figure 3.13** shows the path followed by the cameraperson. The filming path was divided equally into spans of ten minutes, resulting in seven respective sets of images (I-VII). For example, Image I shows the first ten minutes whilst VII shows the last ten. Furthermore, the numbered dots on the associated maps show the locations were the camera stood at sequential key events.

3.3.4.1. Path I

illustrated in **Figure 3.7**, begins when fire units are just arriving to the settlement and starting to develop the strategy to contain and extinguish the fire. At point 1 (02:44 min), dense grey smoke and flames on the roofs can be observed. At point 2 (05:11 min), in the background of the video, flames appear at the height of the ceiling. At point 3 (06:48 min), flames engulf at least six dwellings. Later, at point 4 (08:34 min), there is a wider view of the event where the smoke plume is completely vertical, indicating in that moment the wind is not blowing strongly in a specific direction.

Figure 3.7. Screenshots of key events in Path I.

3.3.4.2. Path II

shows the path along of the front road of the informal settlement. **Figure 3.8** below illustrates the points described. At point 1 (10:50 min), electrical flashes can be seen through the smoke, and sounds resembling short-circuits are heard. At point 2 (12:33 min), flames can be seen over several roofs behind the smoke. Beside the smoke cloud on the left, a thin black plume begins to surge in the southeast direction. At point 3 (13:38 min), grey smoke in the sky can be observed. At point 4 (16:44 min), the vegetation on the houses catches on fire and the flames surpass the roof level. The first houses that were on fire (point 3, path I, **Figure 3.7**) are now collapsed. At point 5 (18:43 min), it can be observed that the fire is spreading quickly since approximately 8 houses are on fire (more houses than in **Figure 3.7** path I point 3 which is the same location). Finally, at point 6 (19:58 min), the houses which recently caught fire had flames over the roof and the fire is spreading.

__Figure 3.8.__ Screenshots of key events in Path II.

3.3.4.3. Path III

shows the main street and the front road of the informal settlement. **Figure 3.9** below illustrates the points described. At point 1 (21:20 min), the smoke plume was dense and dark grey, and it was moving towards the south. Some suppression activities illustrate spraying of water along the ceiling. The hose stream penetrates the (weak) ceiling and the cameraman gets wet. At point 2 (25:38 min), grey smoke can be seen, and the fire appears to be decreasing in intensity. At point 3 (26:12 min), around 60% of the houses observed to be burning are now extinguished. At point 4 (27:33 min), the cloud of smoke looks scattered but dark. At point 5 (28:19 min), a wider view of the event can be seen. The smoke in the sky is light grey and scattered. Later at point 6 (29:56 min), another plume of a dark grey colour is accompanied by flames appearing in the right corner of the screen. At that moment, the fire is at the entrance of the front road of the informal settlement.

Figure 3.9. Screenshots of key events in Path III.

3.3.4.4. Path IV

At point 1 (30:57 min), very light grey smoke can be faintly seen. At point 2.a (31:30 min), flames and a dark, dense smoke column can be observed at the right side of the screen. Also, a less dense and grey cloud of smoke can be observed at the left side of the screen. At point 3 (35:55 min), most of the fire is extinguished and only 20% of the remaining area is on fire when compared to point 1, path III, **Figure 3.9**. At point 4 (36:36 min), the fire seems to be under control compared to earlier (point 6, path II, **Figure 3.8**), but the houses on the left side of the fire are now on fire (left side of point 4). The smoke appears disperse and light grey. The cameraperson returns to point 2.b (38:27 min), where the fire at this location is now controlled when compared with the first description of point 2.a at the same location. **Figure 3.10** below illustrates the points described in this subsection.

Figure 3.10. Screenshots of key events in Path IV.

3.3.4.5. Path V

covers the main street, the back road, and the side alley of the informal settlement. **Figure 3.11** below illustrates the points described. At point 1 (40:38 min), grey smoke is observed. On closer inspection, at point 2 (41:20 min), flames can be seen at the smoke′s source. The hidden alley seen in the background is the region given the name of ‘Sector 3’ by the firefighters. Then at point 3 (45:35 min), firefighters and residents are standing, and light grey smoke can be seen. At point 4 (47:25 min), the alternative alley to reach the fire from the back road can be seen. It has stone steps and walking is uneven and difficult. At point 5 (47:59 min), light grey smoke in the alley is at head height.

Figure 3.11. Screenshots of key events in Path V.

3.3.4.6. Path VI

follows a path back to the start. At point 1 (53:57 min), grey and scattered smoke can be seen on the screen. Then at point 2 (55:53 min), the fire is almost extinguished after the last observed reignition of the fire (point 2, path V, **Figure 3.11**), but smoke is still observed. Later at point 3 (56:55 min), the fire is almost extinguished in comparison to how it was (point 4, path IV, **Figure 3.10**) with an estimated 10% of the fire remaining. At point 4.a (57:10 min), the fire is almost extinguished with just an estimated 25% left at this location, and several houses appeared to have collapsed. The house on the left is completely involved in fire. At the same location, point 4.b (58:11 min), the alley is fully covered with white smoke, which is moving up the street. **Figure 3.12** below illustrates the points described above.

Figure 3.12. Screenshots of key events in Path VI.

3.3.4.7. Path VII

The cameraperson is back to the location he started. **Figure 3.13** below illustrates the points described. At point 1 (62:27 min), the fire is already extinguished but smoke is still observed. At point 2 (68:05 min), there is light grey smoke that looks sparse in the sky. Finally, at point 3 (70:13 min), the cameraperson declares the fire as being under control and then finishes the transmission.

Figure 3.13. Screenshots of key events in Path VII.

3.3.5. Results - behavioural response and management actions

The available video footage enables for a timeline to be developed and for the analysis of the behavioural and fire response actions performed by the inhabitants of the community, firefighters and even police officers. In this section, a brief description of this timeline with observed behaviours are provided. Analysis of the behavioural instances will be discussed in Section 3.4. It should be noted that the behaviour of the inhabitants could change in relation with the magnitude and severity of the fire, meaning that a different fire would show different human behaviour. Therefore, the data shared in this chapter is only representative of this particular fire and of the human behaviour of a particular group of people at a specific moment of time. In a similar manner to the previous section, the description of the actions will be presented into spans of ten minutes to correspond to timings illustrated in Section 3.3.4.

Minute 00:00 to 10:00. At the beginning of the video, when the fire units are on their way, a man is giving directions to the fire units from the middle of the street. When the units arrive at the site, a group of approximately 45 people are gathered at the entrance of the settlement. They predominately are comprised of women, children, and animals (dogs). Then, more firefighters arrive, including the chairman of the Fire Corps. As the fire is developing, men begin to help the firefighters, mainly extending the hoses (**Figure 3.15**.a). A man approaches the chairman and tells him "*You need to attack from the other side of the site, you just need to move 25 m.*" The firefighter decides to go and check. Near the middle of the front road, there is a hallway, identified as 'Sector 3', which leads into the middle of the burning area. This hallway is covered with smoke and flames. A woman can be observed watching this hallway and talking on the telephone. After a while, she decides to enter (Point 2, Path I, **Figure 3.7**). She remains in the area despite the impending danger from the fire and smoke surrounding her. Later, near the end of the front road, around six local men are helping firefighters. One uses his shirt as face protection from the smoke, leaving his upper body unprotected. At the same time, several men are lowering a blanket with their possessions inside from the second story of a dwelling to the ground (**Figure 3.15**.b). A fire is in the adjacent dwelling. Possessions are stored in an annex just adjacent to the front entranceway. Several women stand near these possessions and are communicating on cell phones.

Minute 10:01 to 20:00. Many fire units and firefighters are in the region, and local men continue to assist them with hose allocation – including young boys who attempt to help after seeing older men try. It should be noted that the people helping are all male (predominately appearing between the ages of 20 and 35 years old). At this point, the police arrive on site and begin to direct civilians out of the fire affected region. Residents start to retreat beyond a plastic caution tape defining a perimeter that the police are setting up. This perimeter had the intention of clearing the region, allowing the firefighters to move and work freely. At one point in the video, a policeman says, "*Let's park the motorcycles near the firefighters' trucks, we need to prevent vandalism*." This indicates that they are there to keep the population in control and the fire units safe. A line of police motorcycles is seen later in the video footage. During this time interval, the police officers (20 of them) begin forming a perimeter line that is continually relocated away from the fire affected region. The perimeter slowly moves the residents who had already evacuated away from the settlement to a point where they would not be able to see into the settlement (see **Figure 3.15**.c). The police officers appear not to let people return, and when they see a resident near the firefighters, they begin to guide them to the perimeter line.

Minute 20:01 to 30:00. This time span (and the next) is mostly related to the management done by the Fire Corps and the police. Firefighters can be seen working on the fire with administrative firefighters (members of the Costa Rican Fire Corps who do not fight fires but oversee office paperwork) supporting them by bringing hoses or oxygen tanks. At one point, the chairman of the Fire Corps approaches the middle of the front road, in the hallway previously identified as ‘Sector 3’. He begins to assess the sector and decides to work inside this hallway; firefighters can then be seen going back and forth to ‘Sector 3’. Meanwhile, outside the settlement, police officers are closing the main street and setting up another perimeter further back.

Minute 30:01 to 40:00. At the beginning of this time span, a firefighter can be seen running towards the entrance to receive orders from another firefighter. This one is asking for reinforcements and says into the radio: "*Send me all the water you can*." At the entrance, some firefighters that had been working since the beginning of the emergency are taking off their equipment to rest.

Minute 40:01 to 50:00. In this lapse of the video, the cameraperson moves to the side alley. When he is walking towards the side alley, he says that "*Due the lack of hydrants, at the beginning of the fire, the water supply was given by several enterprises near the area, then the source of water was received by the cistern trucks*." When he arrives at this region, some men can be seen together taking care of their belongings, including furniture and clothing, on one side of the alley. Afterwards, policemen that were near the site begin trying to evacuate the dwellers but are ignored. Moving deeper into the alley, a group of men (approximately 30) can be observed moving back and forth to the fire affected region carrying buckets (**Figure 3.15**.d). Following this, a man yells "*we need more hoses*" and begins to run. Behind him, there are two men following him to help. Deeper in the alley, a man is climbing a roof and starts to run over the rooftops (**Figure 3.15**.e). The people at the border of the alley are looking around, and they tell the guy on the roof that he should watch out for the electrical wires near his head. Later, a firefighter moves into the area with more hoses, so the men in the surroundings begin to pull, extend, and connect the hoses. Then, more men who were watching approach to help, but the firefighter shouts "*People! Order!*"

Minute 50:01 to 1:00:00. It is observed that getting out of the settlement is difficult. The configuration of the alleys looks like a labyrinth and the cameraperson comments to this effect and is lost. He receives help from the residents and some policemen until finally he returns to where he was before entering the side alley. When he goes out, another perimeter has been raised at this entrance by the police, and some officers are guarding the region and the belongings that the residents left there. One of the men that was previously helping with the bucket brigade is arguing with an officer who is preventing him from (re) entering. He says that the firefighters sent him to perform a task and now he is trying to deliver the message. It appears urgent and he thinks the message is essential, but the police do not let him through.

Minute 1:00:01 to 1:11:40. Finally, the fire is mostly controlled, but the firefighters are performing secondary investigations to identify remaining hot spots and to collect further information on the fire spread. One administrative firefighter is reviewing the area with a drone (**Figure 3.14**). At this point, some firefighters are getting out of the fire affected region, and the cameraperson says that everything seems under control and the transmission ends.

Figure 3.14. *Aerial drone use.*

Table 3.2 illustrates sample behavioural actions as observed to be taken by the residents which are seen throughout the video footage. Caution should be taken when consulting the table below, as the identification of types of behaviour can be subjected to bias and subjectivity. To remove subjectivity, multiple research team members reviewed these events separately, then the observations were compared. Similar observations were noted. It is acknowledged that this approach has limitations, as further discussed in Section 3.5. It should be noted that these are in no way a comprehensive listing of all behavioural actions occurring or all actions seen on film. For example, many cognitive biases associated with decisional stage actions would require surveying residents to gain insights to their decision-making process. As the film is only from one perspective, quantitative counts of each action are not listed. Instead, a listing of behaviours as observed to correspond to the various stages of the film seen is provided.

Table 3.2

Sample Resident Behaviours.

Sequence time in videos	Resident Behaviours Observed
I (0-10 minutes)	People taking their possessions out of dwellings (these include tables, fridges, stoves, TVs, food bags, plastic containers) trying to save them from the fire (examples seen include the carrying of a full couch by one individual). Family roles are apparent as it is observed that men attempt to fight the fire, children attempt to help men, and women tend to stay with the furniture which often included having a dog present. Women were also using cellphones. (Figure 3.15.a) Two men trying to lower down possessions from dwelling wrapped in a sheet. (Figure 3.15.b) Re-entry into the fire affected region to collect items. This is stopped by assembled police force. (Figure 3.15.c)
I, II (0-20 minutes)	Man telling the firefighter where he needs to work, firefighter follows. People giving advice to the firefighters. Man giving instructions to companions acting as if he knows how to extinguish fire. Residents following the orders of the firefighters and police officers. This involves staying behind a perimeter that was established by the police.
II, III (10-30 minutes)	Children see men helping firefighters with hoses, they try to help as well. Inhabitants start to remove their belongings after they have seen their neighbours do so (identified through proximity by the author). They do this even when there is no direct threat of fire to their dwelling.
IV (30 to 40 minutes)	Group of men and young boys begin to help firefighters with water-buckets (forming a water bucket brigade) after first resident (a man) begins – residents appeared to copy his behaviour though it is unclear to the order of actions that may have occurred off camera. Buckets range in size – small buckets which are practical for firefighting up to drums which are too large to practically move and use for firefighting. (Figure 3.15.d) Men and young boys helping the firefighters without any personal protective equipment, some of them cover their faces with their shirt which leaves their bodies uncovered.
V, VI, VII (40 to 70 minutes)	People moving back and forth in hallways or houses without apparent stress. Man climbing a roof, exposing himself to potential danger from fire or electrical wires. (Figure 3.15.e) Children playing in playground with women. People looking around, watching the fire behaviour and how it is developing.

The following image depicts the behaviours described in the paragraphs and the table presented above.

Figure 3.15. Behaviours observed from the video footage.

3.4. Discussion

While some resident behaviours observed appear to be consistent with existing behavioural framework and behavioural theories, the author have not classified these behavioural actions directly under contemporary behavioural frameworks due to a lack of appropriate evidence from this fire and from other informal settlement fires. Some behavioural frameworks like PADM use methods based on the processing of information from social and environmental cues in the early stages of emergency detection. Others, such as heuristics, the transactional stress model, and security motivation system are also mostly applicable to pre-decisional stages (Kinateder et al., 2014). In the present case study, the video footage does not include imagery from the beginning of the fire, thus, there is little evidence that allows the author to classify the actions performed by the inhabitants using frameworks reliant on pre-decisional behaviour. To validate a provisional PADM theory in the context of informal settlement fires, for example, more diverse case studies would need to be analysed, which rely on both video footage and engagement with residents, to better grasp the full pre-decisional and decisional processes over a range of fire scenarios. As such, using the data from the present case study, a particular theory or framework could not be validated. The data, however, is useful to build upon and should be considered in future research. As for other theories, such as the Theory of Planned Behaviour (TPB) that has been applied to building fire evacuation, the author found that they do not apply to unplanned behaviours like the ones observed in the video footage of the case-study. Finally, the hazard to action chain model theorem is not considered applicable for the case-study (at least not yet), since it has not been determined if this model is suitable to fire emergencies (Kinateder et al., 2014).

Notwithstanding behavioural theories that cannot be linked to El Pochote case-study, there are several behaviours observed in the video footage that are similar to behaviours seen in other fire incidents. As Thompson et al. (Thompson et al., 2018) note in their review of dwelling fires, where evidence of people attempting to tackle fires, movement through smoke, re-entry behaviour, and clear differences between males and females in behaviour and frequency of certain behaviours (males were more likely to exhibit firefighting behaviours whereas females were more likely to alert others and exit the property) has been observed.

More precisely, **Table 3.2** in the previous section illustrates a number of unique behaviours as observed relative to the stage of the video. Internalization or the need to collect an individual′s possessions or objects seems predominate in the early stages of the video (sequence I). It is not clear whether these actions depend on the pre-decisional mindset of the resident, are influenced by the fire itself, or depend on the knowledge that the police officers will eventually stop their access to the site. At this initial stage in the video footage, a gendered response is noted, which appears to follow roles somewhat independent of age of the resident (men are fighting the fire, where women are guarding possessions and children). This observation is then followed by a clear indication of a positive normative social influence regarding residents′ firefighting efforts (II, III, IV). Actions such as removing belongings altogether, and the formation of bucket brigades are more specific positive examples of a normative social influence shared amongst the residents. The remaining footage demonstrates multiple instances of information processing and the milling of groups of people regarding the situation (V-VII). These are only a sample of the behavioural actions exhibited in what appears to be the decision-making stage of the fire event. The behaviours do exhibit a sequential operation of protecting possessions after the defense of their and their neighbour′s structures. It would appear that the authorities′ crowd control influenced the role the residents played.

It should be noted that the behavioural responses of the population observed in this chapter are only specific to the fire event on September 16th and to the degree to which it was recorded on film. Most behavioural actions by residents were in response to the events occurring at that instant, as observed within portions of the footage. Other portions of the footage showed operational measures being taken by the firefighters. For example, there is limited footage of evacuations taking place from the settlement itself. Most of the footage shows re-positioning of belongings to controlled areas by the firefighters and localized resident evacuation from dwellings. The observed evacuation appeared to be carried out by approximately 20 police officers on site, who managed a controlled perimeter, which was re-positioned approximately every 5 min to move residents approximately 10 m further away from the area affected by the fire. Most of the evacuation process began prior to the cameraman arriving but continued during filming.

When it comes to evacuation dynamics, it was observed that upon arrival of the cameraman, approximately 45 people were at the entrance way. These were predominately women and children, as well as people with visible disabilities (wheelchair users for example) and various animals (dogs). The entrance way to the settlement was also used to store possessions. A more severe fire may have provoked different resident responses as well as management of the fire, however, speculation about such differences is beyond the scope of this chapter, as all the informal settlement fires are unique. Consequently, this can affect the response of the population and the way the firefighters manage the situation. Furthermore, it is not possible to generalize the observations made in this case study to other informal settlements without more case studies to compare to.

The author also observed similarities of behaviours to those reported in other literature sources on informal settlement fires. For example, Cicione et al. (Cicione et al., 2019) performed interviews with firefighters in the Western Cape, South Africa, and hypothesized that informal settlement dwellers are often afraid to share how a fire started if it was related to arson or to negligence on their part, because they fear retaliation from other residents, e.g., someone might set their dwelling on fire (Cicione et al., 2019). Also, Kahanji et al. (Kahanji et al., 2019) stated that if an individual knows that they were linked to the start of a fire, they may be unwilling to admit such details, even if accidental, due to fear of reprisal from neighbours who have lost their homes. Similar behaviours can be attributed to the residents of El Pochote regarding information contributions about the fire ignition causes, according to interviewed firefighters.

Other similarities with the case study were found in the research about the 2017 Imizamo Yethu (IY) South Africa fire, described by Kahanji et al. (Kahanji et al., 2019). In this paper, the observations identified the tendency of the inhabitants of the IY settlement to store amounts of hazardous items, such as bottles of kerosene in their homes, and the involvement of the local residents in both trying to save their possessions and trying to evacuate the area, making the access and escape highly restricted. In both fires (IY and the El Pochote case study), the firefighters reported a number of verbal and physical abuses by the local residents during the incident. In the IY fire however, a resident cut a hose being used by firefighters and redirected the water onto their own dwelling (Kahanji et al., 2019). This was not observed in the inhabitants of El Pochote during the fire. It is known that during these conflagrations, an effort to have a police escort was made in both fires. Comparing the answers received by the firefighters interviewed in this study and the commentaries stated in Kahanji et al.′s research paper, it was noted that both fire brigades have experienced theft when attending fires in informal settlements.

Other behaviours, however, were observed both by the firefighters as well as in the video footage. This allowed for the validation of the information reviewed through the interviews since most of the behaviours observed aligned with the perceptions of the fire brigades. For example, as stated by the firefighters, residents took out their belongings outside their houses and located them over the alleys and they were also moving around the fire zone impeding the free movement of the firefighters, leading to the lifting of the perimeter by the authorities. Nonetheless, from the constructive perspective, the community rapidly formed a bucket brigade with the main intention of helping the firefighters to tackle the fire. During the video, the firefighters began to work with them as a team, since both shared the same goal. Finally, it was observed that several inhabitants were trying to get information risking their life, as the woman going back and forth into an alley on fire, or the men walking over the roofs or trying to help to extinguish the fire without any protective equipment that was available to the firefighters.

The methodology used within this chapter is provided for other researchers to follow when collecting information regarding human behaviour in fire events in Costa Rican informal settlements and elsewhere. For the documentation of future case studies, it is proposed that following the steps used herein will assist others for comparing with the author datasets:

1. Stakeholder engagement should be made with both firefighters and the local community. While in the case of this study, it was not possible to engage the residents for confirmation of certain behavioural actions, there was supplemental data generated by the fire brigade, and valuable footage of the fire incident was studied. In the event of video footage to be analysed, subjectivity must be reduced through screening by multiple researchers. Video footage including as much of the settlement as possible and from multiple vantage points may capture more behaviours.
2. Contextual data on demographics and socioeconomic status of the community, from a census for example, is critical to inform analysis of human behaviour.
3. A description of the conditions and informal settlement features should be gathered, such as access, configuration, street widths, alleys, and building make and condition.
4. The fire dynamics observed in the fire event should be described and if possible be explained, including the possible influence of environmental conditions.
5. The timeline of the event and the response by the fire brigades and other intervenors should be depicted, as well as analysis of the human behaviour of the residents.
6. Post-event surveying with community stakeholders to explore behavioural actions observed.

3.5. Limitations and future work

The limitations faced during the research process were mainly related to the absence of information available to the author. There is an extensive gap of knowledge regarding human behaviour in fires in informal settlements, which includes:

- Lack of research and understanding of the subject. There is very limited literature related to human behaviour during fires in informal settlements, and insufficient evidence and insights to observed behaviours and key factors influencing human behaviour during fire emergencies;
- Lack of appropriate behavioural theories and frameworks applicable to this context. The relevance of existing theories cannot yet be evaluated due to limited evidence available on informal settlement fires, and limited research attempts to carry out this type of work; and
- Absence of statistical fire incidence data, and data on sociodemographic and economic factors of informal settlement communities. In Costa Rica, these databases are not updated by any institution, and (to the author knowledge) no one gathers the background or physical features of this settlement.

It is therefore not possible to apply definitive contemporary behavioural frameworks and theories to this case study at this time. Future research should consider testing a range of behavioural models from those illustrated earlier (and others), identifying where and in what sense they may be applicable. If they are not applicable, future research may propose a behavioural model unique to informal settlement fires that can begin to incorporate the range of behaviours seen in multiple communities. It is also considered by the author that it would be a good practice to analyse some frameworks previously developed, as frameworks related to the application of forensic fire investigation principles to informal settlements (Flores et al., 2020) among others can be useful for the creation of a framework suitable for the specific region. By developing such a framework, it would then be possible to create a fire response plan that stakeholders could utilise to mitigate and prevent life loss, injury, and excessive damage. Insights from behavioural response could inform investments in fire risk reduction – mitigation, preparedness, and recovery, as well as response.

Another limitation was regarding the viewpoint of the community members since this study did not include the survey of the inhabitants of El Pochote informal settlement. This should be considered in future studies but may be prohibited due to the complex socio-governance of the communities themselves as well as stringent ethical considerations.

A limited overview of fire behaviour has been supplied to provide context of the behavioural response. There is a lack of research and understanding of enclosure fire dynamics in informal dwellings, which are highly heterogeneous, and with fire behaviour of informal settlement fires in general. In this study, it was observed that informal dwellings did not maintain integrity from the firefighters′ hose streams during the suppression phase. Some of the dwellings filmed exhibited post flashover characteristics with abundant ventilation from gaps in construction driving the fires (see **Figure 3.16**). These dwellings often do not have formal planning (from the structural and fire safety perspective), excessive ventilation and use poor materials and construction techniques, which make them difficult to study.

Figure 3.16. *Dwelling fire in distance, showing ventilation gaps and post-flashover behaviour.*

Another limitation was regarding the subjectivity attached to the identification of the behaviours. The author analysed this video individually, permitting each member to determine the actions that they observed, then the actions were discussed and matching behaviours between analyses were selected. While the author was being objective, there was no strict methodology related to information gathering and reliability analysis from video footage, as used by Kopenhaver-Haidet et al. which used computation reliability coefficients to measure the internal consistency when rated by different individuals (Kopenhaver-Haidet et al., 2009). The information gathered herein provides a descriptive qualitative account of the events within this context.

It is important to reiterate that the observations seen herein may not be generally applicable to all informal settlements in Costa Rica or internationally. Every informal settlement is unique, as is every fire. Various socio-economic differences regionally make comparisons particularly difficult in Costa Rica, as well as varying fire brigade response practices which are highly dependent on community relations. It is encouraged that future researchers should carry out more investigations into fires in informal settlements, including different fires in the same settlements and fires in different informal settlements. This would help to improve the entire research community′s understanding of fires in informal settlements and enable research on potential risk reduction interventions, which could be used for the development of local Community Fire Safety Strategies.

Further research is needed to investigate methods of firefighting used by communities and to learn about informal training that takes place between community members with regards to fire safety, even if it is not referred to as fire safety training – e.g., a mother teaching child to not play with matches or to go near the stove when she is cooking.

This chapter is a first stage. It aims to support future research, being a foundation upon which additional evidence of human and fire behaviour in informal settlements can be compiled. Future researchers are encouraged to collect more information about fire response and behavioural aspects that can be detected when larger fires occur. The author acknowledge that the fire in this case study is not as severe as it could have been under different climate conditions (drier conditions, unfavourable wind direction, etc.). It is understood that the fire was relatively smaller in size compared with other fires that have been documented in Costa Rica in past years in other informal settlements. For example, in November 26th, 2016, the informal settlement ″Los trillizos″ located in Leon XII district, Tibás canton, experienced a 3000 m^2 damage region leaving more than 180 people without housing and had six fatalities. On January 15th, 2020, the ″Los Sauces″ informal settlement located in the Guararí neighbourhood, which belongs to the San Francisco district, inside Heredia canton, had a fire that destroyed 189 houses covering an area of 8400 m^2. The El Pochote case study herein was only 40 houses located in 2400 m^2.

Once additional data is compiled, the author and others will be able to address a more specific fire response framework for the community. Proposing one now for this specific region would be premature. Future work may draw upon other disasters for a resiliency approach should it be applicable, and it should also consider those proposed elsewhere and how they are applicable here. It would, however, be a premature endeavour with only one fire case study to draw upon to enable a framework with supplemented data from other disaster types or other regions where settlements have been more extensively studied.

3.6. Conclusions

This chapter analysed human behaviour in a fire in an informal settlement. Analysis was based on a video footage of a fire in El Pochote, located in San Jose, the capital of Costa Rica. The response principles used by the firefighters to control the fire, the behavioural actions by the local inhabitants during the fire, and the interactions between the firefighters and the locals were explored in this chapter. A number of aspects that make it difficult to study fires in informal settlements were discussed in this study, including the complex social interactions which are highly situational, such as density of the informal settlements, their expansion, education, unemployment, and other demographics that may play a role in human behaviour in fire. As well, it is generally known that many fires in informal settlements are never reported to the fire department because they are managed by the community, and further firefighting support is not needed.

This study contributes to informal settlement fire research by providing a foundation upon which additional evidence of human and fire behaviour in informal settlements can be gathered and compared. While behaviours of the residents were often consistent with the existing behavioural frameworks, e.g., PADM, the author observed that the current frameworks lack empirical evidence to be applied to human behaviour in informal settlements. Nonetheless, these theories can provide a base upon which researchers can build and form theories applicable to the context of informal settlements. To this extent, this chapter outlined and undertook the preliminary research steps needed to show how future studies can better examine human behaviour in informal settlements.

Several key findings were presented that pertain to the behaviours of the firefighters and the locals. According to the members of the Costa Rican Fire Corps, civilians intervene in their fire extinction efforts, thus the firefighters have opted to work alongside the communities rather than fighting against their involvement throughout the fire containment and extinguishment process. However, behaviours that are counter-effective, reported by the firefighters as well as in other studies, were not observed in the El Pochote fire video footage.

Nonetheless, some resident behaviours were observed to mirror those in the existing literature, such as attempting to tackle fires, movement through smoke, re-entry behaviour, and clear differences between males and females in behaviour and frequency of certain behaviours (males were more likely to exhibit firefighting behaviours whereas females were more likely to alert others and exit the property). In addition, novel bold actions by some residents, such as walking on the roofs, passing alleys while firefighting operation was taking place, and blocking the alleys with personal belongings, were observed.

Chapter 4: Legislation for informal settlements

The previous chapter elaborated an exploratory review of human behavior and fire evolution in an informal settlement fire in Costa Rica, it also referred on how emergency services work with the inhabitants for a common goal. This chapter will focus on the legislative side of informal settlements, it considers developed (Canada) and developing (Costa Rica) countries, with the main intention of comparing their code advancement approaches; how both governments are addressing code applicability in their informal settlements; and what are the differences in their approaches.

4.1. Introduction

Building design codes and regulations are meant to protect human lives and structural integrity of the building in the event of a hazard through providing standards that buildings must adhere to (Calder & Weckman, 2020). Codes have historically been prescriptive but have recently began transitioning to performance-based codes (Meacham, 2010). In Canada, codes are developed based upon national governmental resources aiming to advance requirements deemed insufficient or potentially non-reflective of current infrastructure design trends. However, developing countries, generally, do not have the financial or administrative resources to advance their own fire codes and standards in such a manner and instead adopt codes and standards from more established sources to fit their necessities. However, building and fire codes are typically developed with specific scopes and are only applicable to conventional infrastructure and do not address unconventional buildings and non-traditional housing such as informal settlements.

Informal settlements are commonly defined as residential areas where residents have no guaranteed permanency, a lack of basic services and amenities, and housing does not comply with building codes and regulations. They are a growing issue in both developed and developing countries due to a lack of affordable housing, increased urban population growth and economic vulnerability (UN-Habitat, 2015). Informal settlements are at a greater risk of fire and other hazards due to the socio-economic vulnerability of the residents, the physical characteristics of the structures, and the political and institutional marginalization of the settlements (UN-Habitat, 2018). The UN has targeted informal settlements through the

Sustainable Development Goals (SDGs), notably SDG #11: make cities, inclusive, safe, resilient, and sustainable, but also through SDG #1: end poverty in all forms and SDG #10: reduce inequality within and among countries (UN-Habitat, 2017).

The objective of this chapter addresses important interrelated themes to the above: 1) compare Developed (Canada) and Developing (Costa Rica) code advancement approaches, 2) determine code applicability to informal settlements and 3) compare each country's approach to informal settlements.

4.2. Code advancement processes

These countries were chosen for this study due to the differences between how they are addressing the housing and informal settlement issues they have been experiencing. Canada is a developed country with a known affordable housing crisis and informal settlements which can be compared with a country that is also dealing with similar issues, though in different forms. Canada has access to greater economic resources to address these issues, while for Costa Rica to obtain solutions must take different approaches, due to the relative lack of monetary resources to work in housing issues.

Costa Rica was chosen for comparison due to the housing solution efforts the government has been done through the years, aiming to provide decent housing to all Costa Ricans. There are records since 1904 about government actions focused on solving housing problems affecting the country (Guevara Arce, 2020). In 1949, it was established in the Costa Rican Political Constitution that the State has the obligation of providing acceptable housing to the population with limited economic resources (Guevara Arce, 2020). These efforts have placed Costa Rica on top of the region, as Costa Rica is the country with the lowest percentage of urban population living in informal settlements in Latin America (The World Bank, 2020).

4.2.1. Canada

In Canada, building and fire safety regulation is under the jurisdiction of the provinces and territories who can choose to adopt or enforce the national model codes or develop their own codes (Canadian Commission on Building and Fire Codes, 2015a). Canada has five national building model codes: National Building Code of Canada (NBC), National Fire Code of Canada (NFC), National Plumbing Code of Canada (NPC), National Energy Code of Canada for Buildings (NECB) and the National Farm Building Code of Canada (NFBC). The NBC and NFC are the two main model codes that concern the fire safety of newly constructed and existing buildings. The NBC and NFC are designed to complement each other, where the NBC covers fire safety requirements at the time of building construction and reconstruction while the NFC generally covers the ongoing operation and maintenance of fire safety systems of buildings in-use (Canadian Commission on Building and Fire Codes, 2015b).

As model codes, they were created to provide the different building code jurisdictions with a model to follow, to encourage consistency and compatibility across the jurisdictions (Canadian Commission on Building and Fire Codes, 2015a). The codes are developed by the Canadian Commission on Building and Fire Codes (CCBFC) and updated every five years through a broad-based consensus process (National Research Council of Canada, 2020). Proposed code changes are submitted to the CCBFC where they are examined by the appropriate expert standing committee within CCBFC for merit. Committee members are appointed to the committees through nominations under regulatory, industry or general interest categories. If the proposed change is accepted, it undergoes a series of reviews by relevant standing committees within CCBFC, provincial and territorial authorities and the public. Comments received from the reviews are taken into consideration before the proposed change is submitted to CCBFC for final approval. If approved, the change is included in the next edition of the national code (National Research Council of Canada, 2020).

4.2.2. Costa Rica

The current regulations that govern Costa Rica regarding fires and fire safety were created in 2002 from Law 8228 and its Decree No. 37615-MP (Araya, 2022). It allows the Costa Rican Fire Corps to issue technical standardization, which will be mandatory for individuals or legal entities, either public or private, in matters of security, fire protection, and human security (Asamblea Legislativa, 2002). After the creation of the law and decree, the Fire Corps was obliged to create a guide that helps professionals apply the regulations, mainly concerning the processing of plans, which resulted in the creation of the "Manual of technical provisions for human safety and fire protection" in 2005, where the entire regulatory package of the National Fire Protection Association (NFPA) was adopted (Asamblea Legislativa, 2005). In the next years, four more editions were published, mainly updating the information and making it more comprehensible for the users(Engineering Unit (Costa Rican Fire Corps), 2013), as the adoption of NFPA standards has caused confusion in the required fire protection needed for acceptable design. The last version was published in 2020, in this edition the document converts from a manual into a regulation (Araya, 2022), but it must be highlighted that none of these documents addressed how to protect marginalized populations living in informal settlements.

4.3. Informal settlements

Nearly 1 billion people or 32 percent of the world's urban population live in informal dwellings and around 88% (881,080,000) informal settlement dwellers are estimated to be living in developing countries (UN-Habitat, 2017). This means that issues with informal settlements are not equally distributed between developed and developing countries, and it is magnified in the latter. Lack of affordable housing is a growing problem, related to population growth which is estimated to increase by 2 billion in the next 30 years (United Nations, 2022). The growth is expected to lead to increased use and density of existing informal settlements and/or the creation of new ones.

Informal settlements have a higher fire risk due to poor electrical connections and the use of open flames for cooking, warmth and lighting which create ignition sources that generate a latent risk. Additionally, the high density of dwellings and short distances between them, the use of combustible construction materials, the topography of the land, among other factors, are features that can worsen a fire emergency, turning a fire rapidly into a conflagration. Koker et al. found that a dwelling inside an informal settlement can reach flashover within a minute or less after ignition and that downwind neighbour structures can be ignited in less than a minute (Koker et al., 2020).

4.3.1. Canada

Homelessness in Canada has been a growing concern since the 1980s due to less spending and support for social services and affordable housing, and rapid declines in job availability and permanency, resulting in approximately 235,000 individuals experiencing homelessness per year and 35,000 on any given night (Gaetz et al., 2016). It's estimated that 0.010% of the urban population in Canada live in informal dwellings (The World Bank, 2020), which corresponds to approximately 3,000 people. This is without considering the effects of the COVID-19 pandemic where the number of encampments soared across Canada as people decided to abandon overcrowded shelters or felt they were unwelcome to rest in friend's homes (Crawford, 2021). The City of Toronto estimates that in 2021, there were 421 tents and other temporary structures located within the city at 100 different locations, mainly parks and right-of-way passages (City Manager, 2021). The 2021 Streets Need Assessment estimated approximately 7,347 individuals were experiencing homelessness in Toronto, with 163 individuals residing in encampments, however both figures are likely below the actual figure as only public spaces were included and hidden homelessness was excluded (City of Toronto, 2021a).

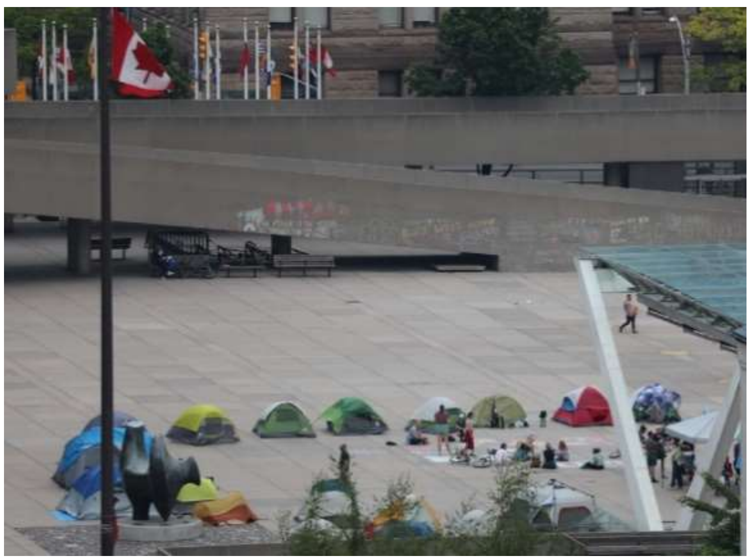


Figure 4.1. *Temporary informal settlement during Summer 2020 located in Central Toronto (Author's photo)*

In 2020, Toronto Fire Services responded to 253 fire incidents in encampments. This represented a 247% increase over incidents in the same period in 2019 (City Manager, 2021), however that number includes incidents of suspected fires, not only actual fires which occurred (FactCheckToronto, 2021). Fire risks in homeless encampments include open flames, unsafe wiring, and power generators as well as unsafe fuel and other flammable material storage (City Manager, 2021). Many of these risks are associated with Canada's colder climate and the need to stay warm along with a lack of fire prevention training or suppression equipment such as fire extinguishers (V. Gibson, 2021). There is little to no active or passive fire protections within homeless encampments.

4.3.2. Costa Rica

In 2018, around 3.9 percent of the urban population in Costa Rica were living in informal settlements (The World Bank, 2020), which meant approximately 195,000 dwellers. In the same year, the Engineering Unit of the Costa Rican Fire Corps reported a total of 50 fires in informal settlements (Engineering Unit (Costa Rican Fire Corps), 2019a), but this data might not reflect the real number of fires since according to the firefighters, several times inhabitants try to extinguish the fire by themselves without calling the emergency services. The houses inside informal settlements are in constant risk of fire, as they are surrounded by potential causes of fires, including short circuits due to electrical connections in disrepair, cooking and lighting with open flame, poor maintenance and manipulation of gas cylinders, attempted controlled burns of wires or dry grass, candles or wood burning without surveillance, as well as children playing with matches, candles, or left alone in their houses (Guevara et al., 2021). In addition to the constant risk of fire, there is a lack of active and passive fire protection, which may worsen the severity of the fire and increases the likelihood of having greater losses.

In 2019, two large fires affected two different informal settlements in Costa Rica. The first one occurred on April 13th in La Carpio, located in La Uruca district of San Jose. Seven people died in a house where 15 people were living. Some of the survivors escaped through the ceiling as the fire started in the only available entrance. The cause of the fire was arson (Engineering Unit (Costa Rican Fire Corps), 2019b).

The second fire occurred on September 16th, 2019, in El Pochote, located in Hospital district of San Jose. In this event, 40 houses located in 2,400 m^2 were burned, leaving approximately 216 people homeless. The cause of the fire was a short-circuit (Guevara Arce, 2020), **Figure 4.2** shows the fire footprint.

Figure 4.2. *El Pochote fire footprint (Photo by Jason Fernández with permission).*

4.3.3. Differences Between Informal Settlements

There is a marked difference between the informal settlements of Costa Rica and the homeless encampments in Canada. Comparing the level of informality, Canada can be considered more informal than Costa Rican informal dwellings, as in the latter, there are physical houses instead of mainly tents. These houses can be multi-storied (see **Figure 4.3**). Tents are the primary form of shelter in Canadian informal settlements as they are the most convenient and available option to residents as municipalities prevent larger shelters, such as tiny houses, from being constructed using legislative restrictions. Additionally, the size of informal settlements differs between the two countries as an informal settlement in Costa Rica can reach up to 25,000 people (around 5,000 families), (MIVAH, n.d.) almost three and a half times the estimated amount people experiencing homelessness throughout Toronto. As Canada's municipalities leverage zoning by-laws and building code provisions to prevent large temporary shelters, homeless encampments tend to be scattered in different areas of cities. In Toronto, tent encampments were found at 59 unique park locations and 41 right-of-way passages(City Manager, 2021).

Figure 4.3. Costa Rican multi-storey informal dwellings vs smaller Canadian tent encampments (Author's photos).

Although living in illegal tenure, the people in Costa Rican informal dwellings have a fixed space in which can remain for years or even decades. For example, La Carpio, the biggest informal settlement in Costa Rica was established in 1993 (MIVAH, n.d.). Whereas in Canada, the primary method of dealing with encampments is to forcefully evict them from the area using building and fire code provisions and municipal zoning by-laws, preventing permanent and/or longer-term encampments (Farha & Schwan, 2020). Additionally in Costa Rica, the residents manage to get basic services as water and electricity, though mostly in an illegal manner. In some cases, national companies develop projects to minimize the informality condition and enhance their living situation. For instance, the National Company of Force and Light (CNFL) started a project of grouped metering and network shielding, providing informal dwellers with a minimum of passive fire protection and legal electricity at an affordable price. In **Figure 4.4**, the left picture shows the cabinets installed for electricity distribution, and the right picture depicts the connections the community did in order to legalize their services.

Figure 4.4. Grouped metering (Author's photos).

Another difference is the ability to trace and census them, although in both cases it is difficult due to their nomad behaviour. It is more probable for people to stay longer in informal buildings than in tents, as the latter posses more ease for location changes. In Canada, the issue of homelessness, affordable housing and social services falls across multiple jurisdictions which means there is no centralized system for surveying the number of people experiencing homelessness. Employment and Social Development Canada (ESDC) conducts voluntary community Point-in-Time counts every few years to count a community's sheltered and unsheltered homeless (Employment and Social Development Canada, 2022). However, these counts are voluntary and may not specify whether "unsheltered" means they live in an encampment depending on the municipality (Employment and Social Development Canada, 2019). There are also no surveys about the different forms of shelter within homeless encampments.

4.4. Building codes and informal settlements

Informal settlements exist in an unclear legal area as they are often situated on land the residents do not own. Additionally, due to the nature of informal settlements, the buildings and structures used are often whatever is available and constructed to provide shelter, without any regards to building or fire regulations. While there are existing frameworks on informal settlements that propose to create policies in order to update land use and ensure informal settlements meet minimum safety requirements (Antonellis et al., 2018) (Farha & Schwan, 2020), there have not been any proposals to incorporate informal settlements in building and fire safety regulations themselves.

In Canada, homeless encampments are not considered permanent buildings and do not directly fall under the authority of building codes. Tents are the most common form of shelter in homeless encampments as one of the few available forms of shelter. Larger shelters, such as tiny homes, are considered permanent shelters and as such fall under building and fire code regulations which municipalities have utilised in order to have them dismantled as they lack active and passive fire protections. Additionally, as a vulnerable population, many of whom lack financial means, any building or structural regulations are unlikely to be followed due to a lack of ability. There are currently no official processes in place to regulate the safety of tent encampments. Municipalities have commonly employed zoning by-laws to criminalize temporary shelters in city spaces and allow police to forcefully evict residents of encampments using those powers. However, these by-laws have come under legal scrutiny and been found to violate Section 7 of the Canadian Charter of Rights and Freedoms that stipulates all Canadians have a right to “life, liberty and security of the person” which the Supreme Court of Canada has interpreted it to include the right to housing (Farha & Schwan, 2020). While there are programs in place for municipalities to provide access to sleeping bags, propane stoves as well as burn bins, in order to reduce the use of open flames for warmth (V. Gibson, 2021) (Samson, 2022), there are few initiatives in place to provide housing or supply residents with safe(r) building materials in encampments, outside of directing them to existing services such as city shelters and social housing programs.

Some cities have started initiatives using tiny homes as an alternative to homelessness and a form of affordable housing (Koutalianous et al., 2021) (Wong et al., 2020). However, this move has not been without resistance. Tiny homes have largely been promoted as a sustainable alternative to traditional forms of housing, however, they occupy a gray area within building codes and pose a number of safety risks, including fire (Ford & Gomez-Lanier, 2017). While some types of tiny homes can fit under existing building codes and regulations, there are prescriptive requirements that tiny houses are non-compliant with by nature of the smaller space (Chown, 2016). Tiny homes lack of fire protection outside of fire alarms and the smaller space impacts egress as well as fire spread within the home (Koutalianous et al., 2021). There is also very little research on the material behaviour in fires of tiny homes and on fire spread within and between tiny homes. It has been observed that fires spread quickly within the homes with very little time for effective fire suppression. In March 2022, there was a fire within a tiny home village for the homeless in Lake Merritt, California where it was reported that three tiny homes were destroyed within ten minutes as fire spread between the tiny homes. One resident stated “the walls were just melting” around her during the fire (Kendall & Lin, 2022).

The City of Toronto settled a lawsuit against an individual who was constructing tiny wooden shelters for homeless individuals. These shelters consisted of a single insulated room with one window and a door, designed to protect against freezing temperatures (Jones, 2020). The City’s position at the time were that the tiny shelters were not legal dwellings and violated municipal by-laws against structures on City-owned land (City of Toronto, 2021b). While not included as part of the legal proceedings, the City also had concerns regarding the fire safety of the tiny shelters as they were made of combustible materials and had not been inspected by Toronto Fire Services to confirm fire safety features (City of Toronto, 2021b) (Jones, 2020).

In Costa Rica, there are no legal and administrative provisions to facilitate the regulation of informal settlements, this generates problems regarding access to basic services, health, accessibility, and security. Additionally, it makes it impossible for the Costa Rican government to apply the corresponding controls and to collect payments for the services provided (Chacon Monge, 2020). However, it was found that dwellers of Costa Rican informal settlements self-regulate their communities, reinforced with jurisdictional support, attaining a certain degree of fire safety. For instance, in Bajo Zamora, an informal settlement visited by the author, minimum distances in alleys must be respected to be able to construct there. Furthermore, community members organized an emergency brigade which is also in charge of fire prevention and mitigation. While tent encampments in Canada have been observed to have some degree of self-governance, if and how they manage fire risks and fire safety has not been explored (Young et al., 2017).

In Costa Rica, there have been several efforts done by different institutions to study, improve and try to formalize informal settlements. In 2007, there was an intent to tailor the national norms and regulations to make them more flexible for people living in informal settlements. This project gathered around 12 public and private stakeholders. Three workshops were carried out through the Commission of Experimental Norms to reform the Urban Development Plan (PDU) of the San Jose Municipality. The main objective was to analyze the experiences these different stakeholders had when applying proposals in informal settlements to create special norms or guidelines that can help to intervene with the urban planning of these settlements. These workshops allowed for several conclusions in different topics to be obtained, such as formalities, general and specific rules for design criteria, minimum access dimensions, design criteria in health, citizen security, and emergencies (Guevara Arce, 2020). This project was abandoned as people with legal tenure began to complain, as they stated that it was unfair for people with no legal tenure of the land to receive special treatments and permissions for their constructions.

Later, in 2017, the National Company of Force and Light (CNFL) - one of the stakeholders involved in the 2007 formalization project -, began grouped metering and network shielding projects in informal settlements. The main objective was to formalize the users to avoid electrical and money losses for the company, but it drove several institutions to look for solutions to improve the settlements they were intervening in. For instance, in Tejarcillos (another settlement visited by the author), after CNFL installed the electrical posts and made the connections, the San Jose Municipality intervened and increased the width of the main road. Also, Ebi, a company in charge of solid waste treatment, donated a hook lift dumpster for the community to throw their waste in one place and make it easier to collect at the site. All these improvements not only enhanced the physical features of the informal settlement but also the feeling of belonging of the dwellers, which in turn, resulted in communities committed to taking responsibilities to keep the informal settlement safe.

In 2021, a law was proposed to the Legislative Assembly aiming to transform, rehabilitate, regenerate, regularize and enhance the condition of the informal settlements in order to provide a better quality of life for the inhabitants. The law would be carried out through the creation of intervention zones, in which urban renewal programs are carried out, to allow for the relaxation of urban regulations and the provision of public services and infrastructure, as well as the granting of property titles (Chacon Monge, 2020). This law is under revision and waiting for the approval of the plenary.

4.5. Lessons learned for Canada from Costa Rica

Code development processes between Canada and Costa Rica differ where Canada uses a broad-based consensus process to update codes, Costa Rica adopted the NFPA Standard 101 and has been slowly updating the information to tailor it to Costa Rican buildings and infrastructure before adopting it as an official regulation. However, while informal settlements are an issue in both countries and expected to grow, neither country has indicated any move towards incorporating or recognizing the risk of informal settlement fires into building and fire codes. However, as noted previously, in Costa Rica, several actors are trying to formalize the informal settlements, although so far it has not been possible. Canada has not made any indication they will attempt to formalize informal settlements, however, decriminalizing homeless encampments and ensuring homeless encampments meet minimum safety requirements and have access to basic services are identified as key principles in *A National Protocol for Homeless Encampments in Canada* (Farha & Schwan, 2020). Canada aims to reduce homelessness by 50% in 10 years through its National Housing Strategy (Employment and Social Development Canada, 2017), however, it has not included regulation or improvement of informal settlements as part of its directives, instead focusing funding on creating new affordable housing options and improving its shelter system (Employment and Social Development Canada, 2020).

With Canadian municipalities' history of criminalizing homeless encampments, following Costa Rica's lead to conduct workshops and studies tailored specifically to informal settlements as a preliminary step is a critical one, not only to fill existing knowledge gaps from a lack of information, but also to generate trust within a marginalized community that has been found to distrust government social services and supports (Herring & Lutz, 2015). Additionally, creating a specific strategy on informal settlements would help address the National Housing Strategy goal of reducing homelessness by 50% as informal settlements, homelessness and affordable housing are all interconnected. It would also help Canada fulfil its human rights obligations under both international and national law.

4.6. Limitations

Statistics on homelessness and homeless encampments in Canada are largely unavailable or patchworked together from different jurisdictions. Homeless encampments are often not reported as their own category and grouped with "unsheltered" and as such, any demographic data may not be entirely applicable. There is also a lack of fire incident data in homeless encampments available which makes it difficult to gauge the true risk and dangers present. In addition to lacking fire incident data, there is a research gap in investigating fire risks and fire spread within North American informal settlements as there are not many studies available. There is also a lack of studies related to the community within informal settlements and if and how they navigate safety risks, such as fire, within encampments.

There is also a lack of information regarding Costa Rican informal settlements' physical characteristics, fire record data, features of the communities such as demographic, social, economic data, and so forth. In addition, the available information is outdated or incomplete, thus, making an accurate characterization of the diverse informal settlements of the country is extremely difficult. Similar to Canada, there is also lack of studies on the community and community organization within informal settlements which was observed during a previous site visit by the author.

4.7. Conclusions

Neither Canada's nor Costa Rica's code development processes lend themselves easily to incorporating informal settlement regulations into their codes. As informal settlements are a globally growing issue, both countries need to develop approaches in order to address informal settlements and informal settlement safety. Costa Rica is currently in an early stage of preliminary investigations. The stakeholders are trying to understand the issue of informal settlements and how to begin addressing it, aiming to find out what are the future steps to propose solutions for different problems related to informal settlements. While there have been some Canadian initiatives to begin addressing homeless encampments, from a government standpoint, priority has been given to homelessness prevention, improved shelter access and quality and increased availability of affordable housing.

It is crucial to conduct surveys and research studies to create and update information on informal settlements and their conditions to fill knowledge gaps. This would give better and more accurate recommendations for each settlement, as all of them have different characteristics that made them unique. Additionally, more research to identify and address fire risks within informal settlements is required in order to better provide recommendations to improve the fire safety of its residents. Fire spread within informal settlements and tent encampments is understudied and would contribute to understanding fire risks in informal settlements. However, while both countries are working to address the issue of informal settlements, with the anticipated increase in informal settlements due to population growth and worsening of poverty and the affordable housing crises, these measures may not be sufficient.

Chapter 5: Characterization and fire risk of informal settlements of different scales

This chapter performs a comparison of the physical features of informal settlements of different sizes within San Jose. To this end four field visits were carried out, allowing to determine the main differences or similarities between small/large-scale settlements. These visits allowed to assess what features inside the settlements increase the fire risk and hinder the fire extinguishment and evacuation processes. This chapter also refers to the current challenges for engineers regarding informal settlements modelling and the usage of contemporary numerical theories not tailored to them.

5.1. Introduction

The global population is expected to increase by two billion in the next 30 years, moving from 7.7 billion currently to 9.7 billion in 2050 and is forecasted to reach a peak of 11 billion by 2100 (United Nations, 2022). This population growth will be unequally distributed, primarily affecting low- and middle-income countries (United Nations (UN), 2018). This will lead to other issues, such as the lack of affordable housing for the most vulnerable and the evolution of existing informal settlements. Informal settlements are defined as residential areas where the occupants do not have legal tenure of the land or dwellings they inhabit; the dwellings may not comply with planning and building regulations; they are typically located in hazardous areas; and are characterized by a lack of basic services and urban infrastructure (UN-Habitat, 2015). Currently, nearly one billion people are living in informal dwellings and approximately 88% of them are located in developing countries (UN-Habitat, 2017).

Fire is one of the principal concerns when considering informal settlements, due to their greater risk of fire spreading and magnified outcomes, as dwellings inside these settlements are commonly built with small spatial separation, allowing a house fire to spread over a wider area in a short time (Spinardi et al., 2020). Previous studies undertaken in the United States have linked fire rates and several social variables, such as poverty, family stability, crowdedness, and the proportion of owner-occupied homes, concluding that in poor communities the fire rate and the fire death rate are higher (Fahy & Maheshwari, 2021). Fahy & Maheshwari also stated that some of the factors that can influence risk in these substandard houses are related to outdated or illegal electrical service, crowding, lack of affordable childcare, and arson.

When considering previous fire science research, it is noticeable that most of the research conducted regarding informal settlements has been focused on South Africa and India, but little research attention has been paid to other regions such as Latin America and the Caribbean, a region with 21% of the urban population living in informal settlements (The World Bank, 2020), owing to its difficult to study nature.

Costa Rica stands out within the region by having 3.9% of the urban population living in informal conditions, whereas neighbouring countries such as Nicaragua (42%) and Panama (22%) reach higher numbers (The World Bank, 2020). In the last decades, Costa Rica has been working towards the reduction of poverty and housing informality, which has resulted in an improvement in the lifestyle of the informal housing dwellers.

In Costa Rica, there are around 418 informal settlements throughout the country, which house more than 220,000 inhabitants. The metropolitan area of San Jose hosts approximately 112 informal settlements, making it the province with the most informal settlements in the country (MIVAH, 2013).

This chapter will address informal settlements from the Latin American region, specifically, it will focus on the understudied Costa Rican informal settlements. Due to the access of the author through collaborations with community stakeholders and ease of localized covid restrictions during the study period, a unique detailed study of these settlements presented herein is possible. Future research should however expand to consider other Latin American settlements when permissible and the procedure detailed herein may be useful to this end.

Conducting visits with public institutions can be a difficult endeavour since time availability can be limited and the coordination procedure excessive. The visits were performed by the author during field inspections already scheduled by the institution.

Previous research led by the primary author explored human behaviour and fire operational response in a real settlement fire in informal settlements in San Jose (refer to (Guevara Arce, 2020) and (Guevara et al., 2021)). This chapter continues this exploratory stage, seeking to perform a characterization of four Costa Rican informal settlements of different scales within

San Jose. The research aim is to determine any differences or similarities in physical features between the settlements and the population's behaviour towards outsiders, and how these characteristics could affect the inhabitant's response to future fire events. This will be helpful as a first step towards defining a framework for fire risk and safety to then move on to an expanded study that would also be useful for other countries within the Latin American region.

5.2. Methodology

Due to the lack of research information available for Costa Rican informal settlements, most of the information gathered in this first stage follows a general exploratory and provisional approach to guide future more holistic research endeavours as will be introduced in the chapter's final discussion.

Globally, informal settlements all have a unique complex socio-politic-economic landscape, meaning that engineered fire solutions posed for one settlement may not apply to another (Rush et al., 2020). Thus, the main objective of this current investigation is to identify differences and similarities between informal settlements of different sizes, describe them, and determine the various fire risk factors that prevail on them within one geographical region.

This study will then help to understand if different approach methods should be used when developing fire safety plans and if they will need to be fitted depending on the informal settlement considered.

The compilation of information has been performed qualitatively with the main purpose of contrasting the differences and similarities between informal settlements of different scales within the capital city of Costa Rica. This comparative approach is chosen as it is essential in this stage to understand if there are strong differences/similarities between informal settlements which can result in using diverse approach methods in future investigations, or if all of the settlements can be treated similarly, without neglecting the features that make each informal settlement unique. For this aim, a series of field visits were conducted. In total, the author visited four informal settlements throughout San Jose, named La Carpio, Leon XIII, Tejarcillos and Bajo Zamora.

It should be noted that the lack of information regarding the year of establishment, population and house density impedes classifying the informal settlements thoroughly. Hence, to classify them, their territorial extension will be the main characteristic considered, being the only verifiable feature found by the author. Therefore, La Carpio and Leon XIII will be deemed as large size informal settlements since they have a territorial extension of 0.64 km^2 and 0.35 km^2 respectively, while Tejarcillos and Bajo Zamora fall under the small size category, with an extension of 0.14 km^2 and 0.04 km^2 respectively (INEC, 2020). Under each category, the settlements have a common level of development in their infrastructure. For instance, the larger ones have more makeshift improvements in their sewage and alleys, in contrast to the smaller ones, which have less development or improvements. These informal settlements are well known in Costa Rica to community members, and they were chosen mainly due to the availability of escort from these community members when performing the field visits.

A naturalistic observation method was employed, which consists in performing observation of the natural environment without the researcher engaging in any direct interaction with the individuals while observing with the main objective of being as unobtrusive as possible to the community. To determine the main points to focus on during the observations, a literature review was performed. The author found relevant studies on risk assessment of informal settlements. Hu et al. found that evacuation factors in informal settlements are in poor condition, where sometimes only one exit is available and clogged with combustible materials (Hu et al., 2022), thus the author considered it relevant to address how many entrances and which dimensions are observed in the settlements chosen. Previous investigations have also studied how the distance between informal dwellings can affect the fire spread, concluding that leaving a free space of approximately three to five meters can work to prevent fire spread between dwellings (Cicione et al., 2019) and (Wang et al., 2020), thus it was also crucial to determine housing distribution and distances between them. Another important factor was to observe construction materials, which will allow to narrow down the information and understand what are the principal fuels the houses may contain. A material database created by Wang et al. could be used to determine the expected heat fluxes and Heat Release Rates of these houses in future investigations (Wang et al., 2020). Prior research by the author observed a great amount of waste (garbage) in the alleyways of two informal settlements in Costa Rica (Guevara Arce, 2020) and (Guevara et al., 2021), but it was not clear whether this pattern was circumstantial or a commonality, therefore it was decided to examine if waste is a common factor in informal settlements and if the amount is similar or if it varies between them depending on their size. Finally, (Flores Quiroz, Walls, & Cicione, 2021) developed a characterization of living conditions in the dwellings of Imizamu Yethu (South Africa), where housing conditions, basic services, and sources of energy were collected. The informal electric supply was strongly linked to a fire risk and the increased likelihood of fires. Therefore, the state of two basic services (electricity and sewage) where observed to study how they can interfere in fire risk, fire extinguishment, and fire evacuation.

For this study and based upon previous research of focus areas for fire risk in informal settlements as defined above, the main comparison points are summarized as follows:

- Quantity, dimension, and condition of the entries;
- Housing distribution and building materials;
- Cleanliness of the informal settlement; and
- Public services, specifically electricity and sewage.

The first visit was carried out on May 7th, 2019, in Roble Norte a sector of La Carpio, located in La Uruca district. The second visit was on February 16th, 2022, in Tejarcillos, located in Alajuelita district. The third and fourth visits were carried out on March 30th, 2022, the first visit that day was Bajo Zamora, located in Purral district, followed by Hacia el Siglo XXI, Nuevos horizontes and Los Diez, three small informal settlements located inside the León XIII district. All field visits were carried out in the morning. It was decided to conduct the studies in the morning as community members indicated that populations would be at their lowest in community spaces in the settlement which would have both a safety aspect and an ease of study not to obstruct residents.

All the informal settlements visited were within a range of 11 kilometres from central San Jose (Central Park taken as a benchmark). **Figure 5.1** shows the informal settlements visited and the distance between the reference point. Site visits were accompanied by the Police (one site as necessitated per safety concerns described below) or the National Company of Force and Light (CNFL) (three sites), the institution in charge of providing electricity within San Jose and the developer of diverse social projects focused on installing the infrastructure to distribute formal electricity in informal settlements of the province.

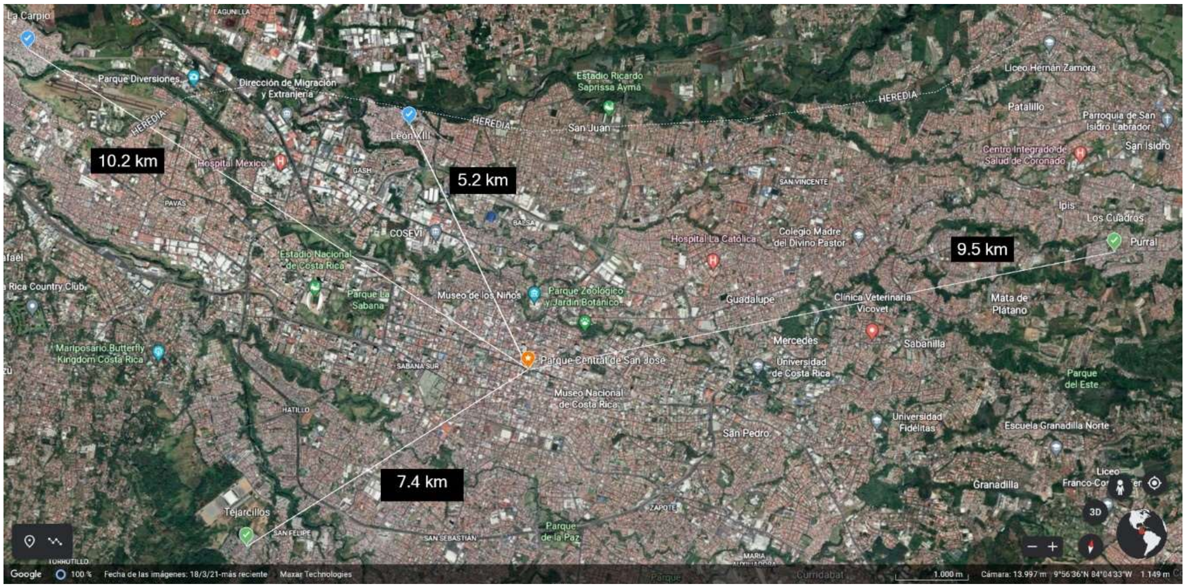


Figure 5.1. Distance between informal settlements visited and the benchmark, retrieved from Google Earth (Google, n.d.-a)

Commonly, informal settlements have known personal safety hazards (Flores Quiroz, Walls, & Cicione, 2021). For this reason, the author originally requested the company of the Police to do the field visit. The only visit with the escort of the Police was the first one, in La Carpio. The remainder were done with the CNFL. The author initially deemed to look for an escort from the police as according to the Costa Rican Judicial Branch these zones have high crime rates (Poder Judicial, 2022). **Figure 5.2** shows a heat map with the ranking of reported crime in these locations, with the zones in red the ones having higher incidences of crimes.

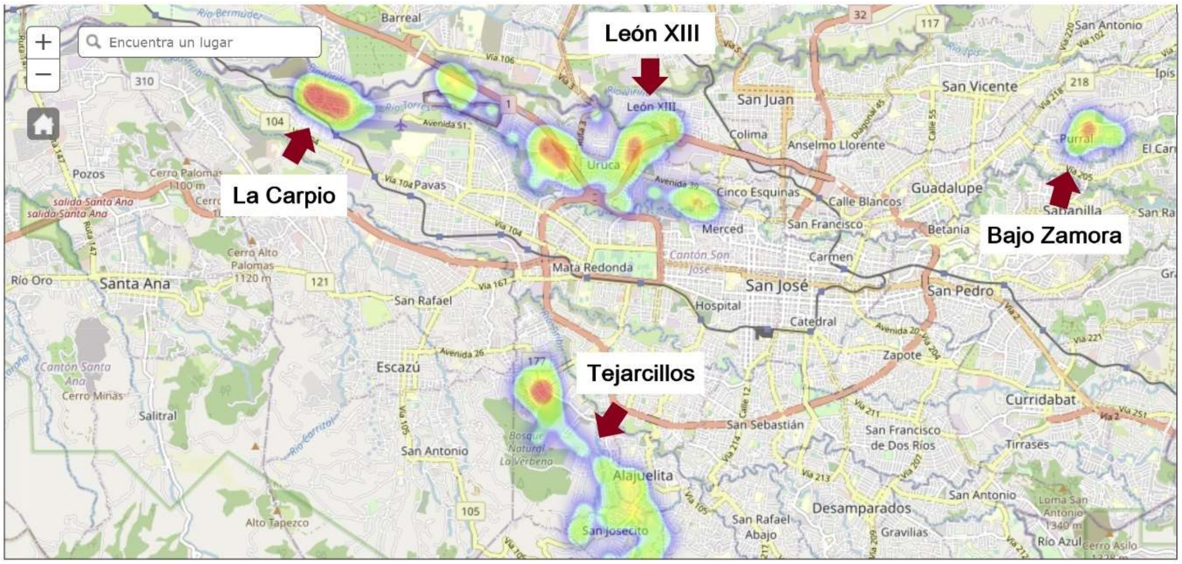


Figure 5.2. Heat map for crime rates in the informal settlements visited (Poder Judicial, 2022).

During the field visits, pictures, measurements, and written field notes were taken to characterize the informal settlement's physical characteristics, such as the dimensions of the alleys, number of accesses to the settlement, terrain characteristics, cleanliness, construction type and materials used to the four-criterion defined above.

Pictures of the inhabitants were not taken. During the visits, some dwellers granted permission to the author to enter their houses to observe the configuration, materials, and belongings inside, although photographs were not taken in these cases, everything was documented by written notes. In addition, the dwellers also provided their opinion about the improvements they have made to their houses. This additional information collected will be useful to define future research.

5.2.1. La Carpio

La Carpio is located in La Uruca district of San Jose Canton. It is comprised of nine sectors, and the one visited by the author is called Roble Norte. **Figure 5.3** shows a map of La Carpio with the boundaries of the sectors. This map was made by the community and is a representation of how they subdivide the settlement. **Figure 5.4** depicts the area covered by the author.

Figure 5.3. Distribution of the nine sectors of La Carpio (CODECA, n.d.).

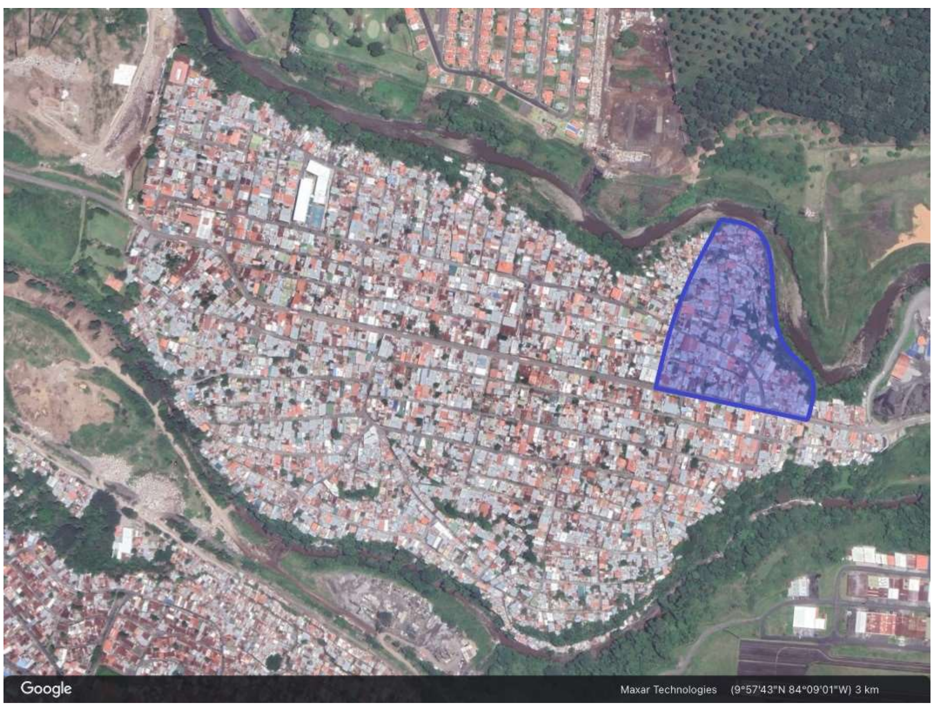


Figure 5.4. Zone visited inside La Carpio, retrieved from Google Earth (Google, n.d.-a).

5.2.2. León XIII

León XII district possesses a vast number of informal settlements surrounding it. The three places visited (Hacia el Siglo XXI, Nuevos horizontes and Los Diez) are in the lower west part of the district, illustrated in **Figure 5.5**. For practicality, in this research, the group of informal settlements visited will be called León XIII.

Figure 5.5. Location of the informal settlements visited, retrieved from Google Maps (Google, n.d.-b).

The difference between La Carpio and León XIII is that La Carpio is a large informal settlement divided by sectors, as shown in **Figure 5.3** and León XIII is a legal district of Tibás canton, which has a vast number of smaller informal settlements surrounding it, refer to **Figure 5.6.** La Carpio was considered completely illegal for several years, but recent efforts made by the Mixed Institute for Social Assistance (IMAS) are achieving the formalization of this settlement by giving land rights to 200 families (Cruz Brenes, 2019). Also, several streets are currently registered in the Ministry of Public Works and Transportation (MOPT), and public institutions such as a high school, police delegation, and clinic have been constructed. On the other hand, León XIII is a legal district where informal settlements begin to arise within its boundaries.

Having several smaller informal communities within a settlement is a shared characteristic of the biggest informal settlements of Costa Rica. In fact, some small informal settlements which used to be autonomous years ago, expanded and merged over time, forming a larger informal settlement, as mentioned by CNFL members during the visits. After merging, the names the settlements used to be known by when unconnected turn into the names of sectors within the emerging one. In other cases, a settlement begins small and concentrated in a single place, and over time it begins to grow, resulting years later in a larger informal settlement.

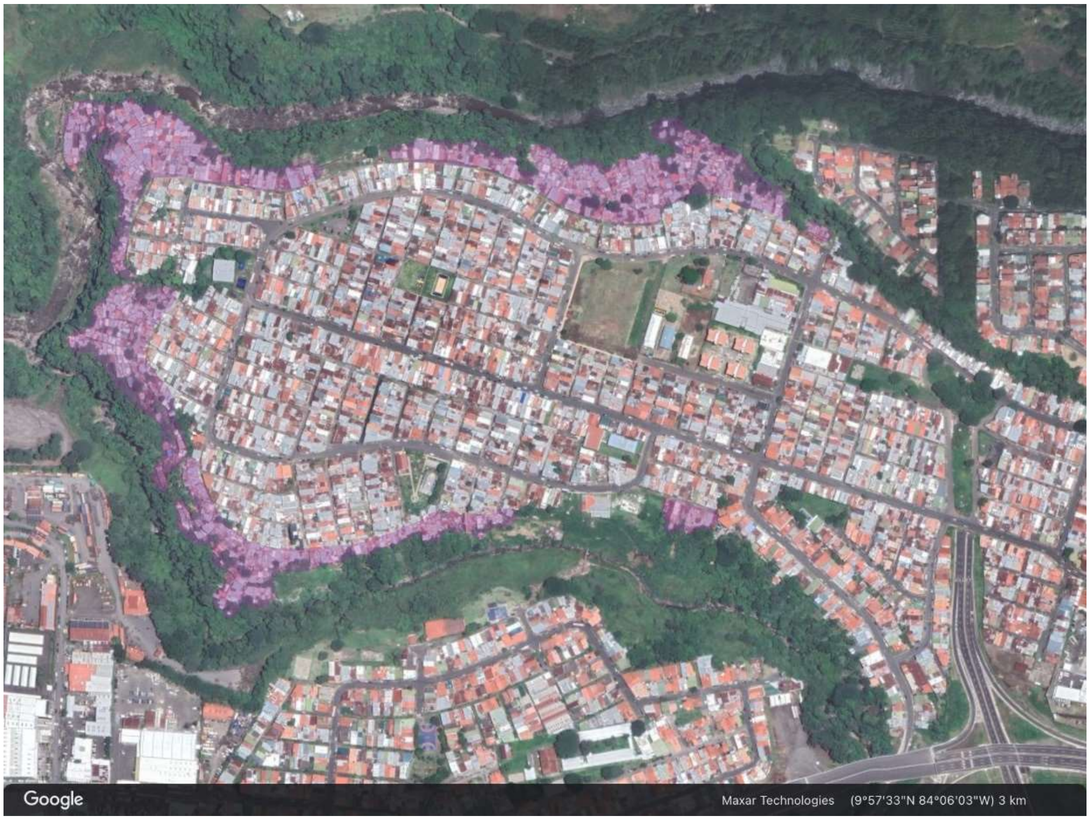


Figure 5.6. *Informal settlements located within Leon XIII boundaries, retrieved from Google Earth* (Google, n.d.-a).

5.2.3. Tejarcillos

Tejarcillos is located within Alajuelita Canton. The visited zone is known as Los Pinos, however, CNFL calls it Tejarcillos, the name that will be also used in this chapter. This was the first small informal settlement visited. The green highlighted part in **Figure 5.7** shows the exact area visited by the author. This settlement was accessed by two paths; the first access was made through the pink path seen in **Figure 5.7** and the second one through the blue path.

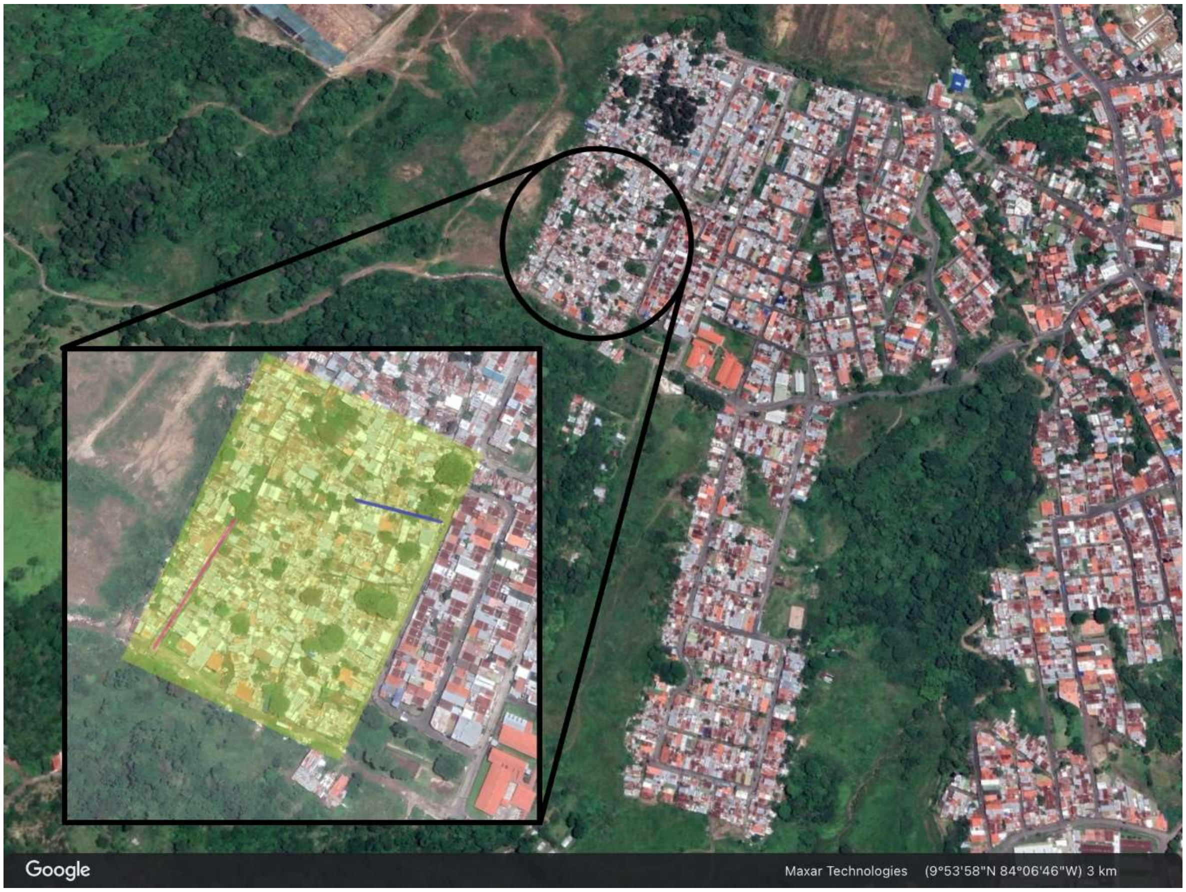


Figure 5.7. Tejarcillos informal settlement, retrieved from Google Earth (Google, n.d.-a).

5.2.4. Bajo Zamora

Bajo Zamora is an informal settlement located inside Los Cuadros informal settlement. The zone visited is called Sector 2 and 3 by the Ministry of Housing and Human Settlements (MIVAH) and called Bajo Zamora by the CNFL. In this chapter, it will be called Bajo Zamora. In **Figure 5.8**, the yellow hatch shows the area visited. The author entered by the path marked with a light blue line and exited through the path marked in purple.

Figure 5.8. Bajo Zamora informal settlement, retrieved from Google Earth (Google, n.d.-a).

5.3. Data collection

The physical characteristics found in these settlements are summarized in **Table 5.1.** Here, these features are divided into categories such as alleys (inner/outer), dwellings (inner/outer), cleanliness, electrical connections, and sewage. By inner and outer, the author is referring to how deep you walk inside the settlement. The outer part is the zone closest to the main streets, comprising the first 50 meters from the entrance. The inner part can be considered as the remaining houses after these 50 meters, the ones which are deeper within the settlement and away from the main streets.

Category | IS		Large scale		Small scale	
		La Carpio	León XIII	Tejarcillos	Bajo Zamora
Alleys	Outer	• Concrete surface • Measured between 2 and 3.2 m wide	• Concrete Surface • Measured around 4 m wide	• Concrete Surface • Measured around 2.5 and 3 m wide • Steep slope (~ 60°)	• Rammed earth surface • Measured between 2.5 and 3 m wide
	Inner	• Concrete surface • Measured between 0.7 and 1.5 m wide • Uneven • Steep slopes	• Concrete or rammed earth surface • Measured 1.2 m or less wide • Unorganized	• Demolished concrete, flat rocks, pallets, wood, or wood sheets over the soil surface • Measured between 1.2 to 1.5 m wide. • Water springs/small river streams on them • Rugs over the alleys to prevent slipping	• Concrete and rammed earth surface • Measured between 1.2 and 2 m wide • Uneven surface • Rugs over the alleys near the river • Makeshift wooden bridges over the river to transit within the informal settlement • Stairs crossing made with car tires filled with rammed earth. 0.6 m wide
Dwellings	Outer	• Made of: → metal sheets (ceilings) → steel tubes (balconies, upper floor structures) → masonry (walls) → concrete (Columns, beams, and floors)	• Made of: → metal sheets (ceilings) → steel tubes (balconies, upper floor structures) → masonry (walls) → concrete (Columns, beams, and floors)	• Made of: → metal sheets (walls and ceiling) → wood (framework of the structure, floors, and walls) → gypsum boards (walls and floors)	• Made of: → thin metal sheets (walls and ceiling) → wood (framework of the structure, floors, and walls) → gypsum boards (walls and floor)
	Inner	• Made of: → metal sheets (walls) → wood (wall frame/structure, floors) → gypsum boards (walls, floors)	• Made of: → metal sheets (walls) → wood (wall frame/structure, floors) → gypsum boards (walls, floors)	• Streams also run below the houses • Dwellings placed over wooden piles • Made of: → metal sheets (walls and ceiling) → wood (framework of the structure, floors, and walls) → gypsum boards (walls and floor)	• Dwellings constructed over steel piles • Made of: → thin metal sheets (walls and ceiling) → wood (framework of the structure, floors, and walls) → gypsum boards (walls and floor)
Cleanliness		• Presence of waste bags • Presence of insects and street dogs	• Presence of waste bags • Presence of insects and street dogs	• Waste bags outside the settlement in a hook lift dumpster • Litter in small proportions • Remains of wood and gypsum waste beside the alleys	• Waste bags outside the settlement • Litter in small proportions
Electrical connections		• In disrepair • Presence of "spaghetti" wires	• In disrepair • Presence of "spaghetti" wires	• In disrepair • Presence of "spaghetti" wires	• In disrepair • Presence of "spaghetti" wires • Wiring at a lower height, around 1.8 m
Sewage		• Makeshift sewer of concrete • Water directed to the nearest river	• Makeshift sewers made of concrete or ditches directly in the ground	• Makeshift using concrete, concrete pipes in combination with ditches dug in the ground. • Deeper inside is more common to find only ditches in the ground.	• Makeshift using PVC pipelines, ditches, or concrete • Directed to the riverbed

Table 5.1. Physical features found in the selected four informal settlements within San Jose, Costa Rica

Besides the information shown in the table, the four informal settlements shared some characteristics such as:

- All the houses are within blocks, built linearly and one beside the other (most of them sharing at least one wall). These blocks are at the same time divided by alleys. Although there is a pattern for housing distribution, the blocks are divided in a complex fashion, making the settlements resemble what can be considered as labyrinths.
- Dwellings in general (outer/inner), are normally between one and two stories in height, except the inner part of La Carpio, which contains a three-story house.
- Two- and three-story buildings have signs of instability, especially those seated on wooden or steel tube piles, to increase their height or to avoid flooding.
- The majority of the dwellings use thin metal sheets, wood, concrete, steel tubes, gypsum, or whatever readily available material.
- The outer alleys' footpaths tend to be somewhat level, while the inner alley paths are uneven, which can result in consequences for the evacuation processes.
- The alleys tend to get narrower the deeper you walk inside the settlement.
- Absence of proper sewage; it is mostly makeshift and without planning.
- Deficiency of fire hydrants and long distances to them when available.

Figure 5.9. *Physical features of La Carpio (Author's photos)*

Tejarcillos has certain unique features. The main one is the presence of water springs and small river streams within the inner alleys; thus, 'potable' water is running in the middle of the path. This results in another set of unique features such as: placing rugs on the paths to prevent people from slipping (as the water springs cause moss on the alleys); the community members started building small wooden bridges with pallets, to allow people to move through the settlement without getting wet (see **Figure 5.11**); the streams also run below the houses, so they place their dwellings over wooden piles to raise them and avoid flooding. In addition, CNFL mentioned that when placing poles for the electrical connections, a high-water table resulted in difficulties during their installation. Concrete houses were not observed in this settlement.

Figure 5.10. *Tejarcillos: houses on wooden piles and makeshift sewages (Author's photos)*

Figure 5.11. *Tejarcillos: wooden bridges and rugs in the alleys (Author's photos)*

Bajo Zamora also showed unique characteristics, such as several makeshift stairs inside the settlement. They were made of old tires filled with rammed earth, with inclinations between 20 and 45 degrees, and the steps having enough space to walk comfortably.

Figure 5.12. *Makeshift stairs inside Bajo Zamora (Author's photo)*

It is a usual feature in informal settlements to have narrow alleys. In this settlement, on the contrary, only one alley was narrow being 1 m wide, and it was short, making it an uncommon informal settlement as it had wider alleys in comparison to other ones previously visited. A community leader mentioned that when she arrived at the informal settlement, the person in charge of giving her a space (lot) within the settlement stated that she must respect two meters alleys where they are not allowed to build or install anything, which implies that this settlement has the creation of unique planning rules.

Related to how they construct, it was observed that some of the houses were placed over steel piles to give them height, presumably to expand them due to a lack of space to grow horizontally. Finally, concrete houses were not observed inside this settlement.

Figure 5.13. *Houses built on steel piles in Bajo Zamora (Author's photos)*

Regarding fire risk, **Figure 5.14** show examples of what can be found in these settlements. The left picture was taken in Bajo Zamora, where a metallic drum full of wood is beside a dwelling. This drum is also used for cooking. The dweller stated that when she cooks, she puts another thin metal sheet as a protection layer on her house, and she also keeps a bucket full of water beside her, in case of an emergency. At the bottom (right beside the drum), a plastic tap can be observed, this one is also used to cook and to fill the buckets. The picture on the right was captured on the outer part of Tejarcillos, where a bunch of furniture is piled up beside a fire bin used for cooking.

Figure 5.14. Metallic drum (Bajo Zamora) and piled couches (Tejarcillos) (Author's photos)

In Leon XIII, one member of the CNFL stated that they have been trying to engage with the community to build a good relationship and communication with them, as this is important for the development of the projects. They commented that the best way to build rapport with them is to show them that they truly want to improve the informal settlement. For instance, during the installation of the electrical poles (to provide legal electricity connections), some community members asked them to install a ramp, and a metal sheet extension on the border of one alley to make it wider and facilitate the transit of people in wheelchairs; a request they were able to comply with even when it was not related to electrical connections.

Figure 5.15. Wheelchair ramp and alley extension in León XIII (Author's photos)

The CNFL projects inside Tejarcillos and Bajo Zamora have also resulted in a general enhancement of the informal settlements as they have given rise to the participation of other public institutions. In Tejarcillos for example, the Municipality of San Jose (MSJ) got involved and increased the width of the main road. In Addition, Ebi, a solid waste treatment firm, provided the community with a container with a hook lift that allows them to dispose of their garbage in one place and facilitate on-site collection. This also led to a feeling of ownership by the inhabitants, which are engaged with the cleanliness of the settlement and with the maintenance of their dwellings by keeping the houses painted inside and outside, improving them by adding ceilings, concrete floors, and taking care of the electrical connections.

In Bajo Zamora, the author noticed a certain degree of organization and planning. A community leader explained how the community has been organizing and creating emergency brigades, which are trained by the National Commission of Emergencies (CNE), doctors or the electrical companies of the country. They also coordinate workshops with the fire corps and ask them for advice. They added that in the near future, they have the intention to locate exit signs in the alleys, to help people evacuate in case of an emergency. The creation of an emergency brigade has helped the community to develop awareness and a sense of responsibility towards fire events. One of the inhabitants of the community commented that she takes care of their neighbours' houses when they are not there in case she perceives a signal of smoke or fire. Also, she added that when she is cooking outside (with a handcrafted stove, **Figure 5.14**), she has a PVC water pipeline (to cook and refill the bucket) and a bucket full of water beside the stove as a precaution in case of fire. All these precautions denote, on a certain level, commitment to the community, a feeling of ownership and willingness to learn and take care of the place where they are living. Juan Pablo Duhalde, the director of social areas of TECHO International, has previously related to the community dynamism in these settlements, stating that people tend to organize by themselves to improve their quality of life (TECHO, 2016).

Finally, it was noted that in larger size settlements such as La Carpio and Leon XIII, little maintenance to the alleys (cleaning) has been done by the inhabitants. In the visit performed in La Carpio, one of the community leaders mentioned that even though they have scheduled more days for waste collection, the inhabitants continue to throw the garbage in the alleys on the days when there is no garbage collection, making the alleys blocked with waste most of the time.

5.4. Discussion

The visits performed helped fulfill the main objective of the investigation, which was to determine differences and similarities between informal settlements of different sizes and the diverse fire risk factors each community might have.

When comparing the physical features of all the settlements visited, it was found that they shared some characteristics such as having narrow alleys (in major or minor proportions), lack of potable piping, absence of proper sewage, issues with the electrical connections, irregular terrains (slopes), uneven pathways, deficiency of fire hydrants and long distances to them when available. Settlements of similar sizes observantly shared more similarities than those of differing sizes. These divergences are mostly related to three categories: cleanliness, alleys, and dwellings. Concerning cleanliness, smaller settlements were cleaner (less waste throughout the settlement) than the larger ones; the alleys in the smaller settlements were a little bit wider than in larger ones; and in the smaller settlements, no concrete houses were found.

Related to fire risk, several factors that can worsen a fire emergency were observed. For instance, in Bajo Zamora one dweller commented about having a water bucket beside a makeshift stove meanwhile she was cooking, but grease fires must not be extinguished with water as they can splash and allow the fire to spread and also injure bystanders. Rubbish is another concern as during a fire, it can work as a combustible material contributing to the fire spread. Rubbish coupled with narrow alleys also hinder the evacuation and extinguishment processes (see **Figure 5.9**). In addition, as observed in Bajo Zamora (**Figure 5.12**), some paths are made with rubber tires which can work as an enhancer of the fire, as they are made of very combustible compounds, such as carbon, oil, benzene, toluene, rubber, and sulfur (Poole, 1998), which can be dangerous for the people as they release toxic and carcinogenic gases when burning (Environmental Engineering and Contracting, 2002).

Moreover, concrete houses (when built) can work as a firewall for other surrounding dwellings. In previous studies, it has been found that the existence of an adjacent dwelling, which changes the fire dynamics of the initial burning stage, can delay the flashover of the burning dwelling (Wang et al., 2022), slowing down the fire spread as well. In their absence, such as in smaller settlements, the fire spreads faster resulting in more dwellings affected by the fire.

Sewage was reviewed due to flooding concerns and their implications in fire. During the rainy season, the main cause of fires in Informal Settlements is related to short circuits (Engineering Unit (Costa Rican Fire Corps), 2019a). During this season, sewers are not able to cope, causing flooding which, combined with lower electrical cables that can fall can result in danger of electrification. Then if a fire and flooding occur at the same time, the fire extinguishment and fire evacuation processes can be severely affected. Another concern with fire evacuation is exemplified in Tejarcillos, where rugs and wooden bridges are located throughout the settlement, which can make evacuation more difficult and dangerous for people trying to escape and firefighters trying to enter to put out the fire, as they can slip, trip, or fall. The paths may also be engulfed in flames due to the combustible nature of the ground coverings.

Another difference between informal settlements or different scales were related to:

(1) the organization of the community and how they manage their affairs between them or the government: In larger informal settlements, commonly there are more than one community organization, different to smaller ones where there is only one community organization. For instance, in La Carpio, there are two community organizations which try to enhance the settlement, but are non-cooperative with one another, resulting in significant complexity when implementing solutions to diverse issues. On the other hand, in smaller informal settlements, it was noticed that the community members try to set their own planning rules (such as a minimum free space in alleys, etc.) and create emergency fire brigades making efforts to keep the place as safe as possible.

(2) the maintenance of the settlement: It was noticed that smaller informal settlements were committed to taking care of the community with the cleanliness, and being aware of their neighbour's properties, as they commented regarding watching their neighbour's house in their absence, in case there is any sign of a fire outbreak. On the other hand, larger informal settlements display poor maintenance of their alleys and there was not enough communication with inhabitants to determine if they have fire safety practices between them.

Regarding fire risk and actions to minimize them, smaller communities try to develop their emergency plans with advice of some public institutions, reflecting a consciousness of the danger under which they live, even though their fire extinguishment techniques are not the most adequate (using water to extinguish fires where oil can be involved). There is no detailed information about how the bigger communities manage their fire risk, but community leaders of La Carpio and firefighters mentioned that in case of short circuit the inhabitants throw sand to where they believe is the start of the fire. Fire safety and education plans were not commented by the community members or leaders, but this does not imply they do not have them, or they do not actively work on them.

All the features previously mentioned pose that fire safety measures may change depending on the informal settlement considered. Although they shared some characteristics, safety measures vary, a fact that should be strongly considered when implementing fire safety plans.

When referring to potential future fire modeling, there are a variety of complexities associated with informal settlements, which include (but are not limited to):

Dwelling features and fuel loads. The dimensions, shapes, arrangement and number of openings, fuel loads and location within the settlement are highly variable between dwellings (Wang, Beshir, et al., 2020). Besides, the different range of materials used for construction and cladding contribute to the fire development, spread, and severity in different ways and phases (Wang, Bertrand, et al., 2020).

Burning behaviour. There is scarce information on fire dynamics and fire behaviour in informal settlement fires. Recent studies and large-scale tests have been focusing on gathering information to characterize them. For instance, Wang et al. performed a full-scale experiment on exemplar informal settlement dwellings and found that as metal sheets deform or walls fall, the air leakages change in the dwellings, consequently changing the ventilation factor, heat release rates and temperatures post flashover (Wang, Beshir, et al., 2020).

Mathematical correlations. The thin-wall boundaries of informal settlement dwellings coupled with natural leakages make them less predictable when using contemporary fire safety theories for Heat Release Rate, temperatures, flashovers, and flame shapes, since they were based on thermally thick-wall dwellings with well-sealed compartments, impeding the proper replication of the data (Wang et al., 2022). Also, the heat transfer for informal settlement dwellings is dominated by radiation instead of convection as in thermally thick dwellings (Wang, Beshir, et al., 2020).

Layout changes. The layout of houses in informal settlements may change due to fast population migration and as a consequence of fires. After a fire, the recovery process begins almost immediately after the fire services leave the area, resulting in a different settlement layout within days.

Path obstructions. Rubbish or waste bags are usually spread throughout the alleys of the settlements, but it is difficult to know with exactitude when and where those obstructions will be located.

Human Behaviour. There is a lack of theories supporting human behaviour in informal settlement fires, but in previous research it was observed a "stay and defend" posture by the inhabitants during emergencies (Guevara et al., 2021). This is a critical life safety decision influenced by many factors such as gathering personal belongings, observing neighbours response, age, family, and cultural factors, etc., that supports a "defend in place" strategy

(Johnson et al., 2012). Furthermore, during fire evacuation in emergencies, heterogeneity in people's behaviour and the interaction between them and the environment plays an important role (Rendón Rozo et al., 2019), which makes it difficult to predict how the population is going to behave, especially in these settlements.

These features impede the generation of either fire dynamics, fire spread or fire evacuation modeling precisely, since it has attained a level of uncertainty that can result in misleading outcomes. Through experimental data collection, it should be possible to achieve improvements on the accuracy of informal settlement fire risk assessments, by giving foundational knowledge to refine numerical and theoretical modelling of fire spread between informal settlement dwellings (Wang et al., 2022). Cicione et al. stated that even with powerful software such as Fire Dynamics Simulator, predicting fire spread rates between fragile dwellings is difficult since there are numerous unknowns that are inherent in informal settlements (Cicione, Collen, et al., 2020).

5.5. Towards a framework for analyzing settlements for fire risk

This research works as an exploratory step towards establishing a framework for more formalized data collection for a number of settlements inside a specific zone. In this first stage, brief observations in some informal settlements were done. The next research step will be comprised of determining which data should be collected and how the process should be carried out. Initial assumptions include performing thoroughly characterization of more settlements within the study zone, analysis on fire dynamics and fire response by the population and emergency services, going through fire reports and investigation to determine fire causes and consequences, and collecting information of inhabitants with previous experiences with fires, among others.

Some of the strategies and tools that can be useful to collect more data on informal settlement characterizations and fires can be: performing naturalistic observation (as already done in this work), formal interviewing, and data collection of fire reports and fire investigations. At this point, it is difficult to propose mitigation strategies as they are constrained by inadequate data on incidence, impacts, and causes, mainly due to a lack of capacity and resources for data collection, analysis, and modelling (refer to (Twigg et al., 2017)).

Data for modelling is needed whether evacuation, dynamics or structural. Without most of these, the equations can result in variations of predicting conditions without strong certainties (Wang et al., 2022). Models may not be able to represent accurately what really happens during those fires, as there are several degrees of uncertainty attached to each settlement and their population, such as how are they going to behave, or what will be the state of the alleys at the moment of the emergency.

After gathering data, it is necessary to compare it and reclassify it as it generally varies depending on the institution consulted. It is difficult to find reliable information about a specific informal settlement. Additionally, there is scarce information regarding demographics, topography, fire data, house, and population density, etc. which limits the understanding of the real situation. This study also intends to demonstrate that it is necessary to create bonds between different public institutions for information gathering and standardization.

This research only performed visits in four informal settlements amongst 112 that already exist inside San Jose, which might not represent with exactitude the features of all the existing informal settlements. A greater sample number is necessary to make quantifiable remarks between settlements. For now, the author makes only qualitative discussion points. Additionally, the site visits were performed alone, therefore, there is a certain degree of subjectivity in the opinions written herein, as the author was unable to compare its perceptions against other collaborators. Future work should include larger teams to address more informal settlements and avoid subjectivity.

The author encourages researchers to create a database of the primary features of informal settlements of different scales, to be able to make a comparison of differences between them. Also, it is encouraged to gather information about fires in these informal settlements, to compare how the population behaves and if the characteristics of the settlement -either physical or behavioural-interfere when responding to fire emergencies.

5.6. Conclusions

The research herein has strong usefulness towards community organizations and planning for fire response. The data sets though are limited in number and an overarching study should be considered. With Covid restrictions now decreasing, field studies should be easier to organize and collect the requisite information.

The present chapter allowed the author to accomplish their objective regarding finding the differences and similarities between informal settlements of different scales in San Jose, Costa Rica and to define a second stage framework for further data collection and towards a full fire risk framework. To achieve this, several field visits were performed, which allowed the author to conclude that there are clear physical differences between informal settlements of different scales, while the settlements of similar scale shared several similitudes. Those differences were mainly related to the organization and maintenance of the informal settlement. In smaller informal settlements, the people were more organized within the settlement and cleaner than larger ones, demonstrating a reduced fire risk. About the organization, it was found that larger informal settlements have several community organizations that sometimes conflict with each other, making the enhancement of the informal settlement difficult. Finally, it is concluded that even though the informal settlements share some similarities, all of them are different from each other and they cannot be addressed all in the same way.

Chapter 6: Material testing procedures

From previous research performed by the author, it was established the necessity to create a test procedure to determine the fire behaviour of innovative or current materials that can be used in future informal settlement housing construction. For this aim, testing procedures for samples in two different settings were performed, as well as a temperature tree that will allow the author to determine the temperatures gotten and the steadiness of the measurements at different heights from the heat source depending on the fuel used to carry out the tests. This chapter establishes a simplified test procedure for the quick study of materials that could be considered in informal settlement construction.

6.1. Introduction

It was previously discussed that houses in informal settlements are built from any available material, but there is a dearth of information impeding the understanding of fire spread and fire dynamics in these settlements (Cicione et al., 2019). Recent large-scale tests in informal settlement houses have been carried out aiming to minimize this knowledge gap, for instance, Walls et al., performed tests on fragile dwellings made from steel tubing frames and cladded with galvanized steel sheeting. This full-scale burn tests presented three fire types, a smoldering fire test, a 25 kg/m^2 wood fire load test and a 'representative' shack fire test, with the aim of understanding fire spread and fire dynamics and assessing the performance of active fire protection devices (Walls et al., 2017b). Furthermore, Cicione et al, also conducted research in two full-scale fragile dwellings, one using a corrugated steel sheeting clad and the other one with timber cladding, both with the objective of comparing the results to numerical models and computational fluid dynamic models (Cicione, Beshir, et al., 2020). Additionally, Cicione et al., performed experimental testing on the effects of leakages and ventilation conditions on informal settlement fire dynamics, where three fragile dwellings clad with corrugated steel sheets, that were fixed to SA (South African) pine timber frames and lined with cardboard were burnt (Cicione et al., 2021).

Small scale tests have also been conducted, such as the database created by Wang et al., where a total of 345 cone calorimeter tests were conducted on 32 different typical combustible materials collected from informal settlements. This allowed observing that 70% of the materials tested will ignite before flashover (Y. Wang, Bertrand, et al., 2020). All of these tests were developed considering South African informal settlement houses, although it was stated that this research is applicable worldwide (Walls et al., 2017b), some modifications must be considered for fitting in Costa Rican informal settlements, including the construction method, the materials used, and the housing planning and building.

These recent tests motivated the author to include a chapter describing procedures to evaluate the thermal characteristics of innovative materials and their feasibility for the construction or protection of informal settlement houses against fire hazards. This chapter includes the description for testing samples of two sizes, on two different test scenarios, one using large-size samples in pool fires (large fires), and the other using smaller samples in cone calorimeter tests (small fires). Both methods are controlled and repeatable and will allow understanding the behaviour of materials under fires. Pool fires are defined as the combustion of flammable liquid or evaporating substances at their base with a diffusion flame, it includes basic observations on fuel evaporation, the diffusion process in the fire plume, the combustion process, radiative heat transfer, and soot formation (Chen et al., 2023). Cone calorimeter tests by their part are laboratory-based tests that provide relatively simple data such as mass loss, heat release rate, and time of ignition, among other parameters that can be used in the assessment of the fire hazard of a given material (Drysdale, 2011) (Dewaghe et al., 2011). To this end, pool fires will allow observing heat transfer throughout the material, meanwhile, cone calorimeter tests will help determine the combustibility of the material. Upon successful performance of the material, a model on heat transfer can be built subsequently, which may help establish a larger-scale fire resistance compliance test, helping on reducing the costs of the material research.

Finally, a thermocouple tree holding nine thermocouples at different heights was constructed above the heat source, aiming to gain a better understanding of the temperatures experienced in methanol pool fires and their consistency of them over time.

6.2. Samples preparation

For these procedures, two samples will be used to determine thermal material properties, both will be square samples. The first type of sample will be denominated Type A, it will be deemed as the larger one and it will be used in pool fires; the dimensions should be approximately 30x30 centimeters, with a thickness of around 7.5 centimeters. The second type of sample will be denominated Type B, it will be considered as the smaller one and will be used in cone calorimeter tests; the samples will be around 10x10 centimeters, with a thickness of approximately 2.5 centimeters.

6.2.1. Type A

To prepare the 30 cm samples for testing, a total of six holes will be marked and drilled into the sample from the unexposed surface. The holes must be drilled in a circle with a 50 mm radius, each hole being 60 degrees apart from the other, as can be seen in **Figure 6.1**. The drill depths to do are 25 mm, 50 mm and 73 mm, the sample included two holes for each depth. The drill bit used should be of the same diameter as the thermocouple or if a bigger one is used then rockwool should be used to maintain them in place and snugly. If the material has uneven surface along it, the drill press must be recalibrated for each hole to ensure consistency and avoid going through the sample.

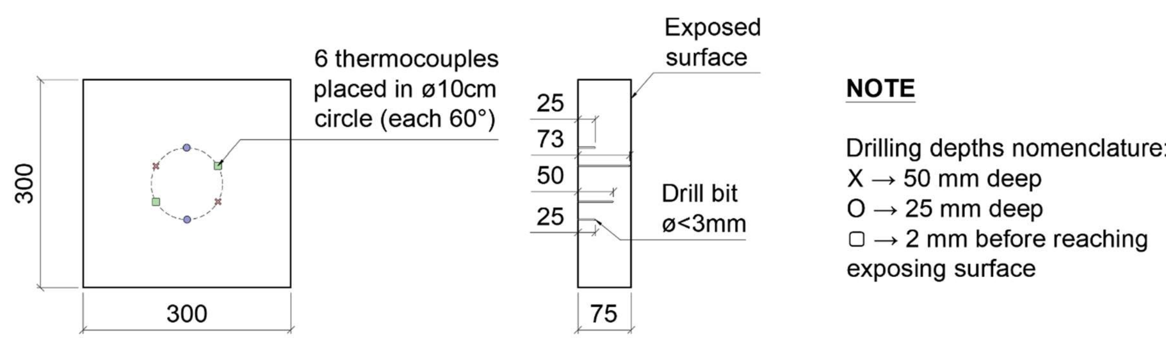


Figure 6.1. *Example of the drilling plan*

A total of eight thermocouples must be placed in and on the sample. Six of the thermocouples must be placed inside the sample, another one must be placed on the exposed surface of the sample, and the last one must be placed on the unexposed surface of the sample. Each of the six thermocouples inside the sample must be held in place using Rockwool insulation if the drill bits used to perform the holes were bigger than the diameter of the thermocouple. The insulation must be packed around the thermocouples, being careful of avoiding placing the insulation at the tip of the thermocouple to ensure an accurate temperature reading. The thermocouple on the unexposed surface must be taped to the sample with aluminum tape to reduce the movement involved and to ensure the thermocouple is reading the temperature continuously at the surface. The thermocouple on the exposed surface must be placed between the frame (described further) and the sample to reduce any movement and keep the thermocouple against the surface of the sample. In addition, one of the lateral sides of the sample must be painted in a speckle pattern with spray paint to allow for Digital Image Correlation (DIC) to be performed to calculate the strains that the sample is experiencing (Refer to **Figure 6.2**).

Figure 6.2. *Example of painting pattern for Digital Image Correlation*

6.2.2. Type B

For the 10 cm sample preparation, only one hole must be drilled, and it should be done in the middle of one of the sides of the sample as shown in **Figure 6.3** a) The objective is to place the thermocouple in the center of the sample thickness to gather the temperature data at that point, therefore, it does not matter if the drill bit is not large enough to reach the middle of the sample height. If the sample does not allow for the perforation of the hole in one of the lateral faces, then it can be done in the unexposed face of the sample as shown in **Figure 6.3** b). The holes must be perforated with a drill bit with the same diameter as the thermocouple, making it fit snugly into the sample.

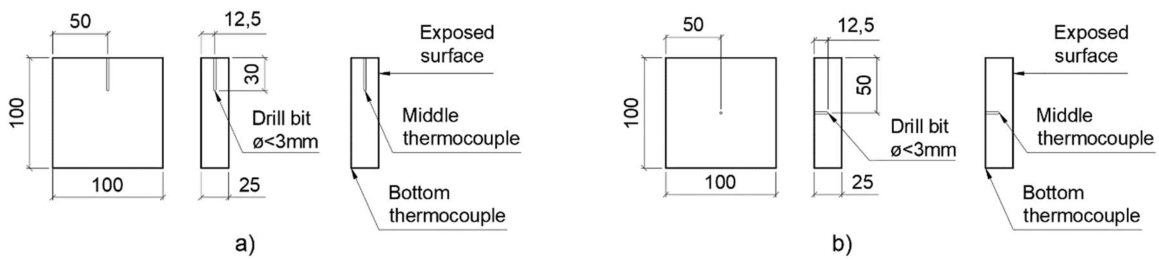


Figure 6.3. *Drilling plan for small samples*

For these types of samples, only two thermocouples will be used, as it can be considered that the surface will have the same temperature as the cone due to the short distance between the sample and the heating coil of the cone (25 mm). One of the thermocouples must be located in the previously drilled hole and the second one should be stuck to the unexposed surface using aluminum tape to avoid the displacement of the thermocouple resulting in inaccurate temperature measurements.

Before conducting the fire tests a database of all the samples to be tested must be created, including code identifiers (labels), dimensions, weight, along with images of each face of the sample. The database should be continuously updated if more samples are added.

6.3. Test set up

6.3.1. For Type A samples

This test will be performed using a heat-resistant steel pan, which will be filled with liquid fuel that will be ignited afterwards. This pan will be placed over one layer of bricks, which will serve as heat protection for the floor underneath (to avoid cracking), as well as to ensure that no fuel will reach the direct floor causing fire spread in case of splashes occur during testing. If testing in a laboratory with connection holes to adjacent levels, bricks will also serve to avoid fire spreading to the floor below. **Figure 6.4** shows a sketch of the pan used for these fire tests.

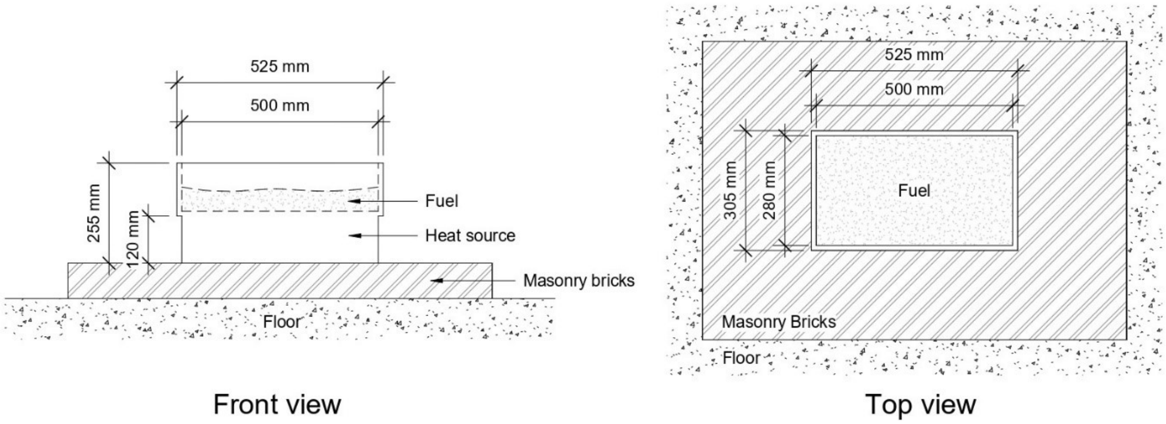


Figure 6.4. *Steel tray dimensions and location detail*

A distance of 20 cm should be left between the exposed surface of the sample and the top of the fuel tray. To elevate the sample over the fuel pan, a frame was built of galvanized steel slotted angles and stainless-steel threaded rods as shown in **Figure 6.5**. This free space can be modified depending on the author's criteria by adjusting the location of the threaded rods in the slotted elements of the frame. When testing bricks can be placed over the feet of the frame to increase its stability.

Figure 6.5. *Galvanized steel frame*

Between the two threaded rods where the sample will rest, there is a 25 cm space to allow for any deflection to be caught on camera (the sample may be roughly 30 cm in length). The fuel used for this procedure is methanol which helps when using narrow-spectrum illumination technology due to the lower soot production. Fuel can be changed depending on the author’s requirements or necessities, such as temperature, the heat of combustion, and soot production, among others. Previous tests have also used kerosene and acetone, but methanol represents the least soot-producing fuel while kerosene represents the most soot-producing fuel (Nicoletta et al., 2021).

Blue light technology along with cameras with extra lenses and a shutter timer attached are used to get images at a determined time with the goal of capturing any deflection in the sample tested. The blue light must be projected onto the sample and a blue lens along with a polarizing lens must be implemented over the lens of the camera. This strategy is used to filter out the flames to provide a clear image of the sample. The cameras used must be able to set at least a framerate of 0.5 frames per second, an ISO of 2000, an aperture of f/13, and a shutter of 1/800. An example of a test setup can be seen in **Figure 6.6**. The images collected will then be introduced into a Digital Image Correlation (DIC) software program to evaluate the thermal deflections suffered by the tested sample.

Figure 6.6. *Example of Type A test set up.*

6.3.2. For Type B samples

This is a laboratory test performed with a cone calorimeter, where the sample is located amidst a load cell and the heating coil (refer to **Figure 6.7**). The latter will emanate a heat flux previously determined and calibrated in the equipment by the author. The Cone

Calorimeter apparatus is useful in allowing for controlled and repeatable tests (Chorlton & Gales, 2020). In this test, the sample will be isolated in all the side faces and in the bottom, in order to achieve a unidirectional heat flux which will result in the harshest fire condition the sample can experience during a fire, allowing to determine the heat transfer capacity of the material, among other characteristics. This isolation can be achieved by wrapping all the sides with fiberglass and tying it together with an aluminum cord as shown in **Figure 6.8**. For more detail on testing and procedure with the cone calorimeter, it is recommended to consult the standard ASTM E1354 (ASTM International, 2022).

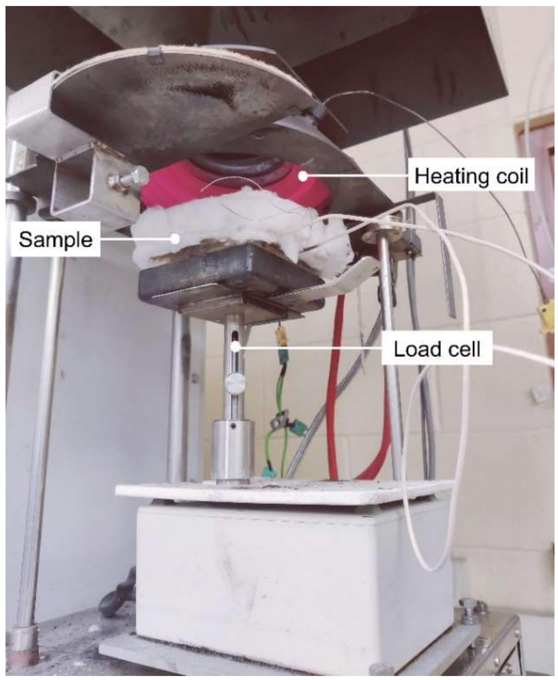


Figure 6.7. *Example of Type B test set up.*

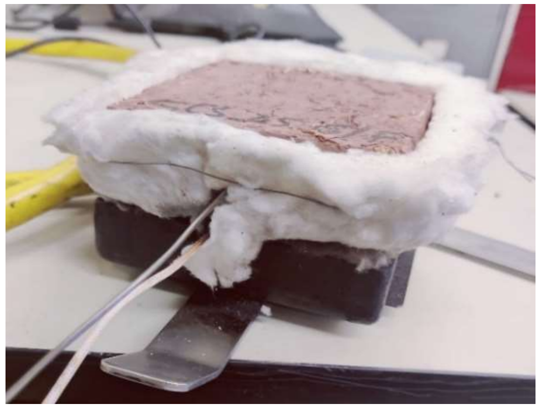


Figure 6.8. Sample wrap up.

6.4. Heat source temperature assessment

6.4.1. Thermocouple tree

For running pool fire tests, the author chose methanol as the main fuel. The amount of methanol to use will depend on the time needed, for 30-minute tests 8 liters will be enough, meanwhile for one-hour tests 16 liters will be enough. To determine the consistency of the temperatures gotten by the fuel used, the frame built to hold the samples was rearranged to create a thermocouple tree where nine thermocouples were placed starting at 10 cm until 90 cm over the fire pan edge. **Figure 6.9** shows a sketch of the tree built and **Figure 6.10** depicts the test in progress.

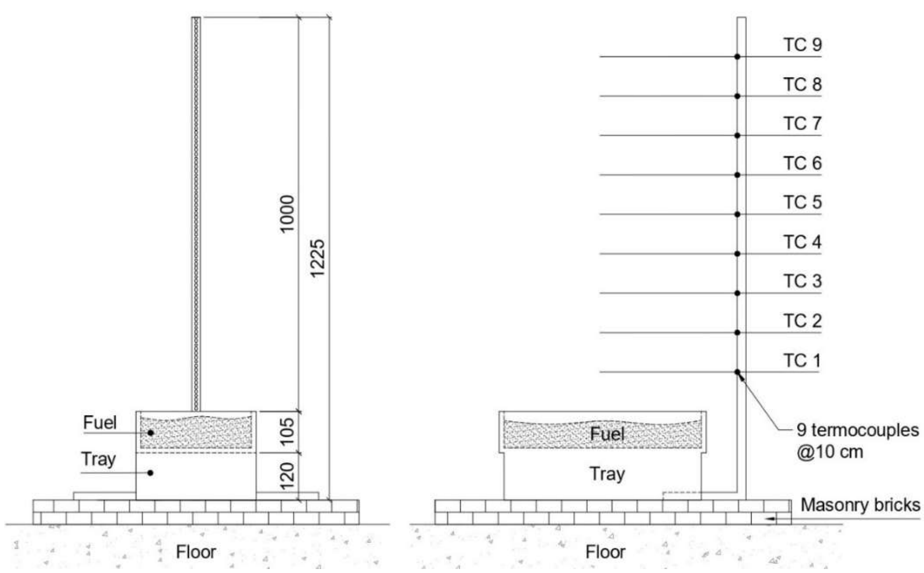


Figure 6.9. Sketch of the thermocouple tree built.

Figure 6.10. Thermocouple tree test

For the tree measurement tests, it was determined to set a fire that burns for approximately one hour (16 liters of methanol). Each bottle of methanol contains roughly four liters of fuel, they are filled manually thus the amount poured inside will depend on who filled them. According to the total duration of the test, it is estimated that the bottles contained more than four liters of fuel as the fire lasted 75 minutes. From this test the graph shown in **Figure 6.11** was obtained, it displays the temperatures gotten for the 75-minute-long methanol pool fire test.

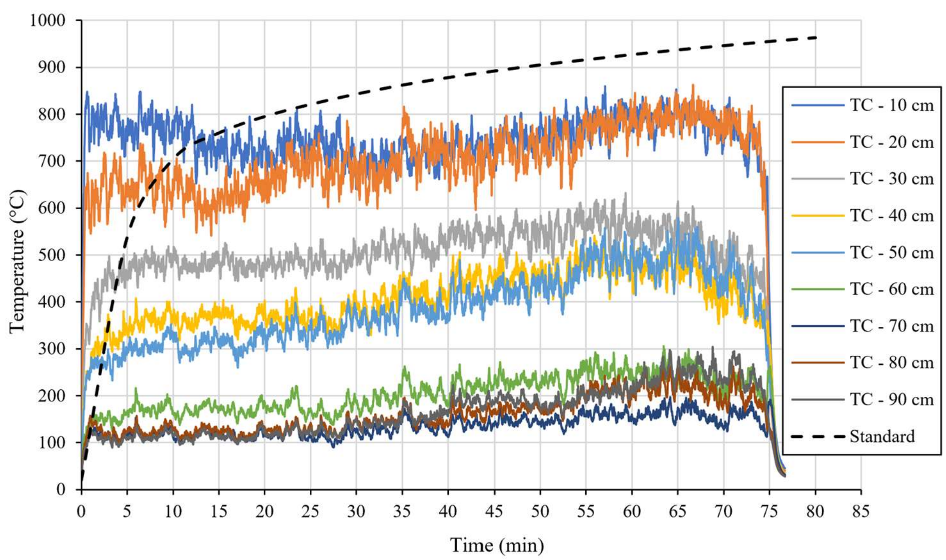


Figure 6.11. Tree temperature measurements.

It is observed that the temperatures are stable throughout the tests, with the variations being related to the normal movement of fire. The thermocouple located 10 cm from the heat source, reached a maximum temperature corresponding to 850°C, while the farthest thermocouple (90 cm above the fuel tray), reached a maximum temperature of 200°C.

6.5. Evidence of the procedure application

6.5.1. Type A tests

Figure 6.12 shows the graphic obtained for one of the tests previously performed (tests N° 3) using the described procedure. For the samples tested, the average of the ten temperatures surrounding the maximum value were taken, to avoid using the peak temperatures, which might not be the precise maximum value. **Figure 6.13** displays the average temperatures gotten for the samples tested, noting that zero distance is considered the bottom of the sample (exposed surface) meanwhile 75 mm is the top of the sample (protected surface). Appendix A shows complementary information on the tests performed.

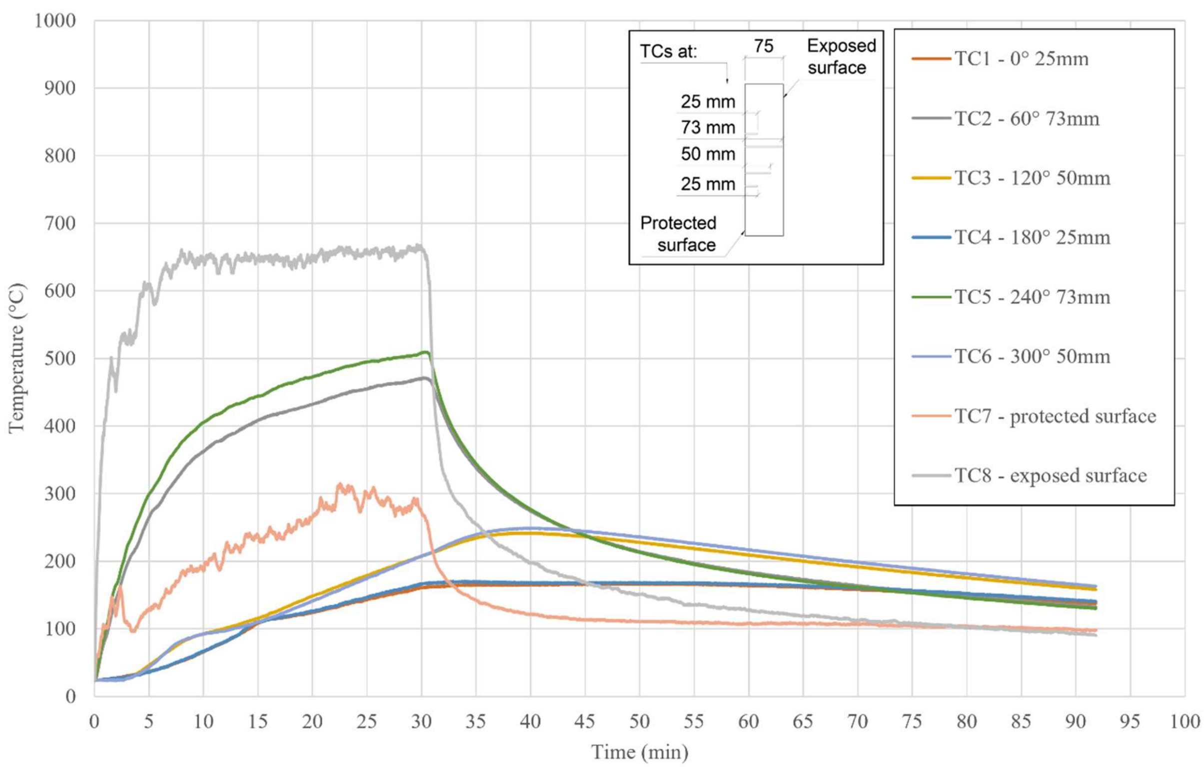


__Figure 6.12.__ Example of results gotten from Type A samples (pool fires)

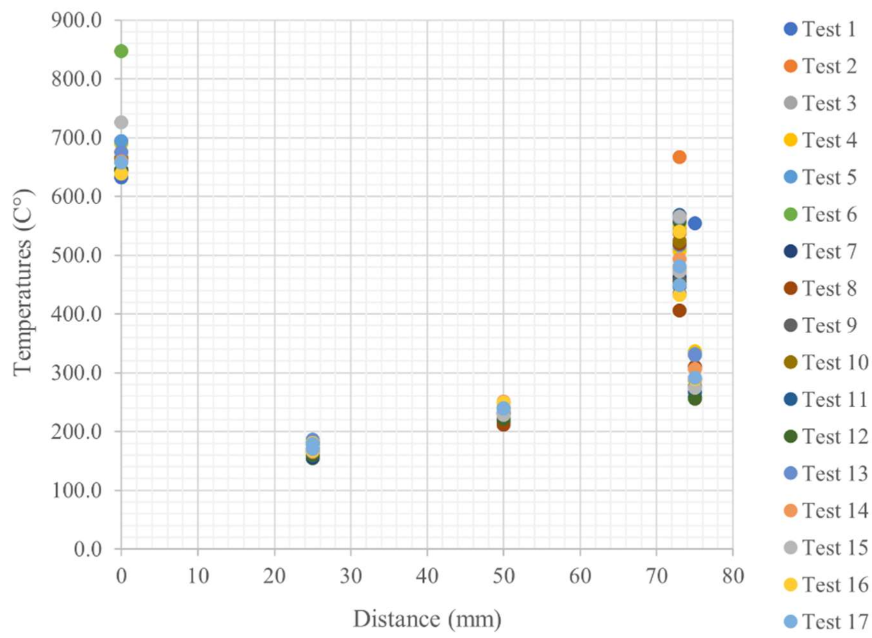


Figure 6.13. *Summary of temperatures obtained for Type A tests*

In **Figure 6.12** it can be observed that the maximum temperature reached on the exposed surface was 665°C, 509°C at a depth of 73 mm, 248°C at a depth of 50 mm, 169°C at a depth of 25 mm, and 308°C on the protected surface. Immediately after the fire goes out (approximately at 32 minutes), the temperature on the protected surface decreases to 259°C, after that, it can be observed in the graphic how the temperature is still being transferred inside the sample, mostly in the thermocouples located at 50 mm and 25 mm. It was noticed that the maximum temperatures for the exposed and protected surfaces, along with the thermocouples with depth of 73 mm reached their maximum temperatures at the end of the heating phase, however, the thermocouples at depths of 50 mm and 25 mm reached their maximum temperatures during the cooling phase. The sample cooled to a unified temperature of roughly 180°C read by all thermocouples, then proceeded to cool until reached 100°C. The difference in the temperature readings between two thermocouples situated at the same depth in a test can be related to thick variations throughout the samples crafted. This type of test allows to determine the thermal behaviour of the material under fire and to observe the heat transfer throughout it.

The Eurocode as well as other international standards such as ASTM, have been used to build the Canadian codes, thus fire-resistance testing and analysis developed using these standards are usually acceptable to Canadian officials (Canadian Wood Council, n.d.) (CSA, 2019). In the Eurocode 2 for the design of concrete structures, temperature profiles for conventional concrete elements can be found as well, including isotherms for slabs that also can be extended to analysis of walls exposed to fire. **Figure 6.14** display an isotherm for a slab of 200 mm depth, with the allowed temperatures for different distances from the exposed surface, it also depicts the fire resistance curves with the limits for a certain fire resistance time in the element tested.

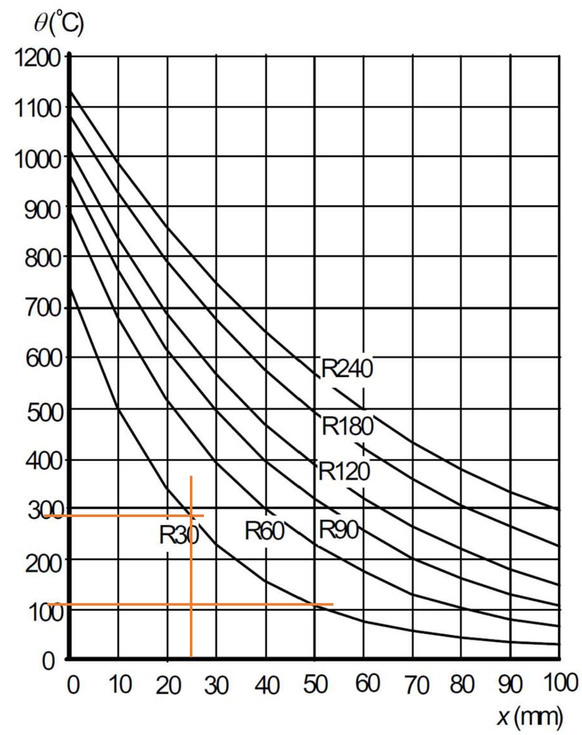


Figure 6.14. *Temperature profiles for slabs (h=200mm) for R60 and R240* (CEN, 2004)

The sample taken from the Eurocode is more thermally thick than the one tested by the author, even though the thickness is a limiting factor, the values displayed in the isotherm will be close in terms of 2D heat transfer, as the difference between them is small.

When comparing the temperatures obtained for the sample tested at 25 and 50 mm from the exposed surface, against the data of shown in the isotherm, it is observed that at 25 mm the sample reached 210°C after 30 min tests, and after the extinguishment of the fire, an increase of the temperature was noticed, reaching the maximum value of 248°C after 37 min test. At

50 mm from the exposed surface, the sample reached approximately 170°C after 30 min test. From **Figure 6.14** it is observed that for a fire resistance of 30 minutes, the threshold temperatures are 280°C at 25 mm and 110°C at 50 mm, the sample tested, complies with the temperature at 25 mm but the temperature at 50 mm is higher, allowing to conclude that the material will not be suitable for fire protection if used in housing construction.

Building codes imply that a fire rating is required for a specific type of occupancy. Buildings in higher importance categories such as schools or community centers are frequently asked for long fire resistance times. Fire resistance incorporates a heat transfer criterion. The heat transfer also will affect the stability and integrity of the material. A comparison is made herein to consider the heat transfer observed in the tests used, and the heat transfer which would be expected in a fire resistance (Standard) test. In this comparison, the author's test was less severe in time and temperature than the time and temperature expected from the standard fire (**Figure 6.11**), but even with less severe temperature, the heat transfer results indicate that the transmission for the material examined is worse when compared to concrete under a more severe standard fire exposure. For example, this comparison illustrates that if a standard fire test is performed with this bespoke material, the material is unlikely (there are other factors to consider as well) to have a fire resistance rating greater than 30 minutes when compared to the concrete material. The test performed by the author is convenient because it is a low-cost test that is indicative of expected heat transfer behaviour that may be observed in a more costly standard fire testing; thus, the proposed method is very practical and provides useful information for planning future test regimes.

In this set of tests, the samples were completely exposed to fire, as Digital Image Correlation (DIC) analysis was intended to be done afterwards, aiming to determine thermal strains in the material. In future tests, all the lateral sides of the material will be insulated as well as the top surface, in order to resemble the tests done in the Cone Calorimeter but on a slightly larger scale. The aim is to compare the information to analyze how the material behaves in two different sizes under two different tests.

6.5.2. Type B tests

Figure 6.15 depicts the graph obtained from a test using the specified approach. For this test, the cone calorimeter was set up to emit a heat flux of 50 kW/m^2 and the sample had 6% fiber in its composition. The maximum temperatures reached by the specimen during the test were 506°C in the thermocouple located in the middle of the sample, and 438°C for the bottom thermocouple. If compared with concrete, using the ASTM E119 fire-resistance test standard, the acceptance criterion establishes that the maximum temperature the unexposed side of the material can reach during a fire test is 139°C above its initial temperature (ASTM International, 2020). In both tests (pool fire and cone calorimeter) the material surpassed the acceptance criterion temperature, allowing to discard of the material as a thermal insulator since the temperatures reached on the unprotected side are high and will compromise other materials close to it.

For example, if used besides other materials, such as wood members, the temperature reached at the bottom of the sample can easily start charring the wood, as it is estimated that wood pyrolysis starts between 200°C to 300°C (Frangi & Fontana, 2003). For this material, the heat transfer was uniform and continuous however steady state was not reached during the time tested. More information about the tests performed can be found in Appendix A.

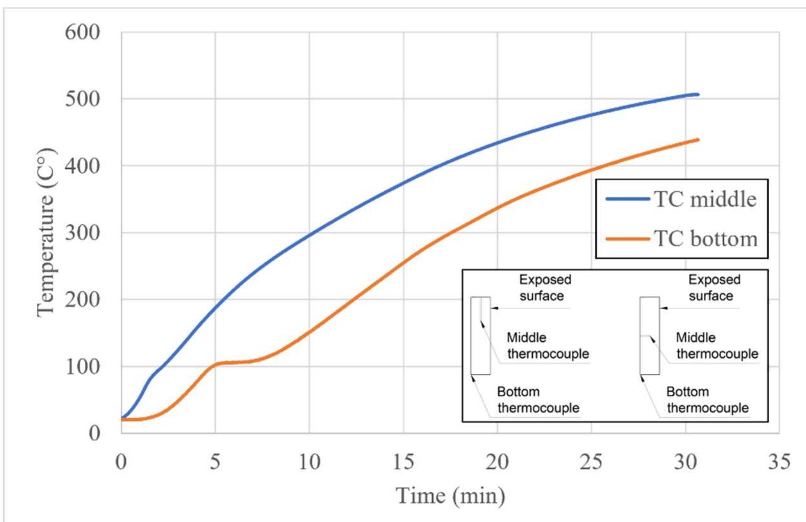


Figure 6.15. Example of results gotten from Type B samples (cone calorimeter)

6.6. Final thoughts

The procedures described above allow the researcher to get an initial insight into different or innovative materials that are proposed to be used in informal settlement housing construction or fire protection. It will help discard or go further on the implementation of these materials in an easy and economical manner. The procedures work efficiently as a starting point for determining the fire behaviour of a material and if they are suitable for the stated purpose. Additionally, they allowed the author to compare the results with standards or fire codes and find out if they comply or not with the current regulations.

The data collected through the described procedures contributes by generating information that can be further used for model development of the thermal heat transfer through the material. The temperature data can be used to validate the models along with other parameters such as specific heat, heat capacity, and thermal conductivity, among others.

One of the limitations of the use of thermocouples when testing is that the moisture inside the sample starts evaporating and the water coming out produces a cooling effect in the reading of the thermocouple, slightly affecting the accuracy of the readings obtained.

The procedure can be modified depending on the materials used, sample dimensions, literature review, desired parameters to be tested, and so forth. If higher temperatures need to be reached, other fuels can be used as long as the necessary literature review is conducted, in addition, to thoroughly investigating the new fuel before using it. Calculations such as flame height, maximum temperature, heat flux, and ceiling temperature to avoid active fire systems getting activated, among others are recommended to be considered.

The examples used in this chapter from previously done tests, allowed to determine straightforwardly that the results of the material tested was not good enough to meet the acceptance criteria of the current standard regulations and allowed to conclude that it will not be a safe material to be used for fire protection in informal settlement houses.

Chapter 7: Conclusions and Recommendations

7.1. Summary

This research works as an exploratory phase toward establishing a framework for fire safety in informal settlements. To this end, further steps must be taken, such as (1) suggesting a method for data collection, that allows considering the different features (physical and behavioural) for a number of settlements inside a specific zone (San Jose in this case); (2) to find a way to compare data between public institutions, which will allow obtaining realistic information on the communities under study, (3) as well as to propose actions for the collection of data on fires in these settlements. In this first stage, brief observations in some informal settlements were done.

Chapter 3: analyzed human behaviour in a fire in an informal settlement. The analysis was based on video footage of a fire in El Pochote, located in San Jose, the capital of Costa Rica. The response principles used by the firefighters to control the fire, the behavioural actions of the local inhabitants during the fire, and the interactions between the firefighters and the locals were explored in this chapter. A number of aspects that make it difficult to study fires in informal settlements were discussed in this chapter, including the complex social interactions which are highly situational, such as the density of the informal settlements, their expansion, education, unemployment, and other demographics that may play a role in human behaviour in fire. As well, it is generally known that many fires in informal settlements are never reported to the fire department because they are managed by the community, and further firefighting support is not needed.

This chapter contributes to informal settlement fire research by providing a foundation upon which additional evidence of human and fire behaviour in informal settlements can be gathered and compared.

Existing behavioural theories can provide a base upon which researchers can build and form theories applicable to the context of informal settlements. To this extent, this chapter outlined and undertook the preliminary research steps needed to show how future studies can better examine human behaviour in informal settlements.

From Chapter 4: it was concluded that neither Canada's nor Costa Rica's code development processes lend themselves easily to incorporating informal settlement regulations into their codes. As informal settlements are a globally growing issue, both countries need to develop approaches in order to address informal settlements and informal settlement safety. Costa Rica is currently in an early stage of preliminary investigations. The stakeholders are trying to understand the issue of informal settlements and how to begin addressing it, aiming to find out what are the future steps to propose solutions for different problems related to informal settlements. While there have been some Canadian initiatives to begin addressing homeless encampments, from a government standpoint, priority has been given to homelessness prevention, improved shelter access and quality and increased availability of affordable housing.

Chapter 5: has strong usefulness towards community organizations and planning for fire response. The data sets though are limited in number and an overarching study should be considered. With Covid restrictions now decreasing, field studies should be easier to organize and collect the requisite information.

The present chapter allowed the author to accomplish their objective regarding finding the differences and similarities between informal settlements of different scales in San Jose, Costa Rica and to define a second stage framework for further data collection and towards a full fire risk framework. To achieve this, several field visits were performed, which allowed the author to conclude that there are clear physical differences between informal settlements of different scales, while the settlements of similar scale shared several similitudes. Those differences were mainly related to the organization and maintenance of the informal settlement.

Finally, the procedures described in Chapter 6: allow the researcher to get an initial insight on different or innovative materials that may be able to be used in informal settlement housing construction or fire protection. It will straightforward contribute to discard or go further on the implementation of these materials. It also serves as a starting point to determine the thermal properties of a material and if they are suitable for the purposes stated, by comparing the results with current standards or fire codes to find out if they comply or not.

The procedure can be modified depending on the materials used, samples dimensions, literature review, or advice given from previous research, and so forth. If higher temperatures need to be reached, other fuels can be used as long as the necessary precautions are taken, and the safety operation procedures of the facilities are obeyed.

7.2. Conclusions

The following conclusions were drawn from the field visits, the analysis of photos and videos of fires in informal settlements, the review of computational modelling, and the experimental tests described in this thesis:

- ***Behavioural frameworks -*** Observations on behaviours of the residents were often consistent with the existing behavioural frameworks, e.g., PADM, yet the author observed that the current frameworks lack empirical evidence to be applied to human behaviour in informal settlements.
- ***Behaviours of the firefighters and the locals -*** According to the members of the Costa Rican Fire Corps, civilians intervene in their fire extinction efforts, thus the firefighters have opted to work alongside the communities rather than fighting against their involvement throughout the fire containment and extinguishment process. However, behaviours that are counter-effective, reported by the firefighters as well as in other studies, were not observed in the El Pochote fire video footage.
- ***Roles in community members -*** some resident behaviours were observed to mirror those in the existing literature, such as attempting to tackle fires, movement through smoke, re-entry behaviour, and clear differences between males and females in behaviour and frequency of certain behaviours (males were more likely to exhibit firefighting behaviours whereas females were more likely to alert others and exit the property). In addition, novel bold actions by some residents, such as walking on the roofs, passing alleys while firefighting operation was taking place, and blocking the alleys with personal belongings, were observed.
- ***Adoption of new measurements -*** Fire spread within informal settlements and tent encampments is understudied and would contribute to understanding fire risks in informal housing. Costa Rica and Canada are working to address the issue of informal housing, with the anticipated increase in informal settlements due to population

growth and worsening of poverty and the affordable housing crises, these measures may not be sufficient.

- ***Comparison between different scale settlements -*** In smaller informal settlements, the people were more organized within the settlement and cleaner than larger ones, demonstrating a reduced fire risk. About the organization, it was found that larger informal settlements have several community organizations that sometimes conflict with each other, making the enhancement of the informal settlement difficult. Finally, it is concluded that even though the informal settlements share some similarities, all of them are different from each other and they cannot be addressed all in the same way.
- ***Compatibility of the results:*** Observations herein may not be generally applicable to all informal settlements in Costa Rica or internationally. Every informal settlement is unique, as is every fire. Various socio-economic differences regionally make comparisons particularly difficult in Costa Rica, as well as varying fire brigade response practices which are highly dependent on community relations.
- ***Informal settlement modelling -*** Data for modelling is needed whether evacuation, dynamics or structural. Without most of these, the equations can result in variations of predicting conditions without strong certainties (Wang et al., 2022). Models may not be able to represent accurately what really happens during those fires, as there are several degrees of uncertainty attached to each settlement and their population.
- ***Material testing:*** thermocouple accuracy for readings is the main limitation of the test procedures proposed. However, they allow assessing materials in an easy and economical way, allowing to save time and economical resources.

The study of informal settlements in Costa Rica is still a new subject with vast uncertainties and knowledge gaps. To keep improving on closing it, efforts from the social and engineering point of view need to be made, individually and combined. From the social point of view, involvement with more vulnerable communities within the country and the creation of bonds between public and private organizations are crucial to reducing the level of uncertainty in socio-economic affairs.

From the engineering point of view, a lot of empirical data needs to be collected and, more importantly, analyzed. The establishment of agreements with the Costa Rican Fire Corps for data collection and analysis is an important step for the beginning of mutual collaboration between researchers and first responders.

A valuable contribution from the social and engineering fields combined would be the study of current behavioural frameworks or develop an overview of what has been published related to fire safety in informal settlements, to determine the most applicable behavioural theories that can be validated or tailored to be suitable for informal settlements. Finally, the author encourages researchers to look at the vast field to study that is present in Costa Rican informal settlements and try to contribute by generating information that aims to improve their fire safety.

7.3. Recommendations

Essentially, the research presented herein expands the knowledge of fire safety in Costafroman informal settlements. Observations made throughout this thesis have identified areas where future research needs to be performed. The work conducted herein establishes the first steps towards creating a framework for fire safety for Costa Rican informal settlements. Based on this, the following recommendations are derived:

- ***Data Collection -*** to compile information regarding demographics, topography, housing and population density, building materials, fire statistics not limited to: fire risk, fire evacuation, fire dynamics, and structural behaviour in fires; which are necessary to improve the understanding of the real situation. This data will help by providing a basis to validate software modelling equations, which may subsequently contribute to improving fire safety of informal settlements. Creating bonds between different public institutions will be crucial for information gathering and standardization.
- ***Fires in informal settlements -*** more investigations into fires in informal settlements must be done, including different fires in the same settlements and fires in different informal settlements. Initial assumptions include analysis on fire dynamics and fire response by the population and emergency services, going

through fire reports and investigation to determine fire causes and consequences, and collecting information of inhabitants with previous experiences with fires, among others. This will allow for investigation of possible risk reduction interventions, which could then be used for the development of local community fire safety strategies.

- ***Fire response -*** It is encouraged to collect information about fire sizes, fire response and behavioural aspects observed within the informal community when larger fires occur. This information will be useful to compare between informal settlement, how the population behaves and if the characteristics of a specific settlement -either physical or behavioural- interfere when responding to fire emergencies.
- ***Informal settlement characterization*** – thoroughly characterization of more settlements within the study zone needs to be done. It is encouraged to create a database of the primary features of informal settlements of different scales, to be able to make a comparison of differences between them, this would give better and more accurate recommendations for each settlement, as all of them have different characteristics that made them unique.
- ***Sample amplification*** – for this thesis only four visits, amongst the 112 informal settlements that exist inside San Jose were performed, which might not represent with exactitude the features of all the existing informal settlements. A greater sample number is necessary to make quantifiable remarks between settlements. To this end, conduct surveys and research studies to create and update information on physical features of informal settlements and their conditions must be done in order to fill knowledge gaps.
- ***Engagement with community members*** – engagement with residents should be included in future studies if safety and ethics can be ensured. Further research is needed to investigate methods of firefighting used by communities and to learn about informal training that takes place between community members with regards to fire safety, even if it is not referred to as fire safety training.
- ***Subjectivity*** – must be reduced through screening by multiple researchers. Multiple research team members must review the events under study separately,

then the observations must be compared. The site visits described herein were performed alone, therefore, there is a certain degree of subjectivity in the opinions written. The author was unable to compare its perceptions against other collaborators. Future work should include larger teams to address more informal settlements and avoid subjectivity.

- ***Resiliency*** **–** future work may be based on other disasters for a resilience approach if applicable, and it should also consider those proposed elsewhere and how they are applicable here. It would be a premature effort to have a single fire case study on which to build a framework with complementary data from other types of disasters or from other regions where settlements have been studied in more depth.
- ***Material testing*** **–** whenever performing fire tests be sure to be well prepared by taking the necessary fire training and following all the safety measures of the facility employed, from using Personal Protection Equipment, to using manual fire extinguishing equipment such as fire extinguishers, fire blankets among others.

Bibliography

Agyabeng, A. N., Peprah, A. A., Mensah, J. K., & Mensah, E. A. (2022). Informal settlement and urban development discourse in the Global South: Evidence from Ghana. *Norsk Geografisk Tidsskrift-Norwegian Journal of Geography*, *76*(4), 242–253.

Antonellis, D., Wynne, K., & Gill, D. (2018). A Framework for Fire Safety in Informal Settlements. In *Arup*. https://www.arup.com/perspectives/publications/research/section/a-framework-for-fire-safety-in-informal-settlements

Araya, M. (2022). *email: Historia de las regulaciones de Costa Rica*.

Asamblea Legislativa. (2002). *Ley del Benemérito Cuerpo de Bomberos de Costa Rica*. Sistema Costarricense de Información Jurídica. http://www.pgrweb.go.cr/scij/Busqueda/Normativa/Normas/nrm_texto_completo.aspx?param1=NRTC&nValor1=1&nValor2=48308&nValor3=86218&strTipM=TC

Asamblea Legislativa. (2005). *Propuesta de Manual de disposiciones técnicas Generales al reglamento sobre Seguridad Humana y Protección Contra Incendios*. Sistema Costarricense de Información Jurídica. http://www.pgrweb.go.cr/scij/busqueda/normativa/normas/nrm_texto_completo.aspx?param1=NRM&param2=1&nValor1=1&nValor2=54161&strTipM=FN&lResultado=4&strSelect=sel

ASCE. (2018). Key terminology & Chapter 10 - Structural Acceptance Criteria. In K. LaMalva (Ed.), *Structural fire engineering*.

ASTM International. (2020). *Standard Test Methods for Fire Tests of Building Construction and Materials ASTM E-119*.

ASTM International. (2022). *ASTM E1354-22c Standard Test Method for Heat and Visible Smoke Release Rates for Materials and Products Using an Oxygen Consumption Calorimeter: Vol. 04.07*. https://doi.org/10.1520/E1354-22C

Aucoin, D., Young, T., Kinsey, M., & Gales, J. (2019). Modeling human behavior in emergency stadium fire evacuations. *Interflam 2019: 15th International Conference and Exhibition on Fire Science and Engineering*, 695–704.

Bode, N., & Codling, E. (2019). Exploring Determinants of Pre-movement Delays in a Virtual Crowd Evacuation Experiment. *Fire Technology*, *55*, 595–615. https://doi.org/10.1007/s10694-018-0744-9

Bonilla Ortiz-Arrieta, L., & Silva, M. J. (2019). Asentamientos informales en América Latina: epicentro urbano de los desafíos del desarrollo sostenible. In *Planificación multiescalar: las desigualdades territoriales.: Vol. II* (pp. 81–99). CEPAL.

Calder, K., & Weckman, E. (2020). Identifying Implicit Risk in the National Building Code of Canada. *International Performance-Based Codes & Fire Safety Design Methods Conference*.

Campos Gómez, I. (2018). Respuesta de Costa Rica al cuestionario Asentamientos informales y derechos humanos. In *Ministerio de Vivienda y Asentamientos Humanos*.

Canadian Commission on Building and Fire Codes. (2015a). *National Building Code of Canada: 2015*. National Research Council of Canada. https://doi.org/https://doi.org/10.4224/40002005

Canadian Commission on Building and Fire Codes. (2015b). *National Fire Code of Canada: 2015*. National Research Council of Canada. https://doi.org/https://doi.org/10.4224/40002009

Canadian Wood Council. (n.d.). *Fire Resistance*.

CEN. (2004). Annex A (informative). In *Eurocode 2: Design of concrete structures - Part 1-2: General rules - Structural fire design* (pp. 63–71).

Chacón, E. (2019, November 12). *Asentamientos informales: ¿Una bomba de tiempo para incendios?* Trece noticias.

Chacon Monge, L. F. (2020). *Law Project: Ley de transformación y titulación de asentamientos humanos informales e irregulares* (No. 22222). Asamblea Legislativa. http://www.asamblea.go.cr/Centro_de_informacion/Consultas_SIL/SitePages/ConsultaProyectos.aspx

Ley de transformación y titulación de asentamientos humanos informales e irregulares, (2020) (testimony of Luis Fernando Chacón Monge).

Chen, Y., Fang, J., Zhang, X., Miao, Y., Lin, Y., Tu, R., & Hu, L. (2023). Pool fire dynamics: Principles, models, and recent advances. *Progress in Energy and Combustion Science*, *95*, 101070. https://doi.org/10.1016/J.PECS.2022.101070

Chorlton, B., Forrest, B., Weckman, E., & Gales, J. (2021). Performance of Type X Gypsum Board on Timber to Non-standard Fire Exposure. In John Wiley (Ed.), *Fire and Materials* (pp. 885–900).

Chorlton, B., & Gales, J. (2019a). Evacuation modelling procedures for improving timber fire design. *Canadian Society for Civil Engineering (CSCE)*.

Chorlton, B., & Gales, J. (2019b). Evacuation modelling procedures for improving timber fire design. *Canadian Society for Civil Engineering (CSCE)*.

Chorlton, B., & Gales, J. (2020). Fire performance of heritage and contemporary timber encapsulation materials. *Journal of Building Engineering*, *29*, 101181. https://doi.org/10.1016/j.jobe.2020.101181

Chorlton, B., Harun, G., Gales, J., Weckman, E., & Smith, M. (2018). An Investigation into the Resilience of Glulam Timber Beams after Fire Exposure. *Canadian Society of Civil Engineering (CSCE)*.

Chown, A. (2016). *Tiny Houses in Canada's Regulatory Context: Issues and Recommendations*. https://mhaprairies.ca/wp-content/themes/mhapp/pdf/Tiny Homes_Discussion Paper_2016-10-02 AC.pdf

Cicione, A., Beshir, M., Walls, R. S., & Rush, D. (2020). Full-Scale Informal Settlement Dwelling Fire Experiments and Development of Numerical Models. *Fire Technology*, *56*(2), 639–672. https://doi.org/10.1007/s10694-019-00894-w

Cicione, A., Walls, R., & Kahanji, C. (2019). Experimental study of fire spread between multiple full scale informal settlement dwellings. *Fire Safety Journal*, *105*, 19–27.

Cicione, A., & Walls, R. S. (2019). Towards a simplified fire dynamic simulator model to analyse fire spread between multiple informal settlement dwellings based on full-scale experiments. *Fire and Materials*. https://doi.org/10.1002/fam.2814

Cicione, A., Walls, R., Stevens, S., Sander, Z., Flores, N., Narayanan, V., & Rush, D. (2021). An Experimental and Numerical Study on the Effects of Leakages and Ventilation Conditions on Informal Settlement Fire Dynamics. *Fire Technology*, *58*, 217–250.

Cicione, Antonio., Collen, W., Spearpoint, M., Gibson, L., Walls, R., & Rush, D. (2020). A preliminary investigation to develop a semi-probabilistic model of informal settlement fire spread using B-RISK. *Fire Safety*. https://doi.org/10.1016/j.firesaf.2020.103115

City Manager. (2021). *COVID-19 Response Update: Protecting People Experiencing Homelessness and Ensuring the Safety of the Shelter System*. https://www.toronto.ca/legdocs/mmis/2021/cc/bgrd/backgroundfile-167471.pdf

City of Toronto. (2021a). *2021 Street Needs Assessment*. https://www.toronto.ca/legdocs/mmis/2021/ec/bgrd/backgroundfile-171729.pdf

City of Toronto. (2021b). *City of Toronto reaches settlement on tiny shelters*. City of Toronto. https://www.toronto.ca/news/city-of-toronto-reaches-settlement-on-tiny-shelters/

CODECA. (n.d.). *Boundaries of La Carpio Informal Settlement*.

Costa, A., & Hernández, A. (2010). Análisis de la situación actual de la regularización urbana en América Latina. *Revista INVI*, *25*(68), 121–152.

Costa Rican Fire Corps. (2019). *Despacho de Comunicaciones. Incendios estructurales en Precarios.*

Crawford, B. (2021, August 4). Encampments "an expression of the human right to housing," poverty advocate says. *Ottawa Citizen*. https://ottawacitizen.com/news/local-news/encampments-an-expression-of-the-human-right-to-housing-poverty-advocate-says

Cruz Brenes, F. (2019). *200 familias de la Carpio esperan último proceso para titulación de lotes*. Monumental . https://www.monumental.co.cr/2019/07/09/200-familias-de-la-carpio-esperan-ultimo-proceso-para-titulacion-de-lotes/

CSA. (2019). Annex K (normative) Structural design for fire conditions. In *CSA S16:19 Design of steel structures* (pp. 229–237).

Dewaghe, C., Lew, C. Y., Claes, M., Belgium, S. A., & Dubois, P. (2011). Fire-retardant applications of polymer–carbon nanotubes composites: improved barrier effect and synergism. *Polymer-Carbon Nanotube Composites: Preparation, Properties and Applications*, 718–745. https://doi.org/10.1533/9780857091390.3.718

D'Orazio, M., & Bernardini, G. (2014). Pedestrian and Evacuation Dynamics 2012. *An Experimental Study on the Correlation Between "Attachment to Belongings" "Pre-Movement" Time*. https://doi.org/10.1007/978-3-319-02447-9_12

Drury, J. (2018). The role of social identity processes in mass emergency behaviour: An integrative review. *European Review of Social Psychology*. https://doi.org/10.1080/10463283.2018.1471948

Drysdale, D. (2011). An introduction to fire dynamics. In *John Wiley & Sons, Ltd.* (Vol. 3rd).

Employment and Social Development Canada. (2017). *Canada's National Housing Strategy*. https://www.placetocallhome.ca/what-is-the-strategy

Employment and Social Development Canada. (2019). *Everyone Counts 2018: Highlights – Preliminary Results from the Second Nationally Coordinated Point-in-Time Count of Homelessness in Canadian Communities*. https://www.canada.ca/en/employment-social-development/programs/homelessness/reports/highlights-2018-point-in-time-count.html

Employment and Social Development Canada. (2020). *Reaching Home: Canada's Homelessness Strategy Directives*. Employment and Social Development Canada. https://www.canada.ca/en/employment-social-development/programs/homelessness/directives.html

Employment and Social Development Canada. (2022). *Everyone Counts – Standards for participation in the coordinated count*. https://www.canada.ca/en/employment-social-development/programs/homelessness/resources/point-in-time.html

Engineering Unit (Costa Rican Fire Corps). (2013). *Manual de disposiciones técnicas generales sobre Seguridad Humana y Protección contra Incendios* (4ta ed.). Benemérito Cuerpo de Bomberos de Costa Rica. https://bomberos.go.cr/wp-content/uploads/2020/07/Manual-de-Disposiciones-Tecnicas-2013-vigente.pdf

Engineering Unit (Costa Rican Fire Corps). (2018). *Datos finales de investigación de incendios 2010-2018*.

Engineering Unit (Costa Rican Fire Corps). (2019a). *Análisis e investigación de incendios Enero - Diciembre 2018*. https://www.bomberos.go.cr/estadisticas/

Engineering Unit (Costa Rican Fire Corps). (2019b). *Reporte incendio 13 de abril, La Carpio, Uruca, San José*.

Engineering Unit (Costa Rican Fire Corps). (2019c). *Reporte incendio 16 de setiembre, El Pochote, Barrio Cuba, San José*.

Environmental Engineering and Contracting. (2002). *Tire Pile fires. Prevention, Response, Remediation*. https://archive.epa.gov/epawaste/conserve/materials/tires/web/pdf/gen-067-tire%20pile%20fires-prevention%2C%20response%2C%20remediation.pdf

FactCheckToronto. (2021, June 7). *Claim: In 2020, Toronto Fire Services responded to 253 fires in encampments*. FactCheckToronto. https://factchecktoronto.ca/2021/06/07/encampment-fires/

Fahy, R., & Maheshwari, R. (2021). *Poverty and the Risk of Fire*.

Farha, L., & Schwan, K. (2020). *A National Protocol for Homeless Encampments in Canada*. https://www.make-the-shift.org/wp-content/uploads/2020/08/A-National-Protocol-for-Homeless-Encampments-in-Canada.pdf

Fernandes, E. (2011). *Regularización de asentamientos informales en América Latina*.

Flores, N., Walls, R., & Cicione, A. (2020). Developing a framework for fire investigations in informal settlements. *Fire Safety*. https://doi.org/10.1016/j.firesaf.2020.103046

Flores Quiroz, N., Walls, R., & Cicione, A. (2021). Towards Understanding Fire Causes in Informal Settlements Based on Inhabitant Risk Perception. *Fire*, *4*(3), 39. https://doi.org/10.3390/fire4030039

Flores Quiroz, N., Walls, R., Cicione, A., & Smith, M. (2021). Fire incident analysis of a large-scale informal settlement fire based on video imagery. *International Journal of Disaster Risk Reduction*, *55*. https://doi.org/10.1016/j.ijdrr.2021.102107

Folk, L. H., Kuligowski, E. D., Gwynne, S. M. V., & Gales, J. A. (2019). A Provisional Conceptual Model of Human Behavior in Response to Wildland-Urban Interface Fires. *Fire Technology*, *55*(5), 1619–1647. https://doi.org/10.1007/s10694-019-00821-z

Ford, J., & Gomez-Lanier, L. (2017). Are Tiny Homes Here to Stay? A Review of Literature on the Tiny House Movement. *Family and Consumer Sciences*

Research Journal, *45*(4), 394–405. https://doi.org/https://doi-org/10.1111/fcsr.12205

Frangi, A., & Fontana, M. (2003). Charring rates and temperature profiles of wood sections. *Fire and Materials*, *27*(2), 91–102. https://doi.org/10.1002/fam.819

Gaetz, S., Dej, E., Richter, T., & Redman, M. (2016). *The State of Homelessness in Canada 2016*. https://www.homelesshub.ca/sites/default/files/attachments/SOHC16_final_20Oct2016.pdf

Galea, E. R., Sauter, M., Deere, S. J., & Filippidis, L. (2015). Investigating the impact of culture on evacuation response behaviour. *Human Behaviour in Fire 6th, Interscience Communications Ltd*, 351–360.

Gales, J., Champagne, R., Harun, G., Carton, H., & Kinsey, M. (2022). Fire Evacuation and Exit Design in Heritage Cultural Centres. In *Springer Briefs in Architecture and Technology*. Springer-Nature.

Gibson, L. L., Rush, D., Wheeler, O., Cairns, R., & Walls, R. (2018). *Fire detection in informal settlements*. *October 2018*. https://doi.org/10.1117/12.2501885

Gibson, V. (2021, February 17). 'This kind of living arrangement outside is not safe,' acting fire chief says, as Toronto records first encampment fire fatality of the winter after early morning Corktown blaze. *The Toronto Star*. https://www.thestar.com/news/gta/2021/02/17/man-dead-in-overnight-encampment-fire-in-corktown.html

Google. (n.d.-a). *Google Earth*. Retrieved May 14, 2022, from https://earth.google.com/web/

Google. (n.d.-b). *Google Maps*. Retrieved May 16, 2022, from https://www.google.com/maps/

Guevara Arce, S. (2020). *Analysis of the existing information of La Carpio informal settlement, Roble Norte sector, to create the basis for future research in fire safety.* Tecnológico de Costa Rica.

Guevara, S., Jeanneret, C., Gales, J., Antonellis, D., & Vaiciulyte, S. (2021). Human behaviour in informal settlement fires in Costa Rica. *Safety Science*, *142*. https://doi.org/10.1016/j.ssci.2021.105384

Hallegatte, S., Vogt-Schilb, A., Bangalore, M., & Rozenberg, J. (2017). *Unbreakable: Building the Resilience of the Poor in the Face of Natural Disasters*. The World Bank.

Herring, C., & Lutz, M. (2015). The roots and implications of the USA's homeless tent cities. *City*, *19*(5), 689–701. https://doi.org/10.1080/13604813.2015.1071114

Hu, J., Xie, X., Shu, X., Shen, S., Ni, X., & Zhang, L. (2022). Fire Risk Assessments of Informal Settlements Based on Fire Risk Index and Bayesian Network. *International Journal of Environmental Research and Public Health*, *19*(23), 15689. https://doi.org/10.3390/ijerph192315689

INEC. (2013). Principales Indicadores sobre Asentamientos Informales, Censo 2011. *2013*.

INEC. (2020). *Mapas Sociales de Costa Rica: Asentamientos Informales*. http://mapassociales.inec.cr/mapnew.php

INEC, & MIVAH. (2011). *Distribución geográfica de los asentamientos informales*. https://www.arcgis.com/apps/dashboards/c64416daa19f45d3a41c3c99576b1150

IRIS-Fire. (n.d.). *What we do*. https://www.iris-fire.com/

Johnson, P. F., Johnson, C. E., & Sutherland, C. (2012). Stay or Go? Human Behavior and Decision Making in Bushfires and Other Emergencies. *Fire Technology*, *48*(1), 137–153. https://doi.org/10.1007/s10694-011-0213-1

Jones, A. M. (2020, November 25). City of Toronto threatens to remove tiny shelters built to help the homeless, citing safety concerns. *CTV News*. https://www.ctvnews.ca/canada/city-of-toronto-threatens-to-remove-tiny-shelters-built-to-help-the-homeless-citing-safety-concerns-1.5205109

Kahanji, C., Walls, R. S., & Cicione, A. (2019). International Journal of Disaster Risk Reduction Fire spread analysis for the 2017 Imizamo Yethu informal settlement conflagration in South Africa. *International Journal of Disaster Risk Reduction*, *39*(January), 101146. https://doi.org/10.1016/j.ijdrr.2019.101146

Kendall, M., & Lin, S. (2022, March 21). Oakland: Fire in tiny homes for homeless residents raises safety concerns. *The Mercury News*. https://www.mercurynews.com/2022/03/21/oakland-fire-breaks-out-at-tiny-homes-community-built-for-homeless-residents/

Kinateder, M. T., Kuligowski, E. D., Reneke, P. A., & Peacock, R. D. (2014). A Review of Risk Perception in Building Fire Evacuation. *NIST Technical Note 1840*. https://doi.org/10.6028/NIST.TN.1840

Kinsey, M. J., Gwynne, S. M. V., Kuligowski, E. D., & Kinateder, M. (2019). Cognitive Biases Within Decision Making During Fire Evacuations. *Fire Technology*, *55*(2), 465–485. https://doi.org/10.1007/s10694-018-0708-0

Kobes, M., Helsloot, I., de Vries, B., & Post, J. (2010). Building safety and human behaviour in fire: A literature review. *Fire Safety*, *45*(1), 1–11. https://doi.org/10.1016/j.firesaf.2009.08.005

Koker, N., Walls, R. S., Cicione, A., Sander, Z. R., Löffel, S., Claasen, J. J., Fourie, S. J., Croukamp, L., & Rush, D. (2020). 20 Dwelling Large-Scale Experiment of Fire Spread in Informal Settlements. *Fire Technology*. https://doi.org/10.1007/s10694-019-00945-2

Kopenhaver-Haidet, K., Tate, J., Divirgilio-Thomas, D., Kolanowski, A., Ross, E., & Beth, M. (2009). Methods to Improve Reliability of Video Recorded Behavioral Data. *Res Nurs Health*, *32(4)*, 465–474. https://doi.org/10.1002/nur.20334

Koutalianous, A., Radvak, C., Sawatzky, J., & Jones, S. (2021). *Tiny Homes - An Alternative to Conventional Housing*. https://www.bchousing.org/research-centre/library/housing-forms-designs/tiny-homes

Kuligowski, E. D. (2009). The Process of Human Behavior in Fires. In *NIST Technical Note 1632*. National Institute of Standards and Technology.

Lerner, R., Bornstein, M., & Kagan, J. (1999). human behaviour. In *Britannica Encyclopedia*.

Lindell, M. K., & Perry, R. W. (2012). The Protective Action Decision Model: Theoretical Modifications and Additional Evidence. *Risk Analysis*, *32*(4), 616–632. https://doi.org/10.1111/j.1539-6924.2011.01647.x

Magalhães, F. (2016). *Slum upgrading and housing in Latin America*.

Mazur, N., Champagne, R., Gales, J., & Kinsey, M. (2019). The effects of linguistic cues on evacuation movement times. *Interflam 2019: 15th International Conference and Exhibition on Fire Science and Engineering*, 1903–1914.

Meacham, B. J. (2010). Accommodating innovation in building regulation: lessons and challenges. *Building and Research Information*, *38*(6), 686–698. https://doi.org/https://doi.org/10.1080/09613218.2010.505380

MIVAH. (n.d.). *La Carpio - Reseña histórica*.

MIVAH. (2013). *Informe de actualización de la Base de datos de asentamientos en condición de precario y tugurio de Costa Rica, al año 2012*. https://www.mivah.go.cr/Documentos/precarios/Informe_Asentamientos_en_precario_y_tugurio_Costa_Rica_2012.pdf

MIVAH. (2018). *Puente a la comunidad, proyectos urbanos integrales*. Ministerio de Vivienda y Asentamientos Humanos. https://www.mivah.go.cr/Puente-Comunidad.shtml

MIVAH. (2022). *Reporte nacional de Costa Rica sobre los avances en la implementación de la Nueva Agenda Urbana 2016 - 2021*.

Naranjo, J. (2019, April 5). *Precarios: Hogueras en potencia*. Teletica.

NASA. (2021). *Gas Temperature*. National Aeronautics and Space Administration. https://www.grc.nasa.gov/WWW/k-12/airplane/temptr.html

National Research Council of Canada. (2020). *Canada's national model codes development system*. https://nrc.canada.ca/en/certifications-evaluations-standards/codes-canada/codes-development-process/canadas-national-model-codes-development-system

NFPA. (2021). NFPA Glossary of Terms. In *National Fire Protection Association*.

Nicoletta, B., Gales, J., Kotsovinos, P., & Weckman, E. (2021). Experimental Thermal Performance of Unloaded Spiral Strand and Locked Coil Cables Subject to Pool Fires. *Structural Engineering International (IABSE)*.

NIST. (2021, June 2). *Fire Dynamics*. National Institute of Standards and Technology. https://www.nist.gov/el/fire-research-division-73300/firegov-fire-service/fire-dynamics

OECD. (2001). *Glossary of statistical terms: Informal settlements*. https://stats.oecd.org/glossary/detail.asp?ID=1351

Poder Judicial. (2022). *Estadísticas OIJ - Estadística de delitos enero - junio 2022*. Poder Judicial Online. https://pjenlinea3.poder-judicial.go.cr/estadisticasoij/#

Poole, S. (1998). *Special Report: Scrap and Shredded Tire Fires. USFA-TR-093*.

Quesada Román, A. (2022). Disaster Risk Assessment of Informal Settlements in the Global South. *Sustainability*, *14*(16), 10261. https://doi.org/10.3390/su141610261

Rahman, M. M., Khan, S. J., Tanni, K. N., Sakib, M. S., Quader, M. A., Shobuj, I. A., Uddin, A., & Aryal, K. R. (2022). Holistic Individual Fire Preparedness in Informal Settlements, Bangladesh. *Fire Technology*. https://doi.org/10.1007/s10694-022-01340-0

Rashad, I. (2020). *Civil engineering materials: introduction and laboratory testing* (Taylor & Francis Group, Ed.; First).

Rendón Rozo, K., Arellana, J., Santander-Mercado, A., & Jubiz-Diaz, M. (2019). Modelling building emergency evacuation plans considering the dynamic behaviour of pedestrians using agent-based simulation. *Safety Science*, *113*, 276–284. https://doi.org/10.1016/j.ssci.2018.11.028

Rush, D., Bankoff, G., Cooper-Knock, S.-J., Gibson, L., Hirst, L., Jordan, S., Spinardi, G., Twigg, J., & Walls, R. S. (2020). Fire risk reduction on the margins of an urbanizing world. *Disaster Prevention and Management: An International Journal*, *29*(5), 747–760. https://doi.org/10.1108/DPM-06-2020-0191

Samson, S. (2022, January 21). Winnipeg homeless camps getting burn barrels. *CBC News*. https://www.cbc.ca/news/canada/manitoba/homelessness-camps-winnipeg-fire-death-damage-1.6323803

Sandoval, V., & Sarmiento, J. P. (2018). Una mirada desde la gobernanza del riesgo y la resiliencia urbana en América Latina y el Caribe: Los asentamientos informales en la Nueva Agenda Urbana. *Revista de Estudios Latinoamericanos Sobre Reducción Del Riesgo de Desastres REDER*, *2*(1), 38. https://doi.org/10.55467/reder.v2i1.10

ScienceDirect. (n.d.). *Heat Flux - Overview*. ScienceDirect. Retrieved April 17, 2023, from https://www.sciencedirect.com/topics/chemical-engineering/heat-flux

Sime, J. D. (1995). Crowd psychology and engineering. *Safety Science*, *21*(1), 1–14. https://doi.org/10.1016/0925-7535(96)81011-3

Spinardi, G., Bisby, L., & Torero, J. (2017). A Review of Sociological Issues in Fire Safety Regulation. *Fire Technology*, *53*, 1011–1037. https://doi.org/10.1007/s10694-016-0615-1

Spinardi, G., Cooper-Knock, S. J., & Rush, D. (2020). Proximal design in South African informal settlements: users as designers and the construction of the built environment and its fire risks. *Tapuya: Latin American Science, Technology and Society*, *3*(1), 528–550. https://doi.org/10.1080/25729861.2020.1847531

Strahan, K., & Watson, S. J. (2018). The protective action decision model: when householders choose their protective response to wildfire. *Journal of Risk Research*, *0*(0), 1–22. https://doi.org/10.1080/13669877.2018.1501597

Tancogne-Dejean, M., & Laclémence, P. (2016). Fire risk perception and building evacuation by vulnerable persons: Points of view of laypersons, fire victims and experts. *Fire Safety Journal*, *80*, 9–19. https://doi.org/10.1016/j.firesaf.2015.11.009

TECHO. (2016). *Día mundial de las ciudades: los asentamientos informales son la mayor expresión de la desigualdad de nuestras ciudades*. https://techo.org/dia-mundial-de-las-ciudades-los-asentamientos-informales-son-la-mayor-expresion-de-la-desigualdad-de-nuestras-ciudades/

Templeton, A., Drury, J., & Philippides, A. (2018). Walking together: behavioural signatures of psychological crowds. *Royal Society Open Science*, *5*(7), 180172. https://doi.org/10.1098/rsos.180172

The World Bank. (2020). *Population living in slums (% of urban population)*. https://data.worldbank.org/indicator/EN.POP.SLUM.UR.ZS?end=2018&start=1990&view=chart

Thompson, O. F., Galea, E. R., & Hulse, L. M. (2018). A review of the literature on human behaviour in dwelling fires. *Safety Science*, *109*, 303–312. https://doi.org/10.1016/j.ssci.2018.06.016

Tübke, J., & Vogt, J. (2019). Li-Secondary Battery. In *Electrochemical Power Sources: Fundamentals, Systems, and Applications* (pp. 507–629). Elsevier. https://doi.org/10.1016/B978-0-444-63777-2.00012-8

Tversky, A., & Kahneman, D. (1974). Judgment under uncertainty: Heuristics and biases. *Science*, *185*(4157), 1124–1131.

Twigg, J., Christie, N., Haworth, J., Osuteye, E., & Skarlatidou, A. (2017). Improved Methods for Fire Risk Assessment in Low-Income and Informal Settlements. *International Journal of Environmental Research and Public Health*, *14*(2). https://doi.org/10.3390/ijerph14020139

UN-Habitat. (2015). *Habitat III Issue papers, 22-Informal settlements.* http://habitat3.org/wp-content/uploads/Habitat-III-Issue-Paper-22_Informal-Settlements-2.0.pdf

UN-Habitat. (2017). *Human rights in cities handbook series Volume I. The human rights based approach to housing and slum upgrading.* https://www.ohchr.org/Documents/Issues/Housing/InformalSettlements/UNHABITAT_HumanRights-BasedApproch.pdf

UN-Habitat. (2018). *Pro-Poor Climate Action in Informal Settlements*. https://unhabitat.org/sites/default/files/2019/05/pro-poor_climate_action_in_informal_settlements-.pdf

United Nations. (n.d.). *#Envision2030 Goal 11: Sustainable Cities and Communities*. Retrieved January 21, 2023, from https://www.un.org/development/desa/disabilities/envision2030-goal11.html

United Nations. (2018). *Las ciudades seguirán creciendo, sobre todo en los países en desarrollo*. Noticias ONU. https://www.un.org/development/desa/es/news/population/2018-world-urbanization-prospects.html

United Nations. (2019). *Make cities and human settlements inclusive, safe, resilient and sustainable*. https://unstats.un.org/sdgs/report/2019/goal-11/

United Nations. (2022). *Global Issues Population*. https://www.un.org/en/global-issues/population

United Nations (UN). (2018). *World urbanization prospects*. https://www.un.org/development/ desa/es/news/population/2018-world-urbanization-prospects.html

U.S. Fire Administration. (2020). *Recognizing flashover conditions can save your life*. https://www.usfa.fema.gov/blog/cb-050520.html

Walls, R., Olivier, G., & Eksteen, R. (2017a). Informal settlement fires in South Africa: Fire engineering overview and full-scale tests on "shacks." *Fire Safety Journal*, *91*, 997–1006.

Walls, R., Olivier, G., & Eksteen, R. (2017b). Informal settlement fires in South Africa: Fire engineering overview and full-scale tests on "shacks." *Fire Safety Journal*, *91*, 997–1006. https://doi.org/10.1016/j.firesaf.2017.03.061

Wang, Y., Bertrand, C., Beshir, M., Kahanji, C., Walls, R., & Rush, D. (2020). Developing an experimental database of burning characteristics of combustible informal dwelling materials based on South African informal settlement investigation. *Fire Safety Journal*, *111*.

Wang, Y., Beshir, M., Gibson, L., Stevens, S., Bisby, L., & Rush, D. (2020). How "informal" is an informal settlement fire? *SFPE Europe*.

Wang, Y., Beshir, M., Hadden, R., Cicione, A., Krajcovic, M., Gibson, L., & Rush, D. (2022). Laboratory experiment of fire spread between two informal settlement dwellings. *International Journal of Thermal Sciences*, *171*, 107195. https://doi.org/10.1016/j.ijthermalsci.2021.107195

Wang, Y., Gibson, L., Beshir, M., & Rush, D. (2020). Preliminary Investigation of Critical Separation Distance Between Shacks in Informal Settlements Fire. In *The Proceedings of 11th Asia-Oceania Symposium on Fire Science and Technology* (pp. 379–389). Springer Singapore. https://doi.org/10.1007/978-981-32-9139-3_28

Wang, Y. P., Wang, Y., & Wu, J. (2009). Urbanization and Informal Development in China: Urban Villages in Shenzhen. *International Journal of Urban and Regional Research*, *33*(4), 957–973. https://doi.org/10.1111/j.1468-2427.2009.00891.x

Wang, Y., Ruan, H., Xia, T., & Gibson, L. (2022). Fire Safety of Ethnic Minority Traditional Settlements in Southwest China. *Fire Technology*. https://doi.org/10.1007/s10694-022-01333-z

Weather Underground. (2019). *San José, Heredia, Costa Rica weather history*. https://www.wunderground.com/history/daily/cr/san-josé/MRPV/date/2019-9-16

Westwell, C. (2011). *Fires in informal settlements in India and the Philippines*. Loughborough University.

Wong, A., Chen, J., Dicipulo, R., Weisse, D., Sleet, D. A., & Francescutti, L. H. (2020). Combatting Homelessness in Canada: Applying Lessons Learned from Six Tiny Villages to the Edmonton Bridge Healing Program. *International Journal of Environmental Research and Public Health*, *17*(17), 6279. https://doi.org/https://doi.org/10.3390/ijerph17176279

Wu, F., Zhang, F., & Webster, C. (2013). Informality and the Development and Demolition of Urban Villages in the Chinese Peri-urban Area. *Urban Studies*, *50*(10), 1919–1934. https://doi.org/10.1177/0042098012466600

Young, M. G., Abbott, N., & Goebel, E. (2017). Telling their story of homelessness: voices of Victoria's Tent City. *Journal of Social Distress and the Homeless*, *26*. https://doi.org/10.1080/10530789.2017.1324358

Zeinali, D. (2019). *Flame spread and fire behaviour in a corner configuration*. Ghent University.

Zhang, L. (2011). The political economy of informal settlements in post-socialist China: The case of chengzhongcun(s). *Geoforum*, *42*(4), 473–483. https://doi.org/10.1016/j.geoforum.2011.03.003

Appendix A: Supplementary information for Chapter 6

The following appendix contains information on a series of two different tests performed in a determined material. The samples tested using pool fires will be denominated as Series A where the dimensions of the samples were 29 cm length by 29 cm height and 7.5 cm width. There were two different contents of fiber inside the samples, thus Series A-1 will refer to the samples with fiber content B in the mixture and Series A-2 will refer to the samples with fiber content C.

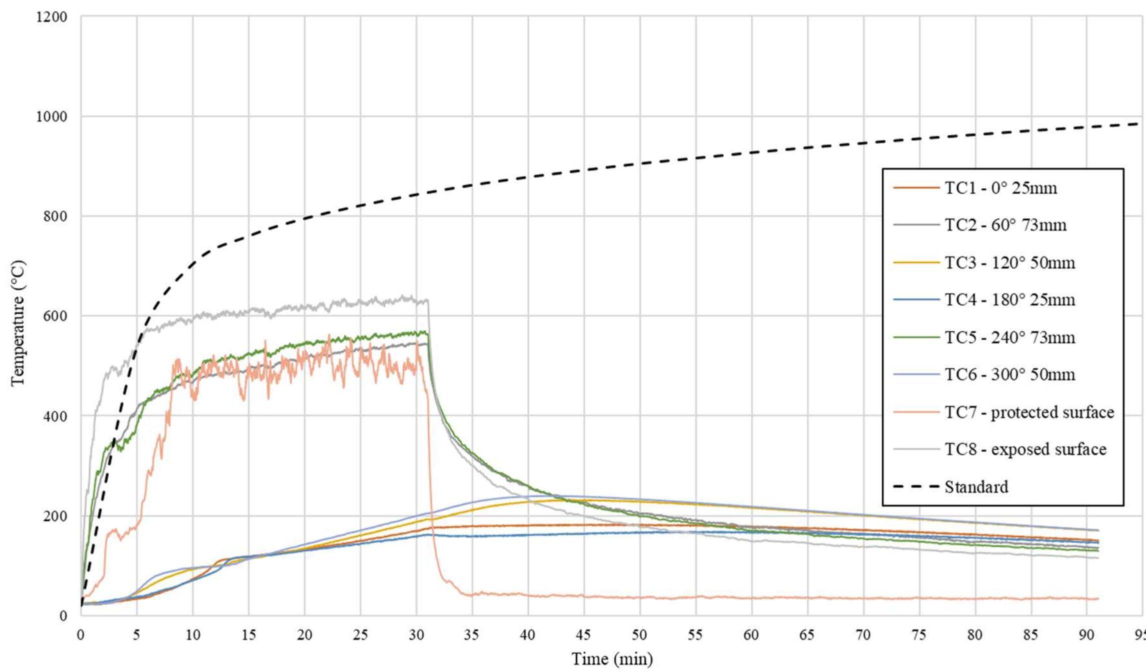
The tests conducted in cone calorimeters will be defined as Series B, the dimensions of the samples were 10 cm length by 10 cm height and 7.5 cm width. Numbering will be used for different compositions in the samples as well. There were three different contents of fiber inside the samples, thus Series B-1 will refer to the samples with fiber content A in the mixture, Series B-2 will refer to the samples with fiber content B in the mixture, and Series B-3 will refer to the samples with fiber content C.

Pool fires

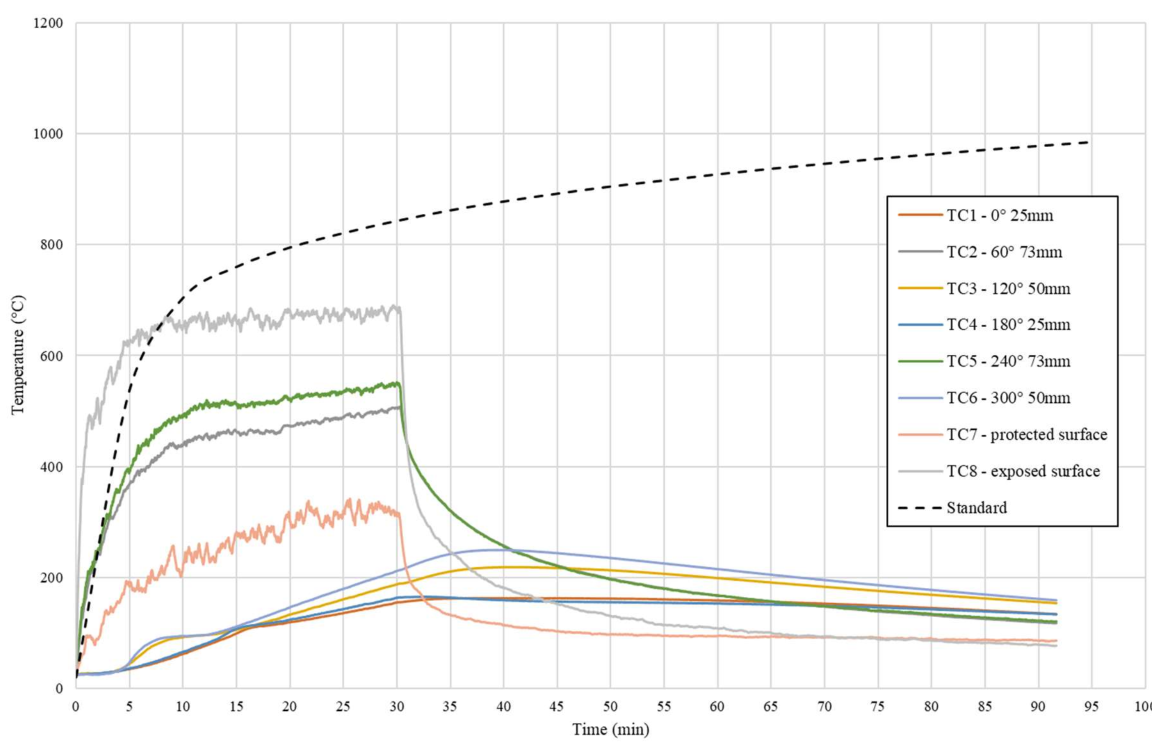
The following table shows a summary of the average temperatures obtained for different depths from the tests. For illustration purposes, the temperature graphics of one of each series (Series A-1.1 and Series A-2.1) will be attached.

Test info	**Average maximum temperature during test (C°)**								**Cooling**
Sample	**Bottom**	**73mm**	**73mm**	**50mm**	**50mm**	**25mm**	**25mm**	**Top**	**Top**
Series A-1.1	631.7	544.1	567.6	231.0	239.2	181.6	167.5	553.8	331.9
Series A-1.2	665.9	537.1	666.7	232.9	229.3	179.5	163.6	307.4	260.2
Series A-1.3	665.1	470.7	509.1	241.3	248.3	166.0	169.7	308.4	259.7
Series A-1.4	693.7	455.3	516.5	239.2	232.6	177.7	183.3	331.4	251.9
Series A-1.5	645.4	539.2	455.7	223.7	232.9	177.3	172.7	288.6	284.8
Series A-1.6	642.7	568.4	433.9	228.9	232.2	159.2	170.8	266.7	632.6
Series A-1.7	645.2	450.9	557.0	222.0	231.3	164.5	159.8	255.7	234.4
Series A-1.8	725.9	472.1	565.1	233.9	228.5	176.8	170.5	274.6	242.7
Series A-1.9	638.7	431.7	540.3	249.2	248.9	180.2	167.2	289.8	231.0
Series A-2.1	688.9	507.0	549.9	218.7	249.6	162.5	165.0	336.8	256.3
Series A-2.2	847.4	459.4	541.4	220.3	219.2	178.2	153.8	288.7	287.2
Series A-2.3	644.4	447.5	462.2	216.9	214.4	154.8	182.0	258.9	238.9
Series A-2.4	663.0	519.1	405.4	229.1	211.2	181.2	159.6	310.0	292.3
Series A-2.5	664.1	523.7	479.3	240.9	236.3	178.3	169.7	277.1	473.3
Series A-2.6	675.6	477.8	563.7	249.0	228.2	165.7	186.3	329.6	286.4
Series A-2.7	659.3	493.3	476.2	228.5	251.2	171.1	165.6	305.9	234.1
Series A-2.8	657.1	480.7	449.3	238.8	239.9	170.0	178.9	290.9	216.2

Series A-1.1 *(Fiber content B)*



Series A-2.1 *(Fiber content C)*



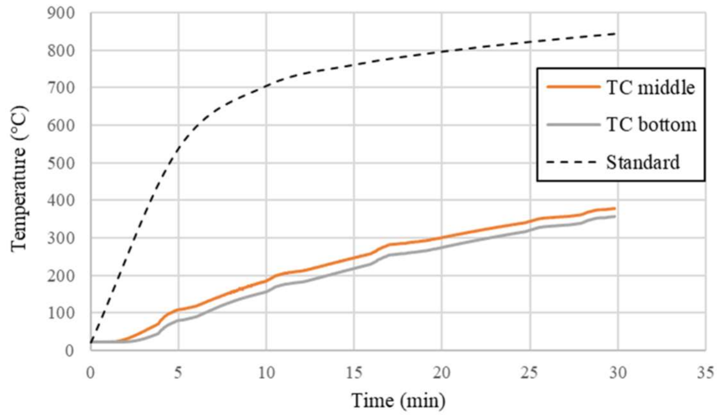
Cone Calorimeter

The following table shows a summary of the maximum temperatures obtained from the test for two different distances from the exposed surface. For illustration purposes of the cone calorimeter tests, different graphics from one of each series under different heat fluxes will be attached (Series B-1, Series B-2, and Series B-3).

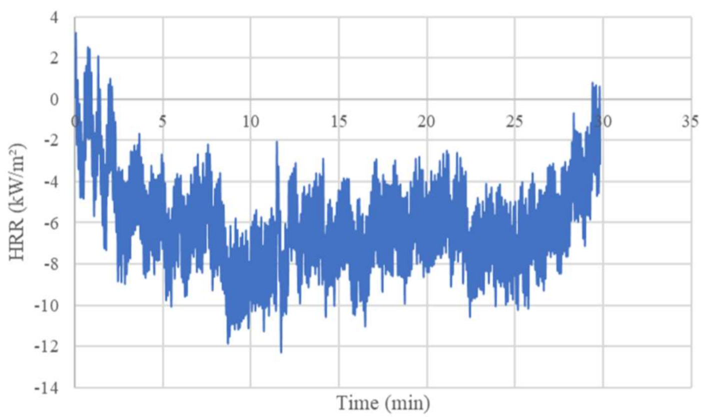
Test info		Average maximum temperature during tests (C°)	
Sample	**Heat Flux (kW/m²)**	**12.5 mm (middle)**	**25mm (protected surface)**
Series B-1.1	30	379.2	357.0
Series B-1.2		359.2	358.1
Series B-2.1		394.0	359.5
Series B-2.2		398.6	357.0
Series B-3.1		413.6	364.6
Series B-3.2		422.2	377.8
Series B-1.3	50	439.2	418.7
Series B-1.4		451.0	402.2
Series B-2.3		500.0	439.4
Series B-2.4		478.4	427.6
Series B-3.3		517.5	439.5
Series B-3.4		506.3	438.7

Series B-1.1 *(Fiber content A)*

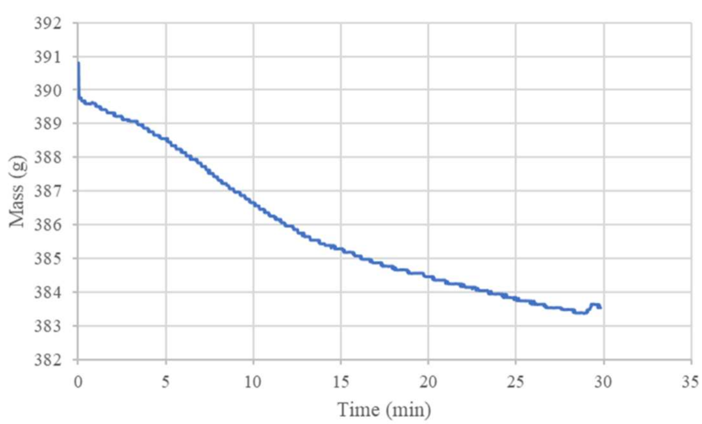
Time – Temperature (C°)



**Time – HRR (kW/m²)*

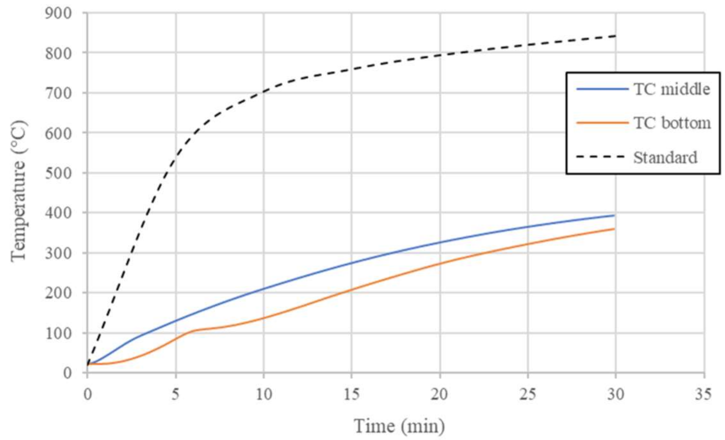


Time – Mass (g)

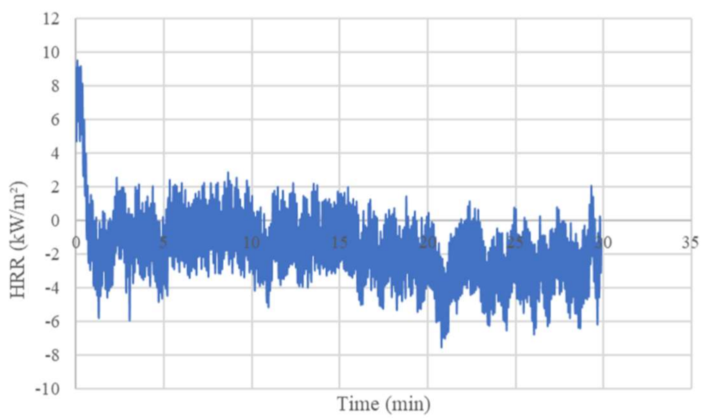


Series B-2.1 *(Fiber content B)*

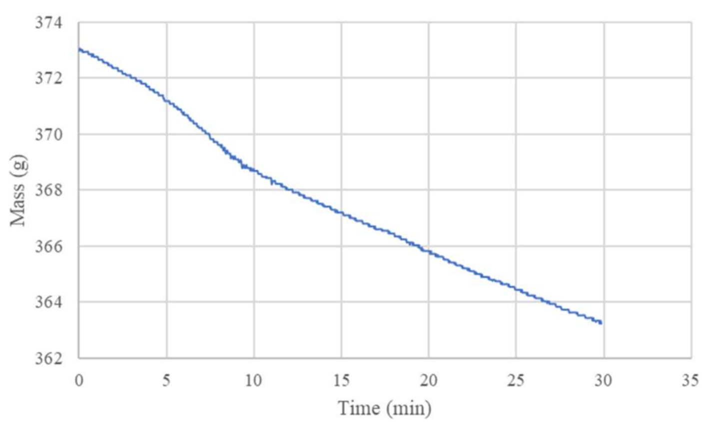
Time – Temperature (C°)



**Time – HRR (kW/m²)*

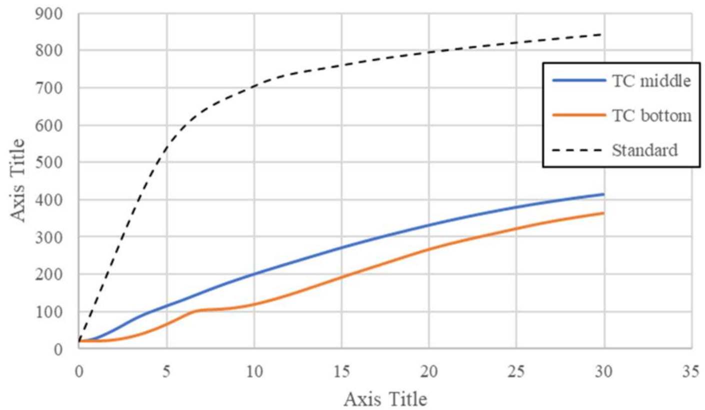


Time – Mass (g)

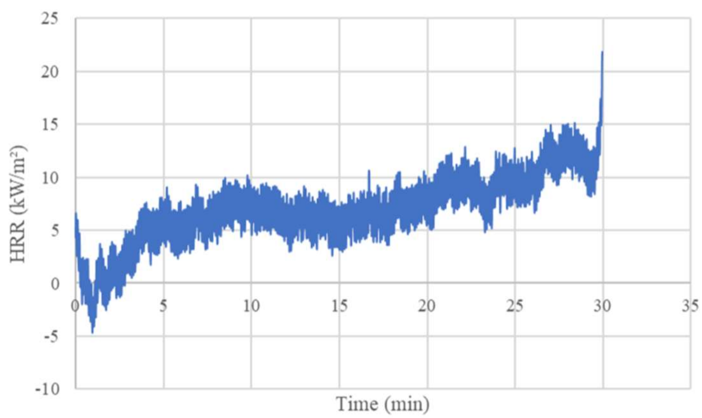


Series B-3.1 *(Fiber content C)*

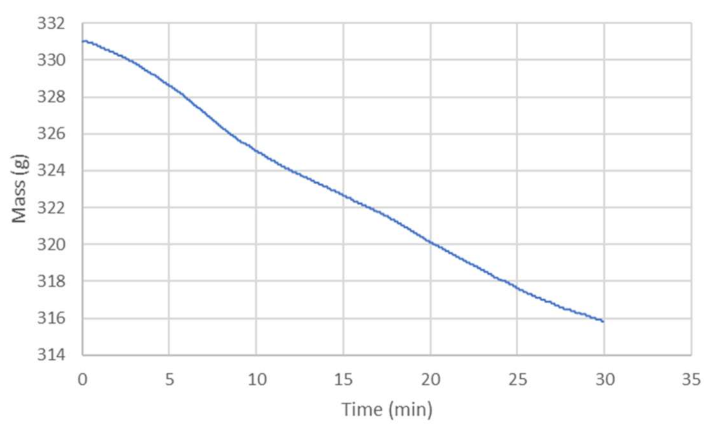
Time – Temperature (C°)



Time – HRR (kW/m²)

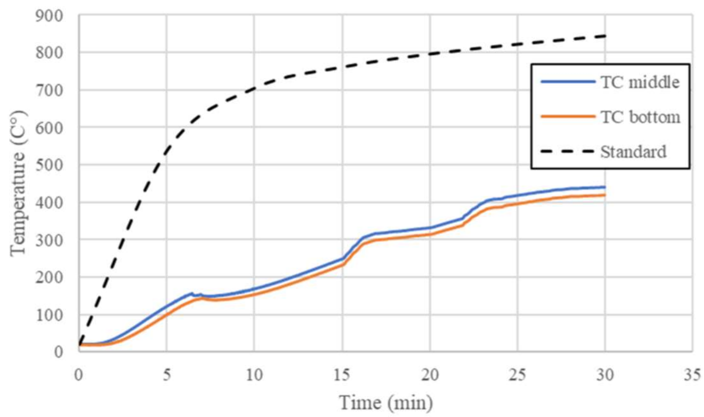


Time – Mass (g)

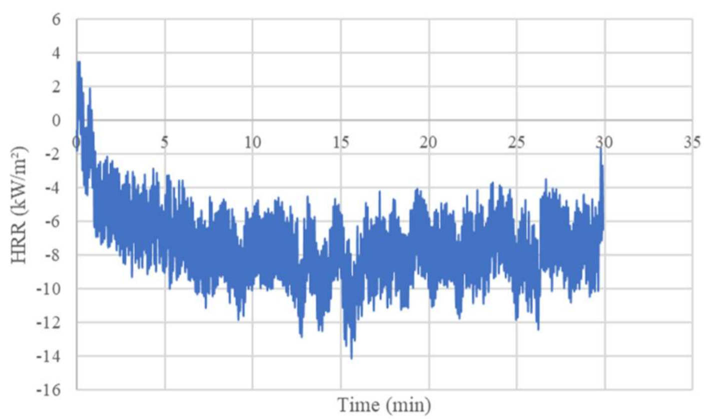


Series B-1.3 *(Fiber content A)*

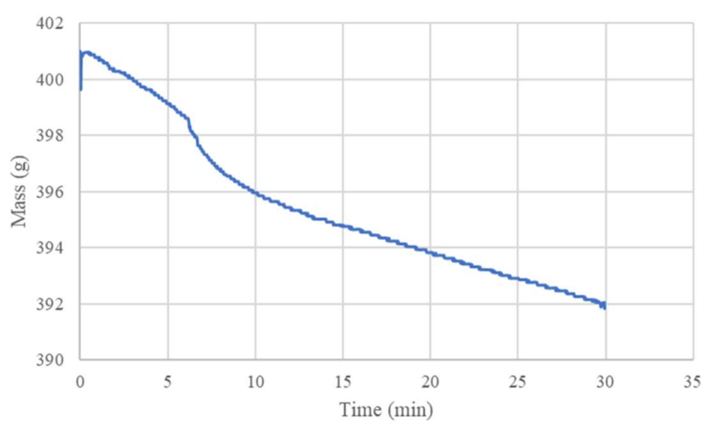
Time – Temperature (C°)



**Time – HRR (kW/m²)*

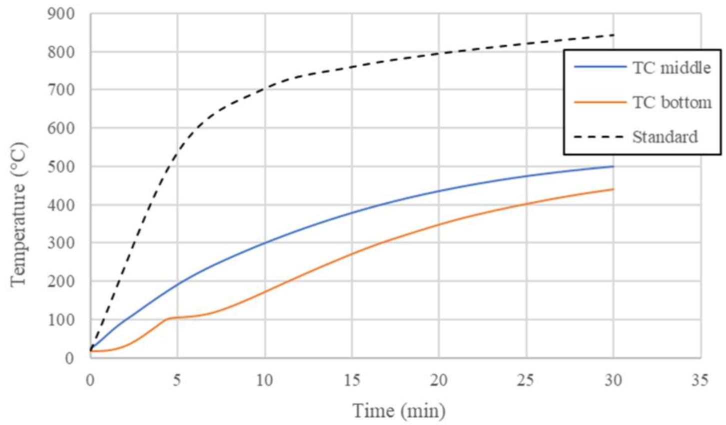


Time – Mass (g)

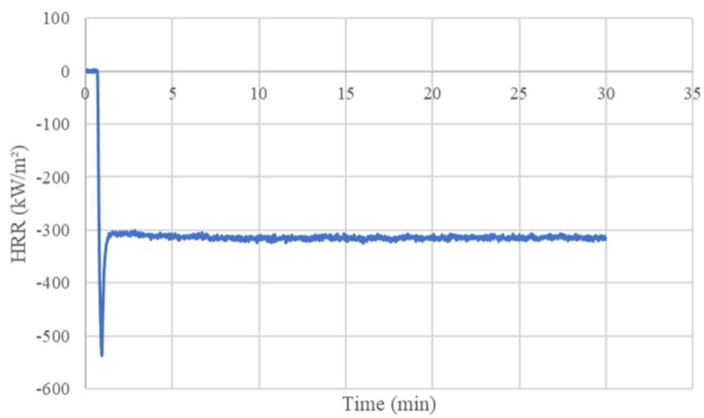


Series B-2.3 *(Fiber content B)*

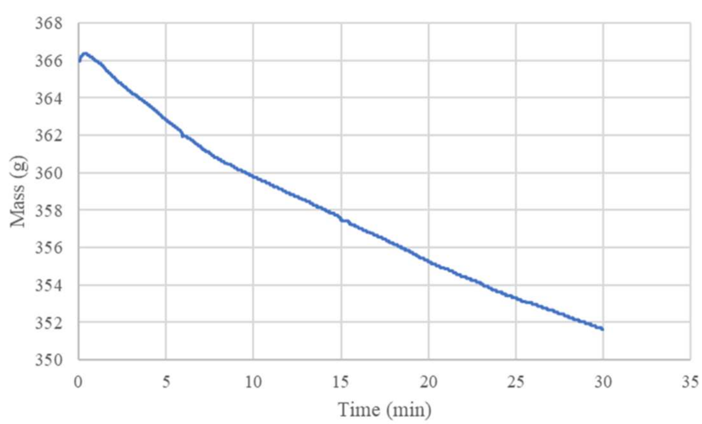
Time – Temperature (C°)



**Time – HRR (kW/m²)*

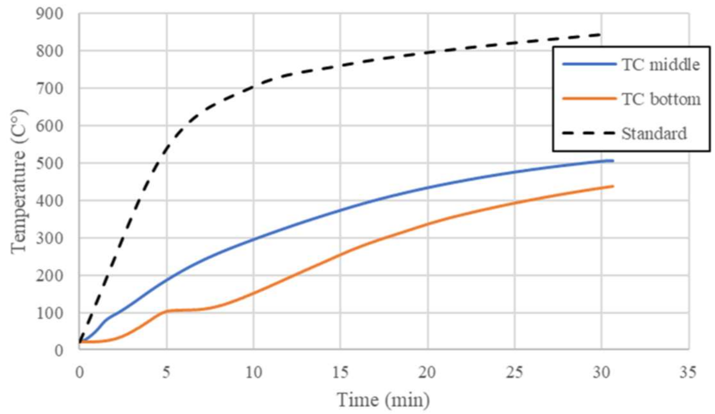


Time – Mass (g)

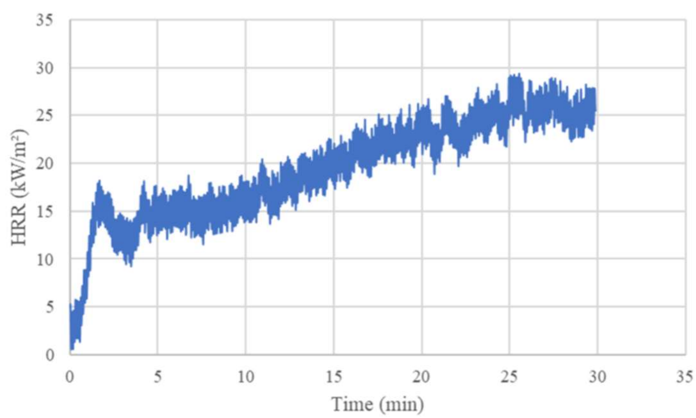


Series B-3.4 *(Fiber content C)*

Time – Temperature (C°)



Time – HRR (kW/m²)



Time – Mass (g)