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Thermal Effect of Firebrand Accumulation in Ceramic Roof Tiles

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Abstract: This paper presents investigations concerning the thermal firebrand reaction due to its accumulation in the top of ceramic roof tiles, commonly applied to the exterior of dwellings in southern Europe. A large-scale fire experiment is conducted, wherein firebrands are placed above the tiles and temperature readings are taken from multiple layers of the building components. The selection of materials for the roof layer assembly was based on recommendations for either fire resistance or high temperature behaviour. The test follows the fire setup recommended in the California Building Code for firebrand deposition. This investigation will allow for a more accurate verification of the firebrand reaction in the roof, including the type of ignition, the creation of smoke and droplets, and even their mechanical ability to withstand elevated temperatures.

Keywords: ceramic roof; insulation layers; temperature vs. time curve; firebrand thermal reaction; firebrand accumulation; wildfires

1. Introduction

The majority of wildfires produce firebrands, which are the primary means of a fire's spread. These firebrands not only affect flora and wildlife but also pose a significant risk to the wildland–urban interface (WUI), where they can ignite the structural components of nearby dwellings [1].

During wildland fires, firebrands break off from surrounding plant or building materials, which can start fresh spot fires by floating up to several kilometres ahead of the main fire front. It is commonly known that firebrands play a critical role in the spread of wildland fires. They have been shown to be mostly responsible for structure losses in the WUI, either by accelerating the rate of fire spread, starting fires directly within structures, or helping the fire travel from dwellings [2]. A crucial step in the process of starting a fire and incidental activity of wildfires in homes is the production of firebrands. Trees and shrubs heat up to the point where they crack and explode into tiny fragments, which are then transported by the wind and create spot fires. These materials are flammable in a wildfire. Considering this, there has been a recent surge in studies on the deposition/accumulation of firebrands as one of the primary causes in a structure igniting. This is due to the fact that flames, which usually originate in wooden components, can be caused by the build-up of firebrands and their extended interaction with flammable materials [3].

The main source of ignition during the 2017 Great Fires in Portugal, according to expert questioners and their reports [4–6], was firebrands. Firebrands reach the homes due

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to the wind's intense action, where they burn for several hours. The firebrands created by wildfires can travel great distances and start additional fires, as recent studies have shown [2,7]. According to reports, these distances are 500 m [8] to 2.0 km [4,5,9] from the location of the active wildfire. In certain instances, these firebrands land on residential roofs, which may contain deposits of solid combustible materials; this can cause an energy transfer when the elements come into contact with the firebrands, and the accumulated material can eventually reach the ignition point [10]. Other research has demonstrated that fire firebrands typically result in an ignition [11]. However, in certain instances, unignited firebrands left on residential roofs may, depending on their size and airflow, cause a heat flow that ignites the roof even hours after the wildfire has started. Numerous studies have been conducted on firebrand characterization [12] and the numerical and experimental prediction of firebrand transportation [13–15]. However, the influence of these studies on the thermal effect of construction elements has been limited.

1.1. Objectives

The main objective is to verify the fire reaction in ceramic roof tiles due to firebrand deposition, in which temperatures will be measured throughout the material layers. Several types of insulation will be tested, which are traditionally used as thermal protections to promote good thermal comfort or humidity.

1.2. Extension in Wildfire Protection Research

To simulate the thermal action of burning shrubs or trees close to an isolated dwelling in a forest area, the same authors have previously suggested new wildfire standard curves [16], as well as the indirect effect of wildfires that result from the accumulation of firebrands that could ignite the dwelling [17,18]. Furthermore, they suggest new construction guidelines that are fireproof for dwellings [9] and provide the basis for a new standard which will protect dwellings from wildfires [19]. The same authors using extensive data from several wildfires inquiries in which some dwellings burned presented a statistical study, in which the weak points that could ignite were identified [6,20], including fire reaction needs to prevent the start of ignitions, heat flux, or firebrand accumulation. An initial experimental fire campaign was undertaken by the same authors [21], in which several construction specimens usually found in the industry were tested for firebrand accumulation, using the test standard from the California Building Code.

1.3. Research Significance

Among wildfire phenomena, research on firebrand transport, generation, and fuel ignition has been prominent. However, the direct ignition of construction elements by firebrands remains understudied. Limited research has focused on firebrands rapidly igniting construction materials. After an extensive literature review, according to the author's best knowledge, there are virtually no studies on the thermal effect of firebrand accumulation in ceramic roof tiles.

After fuel ignition and firebrand generation, which are now popular issues in the scientific community, firebrand transportation has drawn the greatest attention. At the moment, experimental research concerning the particular problem of roof ignition due to firebrand accumulation is scarce. This problem is normally only analyzed in terms of firebrand transportation and deposition [22–25]. Only a little amount of research has been carried out on the peculiar problem of firebrands setting building materials on fire. This work aims to fill this knowledge gap.

2. Previous Studies in Roof Tiles

2.1. Post Wildfire Damage Observations

Roofs stand as one of the most vulnerable elements to wildland fires in dwellings, prompting numerous studies into the specific damages they incur. Xanthopoulos et al. [26] studied damages from past fire events at the WUI in Mediterranean Europe and highlighted that tiled roofs with gaps or broken tiles can create pathways for fire. Additionally, they found that concrete roofs covered with ceramic roof tiles performed better against exterior fire threats compared to ceramic tiled roofs supported by timber trusses. Mitchell and Patashnik [27] concluded that Spanish-style curved tiles, often lacking in construction quality, contribute significantly to building destruction, performing worse than other roofing materials. The vulnerabilities in tiled roofs, particularly evident at tile overlaps and ridges where gaps are prone to occur, are also observed by Blanchi and Leonard [28]. Moreover, gaps at the roof ridge, where tiles may become dislocated or broken, can exacerbate vulnerability [29]. Additionally, roof overhangs, especially with combustible soffits, pose risks, potentially allowing firebrands to penetrate into attic spaces [30]. The accumulation of firebrands in eaves areas can lead to ignition, as observed during the 2009 Black Saturday Bushfire [8]. Roof gutters, particularly when filled with dead vegetation, are also identified as weak points, with potential for flame contact to the edge of the roof and subsequent entry into attic spaces [28,29,31]. Observations by Lopes et al. [32] across industrial sites highlighted the distortion and buckling of steel sheathing roofs, akin to the damages observed in facades of the same material. Polyurethane core sandwich panel roofs experienced detached steel sheaths, facilitating insulation core combustion and fire spread. In contrast, stone plane roofs remained intact due to their non-combustible nature, although equipment such as air conditioning units and copper piping insulation showed evidence of burning marks [32]. An analysis of recent wildland–urban interface (WUI) fires in Europe has also been conducted by Vacca et al. [25]. This study highlights several key observations regarding the effectiveness of different building materials in fire prevention. Notably, asbestos cement-based sheet roofs were found to be effective in preventing fire spread, although they resulted in elevated indoor temperatures. Additionally, skylights, predominantly made of polycarbonate plastic, were damaged by fire exposure and acted as potential entry points for embers, thereby igniting materials within buildings. Furthermore, the study identified several vulnerabilities in roofing. Despite the fire resistance of clay tiles, they can break under high temperatures, allowing embers to penetrate. Moreover, eaves, vents, and gutters were found to be susceptible to fire due to exposure and the accumulation of debris. In comparison, metal gutters demonstrated superior fire resistance compared to their PVC counterparts. Roof areas beneath overhanging tree branches often accumulate flammable materials, thereby increasing the fire risk. Finally, while PVC gutters may deform under heat, metal gutters offer better resistance by containing burning debris and minimizing the involvement of external elements.

2.2. Review of Wildfire Testing

An industrial firebrand generator was used to assess roofing material vulnerability to firebrand attack, as employed by Manzello et al. [33] at the Fire Research Wind Tunnel Facility in Japan. Findings highlighted behaviours like smouldering ignition and the melting of asphalt shingles, particularly in roofs with gutters. The study emphasizes the importance of gutter maintenance in WUI areas and aims to offer scientific guidance for building standards in the USA and Japan. The innovative approach, using controlled firebrands, provides valuable insights into potential risks and underscores the need for preventive measures in WUI regions. The same authors also conducted a comprehensive study [22], involving a parametric investigation of the ignition susceptibility of curved ceramic tile roofing assemblies using a firebrand generator. They also examined the influence of an applied wind field. Across the range of parameters considered, their findings revealed that ceramic tile roofing assemblies are indeed vulnerable to ignition during a firebrand attack. Vulnerabilities were systematically assessed by Quarles et al. [34] in roofing, attic vents, siding, decking, mulches, and attached decks. The test results predominantly provided video and photographic images for integration into the assessment tool, offering conformational data on the importance of window components and screening. The findings highlighted the vulnerability of glass as the most critical component, with window screens reducing radiant heat transmission into the building. Furthermore, results supported heat flux calculations, indicating that curtains behind closed windows with annealed or tempered glass ignite only after the glass breaks. Notably, the dual pane tempered glass window did not break under the 35 kW/m^2 exposure in this test series. An experimental study to investigate whether tile assemblies allow firebrands to penetrate and melt the underlying sarking was conducted by Manzello et al. [35]. Their findings revealed that firebrands successfully penetrated the tile gaps, subsequently melting the sarking material in both types of concrete tile roofing assemblies (flat and profiled tiles), as well as in the profiled tile terracotta roofing assembly when exposed to wind-driven firebrand showers. Interestingly, the flat tile terracotta roofing assembly demonstrated superior performance, likely attributable to its interlocking design. Although not related directly to wildfires, the same authors also conducted an experimental protocol [36,37] to ignite full-scale roofing assemblies, aiming to quantify firebrand production during combustion under various wind speeds. The results show that when only oriented strand board is used as sheathing, a significant number of firebrands collected from roofing assemblies were less than 1 g and 10 square centimetres. Additionally, the experiments on individual building component firebrand generation provided valuable insights into actual urban fire firebrand generation. Recently, Nguyen et al. [38] investigated rooftop ember retention during wildfires through wind tunnel experiments. They found that ember removal is influenced by roof slope, building geometry, and wind flow. Increasing roof slope in certain wind directions resulted in larger ember retention areas. Internal corners, like those around dormers, showed high ember stability. Their findings stress the importance of considering entire building dynamics in assessing ember retention during wildfires. A comprehensive examination of the relationship between wildland–urban interface (WUI) building features and wildfire damage, utilizing the innovative Wildfire Resistance Index (WRI), was conducted by Dossi et al. [23]. The study validated the WRI using data from the 2013–2017 CAL FIRE (DINS) database in California, USA, and the 2017 Pedrógão Grande Fire in Portugal. Their findings revealed that in California, damage correlated with vent screens and deck material flammability, while in Portugal, exterior walls and deck material flammability were significant factors. Furthermore, the study highlighted the WRI's potential as an effective estimator of wildfire damage, indicating a decrease in highly damaged buildings with an increase in WRI. At the moment of the publication of this manuscript a new ISO 6021:2024 [39] was publish, in which the conditions of a standard firebrand generator for testing are proposed. However, according to the authors best knowledge, its application to wildland fire testing in the wildfire scientific community is still low.

3. Experimental Campaign

In this section, a detailed description of the laboratory test procedure is provided, outlining the materials and geometries of the roof tiles specimens used. The temperature measured outputs are also depicted using data from thermocouples during the time analysis.

3.1. Chosen Construction Materials

The materials chosen for the experimental campaign include tiles, bituminous tile use as sub-tiles, and various thermal insulation materials such as cork, impermeable membrane, rigid rockwool, and polystyrene foam (XPS, also known as Roofmate). The decision of choosing these materials is due to their high popularity in the construction industry as thermal insulators for roofs. Their geometry and thermal characteristics are detailed in Table 1.

Table 1. Thickness of thermal insulation materials.

Material	Fire Reaction	Thermal Conductivity (W/m·K)	Thickness (mm)
Tile	A1	0.400	20
Bituminous tile	E	0.099	3
Composite Cork	E	0.050	30
Impermeable Membrane	Broof and E	0.040	2
Rockwool	A1	0.037	60
Polystyrene Foam (XPS)	C or even B.	0.027	30

Ceramic tiles are widely used for their availability, affordability, and A2 fire reaction classification, as they do not produce flames or smoke under fire conditions. This particular solution has been promoted in the scientific community as a good solution to use in new dwellings in order to prevent roof ignition due to firebrand wind deposition [9,40]. In the case of ceramic roof tiles, in new dwellings, it is believed that their possible ignition may be due to combustible debris piling up and poor maintenance during its life time [24].

Composite cork insulation is favoured for its environmentally friendly attributes, with a negative carbon footprint, providing highly efficient insulation as an external layer. Although not entirely fireproof, it demonstrates flame-retardant properties that effectively impede the spread of flames. Its innate resistance to fire and smoke may provide a safer choice compared to other materials. Furthermore, cork serves as a robust barrier against forest fires due to its low combustibility.

Given the widespread adoption of XPS in Europe, particularly within the traditional Roof mate, featuring a standard thickness of 50 mm ensures robust thermal insulation properties. However, due to its anticipated limitations in performance [41] and a maximum service temperature of 75 °C [41,42], it may present weak effectiveness after the external roof layers are subjected to elevated temperatures. For this reason, this material was studied in this work.

For the impermeable membrane usually used to avoid condensation problems, an experimental study may be necessary. This is due to the potential of firebrands to produce elevated temperatures in the roof tiles' exterior surfaces, and the heat flux penetrates the interior layers of a roof, posteriorly igniting them. It was a necessary solution to test considering this risk, since this type of material is needed when promoting house comfort in light of humidity penetration.

The selected rigid rockwool in this study boasted rigidity and featured a treatment layer that renders it impermeable to water while still allowing the flow of water vapour, a characteristic not commonly found in traditional rockwool solutions. Although the fire reaction of this material is close to A2, it was only tested for flame contact according to the European Committee for Standardization [43,44], and new tests for direct firebrand contact showed that it may present some problems [21].

Bituminous tile was also used, since it presents a new solution normally used below old tiles. This solution is being widely used in the rehabilitation of roofs in old dwellings in order to promote higher insulation and prevent rain penetration. This material only presents good thermal behaviour for high temperatures, but according to recent tests [21], for elevated temperatures from direct firebrand accumulation, its performance is poor.

3.2. Chosen Construction Elements

In this study, specimens representing eight roofs were selected, each assemble with a varying combination of materials, as presented in Table 2. The roof specimens, measuring approximately 55 × 30 cm^2 per section with the depth varying depending on the material type, were used. Each roof specimen consists of a base layer of tiles, with variations in insulation materials, as show in Figure 1. There was no single combination of ceramic tiles and membranes since the adoption of this single material layer does not abide by the construction code in Europe.

Table 2. Details of roof specimens studied.

Roofs Specimens	Sub-Tile	Thermal Insulation
Tile and sub-tile (TS)	Bituminous tile	Without
Tile and rockwool (TR)	Without	Rockwool
Tile and cork (TC)	Without	Cork
Tile and XPS (TX)	Without	XPS
Tile, sub-tile, and rockwool (TSR)	Bituminous tile	Rockwool
Tile, sub-tile, and cork (TSC)	Bituminous tile	Cork
Tile, sub-tile, and XPS (TSX)	Bituminous tile	XPS
Tile, sub-tile, and membrane (TSM)	Bituminous tile	Membrane

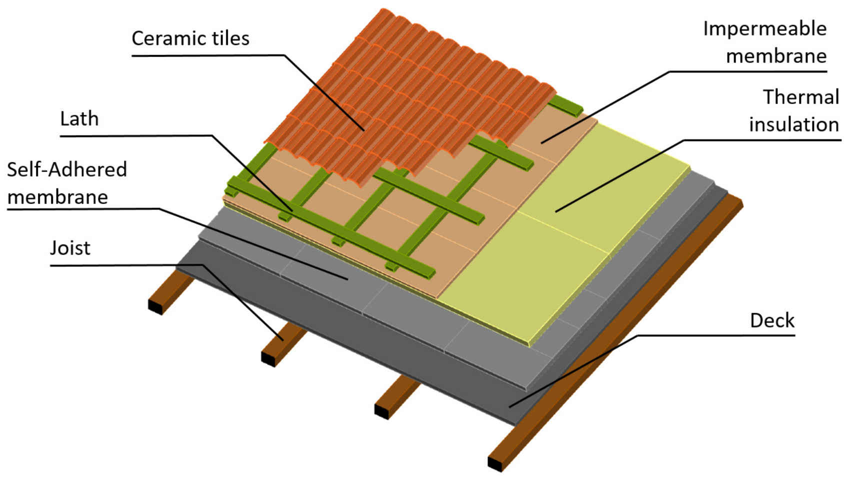
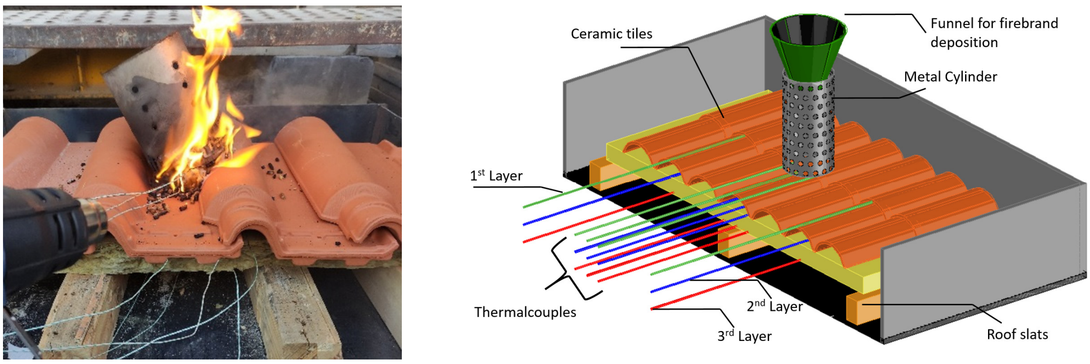


Figure 1. Description of roof layers in southern Europe.

3.3. Test Setup

Chapter 7A-4 [45,46] of the California Building Code provides guidelines that were followed for this test setup, which involves depositing 1.0 kg of firebrands into construction materials or element specimens, which are a ceramic roof tile element used in this study. The roof specimens are equipped with thermocouples (RS PRO-Type K thermocouples, 2.0 m long and 1/0.3 mm in diameter). These thermocouples were strategically positioned on each layer to monitor the transmission of temperature from the firebrands to the specimens. The temperature data are meticulously recorded at a frequency of 1 Hz for a maximum period of 200 min, providing comprehensive data into their behaviour during the cooling stage. In light of findings from multiple research studies [18,47–49] indicating that compressed wood pellets generate more severe firebrand temperatures, they were chosen to simulate the thermal action of firebrands. The process begins by placing 1.0 kg of firebrands in the metal cup and exposing them to an industrial wind blower to simulate the action of the wind at a speed of (1.31 ± 0.13) m/s, which in turn increases the duration and thermal action of the firebrands, causing a pyrolysis process until achieving full ignition, as illustrated in Figure 2. These firebrands are introduced into a cylindrical ignition control area with a 200 mm diameter and placed on the top according to suggestions from previous studies [47] and illustrated in Figure 3a, which found that larger diameters tend to result in greater thermal heat flux and maximum temperatures. The roof specimens had ceramic tile, sub-tile, and thermal insulation materials equipped with eight thermocouples, with two in each layer, while the other roof specimens, equipped with nine thermocouples, had three in each layer, as depicted in Figure 3b.

Figure 2. Illustration of firebrand ignition process under simulated wind conditions.



(**a**) (**b**)

Figure 3. Test setup for firebrand accumulation in construction elements specimens with 3 layers. (**a**) Roof firebrand accumulation test. (**b**) Representation of thermocouple location in the roof specimens.

4. Experimental Outputs and Observations

The temperatures measured by the thermocouples for each layer of every tested roof specimen are presented in this section. The thermal reaction in each part of the roof specimen is investigated under firebrand accumulation, as each part exhibits unique properties that result in different temperature behaviours and fire reactions during the test.

4.1. Measured Temperature

The climatic conditions varied for each test; therefore, the ambient temperature ranged between 20 °C and 30 °C, depending on the day of the experiment, but this had small importance for the thermal output. Figure 4 depicts the temperature measurements obtained from each layer across all tested roof specimens. The results from Thermocouple T5 were excluded from the curve for the tile and sub-tile specimen due to destruction during the test, making the data unreliable. The colours of the first, second, third, and fourth layer are black, blue, green, and orange, respectively, and their positions are depicted in Figure 5.

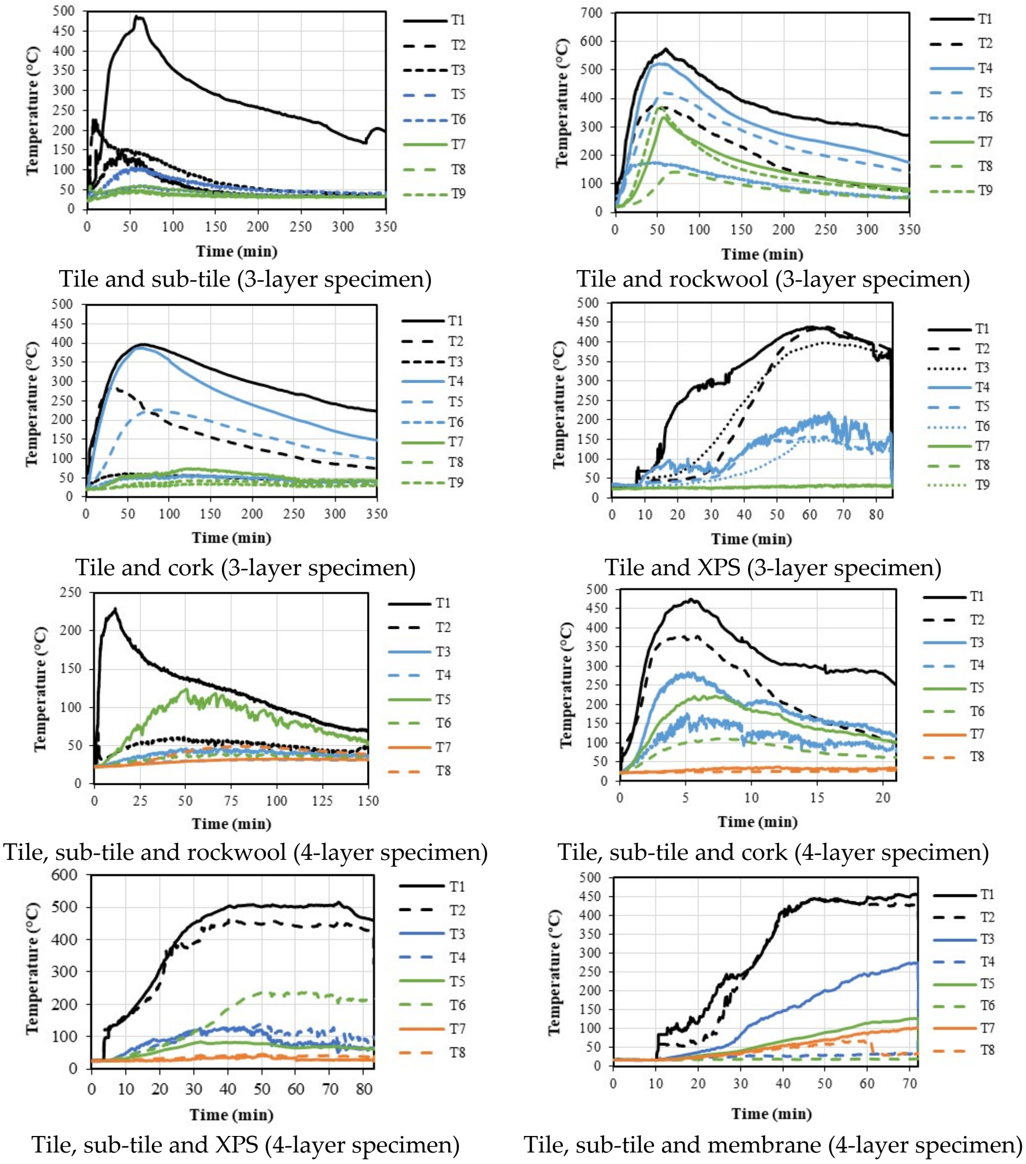


Figure 4. Temperature evolution measured at each layer for all roof specimens tested during exposure to firebrand accumulation.

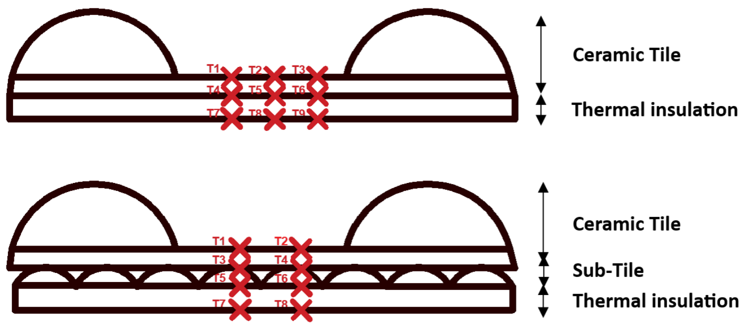


Figure 5. Position and numbering of the thermocouples for 3 and 4 layers.

From Figure 4, it can be noted that the higher temperatures were observed in the first layer, with discernible variations among the different roof specimen tests. Also, a decrease in the maximum temperature of each descending layer was observed across all specimens, except for the TSR and TSX specimens, where the maximum temperature recorded in third layer was higher than that in the second layer.

Figure 6 presents bar graphs showing the maximum temperatures recorded at both the top and bottom of the ceramic tiles for all roof specimens tested. It is evident from this figure that there is a high difference in the maximum temperature within the first layer of roof specimens, ranging from a minimum value of 229.53 °C to a maximum value of 574.84 °C. This difference can be attributed to differences in the climatic conditions during the test. Therefore, this result can be seen as an outlier and it will not be used for future analysis. The maximum temperatures are around 478.8 °C for the first layer (surface contact heat) with a standard deviation of 52.3 °C. This value is aligned with previous temperature readings from prior experimental and numerical campaigns for firebrand accumulation [17,18]. For the second layer, the results tend to be more scattered, with an average maximum temperature of 294.2 °C and a standard deviation of 115.5 °C. This higher scatter is clearly due to the different fire reaction of the insulation materials when subject to high temperatures, something already expected and reported in prior works [21]. From the recordings of the maximum temperatures of the second layer, the impact of using sub-tile (bituminous tile) becomes apparent. It is noteworthy that the temperatures in the roof specimen with sub-tile (bituminous tile) were lower compared to those without it, considering the same thermal insulation material. This can be attributed to the bituminous tile's low combustion rate.

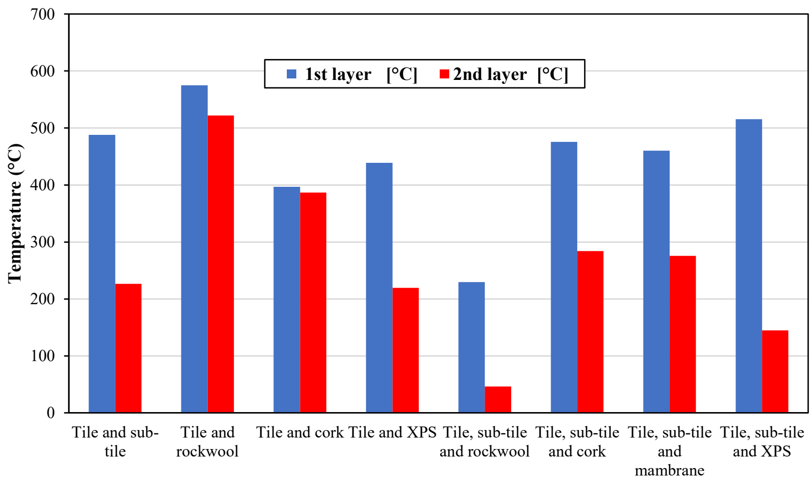
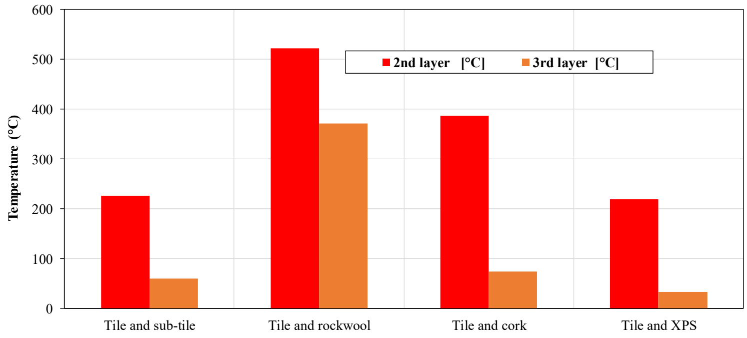


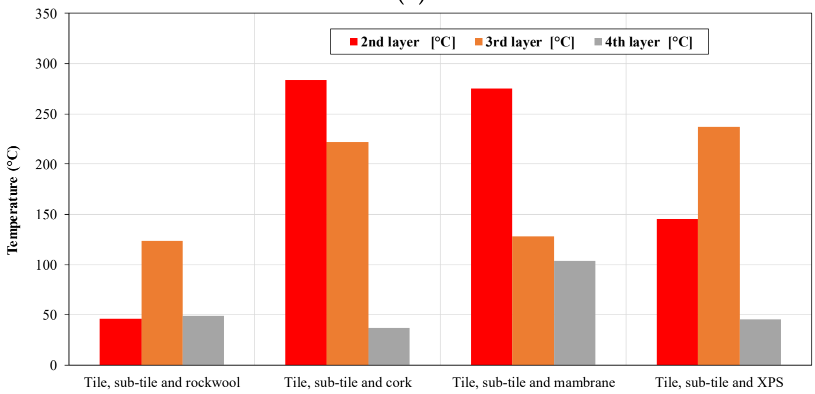
Figure 6. Maximum temperatures recorded in the 1st layer and 2nd layer for all roof specimens.

Figure 7 presents the maximum temperature recorded in each layer. From this figure, it is evident that the use of a bituminous sub-tile without any additional thermal insulation provides moderate temperature resistance, reducing the temperature by approximately 73.5% from the second layer to the third layer (from 226.57 °C to 60.04 °C). For combinations of bituminous tile with insulation materials, the temperature in the third layer varied depending on the type of insulation used, but, in general, it was higher than in the specimen without insulation materials. The bituminous tile layer absorbs some heat but does not offer significant thermal insulation.

Rockwool shows high temperatures in the subsequent layers, with the second layer reaching 522.00 °C and the third layer 371.81 °C, indicating that while it can withstand fire, it does not effectively prevent heat transfer through the layers. This could be due to the limitations mentioned in the study about direct firebrand contact problems [21]. Furthermore, adding a sub-tile layer improves the performance of rockwool by providing an initial heat barrier. However, it can be observed that the temperature spikes in the third layer are due to the melting of the bottom layer of bituminous tile above the rockwool. This is analyzed in Section 4.2.



(**a**)



(**b**)

Figure 7. Maximum temperatures recorded in the 2nd, 3rd, and 4th layers for (**a**) three-layer specimens and (**b**) four-layer specimens.

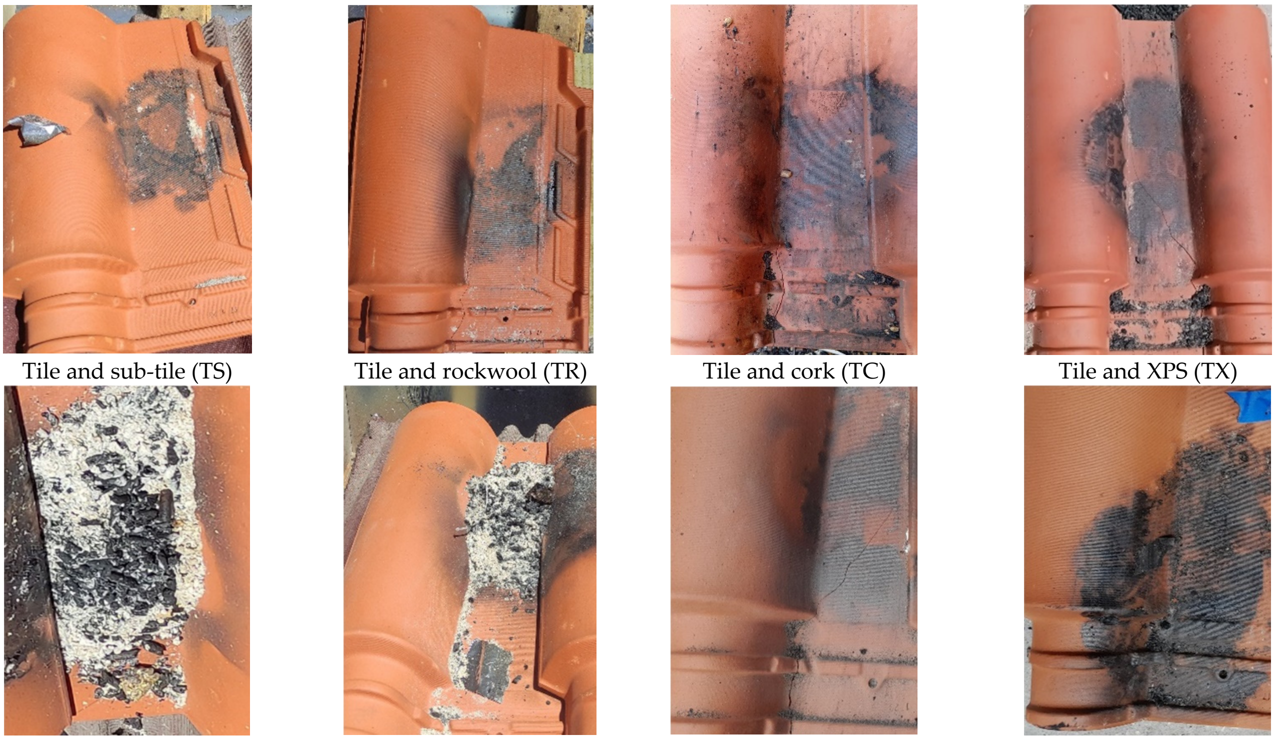
Cork shows a significant drop in temperature between the second layer (386.91 °C) and the third layer (73.96 °C), demonstrating better performance than rockwool. Additionally, the combination of bituminous tile and cork significantly reduces heat transfer. The high temperature in the third layer (222.24 °C) is substantially reduced to 37.12 °C by the fourth layer.

The XPS maintained lower temperatures (33.72 °C) in the third layer but loses its effectiveness at higher service temperatures. Furthermore, the combination of bituminous tile and XPS presented worse behaviour because the temperature increased significantly in the third layer due to the melting of the bituminous tile above it.

The impermeable membrane performs decently, managing to reduce the temperature from 128.07 °C in the third layer to 103.59 °C in the fourth layer. This was not expected, especially due to the small thickness of the specimen.

4.2. Observed Fire Reaction and Ignition

The behaviour of the roof specimen was monitored during and after the firebrand accumulation test, and numerous observations were recorded. Figure 8 portrays images of the tile in each roof specimen after testing. It is noted that the tile in some specimens, such as TS, TSC, and TSM, resisted the impact of firebrand accumulation during the test. However, in other specimens, including TR, TC, TX, TSR, and TSX, the tile showed cracking. This observation complements some findings reported in previous research [20,40,50–52]. Initially, it was believed that the use of ceramic tiles would prevent roof ignition in new dwellings due to firebrand wind transportation and later deposition during wildfires. Using the observations from these tests, it may be possible for a roof made of ceramic tile (on a new dwelling) to either suffer damage or start an ignition due to the combustion of the thermal insulation or extra layer of construction materials. This possibility can indeed happen in extreme events if the cracking is big enough, allowing firebrand penetration into the interior layers (Figure 9).



Tile and sub-tile (TS) Tile and rockwool (TR) Tile and cork (TC) Tile and XPS (TX)

Tile, sub-tile and rockwool (TSR) Tile, sub-tile and cork (TSC) Tile, sub-tile and XPS (TSX) Tile, sub-tile and membrane (TSM)

Figure 8. Tile condition of each specimen after exposure to firebrand accumulation test.

Figure 9. Extreme thermal event of firebrand accumulation that led to severe fracture in the ceramic tile.

The observations recorded during test for each material in each specimen regarding each type of ignition, smoke production, and droplet production are summarized in Table 3. The ignition of materials during the test is categorized into no ignition (NI), smouldering ignition (SI), and flame ignition (FI).

Table 3. Construction material reaction against firebrand accumulation during the test.

Material	Rockwool		Cork		XPS		Membrane	Bituminous Tile
Specimen	TR	TSR	TC	TSC	TX	TSX	TSM	In all specimens
Type of Ignition	SI	SI	SI	SI	NI	NI	NI	FI
Smoke Production	YES	YES	YES	YES	YES	NO	NO	YES
Droplets Production	NO	NO	NO	NO	YES	YES	NO	YES

In all specimens, the bituminous tiles were ignited with the same intensity, with some smoke production and droplet production, which are visible in the TSM specimen, see Figure 10. The flow of these droplets could contribute to the temperature increase in the third layer, as can be well observed in the TSR and TSX specimen, as mentioned in Section 4.1. The rockwool and cork in the specimen without a sub-tile underwent smouldering ignition with significant smoke production. In contrast, the rockwool and cork in the specimen with a sub-tile exhibited low-intensity smouldering and minimal smoke production. The XPS reaction was not included in Table 3 because it melted and evaporated at low temperatures in both roof specimens, with and without a sub-tile. This makes tracking its performance difficult, and it can be concluded that it performs very poorly against firebrand accumulation. The impermeable membrane did not produce flame ignition, smoke, or droplets for firebrand accumulation. This later solution, just like in previous studies [21], presented a good solution for elevated temperatures due to firebrand accumulation.

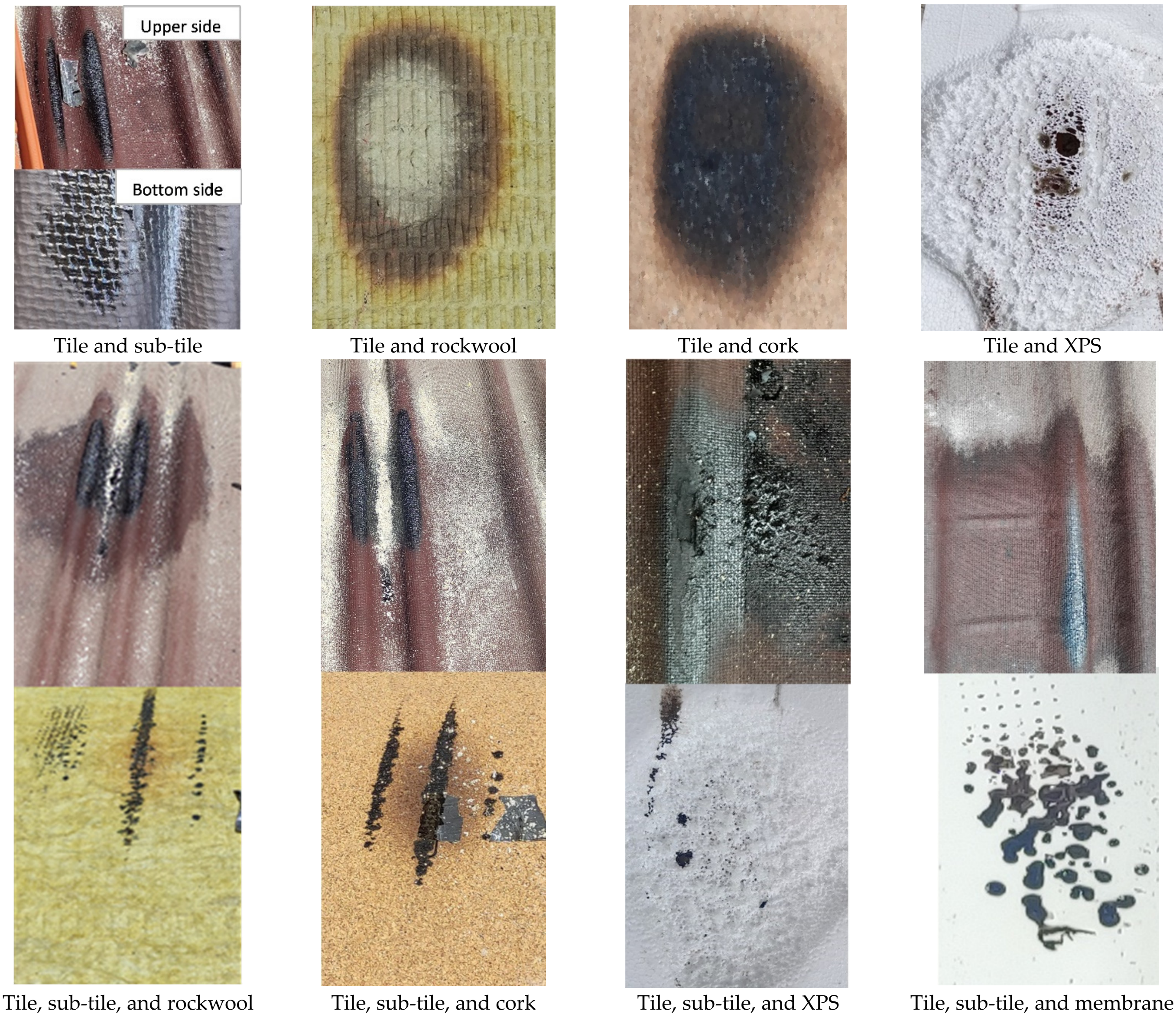


Figure 10. Impact of firebrand accumulation penetration in construction materials for each tasted specimen.

4.3. Firebrand Heat Penetration in the Layers

The impact of firebrand accumulation on the studied specimens was assessed by analyzing heat penetration in each layer, as shown in Figure 10. It can observed that the impact of firebrand accumulation has reached the surface of the last material in all specimens tested, but creating different levels of damage. The firebrand accumulation caused damage to the sub-tile (bituminous tile) on the upper side with nearly the same severity in all specimens containing a sub-tile, and, on the bottom, the melting of the asphalt was clearly evident. Comparing specimens with and without a sub-tile, it can be observed that in the rockwool and cork specimens, the heat penetration was greater in specimens without sub-tile. Regarding XPS, a similar effect was observed in specimens with and without a sub-tile, except for the presence of small droplets resulting from the melting of the sub-tile. As for the impermeable membrane, categorized by fire reaction as B_{roof}, it had very little effect with the presence of bituminous tile melting drops. It is worth mentioning that specimens containing XPS allowed heat transfer on the last side, unlike specimens containing other materials, where the effect was only on the upper side. The insulation materials like cork and the impermeable membrane presented lower damage due to thermal firebrand penetration.

5. Discussion and Conclusions

This study was experimental, including a set of roofs assembled using popular construction materials in southern Europe. The tests included similar needs to the California Building Code, when construction elements are subjected to firebrand deposition. It was concluded that (i) the use of sub-tiles with bituminous material may case unexpected damage during wildfires, and its use should be avoided; (ii) for the tested thermal insulators, the impermeable membrane and cork composite presented the lowest damage due to heat transfer from firebrand accumulation in the ceramic tiles, and the rockwool presented some smouldering and damage, but the extent of the damage penetration was not high; and (iii) some ceramic tiles presented thermal cracking, just after a few minutes, during the firebrand tests, which allows for the hypothesis of using a new roof ignition if the firebrands penetrate in the interior layers of the roof, even without the presence of combustible materials.

5.1. Recommendations for Roofs Against Wildfires

These findings complement the research presented in [9,20], which recommended that the thermal insulation of roofs should always be assembled using materials with a fire reaction ranging from A to B according to [43,53]. Furthermore, as suggested, the roof structure should not allow contact with the interior of the dwelling, and should preferably be made of reinforced concrete (joist and deck). Recommendations for the roof layers can be found in [9], and their assembly should follow this guidance. Also, due to the cracking of the roof tiles caused by firebrand accumulation, it is also necessary to verify the fire resistance of the roof when being impacted by a wildfire, according to [19]. The roof lath (roof batten) that supports the ceramic roof tiles and promotes its connection to the thermal insulation should also be made of incombustible materials, since the heat transfer due to firebrand accumulation is high.

After a wildfire, near a dwelling with observed firebrand transportation due to wind, an inspection of the roof is recommended to identify possible places of firebrand accumulation, which may have damage the thermal insulation. This last one may need maintenance and to be replaced to ensure that the initial design thermal insulation comfort and quality is not degraded.

5.2. Limitations of the Study

The experimental campaign followed approximately the guideline standard of the California Building Code Chapter 7A-4 using static firebrand deposition, which may be a more severe thermal action than simulating firebrand transportation and then deposition using a fire-dragon firebrand generator. In any case, this type of firebrand accumulation has been reported and is likely to occur in extreme situations.

5.3. Future Developments

According to the observations from this study, it was concluded that the combination of construction materials in roofs with standard fire reaction classes [54,55] might be insufficient to avoid any unexpected thermal reaction due to firebrand accumulation which may cause secondary fires in a dwelling. It may be necessary to update future building codes to take these new findings into account. Numerical models need to be developed to study a different combination of materials and promote parametric studies.

Several setups for walls, windows, and doors will be tested in the laboratory for the action of firebrand accumulation, and the conclusions of this work may provide some guidelines for combining the layers of the construction elements. Different construction materials are also expected to be tested in terms of thermal insulation capacity for firebrand accumulation. New results concerning these new fireproof construction guidelines will be publicly accessible at the following link: https://whp.tecnico.ulisboa.pt (accessed on 22 December 2024).

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