TALLINN UNIVERSITY OF TECHNOLOGY
SCHOOL OF ENGINEERING
Department of Materials and Environmental Technology

INFLUENCE OF FACE VENEER THICKNESS ON COMBUSTION PROPERTIES OF FIRE RETARDANT TREATED PLYWOOD

PINNASPOONI PAKSUSE MÕJU TULETÕKKEAINEGA TÖÖDELDUD VINEERI PÕLEMISOMADUSTELE

MASTER THESIS

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Tallinn 2024

(*On the reverse side of title page*)

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THESIS TASK

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Thesis topic:

(in English) *Influence of face veneer thickness on combustion properties of fire retardant treated plywood*

(in Estonian) Pinnaspooni paksuse mõju tuletõkkeainega töödeldud vineeri põlemisomadustele.

Thesis main objectives:

1. Studying the effect of face veneer thickness and fire retardant concentration on fire retardant penetration
2. Examining the effect of face veneer thickness on combustion behaviour
3. Determining the effect of different fire retardant concentrations on combustion behaviour

Thesis tasks and time schedule:

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1.	Comprehensive literature review on fire-retardant treatments for plywood	21.12.2021
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PREFACE

The research presented in this master's thesis was initiated with Palonot Oy and Estonian Plywood AS, aimed at studying the influence of face veneer thickness on the combustion properties of fire-retardant treated plywood. Most of this thesis work was conducted in Tallinn University of Technology, where the facilities and academic support from the university staff was instrumental in facilitating and shaping the direction of this study.

I express my sincere gratitude to my thesis supervisors Percy Festus Alao and Anti Rohumaa, and external consultant Jussi Ruponen, whose guidance, expertise and encouragement significantly contributed to the development and execution of this thesis.

This research aimed to create a better understanding on how fire-retardant treated birch plywood behaves during combustion, specifically focusing on the impact of face veneer thicknesses and fire retardant concentrations on combustion behaviour and penetration.

In summary, the study found that increasing face veneer thickness improved fire performance and fire retardant penetration depth in surface-treated plywood. It appears that thinner face veneers encounter barriers in penetration due to bond line restrictions, whereas in case of thicker face veneers, the penetration is limited by the inherent characteristics of the wood material. Although the diluted fire retardant solution showed higher penetration in some cases, this deeper penetration did not enhance fire performance.

I hope this thesis contributes meaningfully to the existing body of knowledge in fire retardant treatments for wood products and serves as a foundation for further advancements.

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List of abbreviations and symbols

AHRE	Average heat rate emission
FR	Fire retardant
FVT	Face veneer thickness
HRR	Heat release rate
MAHRE	Maximum average heat rate emission
MC	Moisture content
PHRR	Peak heat release rate
Tprot	Basic protection time
THR	Total heat release

1 INTRODUCTION

Plywood as a material has gained popularity due to its high structural strength, flexibility, sound, and thermal insulation properties and is therefore used in various industries ranging from transportation (marine, aerial, land) to construction. The growing importance of global environmental challenges such as the climate change are forcing regulators to impose new restrictions to accelerate the transition from non-renewable to renewable resources. Considering these trends, the global demand for long-lived wood products, including plywood, is expected to increase. [1]

In addition to environmental impacts, regulations related to health and safety are of growing importance. As fire safety standards evolve over time, there is pressure on plywood manufacturers to produce fire-retardant (FR) plywood products that comply with current requirements. Research in this field is necessary to find new solutions for producing fire-retardant plywood that meet safety standards.

In the context of plywood manufacturing, the highly competitive business landscape is driving producers to manufacture fire-resistant plywood more efficiently and cost-effectively while meeting stringent safety standards. Innovative techniques are being explored to achieve sufficient fire resistance without increasing production expenses. The development of fire resistant plywood products by surface treatment presents could present a possibility to gain a competitive edge in the market.

The general aim of this research is to study the combustion behaviour of post-manufacture fire-retardant treated birch plywood. The objectives of the study are the following:

- Studying the effect of face veneer thickness and fire-retardant concentration on fire-retardant penetration;
- Examining the effect of face veneer thickness on combustion behaviour;
- Determining the effect of different fire-retardant concentrations on combustion behaviour.

The study was conducted using Palonot F1-10 fire-retardant chemical, birch (*Betula pendula* Roth*)* core plywood panels and birch veneers of three thicknesses (1,0 mm, 1,5 mm and 2,6 mm). Parameters such as log soaking duration, face veneer thickness, FR spread rate, concentration and retention depth of fire retardant, panel surface temperature during FR treatment, etc. were monitored to ensure consistency in sample preparation. The face veneers were adhered to core plywood panels with regular phenol formaldehyde resin.

There are several properties and variables that affect the combustion behaviour of plywood products, including:

- wood species
- veneer quality (knots, depth of lathe checks, etc)
- plywood properties such as thickness and density.
- type of fire retardant
- type of adhesive
- spread rate and concentration of fire retardant.
- application method of fire retardant (soft coating roller, hard coating roller)
- retention depth of fire-retardant

Hypothesis 1: Face veneer thickness may have a crucial impact on the combustion behaviour of FR-treated plywood.

Hypothesis 2: Using a diluted solution of Palonot F1-10 may improve the penetration capability of the FR chemical.

Hypothesis 3: Diluting Palonot F1-10 with 30% water could be a viable option for more economical use of fire retardant for some veneer thicknesses.

Research question: What is the optimal face veneer thickness to provide good combustion behaviour?

Research question: How does diluting the FR chemical with water impact combustion behaviour and penetration depth, and could this be a viable option for more economical consumption of the FR chemical?

The literature review covers the factors influencing the combustion behaviour of plywood and gives an overview of relevant fire safety standards and certifications. The materials and methods chapter provides a detailed description of the practical work done in this study. The results and discussion chapter presents the results of this study and provides an in-depth analysis and interpretation of the findings in relation to the hypotheses.

Keywords: plywood, fire-retardant treatment, surface coating, master's thesis

2 LITERATURE REVIEW

The literature review is divided into 6 sections. The first section gives an overview of plywood production and applications in general and fire rated plywood products in the European market. The second section covers the combustion behaviour of wood and wood based products. The third section is about the key fire safety standards that relate to this study. The fourth section describes various types of fire retardant treatments for plywood. The fifth section describes the effect adhesives on the combustion behaviour of plywood products. The sixth and final section covers the effect of surface properties on plywood combustion behaviour.

2.1. Plywood products and market overview

Plywood is an engineered wood product made by gluing together thin layers of wood veneers. Normally, each veneer layer is placed with its grain direction perpendicular to the adjacent layers to enhance the strength and stability of the final product. The veneers are bonded by using adhesives under heat and pressure. Alternating the grain direction of each veneer layer helps to counteract the natural tendency of wood to expand, contract, warp, and twist with changes in its moisture content, enhancing its dimensional stability. The layered design of plywood also reduces the impact of wood defects on the panel by distributing weaknesses, such as knots, more evenly throughout the material, enhancing its strength and structural integrity. [1]

Due to its strength, durability and adaptability, plywood is used in various applications across a range of industries. It is used extensively in the construction sector for walls, floors and roof sheathing. Plywood also plays a vital role in the transportation industry, specifically in manufacturing of buses and trains, where it is often used for flooring and interiors. Due to its high planar shear strength, birch plywood is especially well suited for heavy flooring applications compared to other plywood types. The good strength to weight ratio of plywood makes it a suitable product to reduce the overall weight of the vehicle, improving fuel efficiency, while also ensuring durability and structural integrity. Plywood is also widely used in furniture making as it is easy to shape and customize it for products such as tables, chairs and other interior furnishings. [1]

There are also limitations to plywood products, which are mainly related to moisture resistance, fire resistance and cost. Exposure to water and moisture can lead to warping and delamination, compromising aesthetics and durability of the product. In case of lower grade plywood, surface imperfections are a common occurrence. High-quality plywood is often more expensive in comparison to alternative materials. Also, as a wood-based product, plywood is not inherently fireproof. In the event of a fire, it can ignite, burn, and contribute to the spread of flames. Therefore, in applications where fire safety is important, plywood needs to be specially treated to improve its fire resistance. [1]

The industrial plywood manufacturing process is long and divided into multiple automated phases. First, soaked logs are fed to the mill where they are debarked, scanned and cross-cut to obtain peeler blocks. Conditioning (soaking) the logs increases the internal temperature of the logs, which improves the quality of peeling and of the peeled veneer. The blocks are then peeled using a veneer lathe, where the peeler block is rotated between spindles at a constant speed, while the knife carriage steadily advances towards the spindle centre. The exiting veneer mat is cut and sorted into veneers of different quality for core and face veneers. As the next step, the veneers are dried to achieve a moisture content suitable for gluing the veneers into plywood. The dried veneers are scarf-jointed and composed into sheets of required length and width. Adhesive is then applied on the veneers and they are laid up into a cross-banded panel structure. Stacks of lay-ups are then cold-pressed into panel form without heat to enhance the adhesion of glue on the veneers. It is important to avoid waiting times between lay-up and cold-pressing to prevent the glue from drying. After pre-pressing, the veneers are compressed using high temperature and pressure. For phenolic resins, as used in this research, the pressing temperature is usually 125-170 °C and pressing pressure for birch is around 1,5 MPa - 2,0 MPa. After pressing, the panels are sawn into their final dimensions, repaired if needed and then sanded to calibrate the panel thickness and give the panels a smooth surface. After sanding, plywood panels can be coated to provide protection against moisture, physical damage or fire. As the final step, the panels are graded and packaged. [1]

There are several manufacturers in Europe producing fire resistant plywood for various applications. MetsäWood's product Spruce FireResist is made for application in interior panelling. UPM-Kymmene produces Spruce FR structural plywood for both construction and transportation applications. Products belonging to Garnica's FireShield series can also be applied in both transportation and construction, while Koskisen produces Koskibond F fire-retardant plywood only for the transportation sector. [2] [3] [4] [5]

2.2. Combustion behaviour of wood

The most important wood characteristics that influence combustion properties are its density, moisture content, extractives content and carbon content. Wood density and the content of carbon and extractives can vary significantly between species and depend on the proportions of the main structural components of wood: lignin, cellulose and hemicelluloses. Lignin has a higher energy content per unit mass compared to cellulose and hemicelluloses. Wood properties can also vary significantly even within a wood specie, as they are strongly influenced by the growing conditions of a tree. Generally, it can be said that hardwood species have a lower calorific content per unit mass compared to softwoods, as they contain fewer lignin and resinous materials, resulting in a lower carbon content. [6]

A study by Lõhmus [7] investigated the calorific value per unit mass of common hardwood species found in Estonia. The results of this study are shown in the second column of Table 2.1. It can be concluded that although there are slight differences in the caloric values per unit mass, the values are within a comparable range. According to Hse [8], silver birch (*Betula pendula* Roth.), black alder (*Alnus glutinosa* (L.) Gaertner) and aspen (*Populus tremula* L.) are all diffuse-porous species and do not have significant differences in chemical composition, which explains the similar caloric values per unit mass. However, there are noticeable differences in density between these species. The average density values presented in the third column of Table 2.1 originate from The Wood Database [9]. The caloric values per unit volume (rightmost column) have been calculated by the author based on the caloric value per unit mass and density.

Table 2.1 Caloric values of common hardwood species used for plywood in Estonia.

Wood specie	**Caloric value (kJ/g) of stemwood**	**Average density at 0 % MC* (kg/m³)**	**Caloric value (MJ/m³)**
Silver birch (*Betula pendula* Roth.)	19,19	640	12282
Black alder (*Alnus glutinosa* (L.) Gaertner)	19,44	535	10400
Aspen (*Populus tremula* L.)	19,38	450	8721

* MC - moisture content

The data in Table 2.1 shows how the caloric content per unit volume is significantly affected by wood density. Birch wood poses a challenge in terms of fire protection due to its high density. It is not by coincidence that birch has historically been a preferred wood specie for fuel in heating in the Nordic and Baltic states and is a favoured choice to this day.

Wood products will ignite when exposed to high temperature and the presence of oxygen. When these conditions are met, wood responds by thermally decomposing, or pyrolyzing (in the absence of oxygen), into volatile gases and char residue. As the volatile gases mix with surrounding air, they can ignite and cause flaming combustion. [10]

There are two ways for a wood material to ignite: piloted and non-piloted ignition. Piloted ignition is characterized by the presence of a flame or a spark which serves as an ignition source for the volatile gases that are released by thermal decomposition. The mode of ignition is an important concept to understand as it can significantly influence the ignition process. [10]

During thermal decomposition, wood forms an insulating char layer that slows the further degradation by slowing heat transfer as char has low thermal conductivity. The char layer also limits the access of oxygen to underlying wood, which also contributes to the reduction of rate of combustion. In structural applications, the load-bearing capacity of a wood member depends on its cross-sectional dimensions. Therefore, charring rate is a key factor in fire endurance of wood structures. [10]

Thermal degradation of wood occurs in three stages: dehydration, slow degradation and active degradation [10]. The dehydration phase occurs at temperatures up to 150 °C, where the material dries and produces water vapor [10]. Slow degradation occurs in the temperature range of 100 °C to 250 °C [10]. In this stage, wood will eventually become charred and release gaseous products, most of which are non-combustible [10], however, flame formation can also start to occur in the slow degradation phase [11]. Active degradation happens between 280 °C to 500 °C [10]. In this phase, combustible volatile gases are released, which cause flaming combustion [10] as a reaction between oxygen and the gases released from the material [11]. The outlined stages of wood's thermal degradation relate to the decomposition of its main structural components, which release volatiles over different temperature ranges. For cellulose, hemicellulose and lignin these ranges are 240-350 °C, 200-260 °C and 280-500 °C, respectively [12]. However, according to Popescu and Pfriem, the elimination of some volatile gases is terminated at a temperature around 800 °C [11].

Burning rate is the general term used to describe the rate at which a material is consumed by fire. More specifically, burning rate is described by heat release rate, mass loss rate and charring rate. Burning rate varies across different wood species and wood products, and is influenced by wood properties such as wood density, moisture content and chemical composition (carbon content), and external factors like oxygen concentration in the surrounding air and external heat flux. [13]

Heat release rate is considered to be the single most important variable in characterizing and predicting the flammability of products and their resulting fire hazard because the heat released by a burning material can contribute to the growth and spread of fire [14]. Heat release rate is defined as the energy released from a burning object or fire, per unit time [15]. In fire science, quantifying the size of a fire is commonly achieved by measuring the heat release rate, rather than relying on the temperature or geometry of the flames, which tend to remain relatively unchanged [15]. From a thermodynamic perspective, heat represents the energy transmitted between two systems as a result of their varying temperatures [15]. Research by Moghtaderi and Fletcher [16] showed that heat release rate of wood materials is significantly affected by irradiance level (radiant heat flux), wood density, moisture content and orientation of the sample. The findings revealed an increase in heat release rate with rising irradiance levels. Conversely, higher moisture content was found to correlate with a reduction in heat release rate. The research also highlighted a significant disparity in heat release rates between horizontal and vertical orientations. Specifically, the horizontal position demonstrated considerably higher heat release rates, which was primarily attributed to heightened radiative feedback from the flame in this orientation [16].

The emission of smoke and toxic gases is another critical factor in fire testing since a large number of fire casualties result from exposure to toxic smoke rather than direct contact with the flames [17]. Wood or wood based materials used in construction must be selected to minimize the release of toxic substances as slowly as possible when exposed to heat or fire, affording people time to evacuate [18]. It is known that the quantity of smoke and combustion by-products generated are directly correlated to heat release rate and mass loss during combustion [19]. Consequently, if products are engineered with suitable fire performance aligned with their intended use, both the toxicity of smoke during fires and the subsequent fire hazard will diminish [19]. However, according to a paper by Dietenberger and Hasburgh, excessive levels of fire retardants can increase smoke production [20].

Flame spread is an important parameter in wood combustion behaviour and is also one of the pivotal metrics in determining the fire class rating of a product according to EN 13501-1. It has been defined as "the sliding movement of the flaming ignition point over the surface of a solid combustible [20]." The rate of flame spread depends on how quickly the surface reaches heat flux distribution (how fast it heats up from nearby flames and other heat sources). When wood reaches the surface temperature of rapid volatilization (around 300 °C, depending on wood species), the volatile gases being released fuel the fire and increase the rate of flame spread. The rate of flame spread increases with the magnitude of heat exposure from the ignition source and tends to decrease as density, moisture content, surface ignition temperature and thermal conductivity increase. Ceiling flame spread, moving upward along the direction of airflow, is a significant fire safety concern due to its potential to rapidly escalate room flashover, leading to high heat release and production of smoke and toxic gases. On the other hand, downward and lateral flame spread, which move against the airflow direction, require additional external heat sources to sustain their movement on wood products as they receive minimal heating from adjacent flames. [20]

2.3. Fire safety standards and fire testing

Fire safety standards and regulations are evolving over time. European Union regulations require construction works and products to be designed in a way not to endanger the safety of people, domestic animals, property or the environment. These rules have direct implications on the requirements of construction products, which must be tested to ensure compliance with relevant standards before a product can be marketed. [21]

2.3.1. European fire classification standard for construction products EN 13501-1

In the European Union, the fire testing and classification standards for construction products are covered under European Standard EN 13501-1. The European Reaction to Fire classification system is the common standard in the European Union for evaluating the qualities of building materials in the event of a fire. [22]

The EN 13501-1 classification includes three ratings. Euro class ratings are defined by letter-number combinations of A1, A2, B, C, D, E and F. A1 products are classified as non-combustible, A2 refers to limited combustibility and letters B to F are listed as combustible. The second rating is related to smoke emission when the material is combusted. The smoke emission rating is broken down in three categories: s1, s2 and s3 (from highest to lowest performance). The third rating refers to the production of flaming particles and droplets, and is indicated by ratings d0, d1 and d2 (from highest to lowest performance). Wood as an organic material is inherently combustible, therefore the highest possible rating for a wood product to achieve is B-s1, d0. [22]

To achieve the Euroclass B-s1, d0 rating, plywood products must be tested according to the methods specified in ISO 11925-2 (single flame source test) and EN 13823 (single burning item test). Parameters measured in these tests are total heat release (THR), lateral flame spread (LFS), total smoke production (TSP), fire growth rate index (FIGRA), smoke growth rate index (SMOGRA). The tests must be executed by precisely following the instructions provided in the standard, which include a detailed information about the testing apparatus, preparation, and dimensions of test specimens, etc. [22]. The preparation of test specimens for the EN 13823 single burning item test is described in the materials and methods chapter.

2.3.2. European railway standard for fire safety EN 45545-2

The reaction to fire performance requirements for materials used on railway vehicles in the EU are defined in the European Standard EN 45545-2. The operation and design categories outlined in the standard serve as the foundation for determining hazard levels within a classification system. [23]

The operation and design categories include factors such as the type of railway service (e.g., urban or long distance) and intended use of the vehicle (e.g., passenger carriage or freight wagon), the availability of safe areas for evacuation, and other relevant aspects [24]. The hazard levels (HL1, HL2 and HL3) are based on the operational and design categories, and correspond to the identified risks or potential fire hazards associated with the different use applications [24]. Materials and components are categorized according to the hazard levels to ensure specified safety standards and requirements [23]. The reaction to fire performance requirements for the materials depend also on the location of the materials within the design, their shape and layout, and the exposed surface [23]. On this basis, the materials have been classified into subgroups based on their general location (interiors or exteriors) and their specific use (furniture, electro-technical equipment or mechanical equipment) [23].

A set of requirements has been given to each sub-group of materials which defines their ability to contain fire development to an appropriate degree considering the parameters listed above. Table 2.2 highlights some of the relevant product categories for plywood products, their applications, examples and hazard levels assigned to them. The hazard level requirements and values listed in the rightmost column correspond to the maximum MAHRE (maximum average heat rate emission) results in testing according to ISO 5660-1. [23]

Table 2.2 Product requirements based on EN 45545-2 [23]

Requirement	Application	Examples	Hazard level
R1	IN1A: Interior vertical surfaces	Side walls, partitions, room dividers, boxes, interior doors	HL1 - N/A HL2 - 90 kW/m² HL3 - 60 kW/m²
R1	IN1B: Interior horizontal downward-facing surfaces	Ceiling panelling, boxes, hoods, insulation material	
R1	IN1C: Interior horizontal upwards-facing surfaces	Flaps, boxes, hoods, insulation material	
R1	IN4: Luggage storage areas	Luggage racks, stacks, containers and compartments	
R1	IN9B: Folding table downwards facing surface	Bottom surface of a table, exposed vertical sides	
R1	IN7: Window surroundings	Window frames	
R2	IN9A: Folding tabletops	All tables and toilet wash basins	HL1 - N/A HL2 - N/A HL3 - 90 kW/m²
R6	F1C: Seat shell base	External surface of the base shell	HL1 - 90 kW/m² HL2 - 90 kW/m² HL3 - 60 kW/m²
R6	F1D: Seat shell back	External surface of the back shell	

2.4. Fire retardant treatments for plywood

Fire retardants are substances that prevent ignition, suppress the burning process of combustible materials and eliminate causes of fire and conflagration [25] by interfering with a certain stage of wood combustion process through mechanisms that may function physically or chemically, or in a combined way [11]. According to Rudzite and Buksans, "the principle of the retardation process is based either on physical blocking of fire or initiating the chemical reaction that stops the process of combustion [25]." Fire retardant systems can combine several mechanisms of action, for example isolating the surface layer, upgrading the thermal properties and pathway of pyrolysis of the impregnated material, and diluting the pyrolysis gases [11]. These mechanisms can enhance combustion performance by reducing heat release rate at the initial stages of fire and inhibiting flame spread and the production of smoke and volatile gases [11]. Overall, each fire retardant operates in its own way, reducing charring temperature and mass loss rate while increasing mass residue [11].

According to Popescu and Pfriem, most commercial fire retardants work by enhancing the pyrolysis reaction of cellulose, leading to higher char formation. Higher char formation leads to isolation of the surface layer which delays temperature rise, reduces the release of pyrolysis gases and limits the access of oxygen to the underlying material. These effects are characteristic of intumescent fire retardant surface treatments which expand with temperature increase and form a thick, porous, carbonaceous layer that protects wood surface from fire. [11]

The main chemical fire retardant coatings for wood products use halogen-containing compounds (i.e. chlorine or bromine), nitrogen, phosphorous, borax, boric acid, or inorganic metal compounds as their main components. Research has shown that these compounds help inhibit flame spread by radical quenching and by creating foamy or glassy protective layers. [11]

Traditionally, fire retardants have been categorized into two groups, the additive and the reactive kind. The additive type fire retardants have dominated the market space due to their competitive price, high availability and wide range of applications. The additive chemicals are added to the product, however, as a drawback, they need to be used in high quantities. The reactive type is primarily used to bond the fire retardant into the polymer structure. The two systems operate through two distinct mechanisms: gas phase or solid phase. In the gas phase, the gases released by the fire retardant initially lower the temperature, which subsequently decreases the presence of combustible gases. Ultimately, the combustion process is completely halted. In solid-phase reactions, the fire retardants typically generate a carbon layer or convert organic substances into ceramics on the surface, resulting in a reduction of heat conduction, thereby slowing the combustion process. [11]

All fire retardants, depending on their composition, have their own strengths and weaknesses. For example, the durability of fire retardant treatments in humid conditions depends on the water solubility of the chemicals used [11]. High moisture content from the fire retardant can cause the chemical to migrate within the wood structure and crystallize on the surface. Another issue is the loss of fire retardant through leaching when the material comes in contact with water [11]. Consequently, many fire retardant systems are not suitable for outdoor applications. Fire retardants that react and form more complex and insoluble substances within the wood structure are better suited for outdoor use [11]. Some fire retardant treatments have failed to perform well when the product has been used as roof sheathing due to elevated roof temperatures caused by solar radiation, which, in combination with chemicals and moisture can cause the fire retardant to activate prematurely [26].

The fire retardant used in this research, Palonot F1-10, is an ionic liquid based fire retardant that contains bisphosphonate acid and an alkanol amine [27]. Ionic liquids are salts characterized by their ability to remain in a liquid state around room temperature, and have distinctive qualities such as high solubility, remarkably low volatility, incombustibility and low viscosity. They are also viewed as effective preservatives, enhancing wood's resistance to decay while improving reaction to fire properties. [11]

As noted above, Palonot F1-10 is based on phosphorous – a key element commonly featured in fire retardants for wood due to its high effectiveness. Phosphonate acid salts are highly regarded as additives for wood coatings as a result of their effective ability to reduce flammability due to their good fire retarding properties. These compounds can exhibit a dual-action in fire retardation, operating in the condensed phase (enhancing char formation, intumescence, and creating inorganic glass) and gas phase (inhibiting flames). Compared to other fire retardants, phosphorous compounds emit fewer toxic gases and smoke when they burn and are thus considered environmentally friendly. However, a weakness of phosphorous compounds is that they can increase wood moisture content in humid conditions, potentially promoting fungal decay. Therefore, such solutions are better suited for interior applications. [11]

There are several fire-retardant agents already on the market that provide class B fire protection according to EN 13501-1 for wood-based panel products. However, many of the conventional technologies used contain inorganic salts, such as monoammonium phosphate (MAP), diammonium phosphate (DAP) or borates, which are harmful to the environment and are not potent enough to fulfil B-s1-d0 fire class at low retention rates. Additionally, MAP and DAP treated wood products are inclined to lose their fire-retardant capabilities when exposed to moisture. [27] Novel ionic liquid and phosphorous based fire retardants present a promising, more environmentally friendly alternative to MAP and DAP solutions due to the advantages discussed above.

Generally, the application methods of fire-retardant treatments of plywood can be divided into two major categories: 1) impregnation of individual veneers and 2) surface coating of plywood [1].

Impregnating individual veneers involves soaking or pressure-treating them with fire retardant salts and other chemicals before hot pressing. Pressure treatment, utilizing an autoclave, ensures better penetration of these fire-retardant substances into the wood cells. Research has shown that impregnated plywood products perform better in fire tests compared to other treatments [28]. However, this method is more time-consuming than simply coating the top surface. The use of acidic fire retardants can diminish the mechanical properties of the final product [29]. Furthermore, fire retardants can increase surface roughness in treated veneer sheets, impacting gluing quality and adhesion in plywood manufacturing and the effect of fire retardant chemicals on surface roughness should be considered during manufacturing [30]. Pressure impregnation of individual veneers ensures the fire retardant is present in all layers, while surface coating primarily affects the face veneer. Therefore, the mechanical properties of panels treated only by surface coating may be less affected by fire-retardant treatment than those pressure-impregnated prior to pressing.

The most cost-effective fire-retardant treatment is to spread the fire-retardant solution on the plywood using normal surface treatment equipment such as spraying equipment or rollers [31]. Such treatments prolong time of ignition and reduce flame spread in case of a fire [28].

Birch has a high heat of combustion rate, making it challenging to meet the Euroclass B in the EN 13823:2010 test. Birch wood generates large amounts of heat upon combustion, making it difficult to achieve a total heat release (THR) below 7.5 MJ, which is one of the requirements for the Euroclass B standard [32]. This concern could be even more challenging in the case of surface treatment with roller-coating as the penetration of the FR chemical would likely be limited by the bond line. To better understand the combustion behaviour, the penetration depth of the chemical in the veneer/plywood must be examined. Additionally, it is important to understand the coverage of FR inside the material. Deeper penetration within the wood structure would likely result in stronger fire-retardant properties.

2.5. Effect of adhesives on plywood combustion behaviour

In addition to flame-retardant surface treatment or pressure impregnation, plywood fire resistance can also be improved by physical modification of adhesives – adding fire retardant into the adhesive. While this approach may have positive effects in terms of flame-retardancy, altering the resin compound can also have a detrimental effect on the mechanical properties of the panels. Another advantage of mixing fire-retardant into the adhesive compared to surface treatment is the decay rate (or lack thereof). In case of surface treated fire-retardants, the compound would likely wear off over time while the fire retardant within the adhesive is protected by the face veneer from direct external factors causing decay. [33]

A recent study [33] experimented with mixing a phosphorus-nitrogen flame retardant into a melamine urea formaldehyde (MUF) resin, which would work by creating an intumescent layer upon combustion. The study found that the intumescent properties of the resin only emerged after the face veneer layer had delaminated. The shear strength of the panel also decreased after mixing in the flame retardant. However, when the ratio of flame retardant to MUF resin was kept under 0,60, the wet shear strength was still within the requirement of the Chinese national standard for interior use plywood (0.7 MPa). In this study, the flame retardant was only mixed into the adhesive layer between the face veneer and the second veneer layer. [33]

2.6. Effect of surface properties on plywood combustion behaviour

To provide good protection against fire, considerably high retention of chemicals is necessary. In addition to the amount of the fire-retardant chemical used, penetration depth also has an influence on the combustion behaviour of a product. The permeability of wood depends on species, moisture content, the internal structure of wood and dimensions of the elements within the fire retardant compound. [34]

Veneer surface quality is influenced by log soaking temperature [35] and veneer drying temperature [36]. However, log soaking temperature mainly affects the properties on the loose side of the veneer. Research has found that on the tight side, the observed changes in properties relating to soaking temperature were smaller, mainly regarding cell wall failure and the amount of very fine particles loosely bound to the surface [35]. It has been observed that higher soaking temperatures cause the cell wall elements to fail, resulting in a rougher surface structure [35].

According to a study, surface roughness has a notable effect on the equilibrium contact angle, a feature that indicates the wettability of all solid materials. Smoother surfaces induce a higher contact angle, reducing the adhesion of coating materials. The study also explained that the inherent variability in the biological structure of wood causes a high error in measuring the 2D surface roughness Ra. [37]

3 MATERIALS AND METHODS

3.1. Materials

All test specimens used for this research were produced in the TalTech Laboratory of Wood Technology.

Birch core plywood and face veneers

Birch face veneers of 1,0 mm, 1,5 mm and 2,6 mm were peeled and adhered with commercial PF resin on top of industrial calibrated 12 mm thick birch (*Betula pendula* Roth) plywood panels (grade WG/WG) produced by Estonian Plywood AS. The core panels, were overlaid with laboratory-made face veneers. Adhesion was done using a commercial phenol-formaldehyde resin and a commercial hardener provided by Prefere. sanded and treated with Palonot F1-10 fire retardant chemical.

Fire retardant Palonot F1-10

The fire retardant (Palonot F1-10) used in the study was produced and provided for the research by Palonot Oy (Tekniikantie 2, Espoo, Finland). According to the manufacturer, the fire retardant material provides excellent fire safety even at low retention rates. It consists of an aqueous solution of bisphosphonate acid, an alkanol amine and optionally an alkaline agent. The F1 is a protic ionic liquid-based fire retardant, which does not corrode metallic structures or affect the mechanical properties of wood. It also does not contain any substances of very high concern or other indoor air pollutants, and it fulfils ISO 9001 and 14001 standard requirements, which relate to product quality and environmental management requirements, respectively. According to the manufacturer, Palonot treated wood dries quickly and can be piled as wet when treating hot-pressed plywood after sanding, reducing the need for drying time and space. When wet-stacked, the penetration of the chemical continues within the stack. [27] [38] To measure the penetration depth of Palonot F1-10, a reactive chemical Chrome Azurol S was used.

3.2. Methods

3.2.1. Research design and sample selection

To research the effect of face veneer thickness on penetration and combustion properties, industrially manufactured plywood panels were overlaid with face veneers of varying thicknesses (1,0 mm, 1,5 mm and 2,6 mm). The veneered panels were sanded and treated with two concentrations of Palonot F1-10 fire retardant (100% by weight and 70% by weight). After treatment, the panels were unstacked and cut into test specimens. Control samples were manufactured using an identical manufacturing process to that of the FR-treated panels, excluding the application of fire retardant. The FR-treated and control samples were tested according to the cone calorimeter (ISO 5660-1) reaction to fire test, followed by data processing and analysis. Additionally, the potential fire class ratings were assessed through large scale Single Burning Item reaction to fire tests (EN 13823). To determine the depth of fire retardant penetration, a reagent was applied to the cross-section of the treated panels, indicating contact with the fire retardant chemical through colour change. This chapter offers a detailed description of every stage in sample manufacturing and testing.

In total, four different groups of fire test specimens were manufactured:

1. Undiluted (100%) Palonot F1-10 treated ISO 5660-1 specimens.
2. Diluted (70% F1-10 – 30% water by weight) Palonot F1-10 treated ISO 5660-1 specimens
3. Undiluted (100%) Palonot F1-10 treated SBI EN 13823 specimens
4. Control ISO 5660-1 specimens (untreated)

To minimize the effect of the properties of an individual panel and obtain more reliable test results, the samples for each ISO 5660-1 specimen group were produced from two replica panels. In case of EN 13823 single burning item test specimens, each specimen consisted of six assembled plywood panels and only one specimen was produced for each face veneer thickness. The table in Appendix 1 provides a precise overview of the sample groups and the amount of specimens used in reaction to fire testing. The reaction to fire test methods are described in sections 3.3.1 and 3.3.2. In total, 79 reaction to fire tests were conducted during this research, 75 of which were cone-calorimeter tests and 3 single burning item tests.

The reaction to fire tests were conducted in two laboratories: TalTech Laboratory of Wood Technology located in Tallinn, Estonia and MeKA Forest and Wood Products Research and Development Institute located in Pienava, Latvia.

The two laboratories were each equipped with different sensors and equipment for measuring results. For example, the thermocouples attached to both surfaces of the specimens in TalTech allowed to study temperature transfer through depth, while in MeKA it was possible to measure heat release and smoke production parameters.

Diversifying the testing venues allowed to collect a wider range of data, which in turn supports a more thorough and multifaceted analysis of the results, increasing the overall value of this research.

Specimen groups “1” and “2” represent FR-treated ISO 5660-1 specimens of different fire-retardant solutions (100% and 70% by weight, respectively). 10 cone-calorimeter tests were conducted for each face veneer thickness for both groups. Of these 10 tests, eight were conducted in TalTech and two in the MeKA laboratory.

Specimen group “3” refers to the single burning item tests (EN 13828), which were executed in the MeKA laboratory. One specimen was tested per each face veneer thickness.

Specimen group “4” constitutes the reference (untreated) specimens. In this group, five cone-calorimeter tests were executed for each face veneer thickness according to ISO 5660-1. Three tests per face veneer thickness were conducted in TalTech and two in the MeKA laboratory.

3.2.2. Peeling of face veneers and panel pressing

The birch logs used for the production of test specimens were soaked for approximately 48 h at 40 °C before peeling. After soaking and debarking (Figure 3.1), the temperature, dimensions, and moisture content of the logs were recorded. The temperature was measured using an infrared thermometer and moisture content with a dielectric moisture sensor.

Figure 3.1 Soaking and debarking of peeler logs

Veneer peeling (Figure 3.2) was done using the Raute peeling lathe at the TalTech Wood Laboratory of Wood Technology. After peeling, the veneer thickness was measured using a digital thickness gauge and the veneer mat was cut into sheets of 900 mm x 450 mm. Knife pitch configurations are an important influencing factor in veneer peeling because they have a profound impact on veneer quality, namely on surface roughness and thickness variation. Figure 3.3 presents the pitch angle control curve during the veneer peeling and Table 3.1 presents the peeling parameters of veneers produced in the TalTech laboratory. The graph should be read starting from right to left, as the radius from the centre of the log to the knife decreases as the log is being peeled.

Figure 3.2 Peeling of logs with Raute peeling lathe

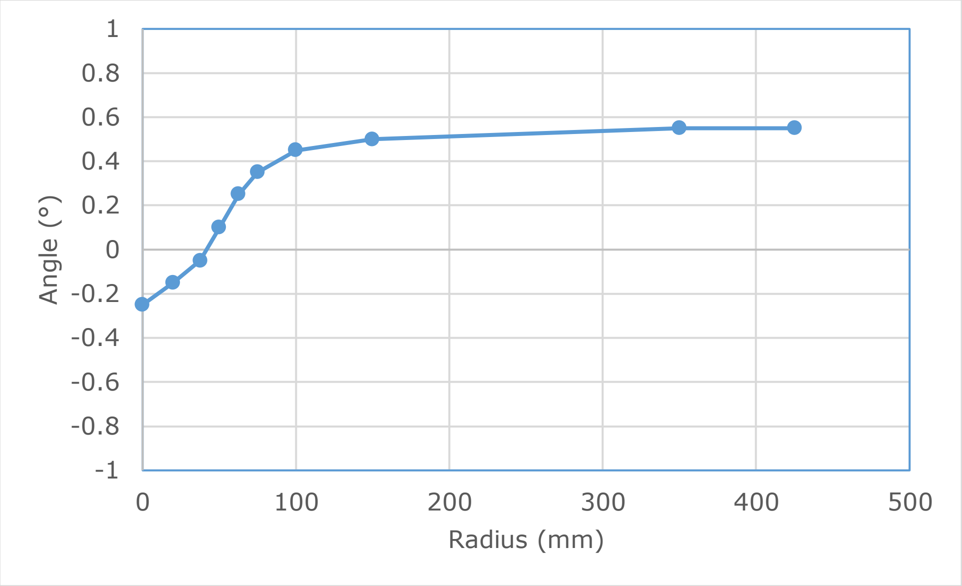

Figure 3.3 Pitch angle control curve used for veneer peeling

Table 3.1 Peeling parameters used in veneer production.

Thickness (mm)	**Nominal thickness (mm)**	**Compressed thickness (mm)**	**Compression (%)**	**Knife angle (°)**	**Peeling speed (m/min)**
1,0	1,05	0,95	10,53	19	60
1,5	1,52	1,4	8,57	19	60
2,6	2,6	2,4	8,33	19	60

The veneers were dried immediately after peeling, using the air circulation veneer dryer (Figure 3.4) at the TalTech Laboratory of Wood Technology. The drying schedules were selected based on prior experience and proven data from previous semesters' work. The drying times for 1,0 mm, 1,5 mm and 2,6 mm thicknesses were 90, 170 and 330 seconds, respectively. The air temperature in the veneer dryer was 170 °C for all veneer thicknesses. After drying, the veneer thickness was recorded again and veneers were placed in the conditioning room, where they were stored until following procedures.

Figure 3.4 Veneer drying with air circulation veneer dryer

The moisture content of the face veneers was determined (Figure 3.5) using the oven-dry method. Nine small samples were cut from different parts of one veneer for every thickness and from each log that was used. Mean values of moisture content were calculated based on the nine samples from each veneer. The target moisture content of 4% to 6% was reached in all cases.

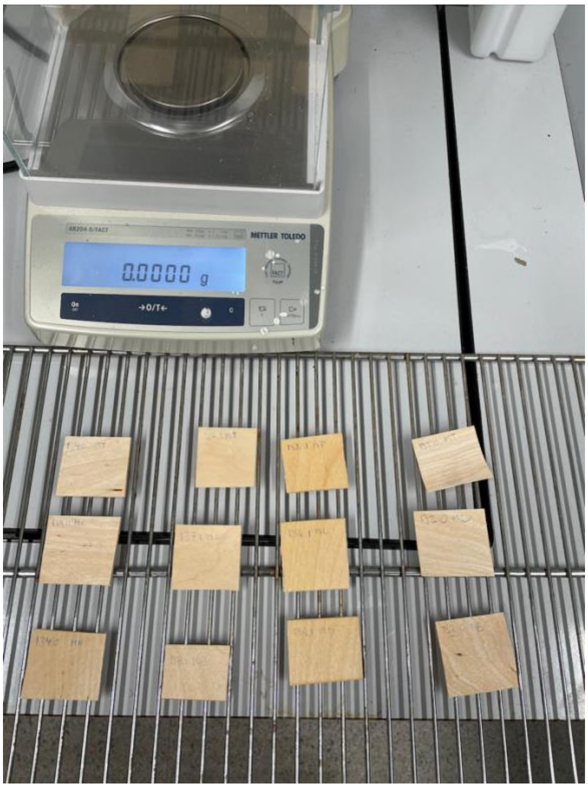

Figure 3.5 Determination of veneer moisture content

The condition of the available plywood panels (2500 mm x 1500 mm) was reviewed before pressing the face veneers on top of the core panels. The core panels were assessed to be suitable to be used in this research, as no delamination or other significant defects were detected. The large plywood panels were sawn to match the veneer dimensions (450 mm x 900 mm), keeping in mind that the grain direction of the panel would be perpendicular to that of the face veneers.

The adhesive was prepared (Figure 3.6) according to the recipe provided by the manufacturer: 68% phenolic resin, 14% hardener and 18% water. The mixing time of the adhesive was 60 minutes at 1100 revolutions per minute. The plywood panels were coated with adhesive using the glue roller, which was calibrated to apply a spread rate of approximately 160 g/m^2. The veneers were placed on top of the core panels in preparation for pressing.

Figure 3.6 Adhesive preparation

After lay-up, the face veneers were cold-pressed and hot-pressed on top of the core plywood panels (Figure 3.7). The hot-press temperature was 130 °C and the pressing pressure 1.8 MPa. The selected pressing time, 11 minutes, was chosen to heat up the panels thoroughly, imitating industrial production. The complete heating of the panels was important because the FR chemical needed to be applied on warm panels. If the pressing time were shorter, the panels would have cooled down too rapidly, and it would not be possible to maintain a sufficient surface temperature for FR-treatment. This would differ substantially from industrial conditions, which this research is attempting to imitate as closely as possible in laboratory conditions.


Figure 3.7 Layup and cold-pressing of face veneers on core plywood panels

The orientation and positioning of each panel in the hot press was marked on the panel edge, making it possible to later connect fire test data to the positioning data and find whether there is a correlation. Temperature deviations were observed immediately after hot-pressing, showing that surface temperature was significantly higher in the centre of panels, compared to the edges. This indicates the temperature distribution of the hot-press is not uniform.

Immediately after hot-pressing, the panel temperatures were recorded using an infrared thermometer. The panel thickness was measured before and after sanding to obtain data about the impact of sanding on face veneer thickness. The panels were sanded using a rotary sander (Figure 3.8) with sandpaper grit size 60 and edged about 25 mm on all sides before FR-treatment.

Figure 3.8 Panel sanding with rotary sanding machine

3.2.3. Treatment of panels with fire-retardant chemical Palonot F1-10 and cutting the test specimens

As the sanding process is time-consuming and only two panels can be hot-pressed at once, the panels were stacked between heat insulation plates to maintain the panel surface temperature after hot-pressing while other panels were being prepared. The surface temperature was measured for each panel immediately before FR-treatment Figure 3.9), which remained around 50 °C (which was also the target temperature). In previous semesters, during the use of higher surface temperature (65 °C to 70 °C), phase separation of the fire retardant and excessive sticking during unstacking of the panels was observed. Therefore, a decision was made to reduce surface temperature at the time of treatment to 45 °C - 50 °C. This was achieved by alternating the order of stacked panels roughly every 10 minutes.

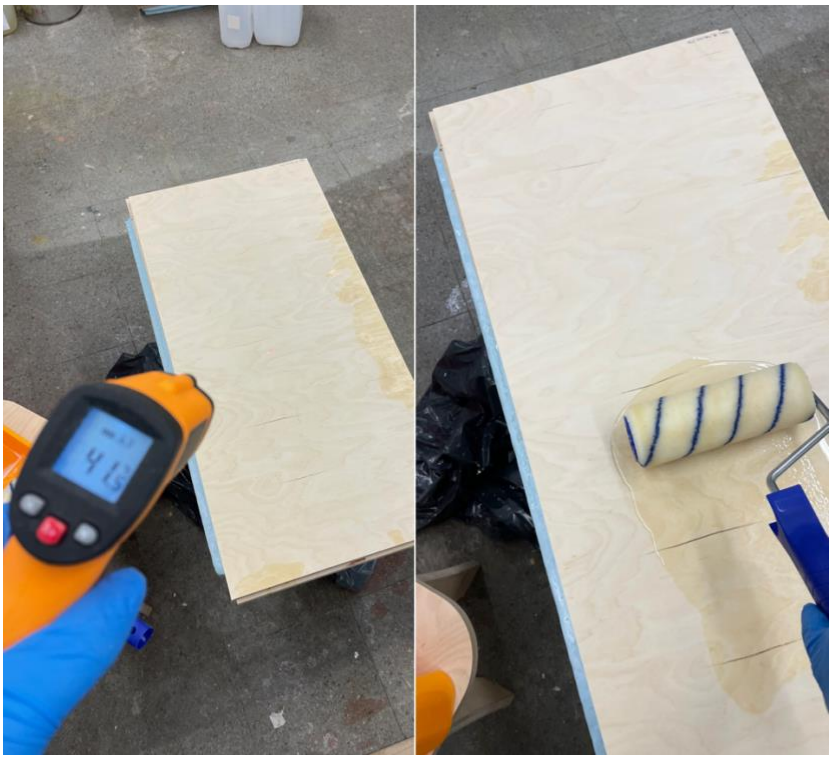

Figure 3.9 Measurement of panel surface temperature and treatment with Palonot F1-10 fire retardant

After sanding, the panels were treated with Palonot F1-10 fire retardant (Figure 3.9) by roller coating with a soft roller. The treatment duration for each panel surface was approximately 3 minutes. The surface temperatures and Palonot F1-10 spread rates were recorded for all panels during treatment. The target spread rate was 300 g/m². The mean spread rate and surface temperature values are presented in Table 3.2. As the data shows, the mean surface temperature and spread rate for all veneer thicknesses were very similar and showed low standard deviations. It was observed that panels of the thinnest face veneer thickness did not absorb the FR solution as well as the panels with 2,6 mm face veneer. This suggests that the thinner face veneers might have become saturated before they could absorb all of the fire retardant applied to the surface.

Table 3.2 Spread rate of Palonot F1-10 and surface temperature of the birch plywood panels at the time of treatment

Face veneer thickness (mm)	Mean surface temperature (°C)	Mean spread rate (g/m²)
1,0 mm	49,3°C (1,25)	305,23 (3,54)
1,5 mm	47,9°C (1,69)	304,53 (1,81)
2,6 mm	48,9°C (0,96)	306,10 (2,95)

Values in brackets refer to standard deviation.

It is important to point out some differences in the manufacturing processes of cone-calorimeter and SBI panels. The panels used for SBI testing were manufactured in the semester preceding the cone-calorimeter material production. Following observations and insights gained from the previous semester's work, some adjustments and improvements were incorporated into the production process.

Specifically, in cone-calorimeter panel production, polyethylene film was used between panels (Figure 3.10) while stacking to prevent the potential transfer of the FR chemical. After unstacking and unwrapping the panels, any remaining FR salt crystals were delicately removed from the panel surface using a damp cloth (Figure 3.11). Additionally, markings indicating the upwards-facing surface were made on cone-calorimeter panel edges. These three process improvements (use of separation material, removal of residual FR and panel orientation markings) were implemented after SBI panel production and were not used in that particular procedure. However, in the case of both SBI and cone-calorimeter panel stacking, weights were placed on top of the stacked panels to avoid air gaps between panels. The cone-calorimeter specimens were cut from the panels based on the scheme shown in Figure 3.12 and conditioned according to ISO 5660-1 prior to testing.

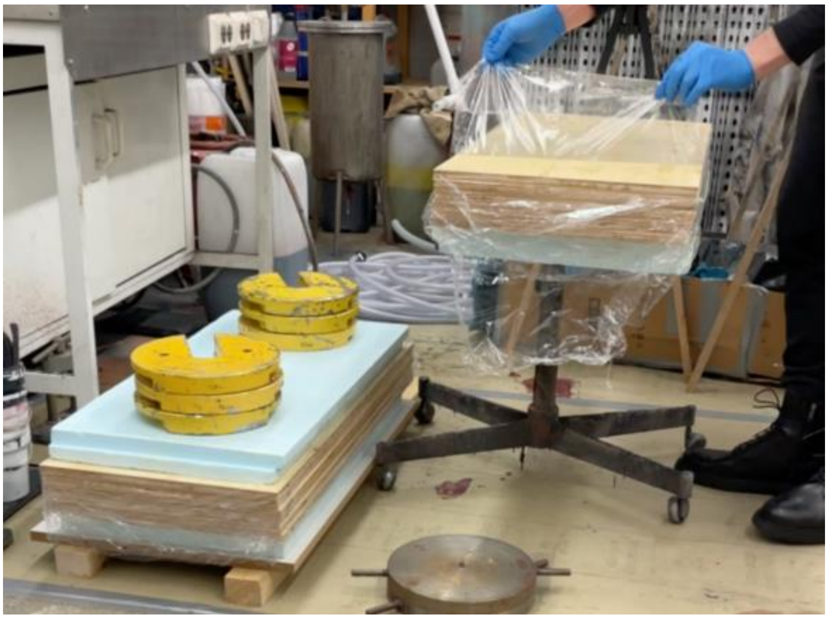

Figure 3.10 Stacking of the FR-treated plywood panels with polyethylene film separation

Figure 3.11 Residual fire retardant salt crystals and their removal from panel surface

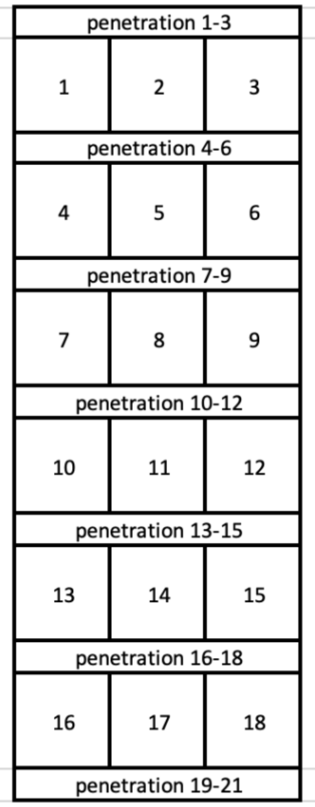

Figure 3.12 Cutting diagram and labelling of cone-calorimeter and penetration specimens

Throughout the cone-calorimeter specimen production process, parameters such as panel temperature during treatment, panel thickness and temperature after hot-pressing were better controlled and measured. The improvements to the production process described above were made based on experience from previous semesters' work and were applied to reduce sources of error and obtain more data from different stages of the process to help better understand the results.

3.3. Determination of density

As density impacts the combustion properties of wood materials, it was important to determine the density of each individual specimen. The density was determined in accordance with the standard ISO 9427:2003 by measuring the length, width and thickness of the specimens using a micrometre and a calliper, weighing them, and dividing the mass of the specimen by its volume [39]. Every specimen was measured and weighed immediately before conducting the reaction to fire tests, and the density was later calculated based on the recorded information.

3.4. Reaction to fire testing

3.4.1. Cone-calorimeter test

In preparation for fire testing according to the ISO 5660-1 standard, the test specimens with dimensions of 100 mm x 100 mm were conditioned in a conditioning chamber at a temperature of 23 °C and 50 % relative humidity until constant weight. The test specimens are weighed and measured for thickness after the conditioning period and before conducting the fire tests to determine mass loss. The edges of the specimens were wrapped in aluminium tape to minimise heat transfer around the edges of the samples, since end grain of wood are susceptible. In TalTech, thermocouples were installed on the top and bottom surfaces of the test specimens (Figure 3.13) to measure surface temperatures during the test. It is important to note that in the fire tests, the surface exposed to the heat source was always the surface that faced upwards during the wet stacking of the panels. The specimens were mounted on a specimen holder with a retainer frame in horizontal orientation at both test facilities. Figure 3.14 presents a schematic diagram of the cone calorimeter equipment.

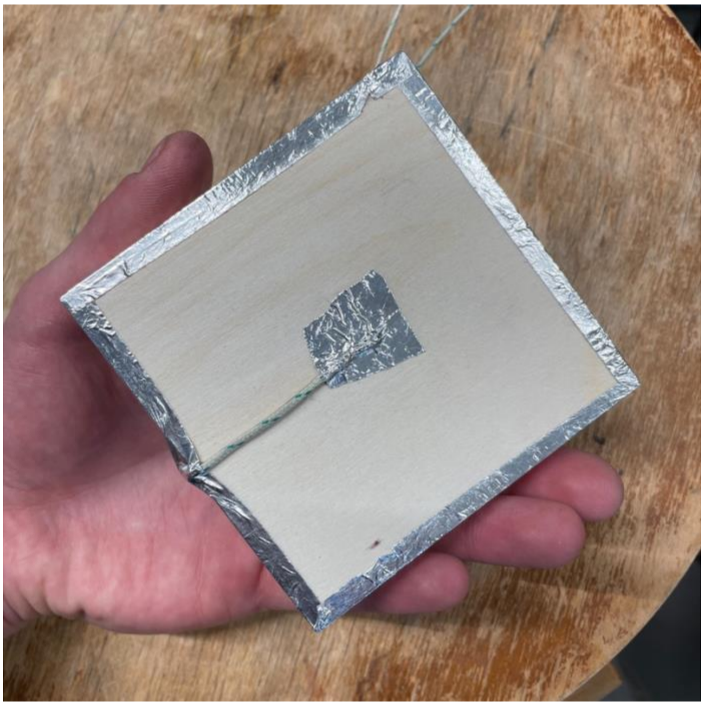

Figure 3.13 Cone calorimeter test specimen with installed thermocouple on top surface

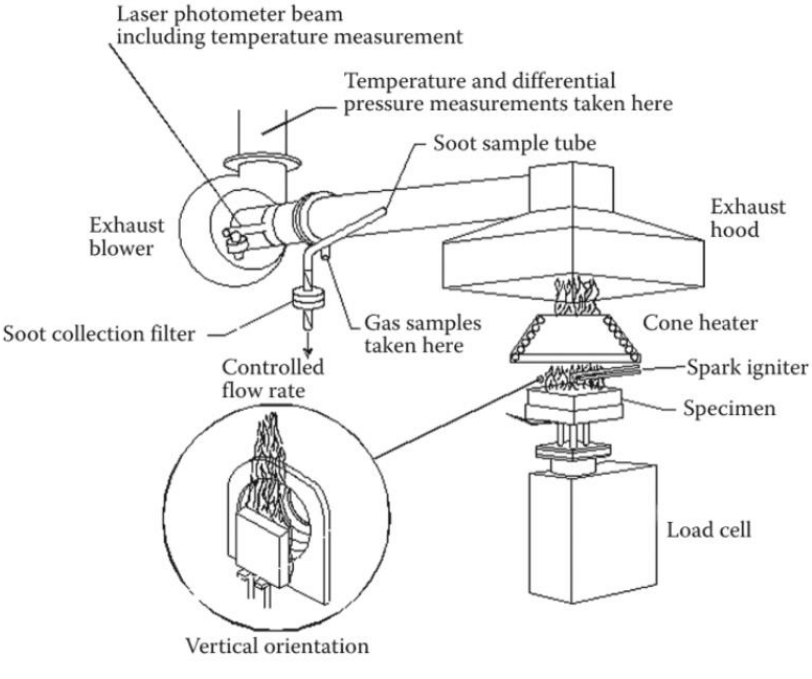

Figure 3.14 Schematic diagram of a cone calorimeter [17]

Small scale reaction to fire tests were conducted at Tallinn University of Technology and at the MeKA laboratory in Pienava, Latvia, according to the ISO 5660-1 cone-calorimeter test method. For FR-treated samples, eight specimens were tested per batch in TalTech Laboratory, and two per batch in MeKA Laboratory. For control samples, three tests per batch were executed in TalTech, and two per batch at MeKA.

The cone heater was calibrated to achieve a constant heat flux of 50 kW/m2, simulating heat exposure in a developing fire scenario [40]. The distance between the cone heater and the surface of the test specimen was 25 mm and the exposure duration for all specimens to the cone heater was 600 seconds (10 minutes). The test specimens were mounted to the sample holder in a horizontal orientation.

Cone-calorimeter testing offers an advantage by providing dynamic data over time, allowing for detailed insight into fire development compared to the SBI test. The equipment available at TalTech allowed to measure temperatures on both surfaces of the specimen, enabling to study temperature transfer through depth. Additionally, observations were made regarding ignition time and instances of surface flashing. On the other hand, the equipment at MeKA laboratory provided the means to study other crucial parameters such as heat release, mass loss and smoke production. Conducting tests at both TalTech and MeKA enabled the collection of a broad range of data and thereby provided a more comprehensive view of combustion behaviour.

3.4.2. Single burning item test (SBI)

Large scale testing according to the Euronorm standard EN 13823 was conducted in the MeKA laboratory in Pienava, Latvia. The specimens were conditioned prior to SBI test in a controlled atmosphere according to the EN 13238 standard at 23 °C room temperature and 50 % RH until constant mass was achieved. The conditioning was conducted at the MeKA laboratory immediately before testing, where the specimens were also weighed and assembled for testing. [41]

The SBI test (EN 13823) simulates a single burning item in the corner of a room, meaning that the test specimen consists of two wings that are assembled to form a corner. According to the official standard, the specimen consists of a long wing (1000 mm x 1500 mm) and a short wing (495 mm x 1500 mm). [32]

For this research, the dimensions of the test specimens were slightly modified to better fit the laboratory scale production capabilities and manage workload. In the current case, both wings were the same size, and the dimensions of the wings were approximately 540 mm x 1500 mm. Figure 3.3 illustrates the positioning of the plywood panels as assembled during the test.

Figure 3.15 Illustration of assembled specimen for the SBI test

Each specimen consists of six plywood panels of two different sizes. The dimensions of the larger panels were 360 mm x 750 mm and those of the smaller panel were 180 mm x 750 mm. The panels were attached to a gypsum plasterboard substrate using screws as mechanical connectors. The ambient conditions during testing were 13 °C and 48 % RH. A propane gas burner was used as the source of ignition, which was calibrated to generate a 30 kW heat release rate. No airgap was used during SBI testing.

3.5. Determination of penetration depth

The penetration depth was studied by applying a reactive chemical (Chrome Azurol S) on the cross section of the FR-treated plywood panels. The reagent changes colour as it comes in contact with the FR chemical, enabling to visually observe the extent of penetration of the fire retardant into the face veneer.

Ribbons, identical in width to the panel from which they were cut and measuring 30 mm in length, were cut from the coated panels. The samples were placed in the conditioning room in a plastic zip bag for storage. The temperature and relative humidity of room were 23 °C and 30 %, respectively. The application of the chemical was executed three weeks after sawing the test specimens.

The reagent was applied to the sawn surface of the test specimens using a regular paint brush. The brushed specimens were left to dry for 30 minutes and then photographed using a Nikon Z50 mirrorless camera with manual preset. The exact amount of Chrome Azurol S applied to the specimens was not measured. The brush was always wetted inside the liquid container in the same way before proceeding to coat the following specimen. When the chemical was applied, it was made certain that the entire surface would be covered with the chemical, preventing any occurrence of dry spots.

The results were analysed by visual evaluation of the images. The extent of penetration was expressed as a percentage estimation of the face veneer thickness for each specimen individually. The author acknowledges that a visual estimation cannot result in an accurate value to describe the penetration, however, it is a useful means to provide a rough estimate.

Each image was divided into three sections of equal lengths, as shown in Figure 3.16. The percentage estimation was made for each section individually. The penetration rating for the entire specimen length was expressed as a weighted average of the estimated percentage values for each individual section. For example, in case of P1/10 shown in the image below, the author estimated the penetration values for each section to be 25%, 45% and 75% for the top face veneer and 40%, 20% and 75% for the bottom face veneer, from left to right. The overall penetration rating for the top veneer would be calculated as follows: (0.25 + 0.45 + 0.75) / 3 ≅ 0.48.

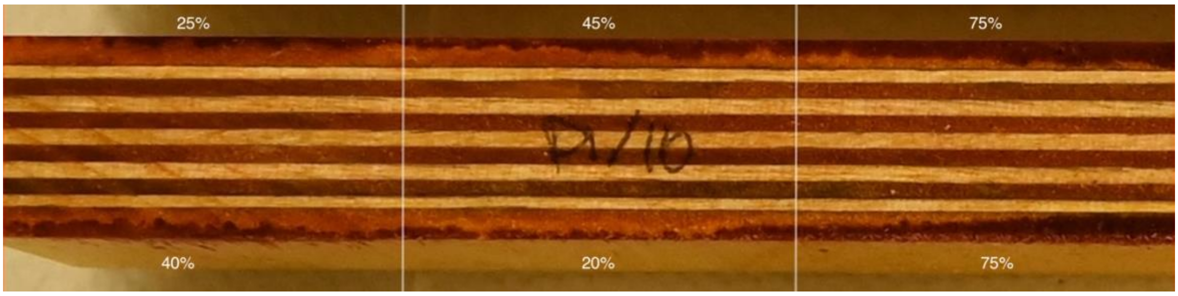

Figure 3.16 Example of a penetration depth specimen used for visual evaluation.

As shown in Figure 3.2, penetration specimen ribbons were cut in between each row of cone-calorimeter specimens. This allowed penetration depth to be evaluated for each cone-calorimeter specimen on four face veneer surfaces – top and bottom veneers on the two adjacent sides. A total of 60 cone-calorimeter tests were conducted with FR-treated specimens, hence 240 face veneer surfaces were visually evaluated to provide an estimated penetration coverage.

4 RESULTS AND DISCUSSION

4.1. Density

Density is an important parameter in combustibility and fire tests. It can affect various aspects of material behaviour such as the intensity, duration and smoke production and is thus important to consider in analysing fire test results [42]. The Table 4.1 presents the average rough density results the cone-calorimeter test specimens that were tested in this research.

Table 4.1 Average density of cone-calorimeter test specimens

Face veneer thickness	**1,0 mm**	**1,5 mm**	**2,6 mm**
Control	721,71 (14,19)	714,88 (6,65)	704,42 (2,25)
70% F1-10	742,82 (9,35)	730,20 (9,77)	714,67 (7,59)
100% F1-10	737,85 (13,05)	730,43 (9,55)	720,09 (10,37)

Values in brackets refer to standard deviation.

The data shows that there are differences in the density of the specimen groups, both with regard to face veneer thickness and whether the material was FR-treated. It is evident that in case of all specimen groups, the density of the material increases as the face veneer thickness decreases. This is likely caused by the density of the industrially manufactured plywood being higher than the density of laboratory-made veneers which the panels were overlaid with. The data also shows that the FR-treated groups always have a higher density in comparison to the control samples of the same face veneer thickness, indicating that density has increased as a result of the fire retardant chemical being absorbed into the material.

The results do not reveal any significant difference in density between the 100 % and 70 % solution of F1-10. It should be noted that the density of the material is also strongly influenced by the characteristics of the unexposed veneer layers inside the panel, such as the number of knots and other wood defects, but also the amount and uniformity of resin distribution.

4.2. Face veneer thickness

The face veneer thickness is an important parameter in the scope of this research and therefore was measured and controlled for in various stages of the manufacturing process. More precisely, measurements to determine face veneer thickness or panel thickness were taken:

1. Before drying of veneers (after log peeling)

2. After drying of veneers
3. Before sanding of panels (after hot-pressing)
4. After sanding of panels
5. Before reaction to fire testing (final thickness of specimens)

4.2.1. Veneer thickness before and after drying

Wood swells and contracts with change in moisture content about 4% in the radial direction, which in case of veneer material corresponds to the thickness of the sheet [1]. Therefore, veneer thickness was measured at various locations across the veneer sheet before and after veneer drying to obtain information about the difference between nominal and actual veneer thickness. Table 4.2 presents the thickness results for veneers that were later FR-treated, and table 4.3 shows the same results for veneers which were later used for manufacturing untreated (control) specimens.

Table 4.2 Veneer thickness results for FR-treated samples after peeling and after drying.

Nominal veneer thickness (mm)	**1,00**	**1,50**	**2,60**
Min thickness after peeling (mm)	1,03	1,60	2,65
Max thickness after peeling (mm)	1,08	1,64	2,75
Mean thickness after peeling (mm)	1,06 (0,04)	1,62 (0,03)	2,70 (0,07)
Min thickness after drying (mm)	0,96	1,56	2,56
Max thickness after drying (mm)	1,02	1,59	2,66
Mean thickness after drying (mm)	0,99 (0,04)	1,58 (0,02)	2,61 (0,07)

Values in brackets refer to standard deviation

Table 4.3 Veneer thickness results for control samples after peeling and after drying.

Nominal veneer thickness (mm)	**1,00**	**1,50**	**2,60**
Min thickness after peeling (mm)	1,10	1,52	2,59
Max thickness after peeling (mm)	1,15	1,64	2,71
Mean thickness after peeling (mm)	1,13 (0,04)	1,58 (0,08)	2,65 (0,08)
Min thickness after drying (mm)	1,05	1,4	2,5
Max thickness after drying (mm)	1,14	1,59	2,63
Mean thickness after drying (mm)	1,10 (0,06)	1,50 (0,13)	2,57 (0,09)

Values in brackets refer to standard deviation.

As the data above shows, the maximum and minimum values of veneer thickness after drying are very close to each corresponding nominal thickness. In case of 1,0 mm and 2,6 mm face veneer thickness (FVT), the nominal thickness value falls between the maximum and minimum values of actual thickness after drying. For 1,5 mm nominal thickness, the minimum and maximum values of actual thickness after drying are slightly greater than the nominal value (1,56 mm to 1,59 mm instead of 1,50 mm), however, the difference remains below 0,1 mm and is thus not expected to have a significant impact.

The results for veneers used in control samples are similar to those of veneers used in FR-treated samples, however there are some differences that should be mentioned. First, the range between minimum and maximum thickness values is higher. This can be attributed to the fact that in case of control sample veneers, two logs were used for each veneer thickness instead of one log as in case of FR-treated veneers. Nevertheless, the difference between nominal (target) and actual average thickness was no more than 0,1 mm in all cases. There are slight differences between the final veneer thicknesses of control group and FR-treated veneers, likely because the Raute peeling lathe was recalibrated in the intervening period between the production of the two sets of veneers, which may have had an impact on the final veneer thickness.

Overall, the nominal and actual thickness of the veneers after drying follow the expectations, with some minor deviations. However, as these differences do not exceed 0,1 mm, they are not large enough to significantly affect the results in the author's opinion.

4.2.2. Panel thickness before and after panel sanding

The thickness of the panels was measured immediately after hot-pressing and after the subsequent panel sanding to determine the effect of sanding on the face veneer thickness. To do that, the thickness of the panels was measured at six different locations before and after sanding. In case of each individual panel, the thickness before and after sanding was measured at the exact same location. It should be mentioned that these measurements were taken only for panels that were later FR-treated. However, the sanding was done using the same methods and equipment and by the same person (the author) in both cases. The Table 4.4 shows the influence of sanding on panel thickness and the extent of material removed in that process.

Table 4.4 Results of average panel thickness removed by sanding.

Face veneer thickness	**Average thickness before sanding**	**Average thickness after sanding**	**Average thickness sanded off**
2,6	16,41 (0,21)	16,28 (0,21)	0,13 (0,07)
1,5	14,31 (0,18)	14,20 (0,17)	0,11 (0,03)
1,0	13,37 (0,15)	13,27 (0,16)	0,10 (0,03)

Values in brackets refer to standard deviation.

As the results above show, some slight variation can be observed in panel thicknesses and in the amount of material removed by sanding. It can be seen from results presented in Appendix 2 that standard deviations of individual panels from measurements before and after sanding remain very similar or the same, indicating that the inconsistencies in panel thickness existed already before the sanding, and were not generally amplified by it. It was not possible to use calibrating wide belt sanding in this research, which is normally used in the industrial scale. However, sanding was still a necessary step to prepare the panel surface for FR-treatment and thus could not be skipped. Overall, the degree of variation in panel thickness within each face veneer thickness appears to be relatively low, suggesting that its influence on penetration and fire test performance is expected to be insignificant.

4.2.3. Final thickness of reaction to fire test specimens and face veneers

The final thickness of the test specimens was measured immediately before conducting each fire test, and was possibly influenced by the FR-treatment as the absorption of the fire retardant chemical into the material can cause swelling of the material. The table 4.5 presents the average results of final specimen thickness for each specimen group. The exact thickness of specimens used for any specific reaction to fire test are presented in Appendices 4, 5, 6 and 7.

Table 4.5 Average final specimen thickness

Face veneer thickness	**1,0 mm**	**1,5 mm**	**2,6 mm**
Control	13,22 (0,12)	14,02 (0,10)	15,95 (0,11)
70 % F1-10	13,32 (0,07)	14,14 (0,08)	16,27 (0,07)
100 % F1-10	13,17 (0,08)	14,19 (0,09)	16,38 (0,07)

Values in brackets refer to standard deviation

The results presented in table 4.5 above show there are slight differences in final specimen thickness between the specimen groups within the same FVT. There is no consistent trend in the results. In case of 2,6 mm and 1,5 mm FVT, the control samples are thinner compared to the FR-treated samples. However, the same does not apply to the 1,0 mm FVT, where the average thickness of control samples is between that of the two FR-treated groups.

The final face veneer thickness was estimated by subtracting the thickness sanded off the panel from the veneer thickness after drying the veneers. The results in Table 4.6 show that the actual face veneer thickness is likely to be slightly thinner compared to the nominal thickness. This is to be expected as the following steps after veneer peeling, such as drying and sanding, reduce veneer thickness.

Average thickness after drying - Average thickness sanded off = Estimated final face veneer thickness

Table 4.6 Estimated final face veneer thickness

Nominal face veneer thickness (mm)	Avg veneer thickness after drying (mm)	Avg thickness sanded off from panel (mm)	Estimated final face veneer thickness (mm)
2,60	2,61 (0,07)	0,13 (0,07)	2,48
1,50	1,58 (0,02)	0,11 (0,03)	1,46
1,00	0,99 (0,04)	0,10 (0,03)	0,89

Values in brackets refer to standard deviation

It is important to consider that this method does not take into account the effect of veneer compression under the hot press, and thus can slightly overestimate the final face veneer thickness. Additionally, this estimation method can only be applied for the veneers used for FR-treated samples as the effect of sanding on panel thickness was not measured for untreated panels. Finally, this method does not allow to differentiate between panels used for 70% and 100 % fire retardant concentrations because the results of veneer thickness after drying are based on average values, and were not tied to individual veneers. It is also possible that the face veneer thickness is increased by the absorption of the FR chemical upon treatment.

4.3. Penetration depth

Penetration depth of the fire retardant was examined and evaluated to create an understanding of how different combinations of FR solutions and face veneer thicknesses impact penetration and reaction to fire test performance.

As explained in section 3.5, the penetration depth was visually evaluated as a percentage on two adjacent surfaces of each cone-calorimeter test specimen. Figures 4.1 and 4.2 present the penetration results for each face veneer thickness (FVT), for top and bottom facing surface veneers during wet-stacking, both as a percentage of FVT (penetration coverage) and in millimetres (penetration depth). The results of top and bottom face veneers are in separate columns.

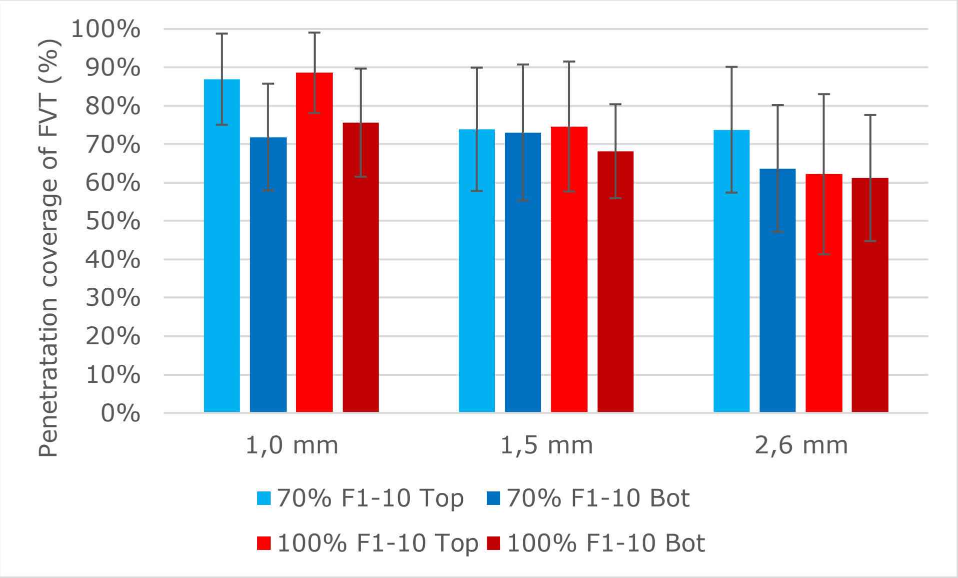

Figure 4.1 Average penetration coverage of top and bottom (Bot) side veneers as a percentage of total FVT

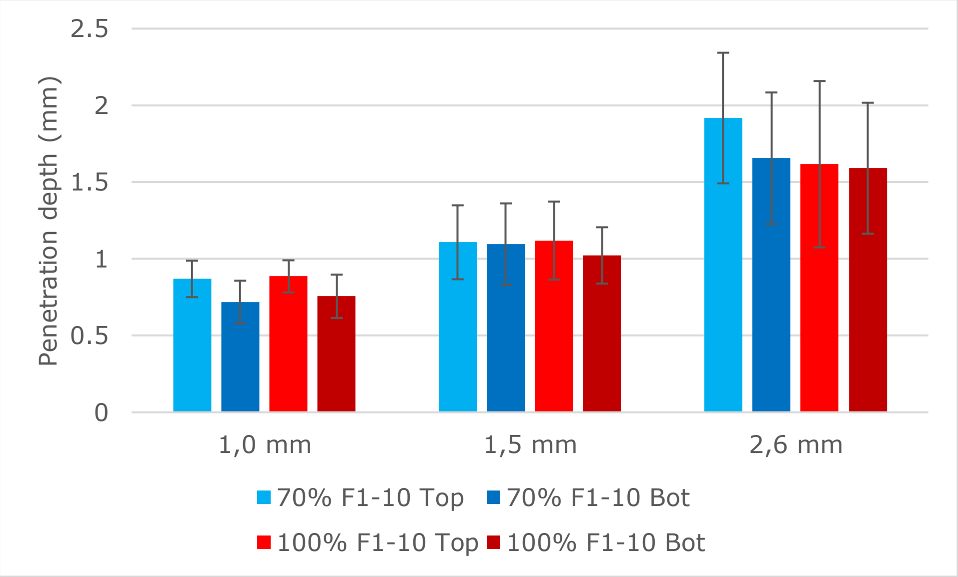

Figure 4.2 Average penetration depth of top and bottom (Bot) side face veneers in millimetres

The results in Figure 4.1 show that penetration coverage typically increases as FVT decreases. There is a statistically significant difference between penetration coverage of undiluted 2,6 mm top surface and undiluted 1,5 mm top surface (P-value = 0,046) as well as between the undiluted 1,5 mm top surface and undiluted 1,0 mm top surface (P-value = 0,003). It can also be seen that in most cases, the coverage of the top surface veneer is slightly greater than that of the bottom veneer in the same specimen group. This difference is the strongest in case of 2,6 mm FVT diluted solution and 1,0 mm FVT for both FR solutions. However, this difference is not statistically significant between any of the top and bottom surfaces within the same specimen group. There is no notable difference between top and bottom surface veneers of 1,5 mm diluted solution and 2,6 mm undiluted solution.

It appears the hypothesis of diluted FR solution being able to penetrate the material further as a result of its reduced viscosity is proving to be accurate to some extent as the penetration coverage is somewhat higher for 70 % F1-10 compared to the undiluted specimens. However, the variances within groups are high enough to prevent the observed differences from being considered statistically significant, implying that further research would be necessary to conclusively confirm the validity of this hypothesis.

When we look at the extent of penetration in millimetres (Figure 4.2), it is clear that penetration depth increases with increasing FVT (whereas penetration coverage percentage slightly decreases with increasing FVT). This suggests that the thinner FVTs are nearing their maximum penetration potential as a result of limitations imposed by the bond line. On the other hand, the 2,6 mm FVT, while showing the lowest penetration coverage, exhibits the highest penetration depth in millimetres, suggesting that the penetration is limited by the inherent characteristics of the wood material itself. In essence, thinner face veneers encounter barriers in penetration due to bond line restrictions, while thicker face veneers confront limitations associated with the wood's properties. Altogether, these findings imply that achieving optimal FR penetration in surface-treated plywood involves considering a delicate balance between FVT and wood properties.

It is important to emphasize that in cone-calorimeter testing (both at TalTech and MeKA), it was made sure the upwards-facing veneer during wet-stacking (top surface) was the same surface exposed to the heat source. This ensures that the lower penetration of the lower surface does not act as an influencing factor in ISO 5660-1 testing.

4.4. Reaction to fire test

4.4.1. Non-piloted ignition

Time to ignition is an important parameter to consider in fire testing as it measures the time for a material to catch fire when exposed to a heat source.

The results presented in Figure 4.3 show a very clear difference in ignition time between untreated and the FR-treated specimen groups. The difference in time to ignition between the control group and FR-treated groups is nearly two-fold, indicating that the FR treatment is successful in extending the time to ignition. However, it can also be observed that time to ignition between different FVTs within the same treatment group remain relatively similar, implying that FVT is not having any significant impact on time to ignition. Regarding the impact of FR concentration on time to ignition, it can be observed that the diluted specimens ignite slightly faster than the undiluted specimens, however, this difference is not statistically significant.

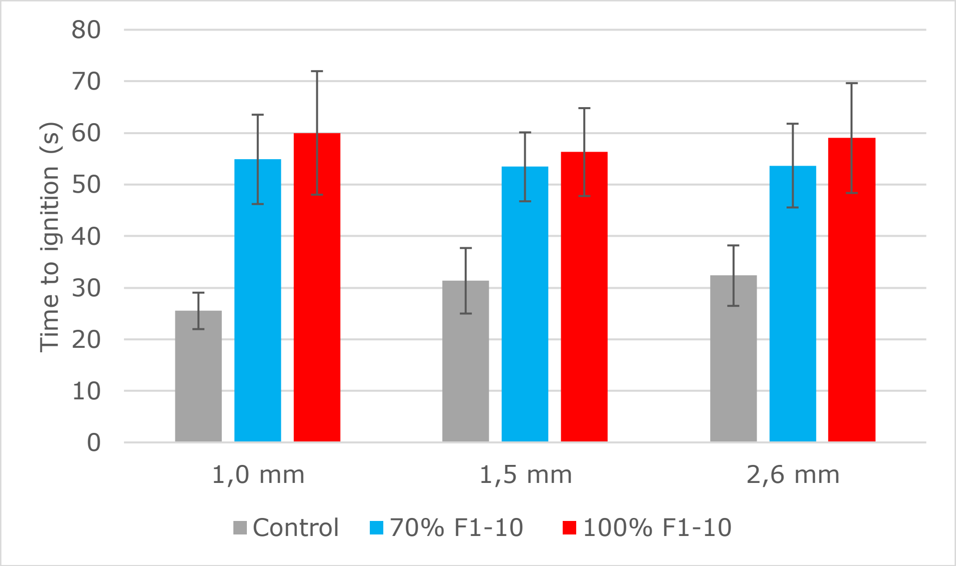

Figure 4.3 Time to ignition results of non-piloted ignition cone-calorimeter tests

Looking at the ignition temperature results presented in Figure 4.4, it can be observed that in case of undiluted specimens, ignition temperature appears to increase with increasing FVT. There is a statistically significant difference between the ignition temperatures comparing 2,6 mm to 1,0 mm FVT (P-value = 0,001) and 1,5 mm to 1,0 mm FVT (P-value = 0,026). However, there is no significant difference between 2,6 mm and 1,5 mm FVT due to the relatively high standard deviations. The results indicate that FVT might play a role in determining the ignition temperature in FR-treated plywood, however this trend is not consistent across all FVTs. Overall, these results speak to the benefit of higher FVT as according to Dietenberger and Hasburgh [20], increased surface ignition temperature tends to reduce the rate of flame spread – a crucial parameter in fire rating classification according to EN 13501-1.

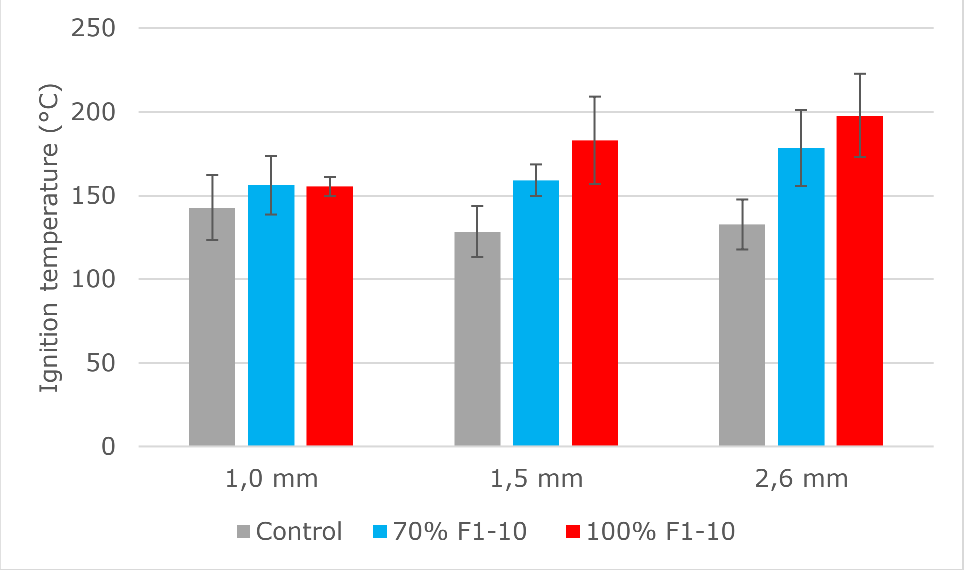

Figure 4.4 Ignition temperature results of non-piloted ignition cone-calorimeter tests

The results in Figure 4.4 show no clear trends in ignition temperature for the of control and diluted specimen groups. However, the undiluted group results indicate that ignition temperature increases with increasing FVT, suggesting that the surface can endure higher heat levels before ignition occurs. Phosphorous-based fire retardants such as the F1-10 are known to promote charring, which restricts the pyrolysis process required to fuel flames [43]. Moreover, the intumescent effect caused by the fire retardant creates a foamed carbon layer that absorbs heat and acts as a physical barrier. This process helps prevent the transfer of air and temperature to the material beneath [44]. These working mechanisms likely account for the observed higher surface ignition temperature. As the penetration results show, thicker face veneers enable deeper penetration of the fire retardant, potentially resulting in a thicker and more efficient carbon and foam layer and enhance the overall effectiveness of the fire retardant.

The temperature-time curve presented in Figure 4.5 shows the top surface temperature increase of control specimens occurs significantly earlier and more rapidly compared to the FR-treated groups. It can also be observed that the rate of increase in top surface temperature is the slowest for 1,5 mm undiluted group. A similar observation can be made looking at the heat release rate (HRR)-time curve in Appendix 3, suggesting that the 1,5 mm FVT with undiluted FR-treatment might perform better in delaying or mitigating heat release in the initial phase of the combustion process compared to other FVTs and treatments. However, this does not imply that the FR-treatment works better with 1,5 mm FVT overall. Despite having a lower penetration depth compared to the 2,6 mm FVT, the fire retardant might be more concentrated nearer to the surface of 1,5 mm FVT. This concentrated FR layer could offer better immediate protection upon ignition, initially slowing down temperature increase and

HRR. However, this explanation is speculative and would require further empirical research for validation.

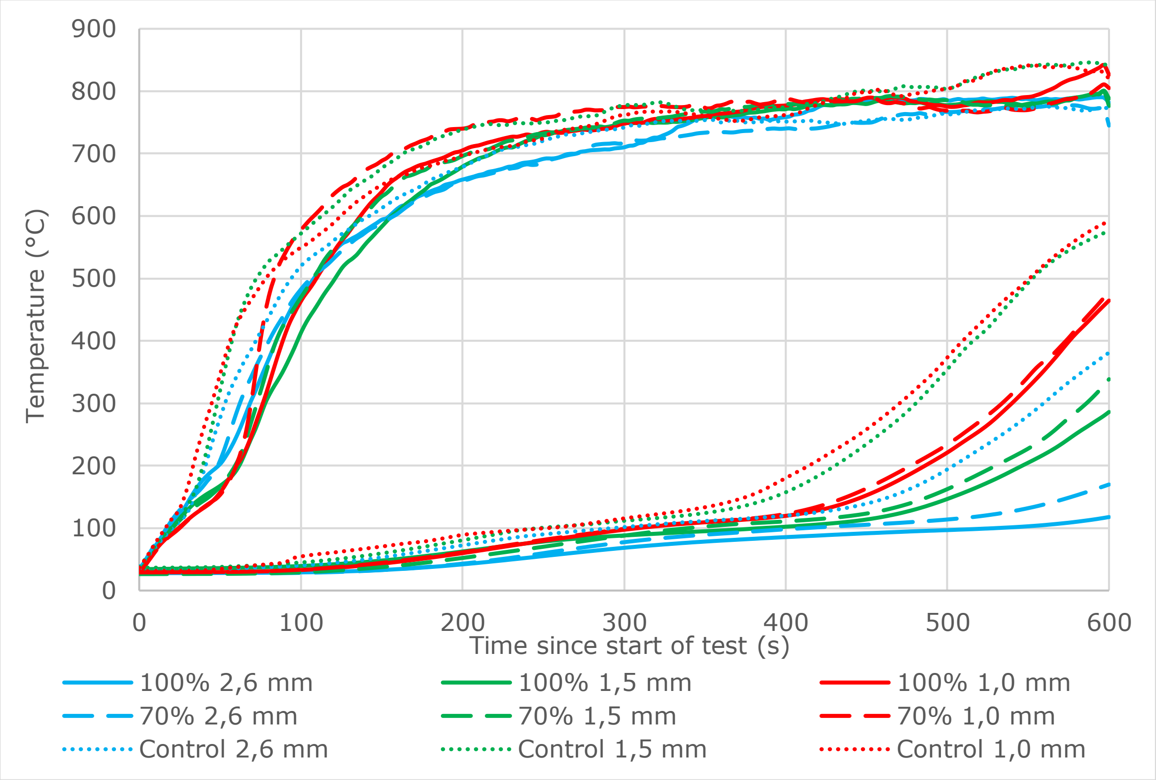

Figure 4.5 Average temperature-time curve of each specimen group, top and bottom surfaces

Looking at the bottom surface temperature, the differences between specimen groups are more easily distinguishable. It can be seen that the temperature increase of untreated groups occur earlier and more rapidly compared to the FR-treated groups of the same thickness. Comparing the specimen groups that have the same veneer thickness but different FR-solutions, we can observe that the 1,0 mm FVT specimens behave very similarly. However, in case of 1,5 and 2,6 mm FVT, the rate of increase in bottom surface temperature is noticeably lower for the undiluted solution, indicating that the effectiveness of the 100% F1-10 solution in reducing the temperature transfer through depth increases with increasing FVT.

It is noteworthy that in case of control samples of 1,0 mm and 1,5 mm FVT, the bottom surface temperature curves follow a very similar path, suggesting that the 1 mm of extra panel thickness resulting from a thicker face veneer does not significantly influence the temperature transfer through depth with untreated plywood. At the same time, it can be observed that the FR-treated 1,0 mm FVT samples show a noticeably higher increase in bottom surface temperature compared to 1,5 mm FVT, indicating that as the FVT increases, so does the effectiveness of FR-treatment in limiting the heat transfer through depth.

The temperature transfer through depth is a crucial parameter to understand for assessing the performance of materials under fire conditions, if the material is intended to serve as a fire barrier or prevent flame spread. Basic protection time (Tprot) refers to the temperature at which the material starts to thermally degrade, which for wood materials, typically occurs at around 270 °C. Tprot is measured on the bottom surface of a test specimen. Table 4.7 shows the average results of Tprot for all specimen groups.

Table 4.7 Basic protection time results

Specimen group	**Average Tprot (s)**	**Tprot reached out of all tests**	**Tprot reached as % of tests**
Control 1,0	454,2 (12,3)	3/3	100%
70% 1,0	522,0 (16,4)	8/8	100%
100% 1,0	530,3 (19,6)	8/8	100%
Control 1,5	465,8 (1,4)	3/3	100%
70% 1,5	570,4 (12,3)	7/8	88%
100% 1,5	572,5 (22,7)	6/8	75%
Control 2,6	558,3 (1,4)	3/3	100%
70% 2,6	N/A	0/8	0%
100% 2,6	N/A	0/8	0%

Values in brackets refer to standard deviation

The results (Table 4.7) show that the FR-treatment is successful in slowing down the temperature transfer through depth. In all cases, when we compare the control group to the FR-treated groups, the time it took to reach the threshold temperature of 270 °C for Tprot was substantially extended by the FR-treatment. The results show that in case of 1,0 mm and 1,5 mm FVTs, the undiluted group takes slightly longer to reach Tprot compared to the diluted group.

It is important to note that the average time to protection by itself does not give the full picture of the results. One should also pay attention to in how many of the cases was the threshold temperature reached. We can see that in case of control specimens, Tprot temperature was reached in all cases. The same is true for FR treated specimens of 1,0 mm FVT. However, in case of FR-treated 2,6 mm FVT, FR-treated specimens never reached Tprot, showing that there was a significant improvement. However, this improvement cannot be quantified as the test ended before the threshold temperature was reached. In case of 1,5 mm FVT, the results are more mixed, emphasizing the need to consider both Tprot along with the frequency of its attainment.

It is important to note that the results of different FVTs cannot be directly compared to one another as the total thickness of the test specimens is influenced by the FVT. For an accurate comparison, the panel thickness needs to remain constant regardless of the FVT.

4.4.2. Piloted ignition

The heat release rate essentially describes the fire intensity and can be considered the most important fire parameter [45]. Table 4.8 presents the THR_{600s} (total heat release over 600 seconds) results of the piloted ignition tests.

Table 4.8 THR600s results of piloted ignition tests

THR_{600s} (MJ/m²)			
	1,0 mm	**1,5 mm**	**2,6 mm**
Control	84,45 (3,72)	80,51 (3,57)	77,39 (9,80)
70 % F1-10	75,11 (2,34)	67,90 (4,00)	62,70 (8,58)
100 % F1-10	68,25 (0,37)	56,45 (0,25)	49,89 (0,28)
THR_{600s} results percentage comparison to control group			
	1,0 mm	1,5 mm	2,6 mm
Control	-	-	-
70 % F1-10	-11 %	-16 %	-19 %
100 % F1-10	-19 %	-30 %	-36 %

Values in brackets refer to standard deviation.

The THR results show that the FR-treatment is successful in reducing the THR_{600s}. The data suggests that the undiluted FR solution is more effective in decreasing the THR compared to the diluted solution. It can be observed that THR_{600s} decreases with increasing FVT across all specimen groups.

Overall, the results show a correlation between increased FVT and higher FR concentration leading to decreased THR_{600s} values compared to the control group, hinting at some possible relationships. It is likely that the thicker face veneers provide more insulation, slowing down heat transfer to, and potentially delaying the ignition of the core material.

The exact working mechanics of the FR chemical Palonot F1-10 are unknown to the author. However, research has shown ionic liquid based fire retardants to improve thermal conductivity [46]. This could help facilitate heat transfer away from the ignition source and to dissipate it more evenly. Both ionic liquid based and phosphorous-based FRs are known to form an intumescent char layer, which helps in reduction of heat transfer and oxygen access to the underlying wood, inhibiting thermal degradation and aiding in fire suppression [47] [43]. As the penetration thickness in millimetres is higher in case of thicker face veneers, the fire retardant can potentially enhance heat dissipation over a larger area of material, improving its effectiveness and fire resistance.

The data in Table 4.9 shows that the peak heat release rate (PHRR) of FR-treated specimens is lower compared to the control group. It can also be seen that the difference in PHRR between the control group and the undiluted group grew as the FVT increased. In all cases except the diluted (70% F1-10) specimens, the PHRR within a group decreased with increasing FVT.

Table 4.9 Average peak heat release rate of each specimen group

Specimen group	**1,0 mm (kW/m^2)**	**1,5 mm (kW/m^2)**	**2,6 mm (kW/m^2)**
Control	344,04 (37,38)	301,65 (24,07)	248,91 (35,33)
70% F1-10	223,04 (1,50)	233,73 (3,65)	175,80 (0,42)
100% F1-10	240,22 (10,63)	146,36 (4,18)	106,91 (5,29)

Values in brackets refer to standard deviation

According to Moghtaderi and Fletcher [16], it is common for wood materials with limited total thickness to form a second peak in heat release rate, which is a result of rapid elevation in the bulk temperature of the remaining material towards the end of the fire test. As previously presented in Table 4.4, there are notable differences in the thicknesses of panels due to the impact of FVT on panel thickness. The phenomena described by Moghtaderi and Fletcher likely explains the situation with thinner FVTs as the specimens with thinner FVT showed a second, higher peak towards the end of the test. To give a better understanding of combustion behaviour in the initial phase of the test, the PHRR results in the first half of the test are shown in Figure 4.6.

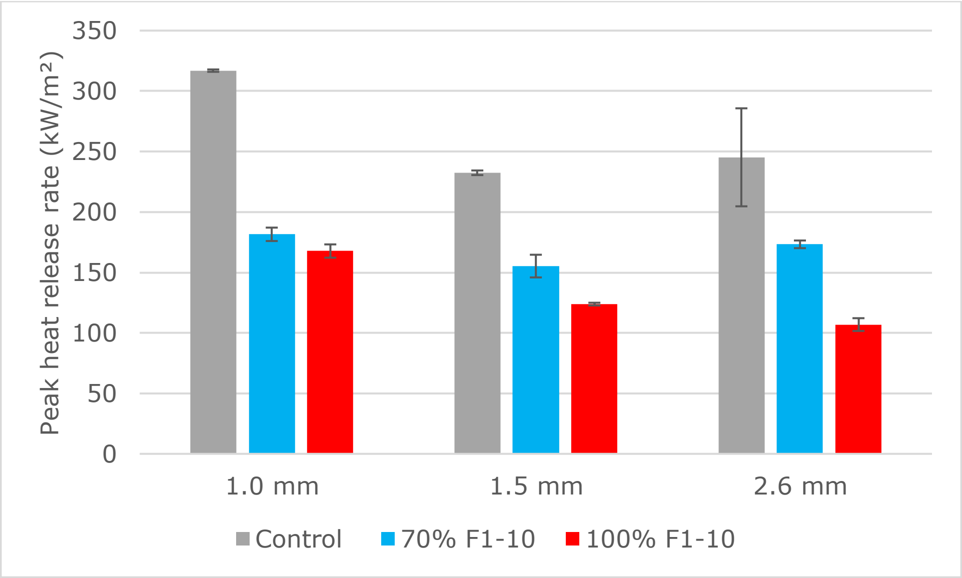

Figure 4.6 Average peak heat release rate (PHRR) results of highest peak in first half of the test

The results in Figure 4.6 demonstrate that FR-treatment notably decreases PHRR in the first half of the test for all FVTs, with the 100% F1-10 solution consistently exhibiting the lowest PHRR across all FVTs. Comparing the two F1-10 solutions within the same thickness category seems to indicate that the effectiveness of 100% F1-10 improves with greater FVT. For the 1,0 mm FVT, the PHRR difference between the 70% and 100% solutions is minimal, but this difference amplifies as the FVT increases.

According to Schartel and Hull [40], a comprehensive understanding of combustion behaviour requires an analysis of the complete HRR-time curve over the entire test duration. The complete curve is crucial to accurately describe fire behaviour, which is heavily influenced by material-specific properties such as char yield, specimen thickness, and the underlying physical and chemical mechanisms that occur during the combustion process [40]. Using simplified characteristic values alone does not convey the complete picture and could lead to misinterpretations [40]. Therefore, an empirical analysis on the HRR-time curve will follow.

The average HRR-time curves in Appendix 3 show all specimen groups on the same figure, where it can be clearly observed how FR-treated specimens (solid and dashed lines) show a substantially lower HRR in the initial phase of the test compared to the control specimens (dotted lines).

According to Moghtaderi and Fletcher [16], in case of wood materials, the typical HRR curve usually displays a distinct sharp peak shortly after ignition. As a char layer gradually forms, due to the low thermal conductivity of this layer, the thermal resistance progressively increases, leading to a decline in the rate of heat release following the initial peak. When the sample has sufficient thickness, this declining trend persists until the HRR stabilizes at a relatively constant rate [16]. However, in materials with limited thickness, a second peak emerges towards the end of the flaming combustion phase. This second peak is the result of a rapid elevation in the bulk temperature of the remaining material. Importantly, the occurrence of the second peak is not an inherent trait of the material itself, but primarily depends on the conditions of the unexposed face [16]. For instance, if the back face lacks insulation, the second peak will not be observable [16]. Examining the HRR curve of control samples reveals a close similarity to the pattern described above. This includes the observation that thinner face veneers (resulting in thinner overall panel thickness) demonstrate a second peak due to the restricted thickness of the material, aligning with the previously described behaviour.

Looking at the HRR curves (Appendix 3) from a bird's eye view, it can be observed that in the first 20-30 seconds of the fire test, the HRR remains near zero. During this phase, the material is dehydrating and absorbing the heat released by the cone-calorimeter, but is not releasing or generating additional heat. The chemical bonds inside wood fibres begin to decompose as the temperature rises, causing the release of flammable gases. The gases mix with oxygen in the air and the spark igniter above the surface of the specimen causes these gases to ignite and produce flames, leading to ignition of the wood (at around 20-30 s). The starting phase of flaming combustion is characterized by visible flames and intense heat release, peaking at roughly 40-70 seconds into the test, depending on the specimen group.

After the initial combustion and first peak in HRR, the wood starts to naturally form an insulating char layer that slows the combustion process. This is characterized by a decreased and relatively consistent HRR from approximately 120 s to 420 s into the test. In case of most specimen groups, we can observe another increase in HRR towards the end of the test. As described in research by Dietenberger and Hasburgh [20], Hao et al. [48] and Sanned et al. [49], is likely a result of material burns through (which is affected by material thickness) and the insulating char layer breaking down, exposing fresh material underneath. The exposed material acts as a new fuel source that starts to rapidly generate flammable volatile gases, leading to a return of higher heat release and another peak in the HRR curve. In the current case, whether and to what extent this phenomenon occurs, is defined by the panel thickness, which in turn is influenced by the FVT. Finally, when the fuel is consumed, or the supply of oxygen is limited, the fire progresses into its final, smouldering phase. In this stage, the material would continue to burn without flames, producing smoke, heat and glowing embers.

Looking at the HRR curve in Figure 4.7, it can be observed that the initial rate of HRR increase is similar for all FVTs, regardless of whether the material is FR-treated or not. The data also reveals that the first peak for all specimens occurs at roughly the same time, at around 50–60 s, regardless of specimen group or FVT. However, the values of the first peak in heat release rate between 100 % F1-10 and control samples of corresponding FVTs differ roughly twofold, indicating that the FR-treatment with higher concentration significantly slows the burning process and reduces the intensity of the fire in the initial phase of the test. The undiluted 2,6 mm FVT shows the most stable HRR throughout the test, as on average, these specimens peaked at around 45 s at 104 kW/m² and stayed below that level until the end of the test.

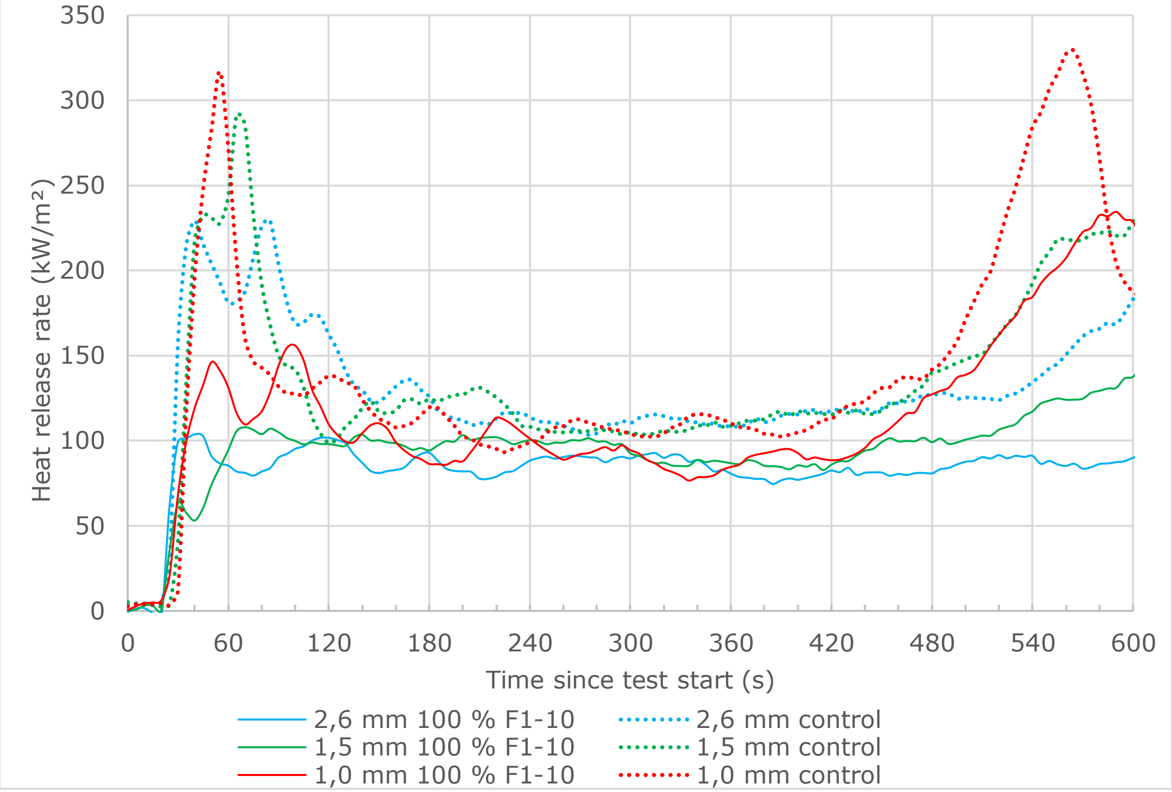

Figure 4.7 Average HRR-time curve of 100% F1-10 and control specimens

Figure 4.7 also illustrates that during the last three to four minutes of the test, the HRR for 1,0 and 1,5 mm FVT samples starts to increase. As explained previously, this is likely to be largely influenced by panel thickness and cracking of the char layer, which increases heat transfer and oxygen access to the underlying material.

Looking at the results of control samples, the HRR levels are significantly higher for all FVTs compared to the corresponding FR treated specimens, indicating that the FR-treatment is effective in overall mitigation of burning intensity. It is also clear that in case of reference samples, all FVTs show an increase of HRR towards the end of the test, whereas the thicker undiluted samples do not. It is noteworthy that for both FR-treated and control groups, the initial and final HRR peaks are higher as the FVT decreases. It can also be seen from the HRR-time curve that the consistent "plateau" level between the first and final peaks is slightly lower for the FR-treated samples.

Of the FR-treated samples, the 1,5 mm FVT seems to have the quickest suppressing effect to the fire, as there is a pullback in HRR after first smaller peak of 63 kW/m² at 45 s. A similar phenomenon can observed in the non-piloted ignition test results (Figure 4.5), where the undiluted 1,5 mm FVT specimens showed the lowest rate of initial top surface temperature increase. These findings suggest that the 1,5 mm 100 % F1-10 group outperforms other FVTs in mitigating the HRR in the initial phase after combustion. This is perhaps best observed in Figure 4.8, which shows the cumulative average heat rate emission (AHRE) as a function of time. In the figure below, at the 60 second mark, the AHRE value for 1,5 mm FVT is approximately 40 kW/m², whereas for 2,6 mm FVT, it is close to 60 kW/m². Until approximately 150 seconds into the test, the cumulative heat release of the 1,5 mm FVT is lower compared to the 2,6 mm FVT group, before their average heat rate emission lines intersect.

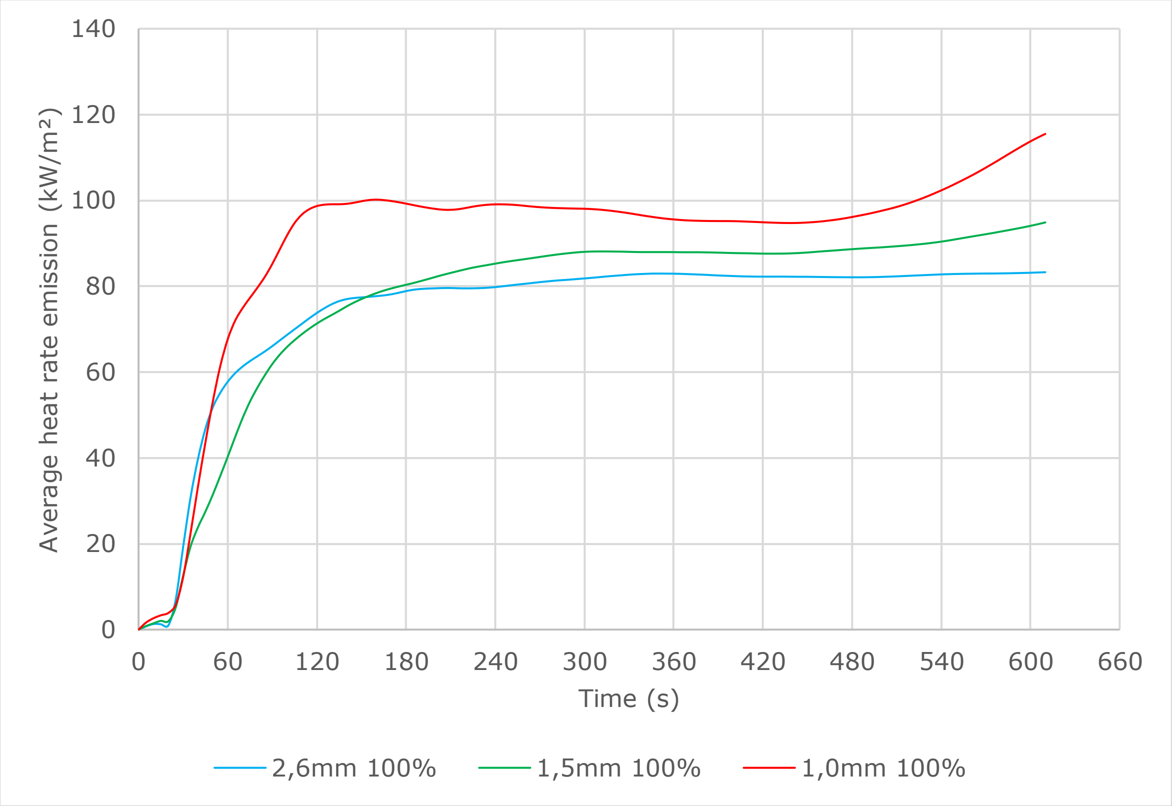

Figure 4.8 Average AHRE-time curve of 100% F1-10 specimens.

As the FR penetration results showed, the 1,5 mm FVT exhibits a penetration coverage of 75%, with a penetration depth of 1,125 mm and an unpenetrated FVT depth of 0,375 mm. In contrast, the 2,6 mm FVT showed a penetration coverage of 62%, resulting in a penetration depth of 1,612 mm and an unpenetrated portion of 0,988 mm. These figures indicate that the unpenetrated part of the 1,5 mm FVT is nearly three times thinner than that of the 2,6 mm FVT. One could suggest that the lower initial rate of heat release for the 1,5 mm FVT may stem from achieving a better balance between FR coverage and penetration depth. The fire retardant might be more concentrated nearer to the surface in case of the 1,5 mm FVT. This more concentrated FR layer could offer better immediate protection upon ignition, initially slowing down temperature increase and HRR. However, this explanation is speculative and would require further empirical research for validation.

The significantly inferior performance of the 1,0 mm FR-treated samples, characterized by higher PHRR, THR and AHRE values, might be related to their reduced absorption capacity compared to other FVTs. This aligns with the higher presence of crystalized FR residue observed on the 1,0 mm FVT panels' surface after unstacking the panels following FR-treatment. Although removed uniformly from all panels by swiping with a moist cloth, the greater amount of FR residue on the surface of 1,0 mm FVT suggests its limited absorption capacity, potentially contributing to its poorer fire performance.

Looking at Figure 4.9, one can see that the 2,6 mm reference, 1,0 mm 100% and 1,0 mm 70% F1-10 behave quite similarly in the first 100 seconds of the cone-calorimeter tests. While the PHRR values across the different groups are vary noticeably, all three groups exhibit a similar pattern of two consecutive HRR peaks that occur nearly synchronously and peak at similar values internally.

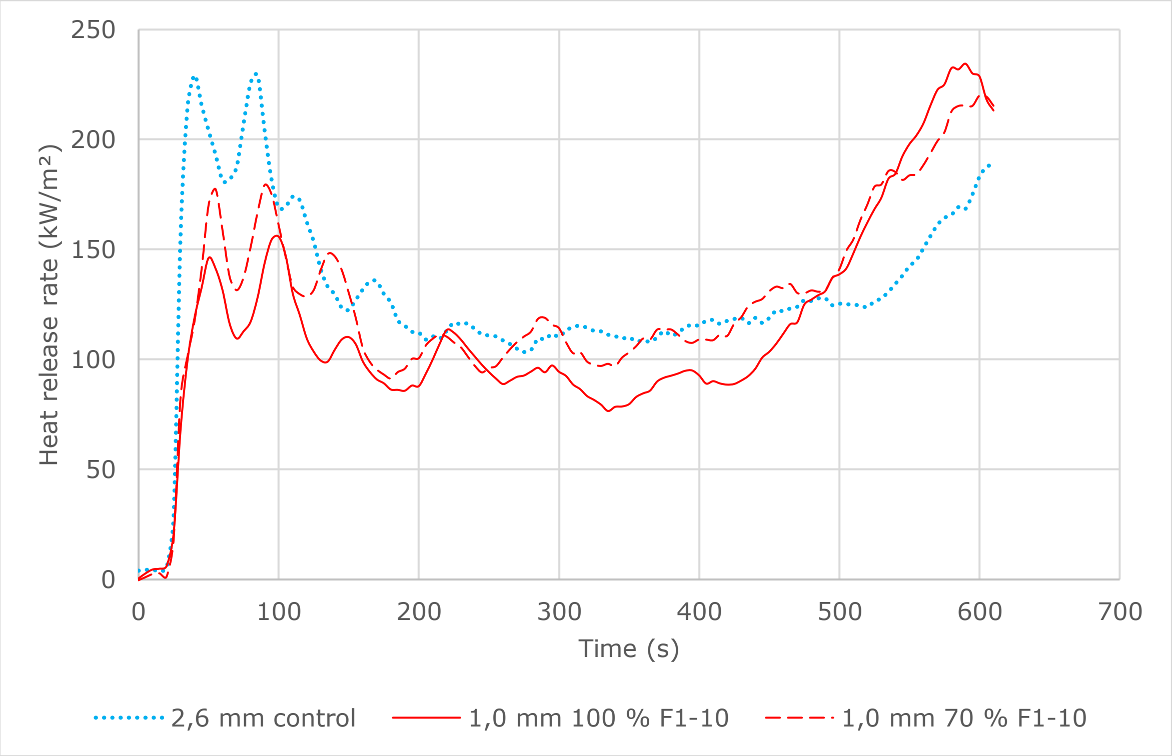

Figure 4.9 Average HRR-time curve of 2,6 mm reference, 1,0 mm 100% F1-10 and 1,0 mm 70% F1-10 specimen groups

The author would suggest that the similarities observed in combustion behaviour can be attributed to a combined influence of FVT and FR-treatment on the charring and ignition processes. In case of the 2,6 mm FVT control specimen, the initial peak in HRR is potentially followed by a natural charring process, briefly insulating and suppressing further burning until the subsequent veneer layer ignites. For the 1,0 mm FVT FR-treated specimens, the thin face veneer is enhanced by the intumescent properties of the fire retardant, creating a char layer similar to the natural charring of thicker untreated veneer. However, the thin FR-treated surface veneer has likely not absorbed enough FR to generate an adequate intumescent layer (as thicker FR-treated veneers have), thus leading to another peak in HRR from a rapid thermal degradation of the underlying veneer layer.

In contrast, it is likely that the 1,5 mm and 2,6 mm FVT FR-treated specimens have retained a higher amount of FR, resulting in the formation of a thicker protective layer that provides sufficient insulation to prevent a subsequent peak in HRR. On the other hand, the untreated 1,0 mm and 1,5 mm FVT specimens possibly lack sufficient thickness for substantial natural charring, failing to create a protective char layer that could delay the ignition of underlying veneers. This could be the reason why they exhibit a single, sharp peak in HRR. The explanations provided above are speculative, aiming to shed light on the observed variations in HRR profiles of the tested plywood specimens and highlight how the FVT and FR treatment may affect charring and the rate of thermal decomposition during the fire test.

The maximum average heat rate emission (MAHRE) is considered to be a good parameter to measure the propensity for fire development in a fire scenario [50] and is the parameter used to define fire hazard levels in the European railway standard for fire safety EN 45545. Figure 4.10 presents the average peak MAHRE values for all cone-calorimeter specimens.

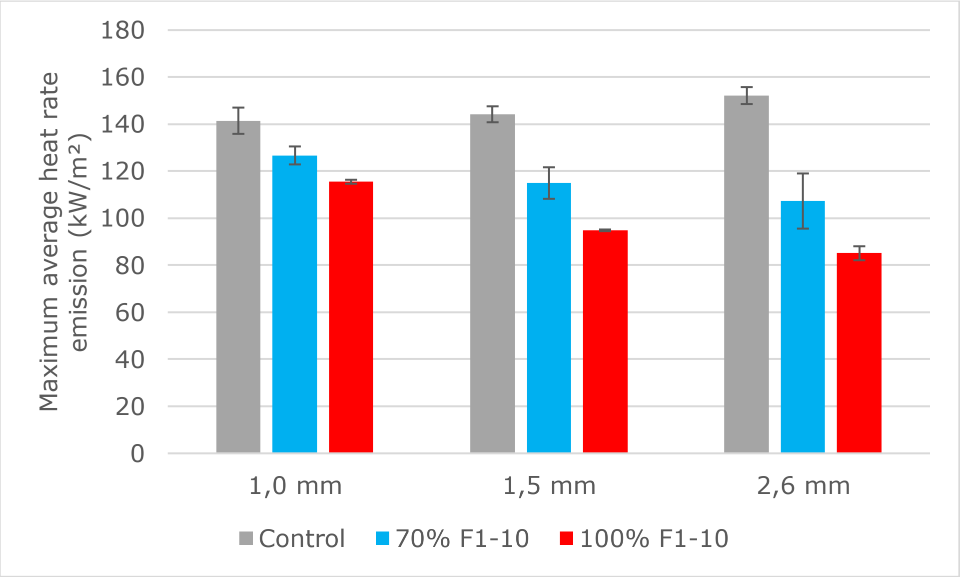

Figure 4.10 Maximum average heat rate emission (MAHRE) results of cone-calorimeter specimens

The results presented above indicate similar trends as observed across several other test parameters. The undiluted FR solution appears more effective in improving the combustion behaviour as the MAHRE values in the case of 100 % F1-10 are noticeably lower compared to both diluted and control specimens. The data suggests a considerable influence of FVT on MAHRE in case of undiluted specimens. Comparing specimens treated with 100 % F1-10, the MAHRE for 2,6 mm FVT is significantly lower compared to both 1,5 mm FVT (P-value = 0,044) and 1,0 mm FVT (P-value = 0,005). In diluted specimens, a similar trend emerges as in case of the undiluted group, yet a statistical difference was not achieved, likely due to higher standard deviations and smaller differences in average values. For control samples, there appears to be a slight tendency in the opposite direction. The MAHRE values are marginally increasing with increasing FVT. Nevertheless, these differences are minimal and lack statistical significance.

Total smoke production is another key parameter in fire testing that also influences product fire rating classification. The results presented in Figure 4.11 show that regardless of FR-treatment, smoke production increases with decreasing FVT. It is also clear that the FR-treatment is successful in decreasing smoke production. Comparing the results of 70 % F1-10 to 100 % F1-10, it is clear that the extent of decrease is greater in the latter. Across all FVTs, the undiluted solution exhibited an average smoke production reduction of 32 %, while the diluted solution displayed an average decrease of 18 %.

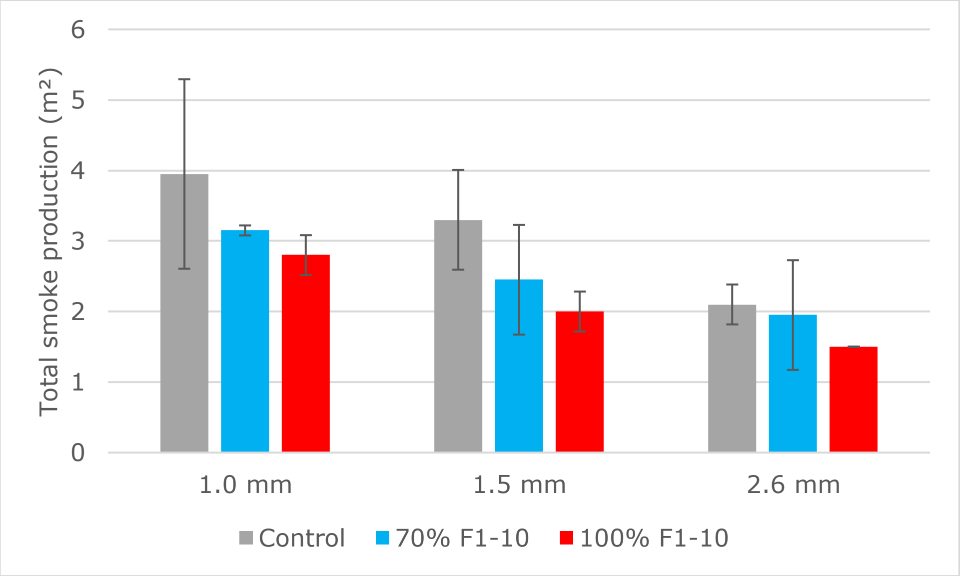

Figure 4.11 Total smoke production results of each specimen group.

There could be several reasons why higher face veneer thicknesses display lower smoke production. Thicker face veneers provide a higher insulation to the underlying core material, slowing down the combustion process and reducing the amount of smoke produced. Higher face veneer thickness could also contribute to a more controlled and uniform burning process, which could result in a more predictable and potentially lower smoke generation compared to thinner face veneers. This is also exhibited in the HRR curve presented in Appendix 3. Additionally, as also discussed previously in case of HRR, the lower smoke production of thicker face veneers could also be related to a higher FR penetration.

Mass loss is an important parameter in fire testing as it can be used to describe the burning rate of a material. The results in Figure 4.12 show the mass loss results for all specimen groups. The data shows that FR-treatment is successful in reducing the mass loss as the FR-treated specimens (both diluted and undiluted) exhibit lower mass loss compared to their respective control groups across all FVTs. The mass loss of undiluted specimens is lower than that of the diluted specimens, indicating that a higher concentration of FR provides better fire resistance.

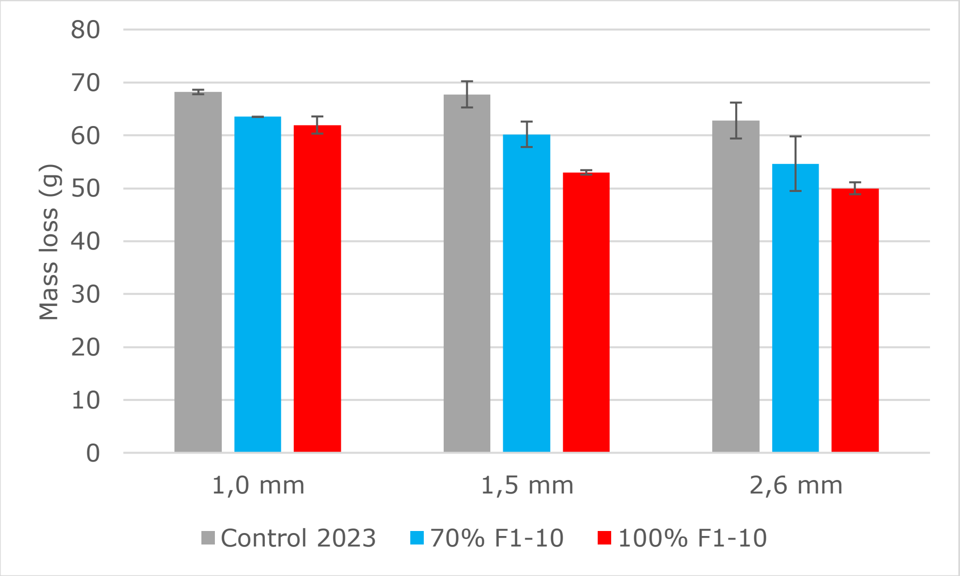

Figure 4.12 Average mass loss of each specimen group

It can also be observed that the mass loss of control specimens slightly decreases as the FVT increases, however, this trend is more pronounced for FR-treated specimens. This indicates that the combination of FR-treatment and thicker face veneer has a stronger impact on reducing mass loss, compared to FVT or FR-treatment alone. Thicker face veneers have a larger mass of wood material that begins to char as it is exposed to heat, resulting in a thicker char layer compared to thinner veneers. This char layer acts as a protective barrier, providing insulation and slowing down the rate of combustion by limiting the access of oxygen to the burning material. Additionally, as the penetration results have shown, the extent of FR-penetration in millimetres was higher in case of thicker face veneers, which allows for a more substantial distribution of FR within the wood structure. As a result, the FR possibly creates a stronger intumescent reaction with a thicker protective foam layer as it expands during heat exposure, resulting in a more effective insulating layer and allowing to dissipate heat across a larger area. The combined effects of the natural charring of wood, and deeper penetration and expansion of the FR could be a possible explanation for the enhanced performance observed when combining thicker face veneers with FR-treatment.

4.5. Estimation of fire safety rating for construction products based on cone-calorimeter test results

The Finnish research institute VTT has proposed the following rule-of-thumb class limits presented in Table 4.10 to predict the fire safety class rating of plywood products based on cone-calorimeter tests at 50 kW/m² heat flux [51]. The official fire safety classification for construction products in Europe is made on the basis of the large scale Single Burning Item (SBI) tests (EN 13823), the results of which are covered under section 4.7.

Table 4.10 Rule-of-thumb class limits to predict European fire safety class ratings for construction products based on cone-calorimeter test data

Euroclass rating	**Time to ignition (s)**	**PHRR (kW/m²)**
B	≥ 40	≤ 100
C	≥ 30	≤ 180
D	≥ 15	≤ 250

The following table 4.11 shows the predicted fire safety class results for the tested specimen groups, according to the rule-of-thumb class limits presented above. It should be noted that according to VTT, "the rule-of-thumb class limits have been set on the safe side, so that a product fulfilling these conditions in a cone-calorimeter test meets the requirements of a certain Euroclass in the SBI test with a high probability [51]."

Table 4.11 Predicted fire safety class for testes specimens based on rule-of-thumb class limits proposed by VTT

Specimen group	**Average time to ignition (s)**	**Average PHRR (kW/m²)**	**Euroclass rating**
Control 1,0 mm	33 (C)	344 (<D)	< D
Control 1,5 mm	31,3 (C)	301,7 (<D)	< D
Control 2,6 mm	32,3 (C)	248,9 (D)	D
70% F1-10 1,0 mm	54,9 (B)	223 (D)	D
70% F1-10 1,5 mm	49,4 (B)	233,7 (D)	D
70% F1-10 2,6 mm	44,9 (B)	175,8 (C)	C
100% F1-10 1,0 mm	60 (B)	240,2 (D)	D
100% F1-10 1,5 mm	59,3 (B)	146,4 (C)	C
100% F1-10 2,6 mm	63,8 (B)	106,9 (C)	C

The letters in brackets refer to the fire safety class corresponding to the results of each category

The results show that all control specimens, regardless of FVT, fall under the Euroclass rating of D or worse, which stands for medium to high contribution to fire growth. The 1,0 mm and 1,5 mm FVT specimens treated with the diluted FR solution, and the 1,0 mm FVT specimen group of undiluted are predicted fall into the Euroclass rating of D, which stands for medium contribution to fire. The 1,5 mm and 2,6 mm FVTs of undiluted solution, and the 2,6 mm FVT treated with diluted solution are estimated to have the Euroclass rating of C, standing for limited contribution to fire. As noted above, the limits for class ratings have been set on the safe side, so it would seem plausible for the 2,6 mm FVT undiluted solution specimen group to potentially be classified as Euroclass B in SBI testing, as it only exceeds the PHRR limit by 6,9 kW/m². The Euroclass B rating is defined as having very limited contribution to fire. Overall, the results presented above show that all FR-treated specimens succeed in achieving the B rating limit value for time to ignition, but none were able to achieve a sufficiently low PHRR for the B rating prediction.

4.6. Hazard level classification for materials used in railway vehicles

As explained in section 2.3.2, the European railway standard for fire safety EN 45545-2 uses three hazard levels (HL1, HL2 and HL3) to categorize materials and products within its classification system, where HL3 is the most demanding hazard level, and HL1 is the lowest. The MAHRE threshold values for hazard levels vary based on end-use application, but for most interior products they are limited to either 60 kW/m² or 90 kW/m². The exact requirements and corresponding hazard levels by product type can be seen in Table 4.12. The hazard level requirements and values listed in the rightmost column correspond to the maximum MAHRE (maximum average heat rate of emission) results in testing according to ISO 5660-1. [23]

Table 4.12 Product requirements based on EN 45545-2 [23]

Requirement	**Application**	**Examples**	**Hazard level**
R1	IN1A: Interior vertical surfaces	Side walls, partitions, room dividers, boxes, interior doors	HL1 - N/A HL2 - 90 kW/m² HL3 - 60 kW/m²
R1	IN1B: Interior horizontal downward-facing surfaces	Ceiling panelling, boxes, hoods, insulation material	
R1	IN1C: Interior horizontal upwards-facing surfaces	Flaps, boxes, hoods, insulation material	
R1	IN4: Luggage storage areas	Luggage racks, stacks, containers and compartments	

R1	IN9B: Folding table downwards facing surface	Bottom surface of a table, exposed vertical sides	
R1	IN7: Window surroundings	Window frames	
R2	IN9A: Folding table tops	All tables and toilet wash basins	HL1 - N/A HL2 - N/A HL3 - 90 kW/m²
R6	F1C: Seat shell base	External surface of the base shell	HL1 - 90 kW/m² HL2 - 90 kW/m² HL3 - 60 kW/m²
R6	F1D: Seat shell back	External surface of the back shell	

The only tested specimen group which achieved a MAHRE value below 90 kW/m² is the 2,6 mm FVT treated with 100 % Palonot F1-10. The results indicate that this material would be suitable for use in applications with HL1 and HL2 hazard level requirements in every product category highlighted in Table 4.12. Additionally, the undiluted 2,6 mm FVT could potentially qualify for HL3 requirement for use in folding table tops. However, the tested materials are not likely to achieve the HL3 requirement for other interior product applications, where the MAHRE threshold value maximum is 60 kW/m². These include vertical and horizontal surfaces, luggage storage areas, window surroundings and seat shell components. [23]

4.7. Single Burning Item test results

The Single Burning Item (SBI) test outlined in the European standard EN 13823 is an essential part of the fire classification system for construction products in Europe and is commonly used for product certification. It should be noted that due to the high workload and expenses related to the production of these specimens, only one specimen per FVT was tested with the objective to provide preliminary large scale testing results. The SBI test, unlike cone-calorimeter testing, yields total values for the experiment's duration rather than providing dynamic data as a function of time.

Table 4.13 presents the classification requirements for relevant fire class ratings according to EN 13501-1. FIGRA (growth rate of the burning intensity) and THR_{600s} (total heat release over first 600 seconds) are determined from the test data to describe how quickly the fire develops and how much heat energy is produced by the tested material. LFS (lateral flame spread) is observed during the test to see whether flames spread across the test specimen's wing during the test. [22]

Table 4.13 Classification requirements for fire class ratings according to EN 13501-1.

Fire class rating	**Classification requirements**
B	FIGRA ≤ 120 W/s;

	and LFS < edge of specimen;
	and THR_{600s} ≤ 7.5 MJ
C	FIGRA ≤ 120 W/s;
	and LFS < edge of specimen;
	and THR_{600s} ≤ 15 MJ
D	FIGRA < 750 W/s

Table 4.14 presents the results of SBI tests conducted on birch plywood specimens overlaid with 1,0 mm, 1,5 mm and 2,6 mm birch face veneers. As the data shows, the 1,0 mm and 1,5 mm FVT specimens achieved the highest possible "B" fire class rating for wood products, whereas the 2,6 mm FVT specimens was rated class "C". Regarding smoke production and flaming droplets, specimens of all FVTs received the highest possible classification "s1" and "d0" as the SMOGRA (smoke growth rate) and TSP_{600s} (total smoke production over first 600 seconds) values were within the permitted limits [22] of 105 m²/s² and 250 m², respectively, and the specimens did not produce any flaming droplets. All specimens were also within the permitted limits of $FIGRA_{0,2MJ}$, indicating that the growth rate of burning intensity was not the limiting factor in achieving fire class rating "B".

Table 4.14 Single Burning Item test results and fire rating classification

FVT	Class	Smoke production	Flaming droplets	$FIGRA_{0,2MJ}$ (W/s)	THR_{600s} (MJ)	SMOGRA (m²/s)	TSP_{600s} (m²)
1,0 mm	B	s1	d0	57,2	6,8	1	30,4
1,5 mm	B	s1	d0	78	7,1	0,9	30,1
2,6 mm	C	s1	d0	60,1	7,7	-*	34,7

* - threshold value for measurement was not reached

The only measured test parameter which prevented the 2,6 mm FVT specimens from obtaining the fire class rating "B" in the SBI test was the THR_{600s}. In case of 2,6 mm FVT, the threshold was exceeded by only 0,2 MJ or 2,7 %. Therefore, it could be said that the 2,6 mm FVT could be a borderline product on the limit of classes B and C in terms of THR_{600s} values.

Interestingly, the THR_{600s} results of the SBI test for 1,0 mm, 1,5 mm and 2,6 mm FVTs show different results compared to the same results of the cone-calorimeter test. The cone-calorimeter results showed that THR_{600s} decreases as FVT increases (see Table 4.8), while the opposite trend can be observed in case of SBI tests. This discrepancy in trends could be attributed to several factors which are discussed below.

There are significant differences between the test setup and conditions of the SBI and cone-calorimeter tests. In the SBI test, the specimen is composed of two large (540 mm x 1500 mm) wings of plywood which are attached to gypsum plasterboard with mechanical connectors and mounted vertically. In case of the cone-calorimeter test, a small (100 mm x 100 mm) specimen is mounted horizontally on the specimen holder. A study investigating the orientation effect on cone calorimeter test results revealed a more constant temperature distribution, lower critical heat flux, shorter time to ignition and longer burning time for horizontal orientation [52]. This example illustrates that the same material can behave differently depending on the mounting orientation during a fire test, even when sample size and ignition source remain the same. However, it should be noted that the same study did not find a difference in THR values between the two orientations. Even so, these observations cannot be directly applied to the present example as in addition to the orientation, the test methods are also different in heat application. The propane burner used in the SBI test, originally designed to simulate a burning waste-paper basket [53], is fundamentally different from the heat source used in the cone-calorimeter test, as the source of ignition is a direct flame. The cone-calorimeter applies a controlled radiant heat flux of 50 kW/m² over the entire surface of the specimen, whereas in the SBI test, the heat release rate of 30 kW is more localized and direct. The combustion behaviour, ignition characteristics and the resulting fire dynamics are affected by differences in heat application [48].

As noted in the materials section, there were slight differences in the manufacturing processes between the SBI and cone-calorimeter specimens. Namely, for the SBI panels, no polyethylene film was used to separate the panels during wet-stacking. This lack of separation could lead to surface-to-surface interaction and transfer of material between the panels, potentially leading to higher variation in retention rates and response to fire tests. Additionally, in case of SBI specimens, the FR residue was not removed from the panel surface after unstacking the panels. This could alter the surface characteristics of the materials as this residue could potentially act as an additional layer of coating, influencing how heat is transferred to the material during the test. It could also affect the thermal degradation and combustion behaviour by changing the thermal properties of the panels. The purpose of removing FR residue from the surface in case of cone-calorimeter specimens was to ensure a higher uniformity of FR retention to reduce localized variations in fire behaviour. Furthermore, in case of cone-calorimeter specimens, it was always made sure the upwards-facing surface during stacking of the panels was always the same surface exposed to the heat source during fire testing. However, this was not followed in case of SBI specimens, which could again lead to higher variation in FR retention within the veneer exposed to the heat, which is also supported by the penetration analysis.

In conclusion, the SBI and cone-calorimeter test results show different trends in terms of the effect of FVT on combustion properties (THR_{600s}). The discrepancy between the trends is likely influenced by the differences in the process of material preparation and testing methods, which are described in detail above. For these reasons, the SBI and cone-calorimeter test results are not directly comparable. However, the SBI results suggest that achieving B s1, d0 fire class rating with fire-resistant plywood is possible with surface coating as the method of FR-treatment, a claim which could not be supported solely by cone-calorimeter tests.

5 CONCLUSIONS

The general aim of this research was to study the combustion behaviour of post-manufacture fire retardant (FR)-treated birch plywood. The specific objectives were to study the effect of face veneer thickness (FVT) and FR concentration on FR penetration; to examine the effect of FVT on combustion behaviour and to determine the effect of different FR concentrations on combustion behaviour.

The fire retardant penetration results show that while in some cases the diluted solution of F1-10 showed higher penetration depth compared to the undiluted solution, possibly due to lower viscosity of the liquid, this increase in penetration depth did not translate to improved fire performance. Overall, while the penetration coverage (expressed as a percentage of FVT) appeared to decrease with increasing FVT, the penetration depth (measured in millimetres) showed the opposite trend. The results appear to indicate that thinner face veneers encounter barriers in penetration due to bond line restrictions, whereas in case of thicker face veneers, the penetration is limited by the inherent characteristics of the wood material.

The cone-calorimeter test results show that generally, the fire performance of FR-treated plywood improves with increasing FVT as the 2,6 mm FVT specimens treated with undiluted FR solution outperformed all other specimen groups in most measured parameters, including ignition temperature, total heat release rate, peak heat release rate, maximum average heat rate emission, mass loss and total smoke production. The reaction to fire test results also show that a higher concentration of FR is more effective in improving the combustion behaviour of FR-treated plywood as the performance of specimens treated with a diluted FR solution was inferior to those with undiluted treatment. Additionally, while undiluted specimen groups showed distinct trends in the impact of FVT on most measured parameters, these trends were less apparent in diluted groups, indicating higher inconsistency in fire performance.

The 1,5 mm FVT treated with undiluted FR solution outperformed other FVTs in suppressing combustion in the initial phase of the fire by displaying a slower increase in heat release rate, average heat rate emission and top surface temperature. This could be attributed to its thinner unpenetrated layer, suggesting a more concentrated FR distribution closer to the surface. However, these observations require further empirical validation to confirm the potential superiority of the 1,5 mm FVT in mitigating early-stage combustion.

While there are some disparities between cone-calorimeter and Single Burning Item (SBI) tests regarding the effect of FVT on combustion behaviour, the SBI results show that achieving a B s1, d0 fire class rating with surface-treated fire resistant plywood is feasible – an outcome not explicitly supported by cone-calorimeter tests. The disparities between the results of the two testing methods likely stem from differing testing methodologies, test conditions and material preparation processes, which impact the combustion properties measured, particularly the THR_{600s} values.

Overall, the findings of this study suggest that as the FVT increases, there is a notable enhancement in both the fire performance and the depth of FR penetration depth in FR-treated plywood subjected to surface treatment via roller coating. While the diluted, less viscous FR solution shows a higher extent of penetration in some instances, this higher penetration rate was not translated into a better fire performance.

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SUMMARY

This research aimed to create a better understanding on how fire-retardant treated birch plywood behaves during combustion, specifically focusing on the impact of face veneer thicknesses and fire retardant concentrations on combustion behaviour and penetration.

Industrially manufactured core plywood panels were overlaid with laboratory-made face veneers of three thicknesses (1,0 mm, 1,5 mm and 2,6 mm), treated with Palonot F1-10 fire retardant of two different concentrations (100 % by wt. and 70 % by wt.). Fire-retardant treated and reference samples were tested according to the cone calorimeter (ISO 5660-1) reaction to fire test and the results were analysed and compared. Additionally, large scale Single Burning Item (EN 13823) reaction to fire tests were conducted to obtain preliminary data on the potential fire class ratings of the tested products. The penetration depth of fire retardant was determined by applying a reagent on the cross section of the FR-treated panels, which changes colour as it comes in contact with the FR chemical.

The results indicate that increasing face veneer thickness generally improves fire performance, with the 2,6 mm face veneer thickness treated with undiluted solution showing the best performance in various parameters. Higher concentrations of fire retardant also enhanced combustion behaviour and consistency of results. Materials treated with undiluted fire-retardant solution of 1,5 mm face veneer thickness showed promising results in terms of initial suppression of heat release rate, possibly due to a higher concentration of fire retardant closer to the surface. The results indicate that the diluted fire retardant solution managed to penetrate the material deeper in some cases, possibly due to reduced viscosity of the chemical. However, the increased penetration of the diluted solution did not translate to improved fire performance.

In summary, the study found that increasing face veneer thickness improved fire performance and fire retardant penetration depth in surface-treated plywood. It appears that thinner face veneers encounter barriers in penetration due to bond line restrictions, whereas in case of thicker face veneers, the penetration is limited by the inherent characteristics of the wood material. Although the diluted fire retardant solution showed improved penetration in some cases, this improvement did not enhance fire performance.

KOKKUVÕTE

Selle uurimistöö eesmärk oli luua parem arusaam tuletõkkeainega töödeldud kasevineeri põlemisomadustest, keskendudes eelkõige sellele, milline on spooni paksuse ja tuletõkkeaine eri kontsentratsioonide mõju põlemiskäitumisele ja tuletõkkekemikaali imendumisele.

Tööstuslikult toodetud vineerpaneelid kaeti kolme paksusega (1,0 mm, 1,5 mm ja 2,6 mm) laboris valmistatud spooniga, mida töödeldi kahe erineva kontsentratsiooniga (100 % massi järgi ja 70 % massi järgi) Palonot F1-10 tuletõkkeainega. Tuletõkkeainega töödeldud ja töötlemata katsekehasid testiti koonuskalorimeetri (ISO 5660-1) tuletundlikkuse testi järgi ning tulemusi analüüsiti ja võrreldi. Lisaks viidi läbi üksiku põleva objekti (EN 13823) tuletundlikkuse katsed, et saada esialgsed andmed testitud toodete võimalike tuletundlikkuse klassifikatsioonide kohta. Tuletõkkeaine imendumissügavus määrati töödeldud paneelide ristlõikele reaktiivse kemikaali pealekandmisega, mis kokkupuutel tuletõkkeainega värvi muudab.

Tulemused näitavad, et pinnaspooni paksuse suurendamine parandab üldiselt tulekindlust, kusjuures lahjendamata lahusega töödeldud 2,6 mm paksusega pinnaspoon toimis enamik parameetrites kõige paremini. Samuti parandas tuletõkkeaine kõrgem kontsentratsioon tulekindlust ja tulemuste stabiilsust. 1,5 mm paksusega töödeldud spoon näitas paljulubavaid tulemusi soojuseralduskiiruse esialgsel aeglustamisel, mis võib olla tingitud tuletõkkeaine kõrgemast kontsentratsioonist materjali pindmises kihis. Tulemused näitavad, et lahjendatud tuletõkkeaine lahus suutis mõningate spoonipaksuste puhul tungida materjalis sügavamale, mis võib olla seotud kemikaali viskoossuse vähenemisega. Suurenenud imendumine aga ei parandanud materjali tulekindlust.

Kokkuvõttes näitavad uuringu tulemused, et spooni paksuse suurendamine parandab tulekindlust ja tuletõkkeaine imendumissügavust pindmiselt töödeldud vineeris. Näib, et õhemate pinnaspoonide puhul on peamiseks imendumist takistavaks teguriks liimikiht, samas kui paksemate spoonide puhul piiravad imendumist puitmaterjali enda omadused. Kuigi lahjendatud tuletõkkeaine lahus näitas kohati paremat imendumist, ei suurendanud see materjali tulekindlust.

APPENDICES

Appendix 1. Overview of sample grouping and fire test specimens

Specimen group	Face veneer thickness (mm)	Treatment	Test method	Number of panels	Samples per panel	Total samples
1	1,0	100 % F1-10	ISO 5660-1	2	5	10
	1,5	100 % F1-10	ISO 5660-1	2	5	10
	2,6	100 % F1-10	ISO 5660-1	2	5	10
2	1,0	70 % F1-10	ISO 5660-1	2	5	10
	1,5	70 % F1-10	ISO 5660-1	2	5	10
	2,6	70 % F1-10	ISO 5660-1	2	5	10
3	1,0	100 % F1-10	EN 13823	6	*	1
	1,5	100 % F1-10	EN 13823	6	*	1
	2,6	100 % F1-10	EN 13823	6	*	1
4	1,0	Untreated	ISO 5660-1	2	2-3	5
	1,5	Untreated	ISO 5660-1	2	2-3	5
	2,6	Untreated	ISO 5660-1	2	2-3	5
				Total: 36		**Total: 78**

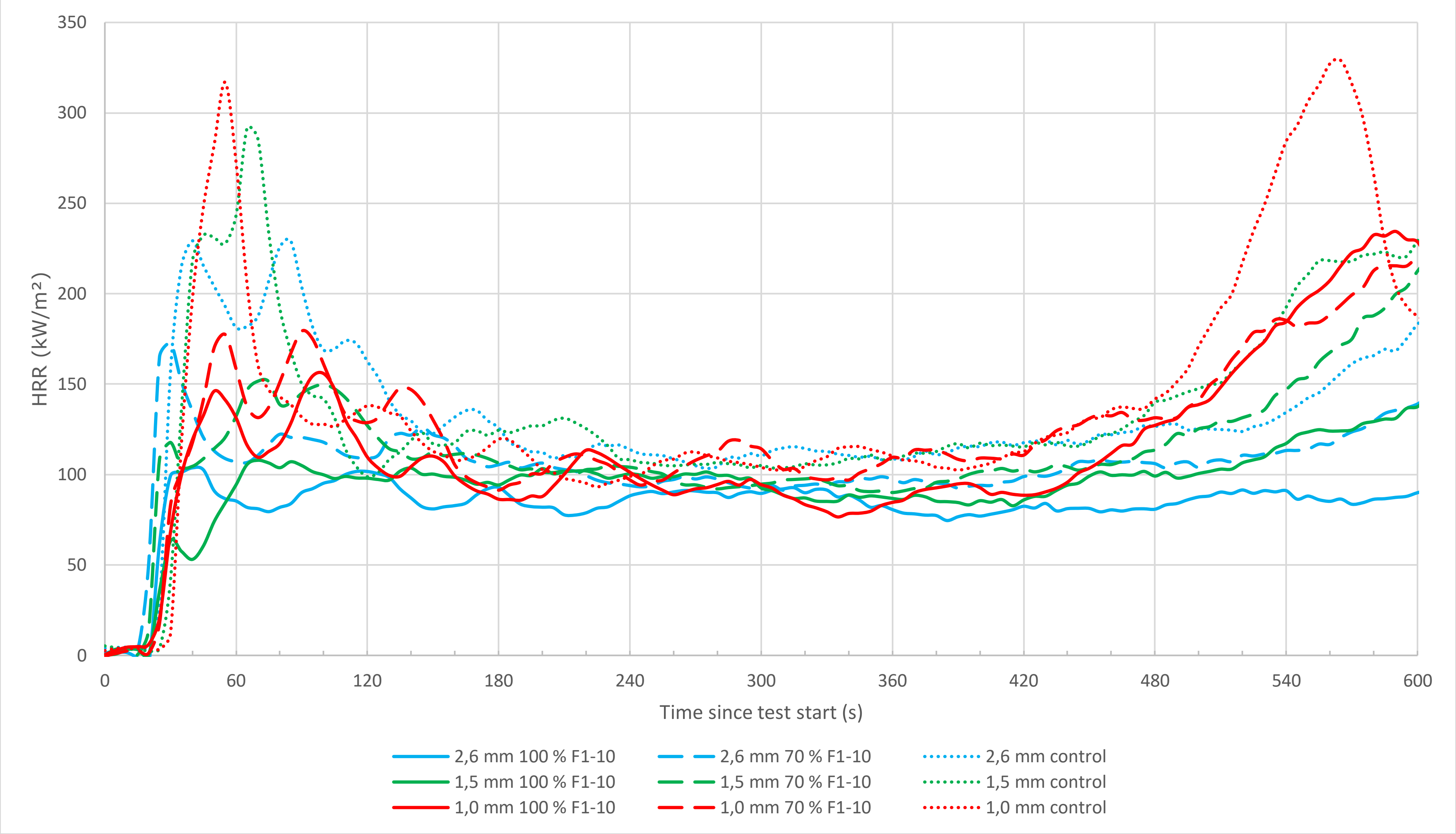
* - six panels were used to make one specimen

Appendix 2. Results of panel thickness removed by sanding

Panel	Face veneer thickness (mm)	Avg. thickness before sanding (mm)	Avg. thickness after sanding (mm)	Avg. thickness sanded off (mm)
P2	2,6	16,48 (0,20)	16,36 (0,16)	0,12
P7	2,6	16,43 (0,24)	16,27 (0,25)	0,16
P8	2,6	16,33 (0,18)	16,21 (0,20)	0,12
P3	1,5	14,42 (0,20)	14,29 (0,18)	0,12
P4	1,5	14,23 (0,13)	14,18 (0,12)	0,08
P9	1,5	14,31 (0,18)	14,17 (0,18)	0,14
P10	1,5	14,27 (0,20)	14,17 (0,20)	0,10
P5	1,0	13,31 (0,16)	13,18 (0,16)	0,13
P6	1,0	13,31 (0,17)	13,20 (0,17)	0,10
P11	1,0	13,47 (0,16)	13,36 (0,17)	0,11
P12	1,0	13,40 (0,08)	13,33 (0,09)	0,07

Values in brackets refer to standard deviation (measurements were taken from six different locations on each panel)

Appendix 3. Average HRR curve of each specimen group



Appendix 4. Piloted ignition ISO 5660-1 cone-calorimeter test results

Specimen ID	FVT* (mm)	Treatment	Ignition time (s)	Peak HRR (kW/m²)	Peak HRR of first peak	THR 300s (MJ/m²)	THR 600s (MJ/m²)	MAHRE (kW/m²)	Total smoke production (m²)	Mass loss (g)	Initial thickness (mm)
P1-1.0-2	1	Control	29	317,61	317,6061	35,56	81,82	137,5	3	67,9	13,20
P1-1.0-3	1	Control	28	370,47	316,2347	35,07	87,08	145,4	4,9	68,5	13,30
P1-1.5-3	1,5	Control	30	284,63	233,7905	36,93	77,98	141,8	2,8	66	14,20
P2-1.5-3	1,5	Control	26	318,67	231,0938	38,05	83,03	147,6	3,8	69,5	14,10
P1-2.6-3	2,6	Control	21	223,93	216,5853	40,85	84,32	149,6	2,3	65,2	15,90
P2-2.6-2	2,6	Control	24	273,89	273,8909	38,22	70,46	154,7	1,9	60,4	16,00
P11/10	1	70 % F1-10	16	221,98	177,63	32,34	73,45	124	3,1	63,5	13,3
P12/13	1	70 % F1-10	21	224,1	185,46	34,34	76,76	129,4	3,2	63,5	13,3
P9/10	1,5	70 % F1-10	16	236,31	161,92	32,64	70,73	119,7	3	61,9	14
P10/13	1,5	70 % F1-10	16	231,15	148,67	30,64	65,07	110,2	1,9	58,5	14,2
P7/10	2,6	70 % F1-10	17	175,5	175,50	29,02	56,63	99	1,4	51	16,3
P8/13	2,6	70 % F1-10	14	176,09	171,03	33,07	68,77	115,6	2,5	58,3	16,2
P5/9	1	100 % F1-10	23	247,74	171,62	28,75	67,99	114,9	3	63,1	13,3
P6/13	1	100 % F1-10	20	232,7	163,83	30,08	68,51	116,1	2,6	60,8	13,2
P3/9	1,5	100 % F1-10	21	143,4	124,64	26,92	56,62	95,1	1,8	52,7	14,1
P4/13	1,5	100 % F1-10	20	149,31	123,05	25,89	56,27	94,6	2,2	53,3	14,2
P1/10	2,6	100 % F1-10	17	110,65	110,65	26,05	50,08	87,2	1,5	50,8	16,3
P2/13	2,6	100 % F1-10	18	103,17	103,17	23,04	49,69	83	1,5	49,2	16,4

*FVT - face veneer thickness

Appendix 5. Non-piloted ignition ISO 5660-1 cone-calorimeter results of control samples

Specimen ID	FVT (mm)	Ignition time (s)	Ignition temp. (°C)	Tprot (s)	Initial mass (g)	Initial thickness (mm)
P1-1.0-4	1	28	173,155	462,5	95,92	13,25
P2-1.0-4	1	48	156,54	460	93,81	13,36
P1-1.0-6	1	23	129,155	440	94,92	13,23
P2-1.5-2	1,5	24	112,45	465	99,84	13,98
P2-1.5-5	1,5	35	130,165	467,5	99,48	14,02
P1-1.5-4	1,5	35	142,815	465	101,06	13,95
P2-2.6-6	2,6	39	141,81	560	111,23	15,87
P1-2.6-2	2,6	30	115,425	557,5	111,29	15,82
P1-2.6-5	2,6	28	140,77	557,5	112,79	15,98

Appendix 6. Non-piloted ignition ISO 5660-1 cone-calorimeter results of 70 % F1-10 samples

Specimen ID	FVT (mm)	Ignition time (s)	Ignition temp. (°C)	Tprot (s)	Initial mass (g)	Initial thickness (mm)
P11/4	1	45	153,38	546	98,58	13,5
P11/5	1	50	142,3	528	98,76	13,33
P11/11	1	63	151,55	522	100,42	13,27
P11/15	1	57	148,37	498	98,76	13,28
P12/4	1	64	196,17	510	98,7	13,28
P12/5	1	46	140,73	540	98,19	13,29
P12/11	1	66	160,82	525	100,98	13,29
P12/15	1	48	155,52	507	97,95	13,38
P9/4	1,5	60	160,56	579	104,58	14,07
P9/5	1,5	52	152,94	567	104,1	14,1
P9/11	1,5	56	171,12	567	101,66	14,14
P9/15	1,5	42	153,8	594	104,37	14,26
P10/4	1,5	51	166,25	567	103,64	14,18
P10/5	1,5	62	165,41	-	105,32	14,22
P10/11	1,5	51	144,17	561	101,3	14,12
P10/15	1,5	21	97,98	558	101,95	14,1
P7/4	2,6	21	116,42	-	115,47	16,36
P7/5	2,6	16	92,94	-	115,52	16,28
P7/11	2,6	52	145,34	-	118,61	16,3
P7/15	2,6	68	184,49	-	116,72	16,31
P8/4	2,6	49	189,59	-	113,91	16,15
P8/5	2,6	49	200,09	-	114,4	16,19
P8/11	2,6	46	154,89	-	117,16	16,22
P8/15	2,6	58	195,74	-	117,43	16,34

Appendix 7. Non-piloted ignition ISO 5660-1 cone-calorimeter results of 100 % F1-10 samples

Specimen ID	FVT (mm)	Ignition time (s)	Ignition temp. (°C)	Tprot (s)	Initial mass (g)	Initial thickness (mm)
P5/4	1	47	154,59	498	97,81	13,1
P5/5	1	50	153,84	540	97,16	13,11
P5/8	1	71	165,34	537	96,15	13,12
P5/15	1	62	148,24	522	96,04	13,3
P6/4	1	43	118,49	528	98,78	13,19
P6/5	1	76	202,29	567	100,09	13,1
P6/11	1	64	152,54	522	95,04	13,14
P6/15	1	67	156,79	528	97,18	13,12
P3/4	1,5	54	170,79	594	103,14	14,32
P3/5	1,5	69	202,67	-	103,29	14,28
P3/11	1,5	80	210,91	534	102,61	14,27
P3/15	1,5	59	190,88	X	102,91	14,22
P4/4	1,5	46	167,4	573,00	103,69	14,09
P4/5	1,5	48	155,3	567	103,4	14,09
P4/11	1,5	53	148,55	570	102,31	14,09
P4/15	1,5	65	217,57	597	105,32	14,23
P1/4	2,6	50	202,86	-	116,09	16,34
P1/5	2,6	47	159,79	-	117,96	16,32
P1/11	2,6	97	465	-	120,48	16,4
P1/15	2,6	59	197,07	-	116,57	16,54
P2/4	2,6	68	213,04	-	119,07	16,46
P2/5	2,6	49	211,55	X	118,78	16,39
P2/11	2,6	66	169,91	-	119,84	16,34
P2/15	2,6	74	230,57	-	115,38	16,35

Appendix 8. Penetration results of specimens used for ISO 5660-1 piloted ignition tests

Specimen ID	FVT (mm)	Treatment	Top side penetration coverage (%)	Bottom side penetration covereage (%)	Top side penetration depth (mm)	Bottom side penetration depth (mm)
P11/10	1	70 % F1-10	83%	52%	0,83	0,52
P12/13	1	70 % F1-10	88%	60%	0,88	0,60
P9/10	1,5	70 % F1-10	58%	80%	0,86	1,20
P10/13	1,5	70 % F1-10	75%	80%	1,13	1,20
P7/10	2,6	70 % F1-10	73%	62%	1,91	1,60
P8/13	2,6	70 % F1-10	64%	84%	1,67	2,19
P5/9	1	100 % F1-10	83%	-	0,83	-
P6/13	1	100 % F1-10	93%	73%	0,93	0,73
P3/9	1,5	100 % F1-10	91%	65%	1,36	0,98
P4/13	1,5	100 % F1-10	73%	63%	1,10	0,95
P1/10	2,6	100 % F1-10	58%	39%	1,50	1,02
P2/13	2,6	100 % F1-10	64%	54%	1,67	1,41

Appendix 9. Penetration results of 70 % F1-10 specimens used for ISO 5660-1 non-piloted ignition tests

Specimen ID	FVT (mm)	Top side penetration coverage (%)	Bottom side penetration covereage (%)	Top side penetration depth (mm)	Bottom side penetration depth (mm)
P11/4	1	100%	72%	1,00	0,72
P11/5	1	98%	73%	0,98	0,73
P11/11	1	90%	70%	0,90	0,70
P11/15	1	79%	63%	0,79	0,63
P12/4	1	91%	90%	0,91	0,90
P12/5	1	87%	80%	0,87	0,80
P12/11	1	71%	62%	0,71	0,62
P12/15	1	83%	97%	0,83	0,97
P9/4	1,5	72%	87%	1,08	1,30
P9/5	1,5	75%	74%	1,13	1,11
P9/11	1,5	97%	95%	1,45	1,43
P9/15	1,5	88%	85%	1,33	1,28
P10/4	1,5	61%	62%	0,91	0,93
P10/5	1,5	78%	64%	1,18	0,96
P10/11	1,5	65%	47%	0,98	0,70
P10/15	1,5	78%	64%	1,16	0,96
P7/4	2,6	69%	43%	1,80	1,11
P7/5	2,6	63%	51%	1,65	1,32
P7/11	2,6	63%	77%	1,65	1,99
P7/15	2,6	100%	63%	2,60	1,63
P8/4	2,6	64%	61%	1,67	1,58
P8/5	2,6	82%	48%	2,12	1,26
P8/11	2,6	63%	75%	1,65	1,95
P8/15	2,6	95%	74%	2,47	1,93

Appendix 10. Penetration results of 100 % F1-10 specimens used for ISO 5660-1 non-piloted ignition tests

Specimen ID	FVT (mm)	Top side penetration coverage (%)	Bottom side penetration covereage (%)	Top side penetration depth (mm)	Bottom side penetration depth (mm)
P5/4	1	90%	74%	0,90	0,74
P5/5	1	100%	91%	1,00	0,91
P5/8	1	92%	43%	0,92	0,43
P5/15	1	90%	80%	0,90	0,80
P6/4	1	90%	85%	0,90	0,85
P6/5	1	83%	73%	0,83	0,73
P6/11	1	89%	68%	0,89	0,68
P6/15	1	77%	-	0,77	-
P3/4	1,5	78%	73%	1,18	1,10
P3/5	1,5	94%	82%	1,41	1,23
P3/11	1,5	68%	71%	1,01	1,06
P3/15	1,5	74%	65%	1,11	0,98
P4/4	1,5	68%	48%	1,03	0,73
P4/5	1,5	78%	67%	1,18	1,00
P4/11	1,5	43%	63%	0,64	0,94
P4/15	1,5	78%	83%	1,18	1,24
P1/4	2,6	63%	47%	1,63	1,21
P1/5	2,6	48%	47%	1,26	1,21
P1/11	2,6	83%	81%	2,15	2,10
P1/15	2,6	30%	66%	0,78	1,71
P2/4	2,6	61%	75%	1,58	1,95
P2/5	2,6	60%	68%	1,56	1,78
P2/11	2,6	70%	65%	1,82	1,69
P2/15	2,6	86%	70%	2,23	1,82