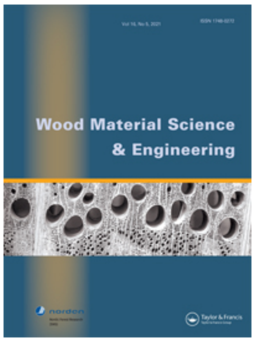

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ORIGINAL ARTICLE

Fire protection provided by clay and lime plasters

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ABSTRACT
Plasters are traditional surface finish materials in timber buildings. Today, the lack of fire performance data and design guidelines place such ecological materials at a disadvantage since plaster is not considered as a fire protection material for timber. This study aims to provide an up-to-date overview of performed fire tests accompanied by investigations on thermal properties of selected ready-mix clay and lime plasters. Design parameters of plasters for the fire design of timber structures are proposed following the safety philosophy of EN 1995-1-2. Numerical heat transfer simulations provide sufficient agreement with furnace test results for undercoat clay plaster. The mechanical fastening system of a plaster (e.g. reed mat) on timber demonstrates paramount importance when determining the charring rate of timber and the fall-off time of plaster. The structural integrity and fire performance of plasters should be further investigated due to their various recipes and numerous fastening systems on timber. Further research in full-scale is needed to confirm the recommended design parameters.

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KEYWORDS
Fire protection; clay plaster; lime plaster; timber structures; fire design; historic building materials

1. Introduction

Clay and lime plasters are traditional surface finish materials extensively used in historic timber buildings to cover walls and ceilings. Today, the global trend towards low carbon design and demand for a healthy indoor environment are the triggers for an increasing interest in the preservation and use of sustainable materials (Umar *et al.* 2012).

Fire safety is of paramount importance when timber buildings are erected or existing ones are undergoing renovation. Primary protection for timber in fire is provided by protection materials. Today, the European fire design standard for timber structures (EN 1995-1-2) comprises only some conventional fire protection materials such as gypsum plasterboards, wood-based boards and stone wool. Hardly any design parameters and thermal material properties are currently available for clay and lime plasters. Consequently, it limits their use in new and historic buildings and additionally hinders an adequate fire assessment of existing historic fabrics (Jackman 2009).

The required fire resistance of timber structures in a certain time limit must be guaranteed by a sufficient load-bearing capacity (R criterion) and prevent the fire spread by means of insulation (EI) criteria. Important design parameters for protection materials are: start time of charring of timber (t_{ch}), protection factor (k_2) that expresses the reduced charring rate behind the protection material and the fall-off time (t_f) of the protection material. For insulation (EI) criteria, the protection ability of each material layer is characterised by the basic protection time ($t_{prot,0,i}$) and position coefficients. Regarding the scope of this study, temperature values of 270°C and 300°C are of utmost interest as they indicate the basic protection time of plaster ($t_{prot,0,i}$) and the start time of charring of timber behind the plaster (t_{ch}), respectively.

In recent years, experimental studies have been carried out to determine these design parameters for clay and lime plaster (Liblik and Just, 2016, 2017; Liblik et al. 2018). Currently, no sufficient research on the thermal properties of plasters at high temperatures is available. Yet, these properties are required to make predictions of temperature measurements in structures exposed to fire. Recently, first studies have been made (Liblik et al. 2019).

Numerous studies exist on clay, sand and soil (Alrtimi *et al.* 2016, Han *et al.* 2016) that provide rather specific material data. Limited studies on plasters' thermal properties and fire performance under standard fire exposure according to EN 1363-1 has been done. However, remarkable research on concrete demonstrates a wide variation of materials' thermal properties, which depend on the recipe and type of constituents in concrete as well as its quality, age, moisture content, etc (Jansson 2013). The transient plane source (TPS) method that determines the thermal conductivity and diffusivity of a material has proven to show an encouraging compliance with the temperature measurements obtained from fire tests (Adl-Zarrabi *et al.* 2005). It has been argued that large-scale fire testing does not give insight in the processes of moisture and vapour movement that can have a large influence on the materials' properties (van der Heijden *et al.* 2011). From the engineering perspective, the spalling of concrete is of utmost importance when determining the fire resistance of a structure. Herein, the scale effect of a test specimen and different boundary conditions in case of fire has not yet been quantified; note that these are not treated as a material property (Janssen 2013).

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This paper deals with the fire performance of plasters in terms of their fire protection ability under standard fire exposure conditions (EN 1363-1). Thermogravimetric analysis (TGA) is performed to illustrate the performance of selected materials' mineralogical composition regarding their mass change up to 900°C. Material thermal properties such as thermal conductivity and specific heat are determined by the transient plane heat source (TPS) method (ISO 22007-2). Numerical investigations with SAFIR software use the material properties obtained with the TPS method to demonstrate the comparison of temperature measurements to the ones obtained in furnace tests. The boundary conditions were determined and all test specimens were climate conditioned. The processes of moisture movement and dehydration in plaster and timber are not tested nor discussed in-depth, but are considered within the limits of chosen test methods. This paper provides an overview of the fire performance of selected clay and lime plasters. Previous studies by the authors are referred for further details. Recommendations for the design equations are given in accordance with EN 1995-1-2. Detailing and further work are discussed as an integral part of this on-going research.

2. Materials

Three different types of clay plasters and two lime plasters were selected. Materials were provided by different manufacturers and their properties (declared by producers) are listed in Table 1. Plasters are distinguished by various parameters due to their wide range of recipes and application purposes. Herein, ready-mix undercoat plasters with a grain size of 0 mm–4 mm (except the light-weight lime plaster, no. 5) that enable to build up multiple plaster layers were examined. Thicker plaster coats are common in historic wall structures, where clay plaster has been covered with a lime plaster coat ensuring its durability in harsh weather conditions (Röhlen and Ziegert 2011). As clay plaster acts as a passive regulator of indoor climate, no additional finish material has usually been applied indoors. This study does not investigate the combination of these plasters as a fire protection material, yet concentrates solely on each plaster and its various thicknesses.

The technical performance of clay plaster is determined by DIN 18947 that categorises plasters by a certain density class. Undercoat plasters principally belong to a density class 1.8 that refers to densities 1610–1800 kg/m^3. Clay plasters have recently been incorporated in EN 13914-2 that guarantees their proper application technique and curing time. Lime plasters are characterised by EN 998-1.

All plasters are manufactured products and no specific details on recipes are available. The selected clay plasters consist of three main components: clay (5–8% of total dry plaster volume), sand and organic fibres such as barley straw, hemp and cattail (*Typha*). The maximum fibre content is not more than 6% of the total volume of a plaster mix. Studies by Ashour *et al.* (2010) indicate that the equilibrium moisture content in clay plasters is not more than 7%, usually around 4–5%. Traditional lime plaster consists mainly of two components: lime and various sands. In this study, plaster no. 4 (Lime) is manufactured according to a traditional recipe that comprises of 10% high-grade hydrated lime CL90, 40% crushed limestone sand and 50% selected sand using a special grading curve. The other is a light-weight plaster (Light lime) that comprises hydrated lime and cement as binders as well as other additives such as perlite. In modern lime-based plasters the additives are added to enhance its insulation and strength performance, thus decreasing its density (Light lime) compared to traditional lime plasters. According to the manufacturer's instructions, water is added to the dry plaster mix for application. Thicker plaster coats were built up layer by layer. All specimens were left curing for a specified time set by producers.

Plasters require a support system when applied on timber surfaces. Traditional substrates are wooden laths and reed-based materials, e.g. reed mat and reed board. In this study, a reed mat is used as a plaster support. Reed mat is a single layer of reed stems bound together with metal wires. Wires can be classified according to EN 10218-1.

3. Experimental work

3.1. Thermal material properties

Plaster is a relatively complex mix of components that comprise different minerals, organic matter as well as air and water that is locked between and in the pores. Thus, the material behaviour at high temperatures is influenced by many parameters such as density, water content, volumetric proportion of components, type of clay/lime and sand, mineralogy, particle size, air voids etc. The determination of material thermal properties are limited to the chosen test methods and present no explicit thermo-physical changes in plaster. In this study, material tests provide input data for heat transfer simulations to calculate their correspondence to the temperature measurements obtained from furnace tests.

The thermogravimetric analysis (TGA) was carried out using NETZSCH STA 449 F3 Jupiter® thermal analyser with differential scanning calorimetry (DSC). The used system

Table 1. Overview of plasters and performed tests.

No.	Plaster	Ambient thermal conductivity [W/mK]	Density /DIN 18947 [kg/m^3] / *density class*	Country of origin	Material tests	
					TGA	TPS
1	Clay_straw	0.91	1.8	Germany	–	x*
2	Clay_hemp	0.91	1.8	Estonia	x	x
3	Clay_cattail	n.a.	∼1700	Estonia	x	x
4	Lime	0.82	1800–1900	Estonia	x	x
5	Light lime	0.14	∼800	Germany	x	x

*Results for mineral clay plaster (without straw) is found in (Küppers *et al.* 2018) Material density class 2.0.

contains a water vapour furnace, which is capable of operating in the temperature range of 40 … 1240°C. The samples were analysed in Al_2O_3 crucibles without lids and in a simulated air environment.

According to the test method, test samples (no. 2, 3, 4) were crushed in a ball mill until analytical particle size was achieved and conditioned on room temperature (23°C). Samples were heated under a mixture of 80% nitrogen and 20% oxygen. A constant heating rate of 20°C/min was applied for measurements of linear heating programme. For reference, gypsum plasterboard was also tested. Additional test series were performed by a constant heating rate of 10°C/min for test samples no. 1 and 5 under similar test conditions. Reference tests were conducted that demonstrated no significant difference in materials' behaviour between different heating rates, thus mass loss started slightly earlier at a lower heating rate. Figure 1 illustrates the test results for all materials (Table 1).

Results indicate a clear distinction between clay and lime-based plasters. Note that no mass change occurs until 100°C since solely dry crushed particles were tested. Test samples of clay plaster mixes retain a rough steady mass until 600°C is reached. Thereafter, a mass loss of Clay_cattail is most significantly recognised. The difference may be attributed to the different type or amount of clay and other compounds (e.g. calcite and dolomite) decomposing at temperatures above 600°C (Lawrence 2006). The lime plaster (Lime) sample presents two distinct mass loss stages. The first stage around 400°C refers to the evaporation of crystallized water. The second step occurs at a similar temperature range with clay mixes, thus the total mass loss (~23%) is more than a double compared to clay plasters and is related to the evaporation of CO_2. Light lime presents notably different scenario of a total mass loss of ~32%. For gypsum plasterboards, a large amount of crystallized water around 100°C is lost that demonstrates its well-known performance as an effective fire protection material delaying the temperature rise. Note that the obtained results do not comply with realistic mass loss values in plaster as the influence of moisture content and fibers was not feasible to study.

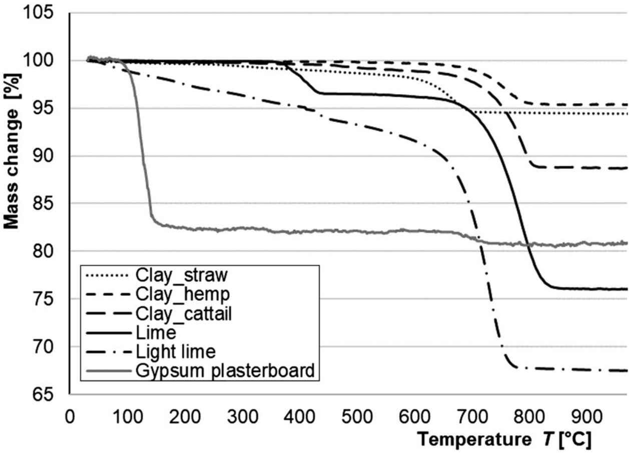
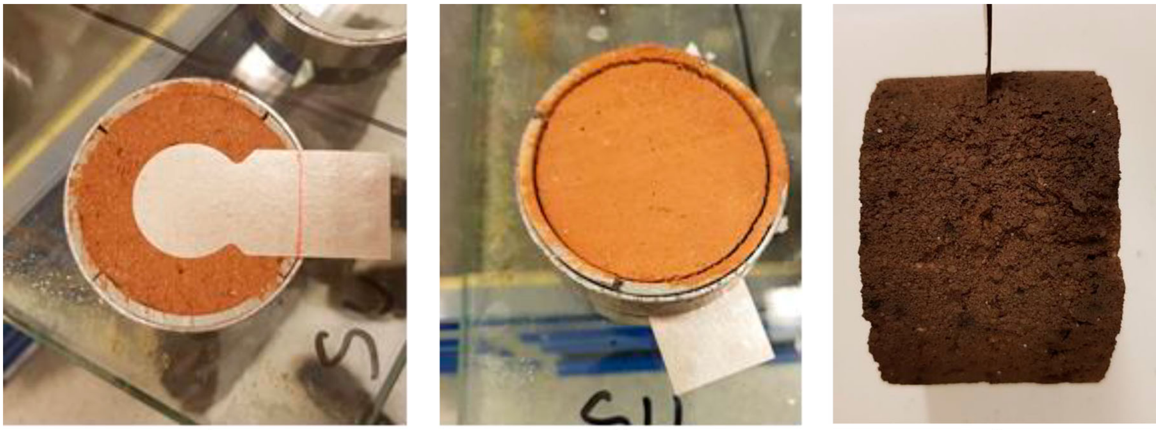


Figure 1. TGA test results.

Thermal conductivity and specific heat were determined by the transient plane heat source (TPS) method (ISO 22007-2). Each test specimen (no. 2, 3, 4) comprised of two test samples with a diameter of 68 mm and height of 25 mm, see Figure 2. Figure 2c documents the test specimen from the side after testing. Test samples were prepared with special accuracy due to the encountered experimental errors related to the insufficient thermal contact between the samples' uneven surfaces. A MICA insulated sensor 4922 (ISO 22007-2) was used in-between the samples, see Figure 2a. Specimens were left for drying at ambient room conditions for about 28 days before testing. Test description of plasters no. 1 and 5 are presented in study by Küppers *et al.* (2018).

Table 2 presents TPS measurements of thermal conductivity λ and specific heat cp for clay plasters – Clay_hemp (plaster no. 2) and Clay_mineral (plaster no.1). The results comprise direct recorded measurements, thus linear interpolation for some temperature points has been made to provide input data for numerical simulations. Both test series presented similar problems in achieving measurements higher than 400°C. Main reason lies behind the water leakage



a) b) c)

Figure 2. TPS testing with Clay plaster_hemp: (a) A Mica sensor placed on top of one test sample; (b) Top view of the prepared specimen for testing; (c) Side view of the specimen after testing.

Table 2. TPS results for Clay_hemp and Clay_mineral.

	TPS Clay_hemp		TPS Clay_mineral*	
Temperature [°C]	λ [W/mK]	cp [MJ/m³K]	λ [W/mK]	cp [MJ/m³K]
20	1.598	1.449	1.192	1.559
50	1.447	1.616	1.109	1.660
90	1.327	1.750	0.998	1.794
130	1.229	1.774	0.968	1.839
150	1.216	1.791	0.955	1.882
200	1.184	1.834	0.923	1.990
250	1.117	1.925	0.869	2.171
300	1.103	1.943	0.816	2.352
350	0.998	1.913	0.755	2.348
400	0.983	1.909	0.694	2.343
450	0.983	1.909	0.709	2.658
500	0.983	1.909	0.724	2.972
550	0.983	1.909	0.666	3.572
600	0.983	1.909	0.608	4.172

*Küppers *et al.* 2018.

and possible vapour pressure emerging in plaster samples that hindered reliable measurements due to the corrosion of the sensor. Furthermore, clay plaster comprises some form of crystallized water (~4% of total volume) that evaporates around 400°C (Röhlen and Ziegert 2011). All plasters showed some form of cracking associated to its higher mass loss rate around 400°C–600°C, received in TGA tests. Additionally, traditional lime plaster requires a long time period to cure which may have influenced the formation of cracks. At room temperature, the recorded thermal conductivity of Clay_hemp was extremely high compared to the one declared by the manufacturer (see Table 1). Further analysis should follow to investigate the porosity, moisture content and transport in plasters.

3.2. Fire tests

Experimental fire tests with selected plasters (Table 1) have been the object of recent research, published by Liblik and Just (2016, 2017) and Liblik et al. (2018). The cone heater of a cone calorimeter (ISO 5660) has been a useful tool in assessing the basic protection effects of plasters for timber members by recording the temperature rise behind plaster (Figure 3). Temperatures were recorded by inserted thermocouples of type K placed in the interface of plaster and timber, see Figure 3a. Specimens were exposed to predetermined radiant heat flux levels in range of 40–75 kW/m² produced by the cone heater, except the light lime which was only exposed to 40 kW/m² (constant) and laid on mineral wool (Wachtling *et al.* 2013). Figure 4 illustrates the recorded temperature for 20 mm thick plasters. A comparison to a gypsum plasterboard type F (GtF) 15 mm is made.

Lower temperature rise indicates better fire protection ability of materials. Lime-based plaster presents increased fire protection ability compared to clay plasters, e.g. temperature to reach 300°C (t_{ch}) is further delayed. Clay_hemp and Clay_straw demonstrate similar performance, except Clay_cattail that presents a slightly longer plateau at around 100°C. Hence, the critical temperature values of 270°C ($t_{prot,0,i}$) and 300°C (t_{ch}) are reached in a similar time range for all clay plasters. Obtained results give reliable information to compare the fire protection ability of different materials. It must be noted that cone heater is not capable of following the standard temperature-time curve (EN 1363-1) after approximately 15–20 min of testing.

Main design parameters for plasters have been determined under standard fire exposure conditions according to EN 1363-1. The set-up of test specimen and a furnace test is presented in Figure 5a and Figure 5b, respectively. Tests were conducted in wall and floor position, where the fire exposed surface area of a specimen was 950 mm × 950 mm and 600 mm × 950 mm, respectively. Figure 6 presents relationship between the start time of charring of timber (t_{ch}) and the plaster thickness (h_p). Plaster thickness was found to be the most significant factor influencing the fire protection ability of undercoat plasters. Details can be found in test reports by Liblik (2016, 2017). There is no furnace test data available for lime plaster and timber. The given design equation on Figure 6 has been discussed by Liblik and Just (2017). The

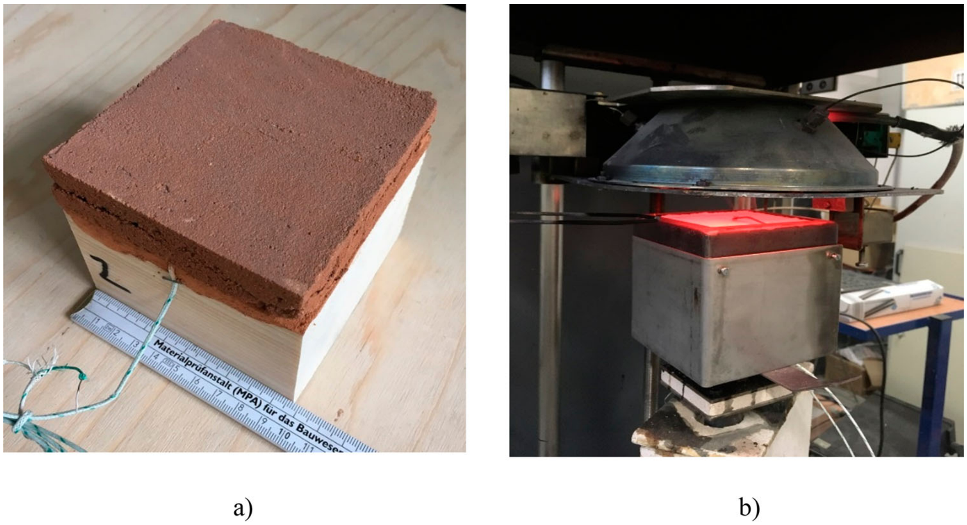

a)
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Figure 3. Cone tests: (a) Test specimen of timber and plaster; (b) Testing with cone heater.

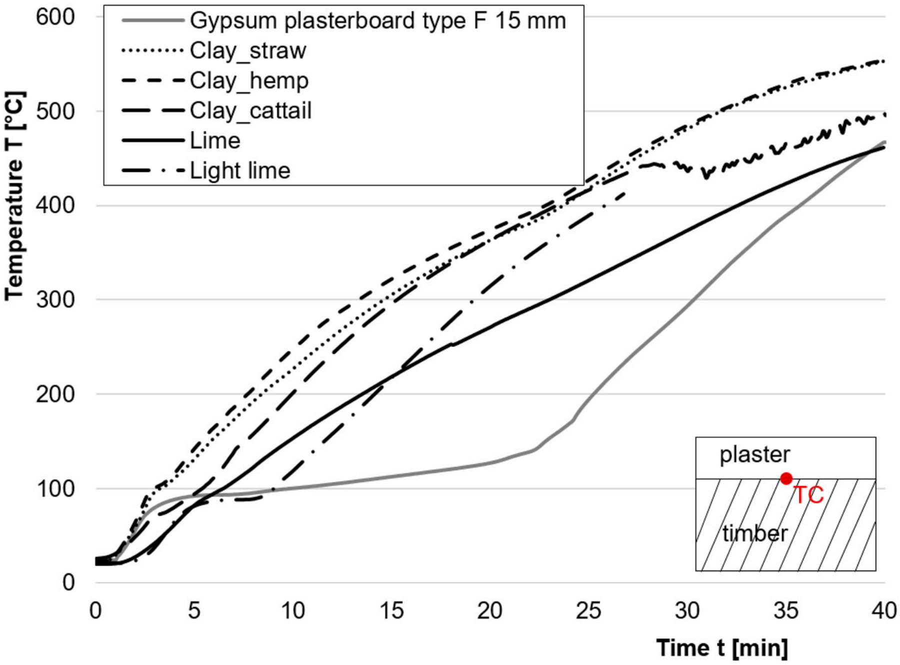

Figure 4. Temperature recorded behind 20 mm plaster and GtF 15 mm.

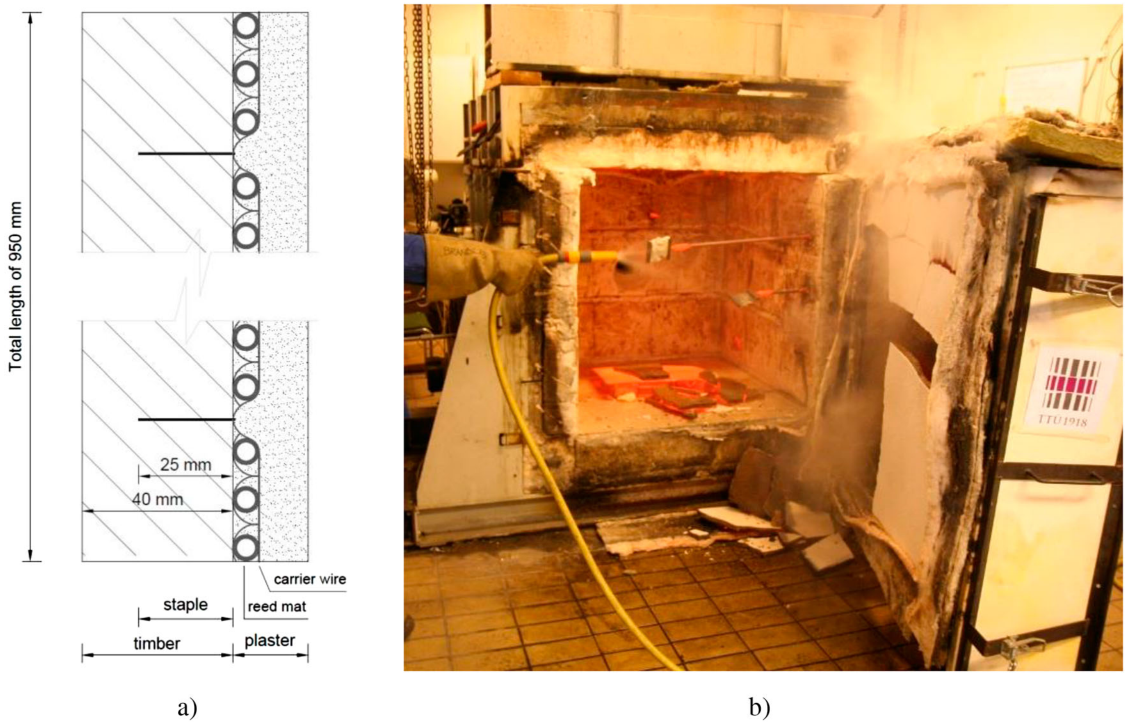

Figure 5. Furnace tests: (a) Section of a set-up of test specimen; (b) Test specimen after a fire test.

equation follows the style of similar equations for gypsum plasterboards (used in Eurocode 5 since 1990-s). The equation is empirical based on relations between time in minutes and thickness in mm.

Furnace test results demonstrate reduced charring rate for timber when protected with plaster (Liblik 2017). Results from cone tests underestimate the charring rate of protected timber in longer fire exposures caused by the lower heat exposure levels. Therefore, the derived design formula for protection factor (k_2) is developed mainly from the furnace test results as an average value (Liblik and Just 2017). The fall-off time of plaster (t_f) is dependent on the substrate and its fastening system on timber, e.g. reed mat fixed with staples (Liblik and Just 2017).

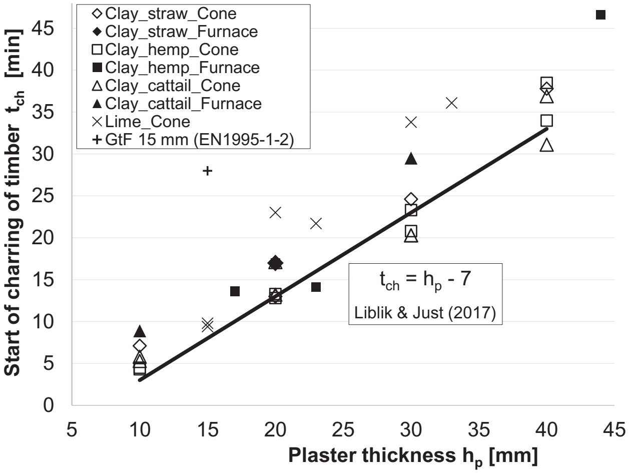

Figure 6. Relationship between the start time of charring of timber and plaster thickness.

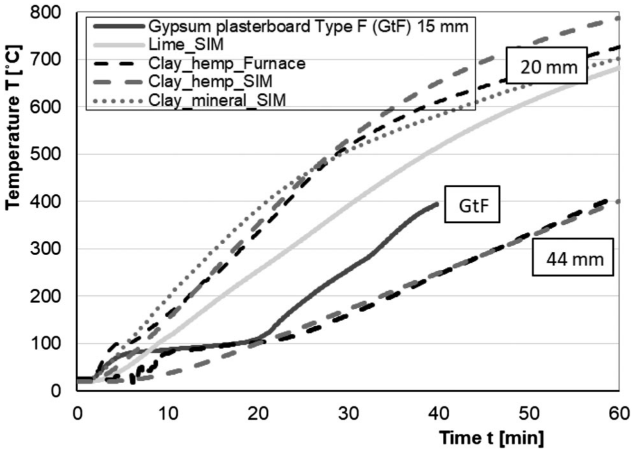

Figure 7. Comparison of temperature curves obtained from the fire tests and thermal simulations.

The plaster coat showed no cracking in cone tests, but in furnace tests (exposed surface area around 1 m^2) some form of cracking was noticed. Yet, no fall-off of plaster (plaster thickness of 17–30 mm) was observed until the reed mat detached from timber. Another scenario occurred for 44 mm clay plaster (Clay_hemp) that demonstrated detachment of first layers (see Figure 6b); some visible cracks started to form after 28 min, the fall-off of pieces of plaster occurred after 60 min of testing. Probable causes lie in the high temperature gradient in plaster and moisture/vapour movements within the whole test specimen; influence of the timber element should not be neglected. This needs further analysis as a future step in this research.

4. Heat transfer simulations

Limited information exists on the numerical simulation of fire protection ability of plasters at high temperatures. One of the first studies was recently published by Küppers *et al.* (2018). Clay_hemp as the only plaster that has been tested in a wide range of thicknesses in furnace (Liblik and Just 2017) is selected for the following investigation.

SAFIR software was used to perform basic one-dimensional heat transfer simulations (Franssen 2012). The software solves the Fourier equation. Software limitations in terms of some physical behaviour are acknowledged. Generally, the moisture transport is considered in the derived effective thermal properties along with other physical phenomena such as cracks and shrinkage (Schleifer 2009).

The test model comprised a 5 cm thick timber element that was protected by a plaster coat. Standard fire exposure stated in EN 1363-1 was followed. For surfaces, the emissivity coefficient was taken as equal to 0.8. On the exposed surface the convective heat transfer coefficient was 25 W/m^{2}K and on the unexposed side the convective heat transfer coefficient was 4 W/m^{2}K and assumed constant according to Eurocode. Material properties obtained from TPS tests were used as input data for calculations.

Figure 7 illustrates the outcome and comparison of the experimental test results with 20 and 44 mm Clay_hemp plaster. Clay_hemp_SIM marks the results received from simulations using material properties presented in Table 2. Density of plaster was selected 1800 kg/m^3 and assumed constant. Due to the TPS measurement problems around ∼400–500°C, the input values for thermal conductivity and specific heat at higher temperatures (500°C–1200°C) were left constant in simulations. For 20 mm plaster, this may result in the overestimated temperature rise after 500°C (Clay_hemp_SIM) in comparison to the measurements obtained in fire test (Clay_hemp_Furnace).

For reference, an additional temperature curve Clay_mineral_SIM (material properties given in Table 2) is presented. A slightly higher constant density value (1840 kg/m^3) was taken for this plaster. As stated in Table 1, this is a similar plaster to Clay_straw and Clay_hemp but has no fibres. Slightly faster temperature rise is noticed for Clay_mineral_SIM in first ∼25 min; however, the calculations underestimate the temperature measurements after 500°C. For both Clay_hemp plasters (thicknesses of 20 and 44 mm), a good agreement in the temperature range of 270–300°C is achieved between the fire test and simulation results. Yet, the measurements at lower temperature range (20–100°C) do not correspond to the ones recorded in furnace tests. In the engineering approach, the physical phenomena (e.g. moisture transport, cracking) are considered using effective thermal properties, which may be obtained by modifying the material thermal properties at a respective temperature range (Schleifer 2009). In this paper, no modification of material properties is made.

Furthermore, the temperature measurements of a gypsum plasterboard type F (GtF) 15 mm is presented (Just 2015), see Figure 7 (GtF). In comparison, thicker plaster coat demonstrates a similar plateau at 100°C and a slower temperature rise after 20 min. It can be concluded that thicker plaster coats present similar fire protection ability as gypsum plasterboards and show encouraging potential in longer fires.

5. Design parameters

In the following, developed design parameters according to the safety philosophy of EN 1995-1-2 are presented for traditional clay plaster. Based on first research studies, the proposed equations may be extended to lime plaster (Liblik *et al.* 2018). The protection ability of examined undercoat plasters (density of 1800 ± 200 kg/m^3) is mainly influenced by its thickness (Liblik and Just 2017). Plaster substrate on timber is of utmost importance to determine the charring rate of timber behind plaster ($k_2\beta_0$) and the fall-off time of plaster (t_f).

The start time of charring of initially protected timber (t_{ch}) depends on the plaster thickness and substrate. For clay plaster applied directly on wood-based surfaces using a reed mat the start time of charring of timber (in minutes) should be taken as

$$t_{ch} = h_p - 7 \tag{1}$$

where h_p is the plaster thickness (mm).

The equation follows the style of similar equations for gypsum plasterboards (EN 1995-1-2). The equation is empirical based on relations between time in minutes and thickness in mm.

For protection phase when $t_{ch} \le t \le t_f$ the basic design charring rates of the timber given in EN 1995-1-2 should be multiplied by a factor k_2. After the fall-off of plaster the charring rates should be multiplied by a factor k_3.

The notional charring rates should be taken as

$$\beta_n = k_2\beta_0 \tag{2}$$

$$\beta_n = k_3\beta_0 \tag{3}$$

where β_0 is the basic design charring rate of timber.

The protection factor k_2 is recommended to be taken as

$$k_2 = 1 - 0.01\, h_p \tag{4}$$

where h_p is the thickness of plaster.

The post-protection factor $k_3 = 2$.

For clay plaster with reed mat as a substrate the fall-off time of plaster can be calculated as

$$t_f = t_{ch} + \frac{l_f - 10}{k_2\beta_0} \tag{5}$$

where l_f is the length of the fastener in timber.

Design parameters are also derived for reed board as a plaster substrate by Liblik and Just (2017). For the calculation of insulation (EI) criteria according to the component additive method (Schleifer 2009, Mäger *et al.* 2018), the basic protection value ($t_{prot,0,i}$) may be taken equivalent to Equation (1). The presented parameters are considered rather conservative, further studies should provide more accurate design values.

6. Results and discussion

Based on the temperature measurements received in cone tests, selected clay plasters did not show significant difference in their fire protection performance (Liblik 2017). However, an addition of lightweight additives may significantly enhance the fire protection ability of plasters (Wachtling *et al.* 2013). According to the furnace test results, plaster with cattail fibre presented delayed start time of charring of timber compared to plasters with straw and hemp fibre. This difference may be argued by variations in moisture content and composition as the TGA tests revealed more than a double mass loss rate for Clay_cattail compared to other clay plasters, see Figure 1. Moreover, such performance may be a result of different porosity in plaster since cattail fibre distinguishes itself from other fibres by its mass, structure and compatibility within plaster mix (Georgiev *et al.* 2014).

Lime-based plaster demonstrates better fire protection ability compared to clay plaster. However, age is known to have an influence on the fire resistance of historic lime plasters (Jackman 2009). Lime plaster achieves its full strength and potential after being fully carbonated. Plasters with different carbonisation times should be investigated in future.

Furnace tests with clay plasters (Liblik and Just 2017) have demonstrated some forms of cracks approx. 15 min after the start of a test. This remarks a temperature value of about 700° C in furnace, which agrees well with the most significant mass loss change received in TGA tests at the same temperature range. The structural integrity of plasters may be further influenced by its declared technical properties such as drying shrinkage and material strength. Apart from the latter, formation of cracks are most likely attributed to moisture movement and temperature gradient within the plaster coat. This was recognised in TPS tests for lime plaster samples as well as in furnace tests with a thicker clay plaster coat (44 mm). The influence of moisture content and transport in plaster should be further studied to determine effective thermal properties under standard fire exposure conditions (EN 1363-1).

The fall-off time of plaster is highly influenced by the substrate (Liblik and Just 2017). The mechanical resistivity and the adhesion of plasters with its substrate are important factors indicating their fire protection ability on timber structures. For example, the protection effect of plaster on a wooden lathwork can only be considered until the start time of charring of timber, see Equation (1).

The performed heat transfer simulations enhance the credibility of furnace test results, e.g. determination of a design parameter t_{ch}. However, the obtained TPS results do not provide information on the specifics about the thermophysical behaviour of plasters, especially at lower temperatures, that should be investigated in further studies. Moisture content in plaster as well as in timber, moisture movement and vapour pressure built-up should be further studied to provide in-depth knowledge about the fire performance of such material combinations.

Large-scale fire testing is necessary for confirmation and determination of design parameters, until then the recommended design values of clay plaster may be used. The presented design parameters contribute to the assessment of the fire performance of existing plasters in historic buildings. Plaster may enhance the fire resistance of structures also in modern timber buildings when combined with boards. Nowadays, clay-based materials are seen as healthy surface finish materials (Klinge *et al.* 2016) and present great potential for low carbon design. First studies on clay boards are done by Küppers *et al.* (2015). This current paper supports product development in this field. Furthermore, lime plasters with light-weight aggregates are used in modern façade systems (ETICS - External Thermal Insulation Composite Systems) which extends the research scope in terms of various fire exposures (Küppers *et al.* 2016).

7. Conclusion

This paper presented new findings on the fire protection ability of selected ready-mix clay and lime plasters. Thermal material properties obtained from TPS method used in numerical simulations provide sufficient agreement with furnace tests in temperature measurements around 300°C. This demonstrates an encouraging potential to predict the start time of charring of timber (t_{ch}) behind clay plaster and its basic protection time ($t_{\mathrm{prot},0,i}$). Test results revealed that the moisture content and movement in plaster and timber should be studied in detail by suitable test equipment. Presented design parameters contribute to the fire assessment of existing structures. Full-scale fire testing is necessary to examine the structural integrity and fall-off of plasters using different substrates, e.g. clay boards.

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