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Properties of clay plaster for the fire design of timber structures

Building with earth and timber has a long tradition. Historically, clay plaster has been used as a decorative surface finish material that has also served as insulation and the primary fire protection for timber walls and ceilings [1] [2]. Nowadays, these materials are being rediscovered as representing healthy and low carbon alternatives to conventional building designs [3] [4]. Timber and earth have a high market potential, but a lack of fire performance data and design guidelines limit their use in practice [5].

The fire behaviour of a construction product or element can be described by its reaction to fire (related to the early development of fire) and fire resistance (after flashover). This paper focuses solely on the fire resistance of timber structures protected by clay plaster systems, following the safety policy defined in EN 1995-1-2 [6]. Currently, this standard does not consider plaster as a fire protection material.

Worldwide, there is limited available data on the fire protection effect of clay plaster tested under standard fire exposure conditions (EN 1363-1 [7]). Previous studies have mainly been carried out with straw bale building elements with clay or lime coatings [8] [9]. One of the few works of research on historic fire protection materials for timber was undertaken by Chorlton et al. [10], however clay plaster was not studied.

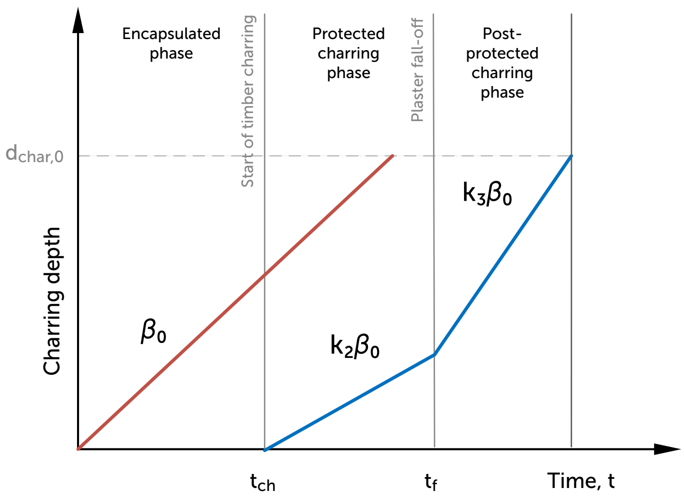
During the previous few years, we have been carrying out various experimental studies at different scales. A research project by Wachtling et al. [11] comprised clay plaster and boards applied on straw bale structures to reach REI 60 (K_2 60) criteria defined according to EN 13501-2 [12]. Studies by Liblik et al. [13] [14] [15] have focused on the performance of construction with clay plaster systems and solid timber elements. In addition, temperature-dependent material thermal properties have been determined for numerical analysis [16] [17] [18].

Plaster requires a mechanical key when applied on timber surfaces. In coastline regions, the Common Reed (Phragmites australis) has been a widely used material as a substrate for plasterwork, i.e. reed mat and reed board. Today, reed boards are being rediscovered due to their good sound and thermal insulation properties, representing a green alternative to conventional insulation materials [19].

The aim of this paper is to provide a compact overview of existing fire research and its latest improvements, focusing on clay plaster systems applied on timber elements. Design values are presented for the Component Additive Method (CAM) by Schleifer [20] and for the Effective Cross-Section Method (EN 1995-1-2). Heat transfer analysis is carried out following a procedure proposed by Mäger et al. [21] for the implementation of clay plaster to the CAM. This research demonstrates the potential of clay plaster systems as a fire protection material both in historic and modern timber buildings.

Fire design of timber structures

The fire resistance of timber structures is influenced by charring that reduces its load-bearing capacity. EN 1995-1-2 defines the charring performance of unprotected and initially protected timber structures (see Fig. 1). The start time of the charring of a timber member can be delayed and the charring rate can be reduced by applying fire protection materials. Today, design values are given for some protection materials such as gypsum plasterboards: the start time of charring (t_{ch}) and protection factor (k_2). The latter is used for the calculation of a charring rate behind protection material before its fall-off (t_f). Basic design charring rates (β_0) are given in EN 1995-1-2.



01 Charring of unprotected (red line) and initially protected (blue line) sides of timber members

For the determination of a building elements' separating function in fire, the Separating Function Method (SFM) (also Component Additive Method) is used [21] [22]. It deals with the entire layered construction by accounting for the contribution of each layer to obtain the fire resistance. The basis of this method is introduced in EN 1995-1-2. Each layer is defined by a protection time ($t_{prot,i}$) which is the time until its fire protective function is lost. This is the time when temperature rises 250 K on average or 270 K at any point on the unexposed side of the considered layer. In view of the current revision of EN 1995-1-2, this value will be also considered as the start time of charring (tch) in the revised Eurocode 5 [23]. Position coefficients ($k_{pos,exp,i}$, $k_{pos,unexp,i}$) are used to consider the influence of adjacent layers. The last layer (fire-unexposed side of a construction) serves the insulating function that is prescribed by the insulation time ($t_{ins,n}$) when the temperature rise on the unexposed side is 140 K on average or 180 K at any point. These temperature criteria are consistent with the insulation criterion requirements set in EN 13501-2. According to the SFM, the integrity (E) criterion is assumed to be fulfilled where the insulation (I) criterion is satisfied.

Materials

This study is limited to clay plasters with a density range of 1610 – 1800 kg/m^3 that corresponds to the bulk density class 1.8 according to DIN 18947 [24]. The composition of clay plaster follows the requirements stated in DIN 18947 and is a mixture of clay, silt, sand and some form of natural fibre such as barley straw, hemp or cattail. Table 1 presents the tested plasters. A jute fabric was used as a reinforcement mesh in the plaster of some of the specimens.

Test specimens comprised a plaster system that was applied directly on a timber panel (i.e. CLT, wooden planks). Two types of plaster carriers were used: a reed mat (Fig. 2) and a 50 mm thick reed board (Fig. 3). A reed mat consists of ca. 6-10 mm thick reed stems with approx. 70 stems per linear metre. Reed board is a rigid board of compressed reed stems. The reed mat was fixed with staples and the reed boards with screws to the timber elements. Plasterwork was carried out by professional craftsmen according to the application requirements set out by the manufacturer. Test specimens were conditioned in a fire-testing hall (normal room conditions) as it would be in practice. Specific details can be found in test reports by Liblik [25] [26] [27].

Experimental studies

Over the last few years, a test programme of different experimental studies has been carried out [13] [14] [17]. Basic material tests comprised a

Table 1 Properties of selected clay plasters

Plaster Mark	Type of fibre in plaster	Grain size [mm]	Therm. conduct. according to DIN 18947 [W/mK]	Strength class according to DIN 18947	Meets requirements of DIN 19847	Country of origin
SU	Hemp	0-4 / 0-2 / 0-1	0.91	S II	Yes	Estonia
SF	Cattail	0-4	n/a	n/a	n/a	Estonia
CT	Barley straw	0-4 / 0-2 / 0-1	0.91	S II	Yes	Germany

02 Application of first plaster layer (plaster CT) and reed mat on timber panel

03 Application of first plaster layer (plaster SU) on reed board (equipped with thermocouples)

thermogravimetric analysis (TGA) to determine the mass change of dry-mix plaster samples and a transient plane heat source (TPS) method to evaluate the thermal conductivity and specific heat capacity. The tests performed and the results are detailed in [17]. The results were used as initial input data for numerical investigations (see "Numerical Analysis" below). Note that the moisture transport and dehydration of plaster was not explicitly studied in this stage.

TGA was performed with a NETZSCH STA 449 F3 Jupiter TG-DSC analyser. Test samples were crushed to a suitable analytical particle size. Different heating rates (K/min) were chosen. Fig. 4 illustrates the main results. The total mass loss of a plaster SF sample was significantly higher compared to plaster SU and CT samples.

TPS tests were performed in accordance with EN ISO 22007-2 [28]. A description of the tests can be found in [17]. The measurement points were limited to max 500°C due to the excessive moisture/evaporation movement in the test samples that hindered further testing. The results are presented in Fig. 9 and Fig. 10 marked as TPS. The relation between determined values is assumed to be linear as illustrated on the graphs.

The fire protection effect of plasters has been determined by fire tests in small and model scales. Here, a brief overview of the furnace tests is presented [25] [26] [27]. Two main sets of tests under standard fire exposure conditions (EN 1363-1) have been performed with solid timber panels protected by: 1) Clay plaster and reed mat; 2) Clay plaster and 50 mm reed board. The main results are described in Table 2 and Table 3, respectively. The basic protection time ($t_{prot,0,i}$) is determined from the temperature recordings, whereas the protection factor (k_2) is derived from the measured charring depth and charring time.

04 Comparison of TGA results

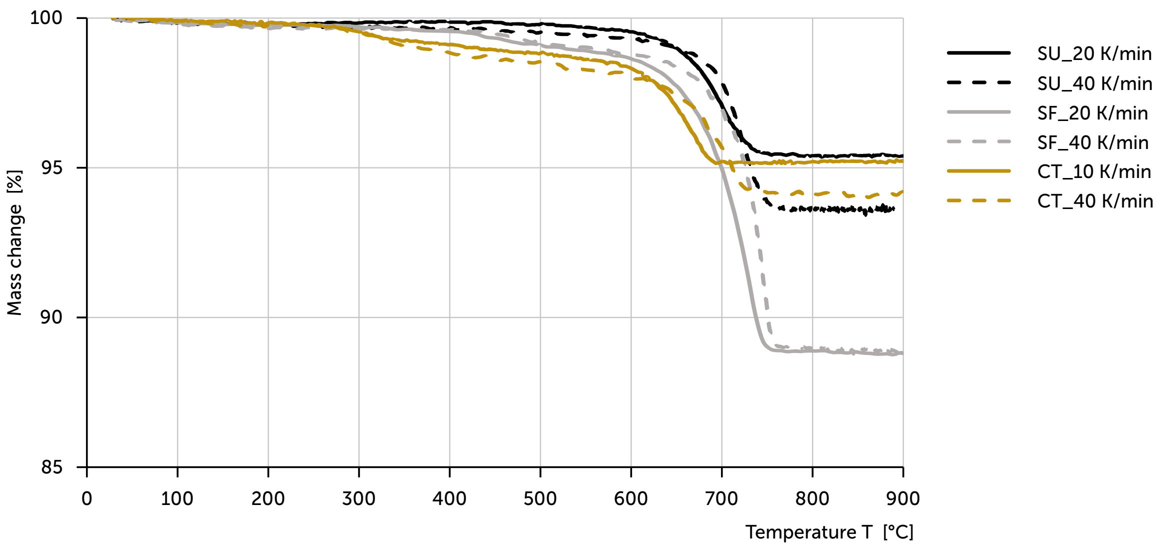


Table 2 Overview of performed fire tests with clay plaster and reed mat on timber

Test No	Position in furnace	Plaster Mark	Plaster thickness [mm]	Basic protection time $t_{prot,0,i}$ [min]	Protection factor k_2	Fall-off time of plaster system t_f [min]	Reference
1	Ver	SF*	10	8.1	0.82	n/a	[29]
2	Ver	SF*	30	32.7	0.57	n/a	[29]
3	Hor	SU	17	12.7	0.86	75	[25]
4	Hor	SU*	17	12.1	0.77	62	[25]
5	Ver	SU	20	18.0	0.88	>90	[25]
5	Ver	CT	20	15.6	0.85	>90	[25]
6	Hor	CT*	20	13.8	–	17	[26]
7	Ver	SU	44	44.4	0.24	63**	[25]

** No jute fabric was used ** Partial detachment of an outer layer*

Table 3 Overview of performed fire tests with clay plaster and 50 mm reed board on timber

Test No	Position in furnace	Plaster Mark	Plaster thickness [mm]	270°C on reed board [min]	270°C on timber [min]	Fall-off time of plaster (not reed board) t_f [min]	Reference
8	Hor	SU	16	8.8	34.7	18.3	[25]
9	Hor	SU*	17	8.2	40.9	17.0	[25]
10	Ver	SU	23	13.4	64.7	n/a	[25]
10	Ver	CT	23	12.2	62.2	29	[25]
11	Ver	SU	44	62.6	114.3	43**	[25]

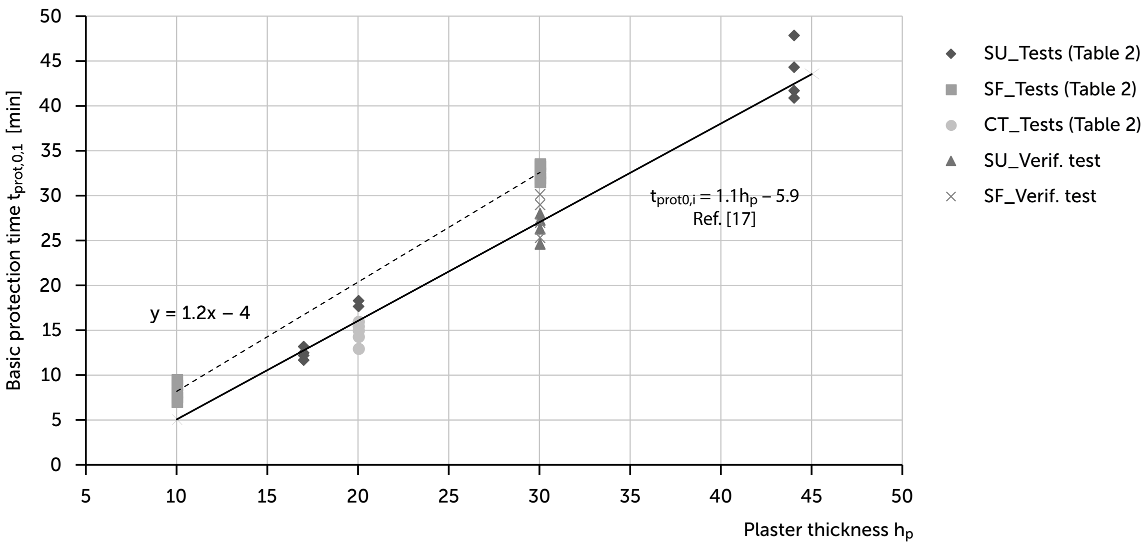
** No jute fabric was used ** Partial detachment of an outer layer*

Visual observation was done through a window opening throughout testing. Regardless of the total thickness of a plaster coat, the first cracks occurred at around 750°C – 830°C in furnace, which is reached after 17–28 minutes from the start time of standard fire exposure (EN 1363-1). This timeframe also corresponds to the times when plaster falls off from the reed board (see Table 3: Test 8, 9). For thinner plaster coats on reed mat, this is also the time when approximately 400°C has been reached on the timber, causing the plaster system to fall-off due to the fixing staples gradually coming loose. This was evident in Test 6 (plaster CT) that demonstrated significantly earlier fall-off time compared to Test 3 and 4. The main reason was an insufficient fastening density of a reed mat. In the case of a thicker plaster coat (Test 7 and 11), the detachment of an outer layer was identified (Fig. 5) resulting from a high temperature gradient and moisture movement within plaster. Fire tests of clay board with lightweight additives and clay plaster coating showed hardly any crack development [11].

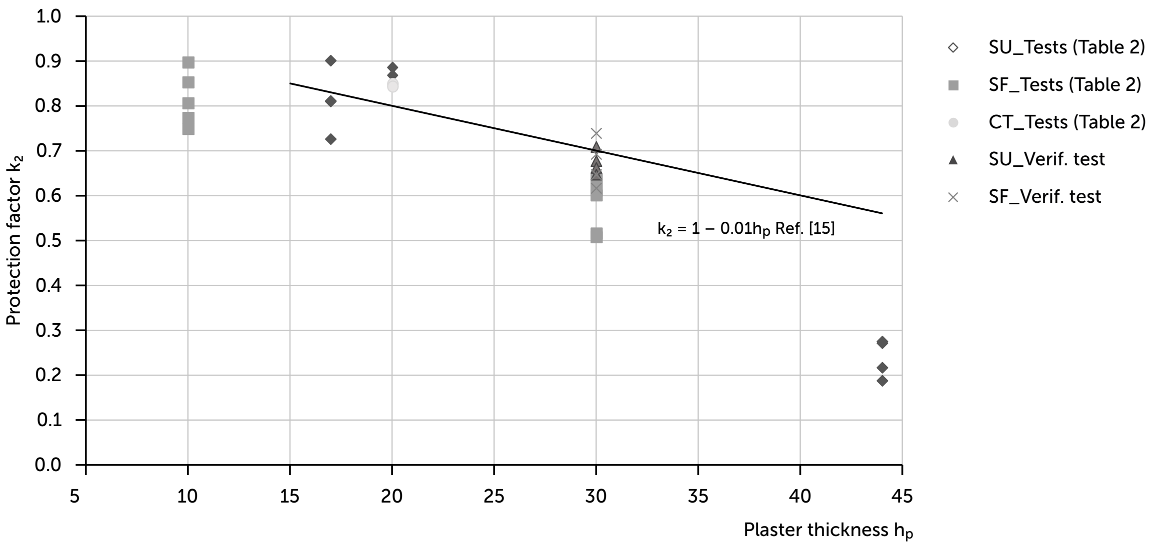
Two additional fire tests in a small-scale furnace were performed for verification [27]. This was done as fire tests with plaster SF demonstrating greater protection effect [29]. Verification tests comprised a wooden panel (38 × 500 × 500 mm) onto which a reed mat and 30 mm thick plaster was applied. Fig. 6 and Fig. 7 present the results of basic protection time $t_{prot,0,i}$

05 44mm clay plaster system after fire test of 80 minutes

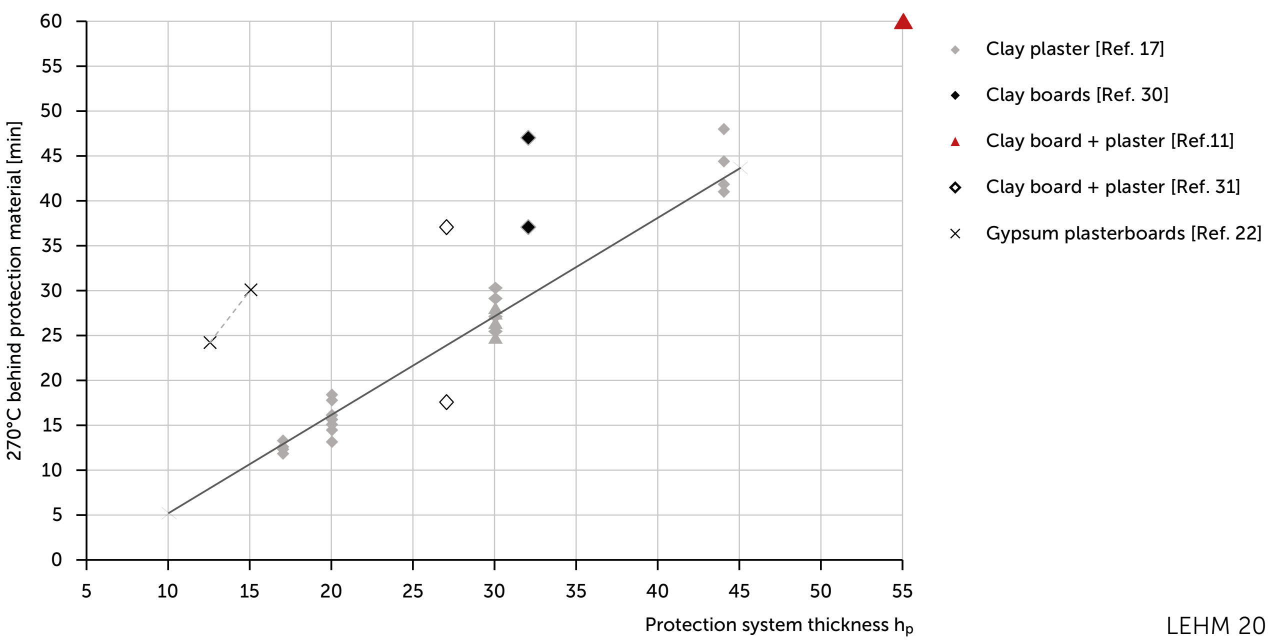
06 Furnace test results of the basic protection times in relation to plaster thickness

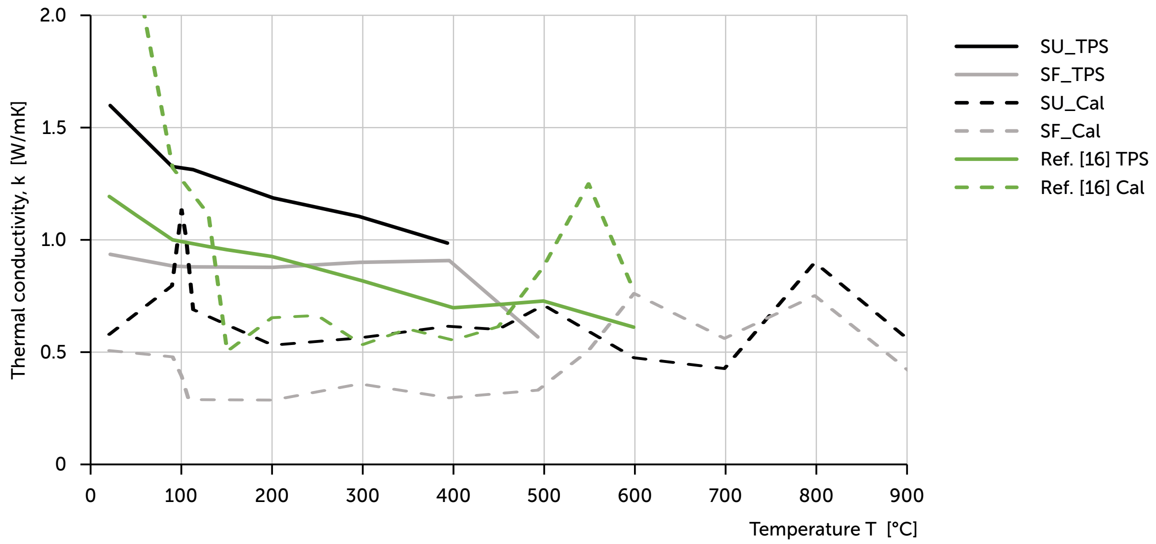


07 Furnace test results of the protection factors in relation to plaster thickness

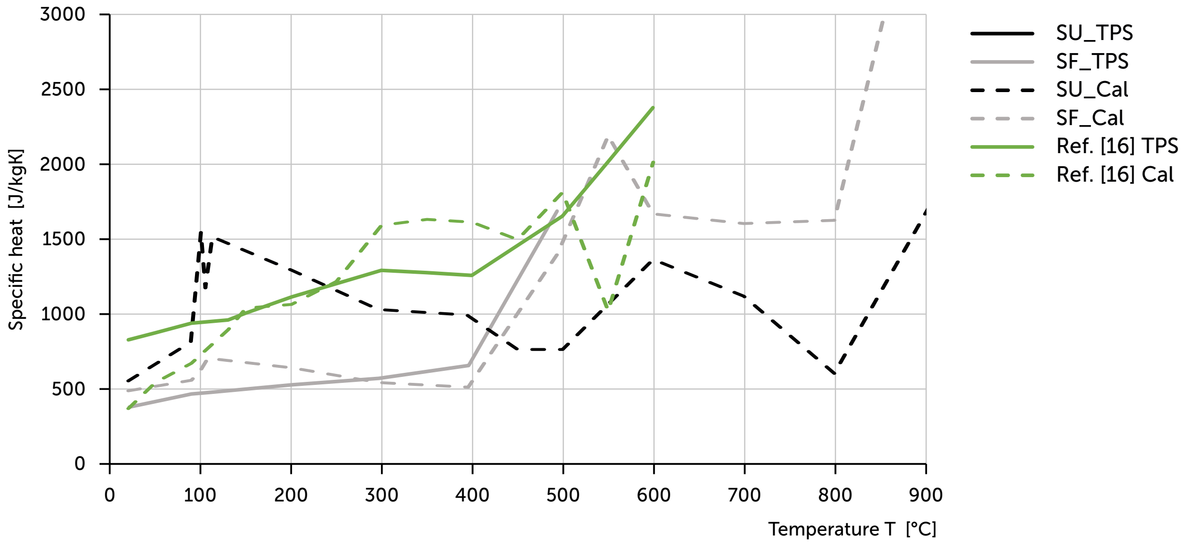


08 Comparison of test results with other material combinations tested in furnace





09 Comparison of measured and calculated temperature-dependent thermal conductivity



10 Comparison of measured and calculated temperature-dependent specific heat

and protection factor k_2 in comparison to previous studies. Verification tests correlated with the test results of plaster SU, confirming that the protection effect of plaster SF in preliminary study [29] was slightly overestimated (dotted line in Fig. 6).

For reference, some test reports were available to the authors. The fire protection system of test specimens consisted solely of clay boards (Ref. [30]) or clay plaster and clay boards (Ref. [31] [11]). Fig. 8 presents the time (in relation to the total thickness of a protection system) when 270°C is reached behind the protection system. For Ref. [30] and Ref. [31], two measurement points are indicated: the lower value refers to the time measured on the cavity insulation and upper value to the time measured on a timber stud. The total test duration of Ref. [11] was 60 minutes at which time the temperature on the timber was around 230°C, so the point on the graph is not accurate but gives a rough estimation. A comparison with 12.5 – 15 mm gypsum plasterboards [6] can be made.

Numerical analysis

Advanced calculation methods are highly favourable as the evaluation of a construction elements' fire resistance by experimental testing is costly, time-consuming and applicable to a certain element configurations. For valid numerical predictions, reliable data of the temperature-dependent thermal material properties are required.

In this study, the effective thermal properties of clay plaster are introduced, which were derived from thermal analysis. The effective thermal properties (SU_Cal and SF_Cal) were determined by using a MATLAB code developed by Mäger et al [32]. The properties were calibrated in accordance with the measurements obtained from the furnace verification tests, thus indirectly considering the formation of cracks, reed mat etc. However, for clarity, these effective properties do not necessary represent real physical material properties at elevated temperatures (i.e. moisture content and movement in the material [33]). The initial measurements (marked as TPS) are presented in Fig. 7 and Fig. 8 along with the calibrated (effective) properties (marked as Cal).

The numerical simulations were performed with a SAFIR v2014a1 computer program [34], wherein the heat transfer by conduction in solid materials is described by a Fourier equation. The material properties are determined by Küppers et al. [16] and presented in Fig. 9 and Fig. 10 marked as Ref. [16]. In this paper, an analogue thermal model was used to run the simulations. The density of plaster was set constant since the mass change of plaster is not significant and has a lesser effect on the results [21].

Fig. 11 illustrates the temperature measurements determined by furnace tests (Table 2) and simulations. The simulations with TPS results as input data (SIM_TPS_SU) show weak correlation with the furnace tests as presenting excessively conservative (faster) temperature rise (dotted line). Simulations with effective thermal properties present good agreement, especially SIM_Cal_Ref. [16].

The basic insulation times ($t_{ins,0,i}$) were developed that correspond to the fire resistance of a single layer without the influence of adjacent layers. A simulation program of configuration 1 defined in [21] was followed. Different thicknesses and densities (1610 and 1800 kg/m^3) of clay plaster were plotted against the temperature criteria of 160°C on the unexposed side. Results are presented in Fig. 12, using the effective thermal properties from previous work by Küppers et al. [16] and SU_Cal (Fig. 9 and Fig. 10). Further work should follow for in-depth analysis.

Design values

Design values in respect to the revised Eurocode 5 are given. The presented values are limited to traditional types of clay plasters that are classified according to DIN 18947 with a density class of 1.8 and strength class of SII. Design values for wall structures are applicable for plaster thicknesses in the range of 17 mm – 44 mm. Floor structures are limited solely to 20 mm plaster thickness applied on a reed mat. The application of plaster must strictly follow the instructions of a manufacturer and design guidelines stated in EN 13914-2 [35].

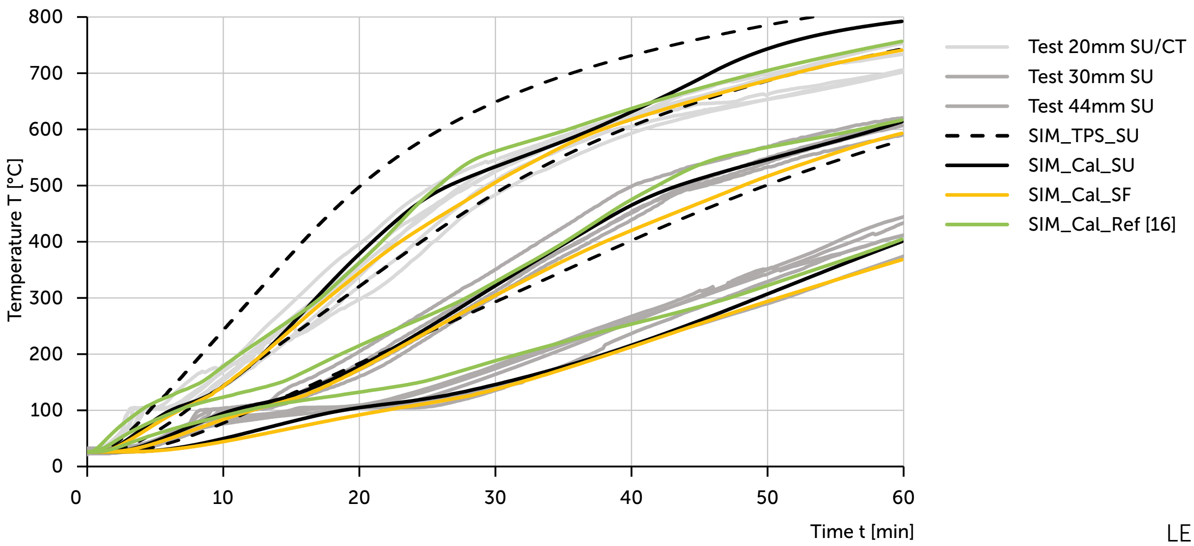
Separating Function Method

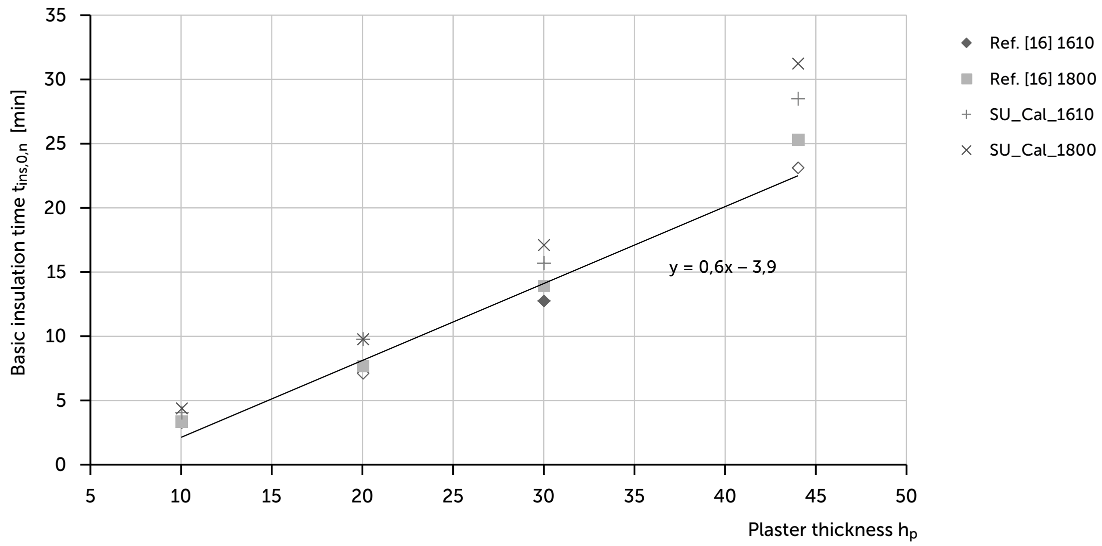
For clay plaster and reed mat on timber structures, the basic protection time ($t_{prot,0,i}$) (in minutes) may be calculated as follows [17]:

$$t_{prot,0,i} = 1.1\, h_p - 5.9 \quad (1)$$

where h_p is the plaster thickness (mm), measured from the timber surface.

11 Measured and calculated temperature rise at the interface of plaster SU and timber (Results of 3 test recordings at different locations on the specimen).





12 Simulation results for the basic insulation times

For clay plaster, the basic insulation time ($t_{ins,0,n}$) (in minutes) may be calculated as follows:

$$t_{ins,0,n} = 0.6\, h_p - 3.9 \tag{2}$$

where h_p is the plaster thickness (mm).

For the position coefficients $k_{pos,exp,i}$ and $k_{pos,unexp,i}$ the generic values for claddings according to Table 5.2 and Table 5.3 of [22] may be used. The values of Table 5.3 apply if plaster is backed by timber.

The design value (1) shall also be applied in the case of a reed board as a plaster carrier on timber.

Effective Cross-section Method

For clay plaster and reed mat on timber structures, the start time of charring of timber (t_{ch}) (in minutes) may be calculated as follows:

$$t_{ch} = t_{prot,0,i} = 1.1\, h_p - 5.9 \tag{3}$$

where h_p is the plaster thickness (mm), measured from the timber surface.

The design value (3) shall also be applied in the case of a reed board as a plaster carrier on timber.

For the encapsulation phase (Fig. 1) when $t_{ch} \leq t \leq t_f$, the basic design charring rates of timber [6] should be multiplied by a factor k_2. After the fall-off time of a plaster system, the charring rates should be multiplied by a factor k_3. The notional charring rates should be calculated as follows:

$$\beta_2 = k_2\, \beta_0 \tag{4}$$

$$\beta_3 = k_3\, \beta_0 \tag{5}$$

where β_0 is the basic design charring rate of timber [6].

For clay plaster and reed mat on timber structures, the protection factor (k_2) may be calculated as follows [13]:

$$k_2 = 1 - 0.01\, h_p \tag{6}$$

where h_p is the plaster thickness (mm), measured from the timber surface.

For clay plaster and reed mat on timber structures, the fall-off time of the plaster system (in minutes) may be calculated as follows [13]:

$$t_f = t_{ch} + \frac{l_f - 10}{k_2\, \beta_0} \tag{7}$$

where:

t_{ch} is the start time of charring (min) (3),
l_f is the length of the fasteners (mm),
k_2 is the protection factor (6),
β_0 is the basic charring rate (mm/min) [6].

Design values (6) (7) apply when the fastening of the reed mat on timber is done with staples (no shorter than 25 mm in length) using a pneumatic gun. Staples shall be fixed a maximum distance of 10 cm apart along each wire of the reed mat.

For clay plaster and reed board on timber structures, the fall-off time of the plaster system shall be calculated as follows:

$$t_f = t_{ch} = t_{prot,0,i} = 1.1\, h_p - 5.9 \quad (8)$$

where h_p is the plaster thickness (mm), measured from the reed board surface.

Discussion

In view of the tested plasters, the protection effect is determined by the plaster thickness. However, studies by Küppers (nee Wachtling) et al. [11] [18] have demonstrated that certain additives may enhance the fire protection ability. For design optimisation, the improvement of clay plaster in fire may be in future interest. Further work should involve thermo-physical investigations to understand the effect of moisture movement and its influence, so that more accurate effective thermal properties could be achieved.

The plaster carrier plays a key role in determining the fall-off time of a plaster system. Experimental tests showed a strong bond between the plaster and the wires of a reed mat, which indicate that clay plaster may provide a long-time protection if properly secured. The moisture movement and detachment of plaster layers should be studied further. An enhanced fire performance has been determined for the material combination of clay plaster and boards [11] [30] [31]. For future research, the adhesion of plaster and fastening systems of clay boards to timber structures should be considered.

Tests with reed boards demonstrated high potential as the charring of timber was considerably delayed (Table 3), despite the early fall-off time of the plaster. The joints of reed boards are highly vulnerable to direct fire exposure. Therefore, the fastening of the plaster should be improved to achieve improved fire protection. Until then, the protection effect is solely dependent on the performance of the plaster itself. A similar behaviour is presumed to apply for plasters applied on historic plaster carriers such as wooden laths.

Conclusion

An overview of the fire performance of clay plaster systems and timber structures is presented. Clay plaster may provide sufficient fire protection when secured properly to its substrate. Design values in view of Eurocode 5 are proposed that provide a knowledge basis to plan full-scale fire testing according to EN 13381-7 [36]. The authors believe this research benefits the fire assessment and design of (existing) clay plaster systems in historic timber buildings and could serve as a basis for new developments.

Acknowledgements

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