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From tradition to future prospects: Clay as fire protection for timber

The growing necessity to mitigate environmental impacts within the construction sector has resulted in a renewed emphasis on natural, low-carbon building materials for future construction. Utilizing timber as a large-scale structural material, along with other natural materials such as clay that corresponds with the aims of developing healthier buildings and embracing circular economy principles [1] [2]. However, incorporating these materials into conventional construction practice presents significant challenges, notably in meeting contemporary fire safety standards [3].

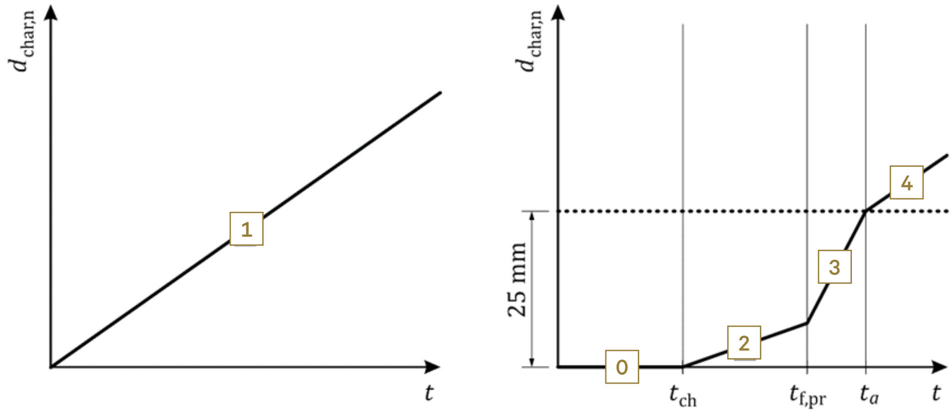
Despite the long history of building with timber and clay [4], and clay's ability to ideally complement timber constructions in reaching thermal mass and sound insulation requirements, the primary fire protection material for timber today is gypsum plasterboard. This passive fire protection measure is commonly used to meet structural fire safety requirements in timber buildings. The verification of timber assemblies can be achieved by means of fire tests or calculations (if available) or both. However, full-scale testing is costly, and the use of results is limited. Consequently, calculation methods are increasingly preferred, as they offer cost efficiency, time savings, and greater design flexibility.

In Europe, the fire part of Eurocode 5 (EN 1995-1-2) [5] outlines principles and application rules for the structural fire design of timber structures. However, it currently does not provide guidance on using clay-based materials as a fire protection material. Similarly, national building codes like a 'LIGNUM' design guideline in Switzerland [6] does not include design parameters to use clay-based materials in timber assemblies. Thus today, this information gap in design standards/guidelines hinders the use of clay in assemblies with fire-protection requirements [7], necessitating full-scale fire tests.

However, fire tests with clay boards [8] and clay plaster on strawbale constructions have shown significant fire resistance performance [9]. In addition, over the past decade, research studies have investigated the fire performance of clay plaster and boards [10] [11], highlighting their future potential. This is also supported by the development of product standards in Germany, DIN 18947 and DIN 18948, respectively [12] [13]. Integrating fire resistance standards for clay-based constructions into national regulations has progressed, especially in the DIN standards for earth blocks [14]. A conservative definition indicates a bearing wall of

01 Timber frame filled with light earth blocks and clay plaster coating

Ceiling in project HORTUS by Herzog & de Meuron Architects / ZPF Ingenieure. Source: authors.



0 encapsulation phase
1 normal charring phase
2 protected charring phase
3 post-protected charring phase
4 consolidated charring phase

a) Initially unprotected sides of timber members

b) Initially protected sides of timber members when $t_{f,pr} > t_{ch}$ [15].

02 The European Charring model

17.5 cm reaching REI 30 and a thickness of 24 cm can achieve REI 60. Projects like the Outdoor Museum Detmold or the HORTUS Project in Basel (Figure 1) [1] demonstrate that required fire resistance is achievable, with 22 cm rammed earth walls reaching REI 90 and clay-timber ceilings reaching REI 60, respectively.

The current revision of European design codes includes a proposal to incorporate clay plaster and boards into the new version of Eurocode 5 Part 1-2, i. e. FprEN1995-1-2:2024 [15]. Incorporating clay materials into this design standard would offer significant opportunities for clay and timber in conventional buildings as a future-looking alternative to current practices. Accordingly, this paper provides an overview of the opportunities that become accessible to planners, designers, and craftsmen as a result of improved design options for timber assemblies. The proposed design model for clay materials allows for increased design flexibility and the exploration of novel material combinations in both new and historic timber assemblies.

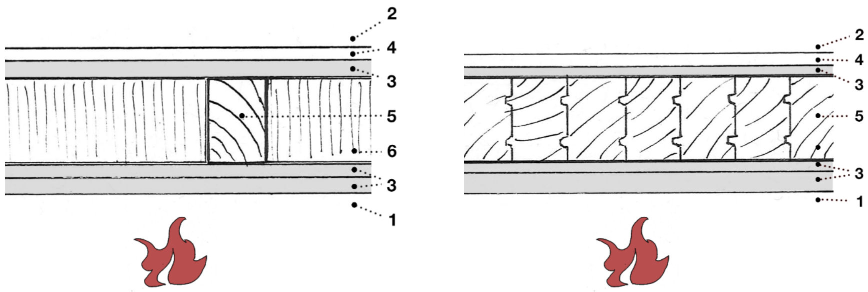
Fire design of timber structures in Europe

The fire part of Eurocode 5 [5] gives the design principles and application rules for timber structures to fulfil a load-bearing function (R criteria) and/or separating function (EI criteria) under standard fire exposure conditions. In the following, main design models are briefly introduced that form the theoretical basis for this paper demonstrating the design concepts of calculating the fire resistance of timber assemblies according to FprEN1995-1-2:2024.

European Charring Model

FprEN 1995-1-2:2024 introduces the European charring model, which is a simplified model for the calculation of the residual cross-section of a timber member assuming linear charring rates during different charring phases. The model is used to determine the load-bearing capacity of timber structures. Figure 2 presents the relationship between charring depth ($d_{char,n}$) and time (t) throughout various charring phases. Figure 2a shows the charring of timber without fire pro-

03 Numbering and function of the layers in the assembly (FprEN 1995-1-2:2024).



1 fire exposed side
2 unexposed side
3 panels as protective layers
4 panel as insulating layer (last layer n)
5 timber member as protective layer
6 cavity (insulation or void) as protective layer

tection, whilst Figure 2b illustrates a design scenario with a fire protection system (i. e. start time of charring of timber (t_{ch}) is delayed and a slower charring rate applies until the failure time of a protection system ($t_{f,pr}$)) [15].

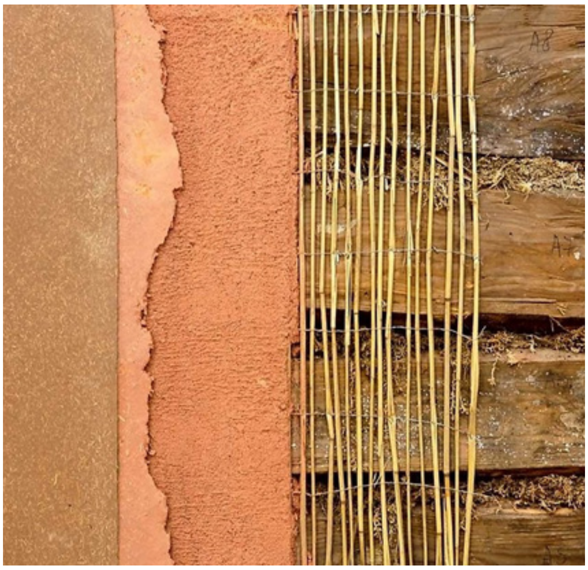
Separating Function Method

According to FprEN 1995-1-2:2024 this method should be applied for the verification of the separating function (integrity and/or insulation) as well as for the calculation of the start time of charring of initially protected timber members and the failure time of the fire protection systems where relevant. The fire resistance according to this method is determined by accounting the contribution of all layers in the entire layered assembly, see Figure 3. Each layer is defined by their specific protection time, which is the time until its fire protective function is assumed to be lost [15]. The last layer (fire-unexposed side of an assembly) serves the insulating function (crucial failure criteria). The insulation time of the entire timber assembly can be calculated from the sum of the protection times and the insulation time of the last layer. This calculation method is consistent with the insulation criterion requirements set in EN 13501-2 [16].

Along with the respective design parameters for the clay plaster and board (proposed in FprEN 1995-1-2:2024), this method allows for flexibly designing timber assemblies with clay materials contributing as a fire protection layer (Figure 4).

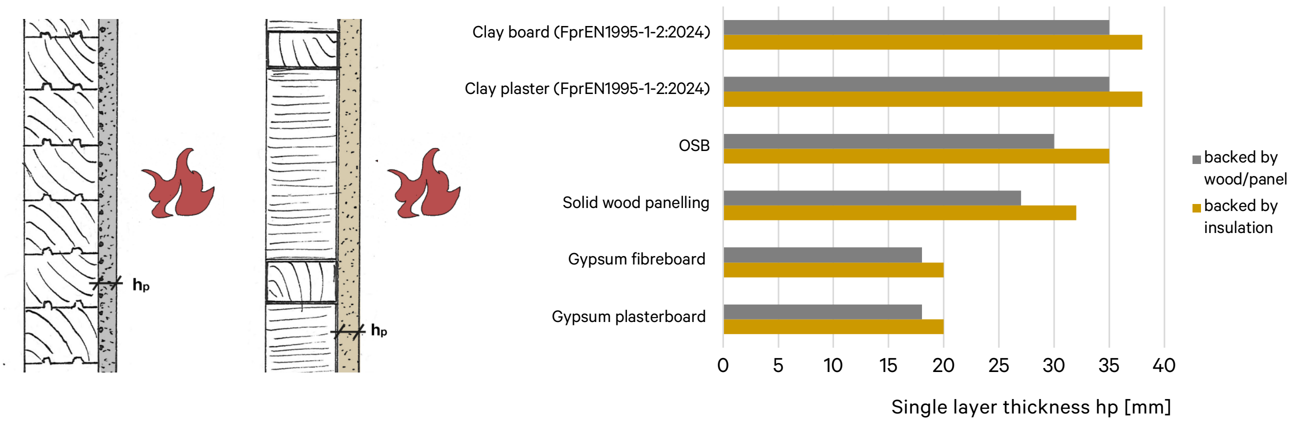
Initially protected timber structures

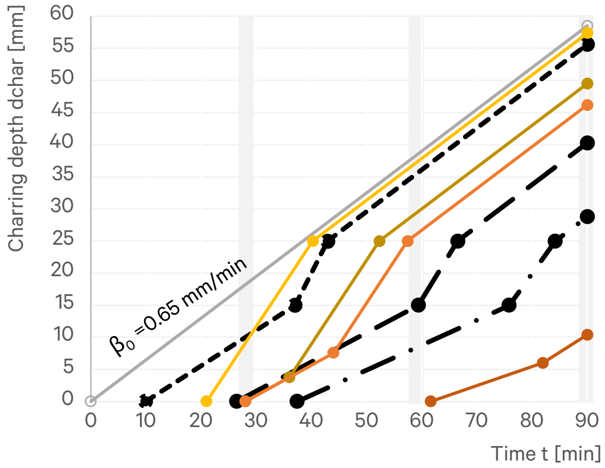
It is a common practice to initially protect timber structures against charring (compare Figure 2a and Figure 2b), as the load-bearing capacity of timber depends on its residual cross-section. FprEN 1995-1-2:2024 provides material-specific design parameters for protection materials, such as the basic protection time, which is the time to reach charring of the whole thickness, or 250 K temperature increase behind the material or product. To illustrate this, the fire protection performance of materials is presented in Figure 5 showing the minimum material thickness required to prevent the charring of timber for 30 minutes. As the fire protection effect is also influenced by the positioning of a layer in the timber assembly, two basic design options are presented based on calculations [15]: a) Fire protection system applied directly on solid timber wall (e. g. CLT) or timber frame assembly with a timber stud width ≥ 80 mm (marked in grey); b) Fire protection system applied directly on an insulation material (e. g. mineral wool), (marked in orange). Based on the illustrated comparison, clay plaster (or board) should be approximately double the thickness of gypsum board to prevent timber against charring.



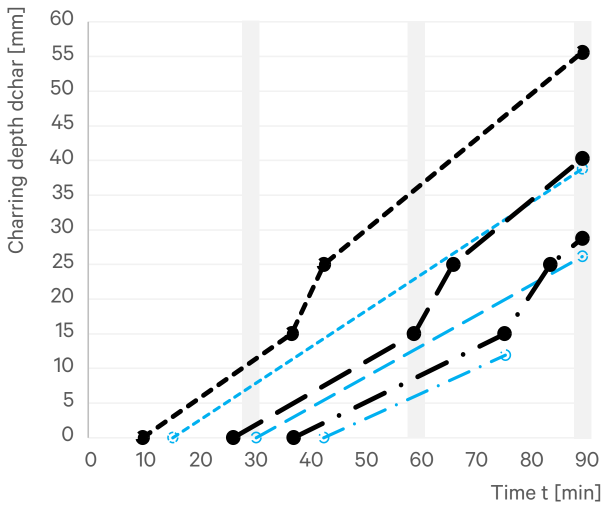
04 Layers of clay plaster system on a log wall. Source: Saviukumaja OÜ.

05 Options for fire protection materials that can prevent timber from charring for 30 minutes.

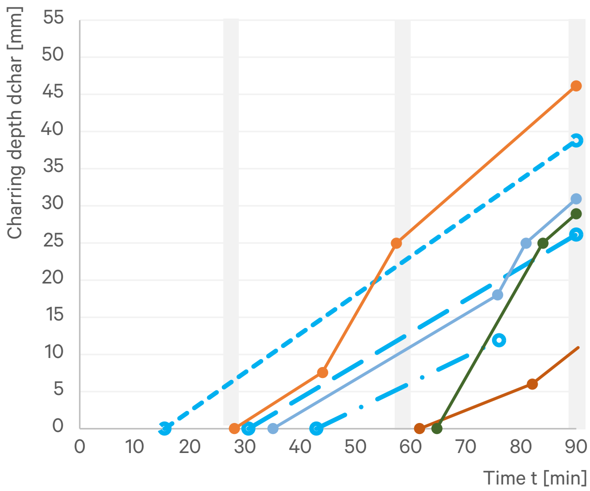




a) Charring of timber structures initially protected by protection materials (acc. FprEN 1995-1-2:2024).



b) Calculation and experimental results of clay plaster systems.



c) Comparison of experimental results on clay materials and gypsum plasterboards.

06 Charring performance of solid timber structures according to calculations acc. to FprEN1995-1-2:2024 and experimental results of clay plaster systems in walls [11].

These options also satisfy the REI30 requirement for timber assemblies since the charring of timber is prevented, i.e. no reduction in its load-bearing capacity (provided that the detailing is strictly followed to fulfil the integrity and insulation criteria). While this approach of design options can be used without further calculations, they might be overly conservative, allowing for potential improvements in the necessary protection thicknesses verified by further calculations.

In view of the load-bearing capacity of timber structures, the total charring depth of timber is a relevant design value to calculate the residual cross-section of timber after a certain time period, e.g. 60 minutes. Accordingly, different materials can significantly delay the start of charring and reduce the charring rate of protected timber. Thus, protection materials (and their thicknesses) may present very different performances regarding the charring performance of timber.

To illustrate this, Figure 6a presents the development of the charring depth of initially protected timber in relation to time in case of wall assemblies. A reference to an unprotected timber is also made. One comparison demonstrates that the charring depth of timber is about 10 mm greater after 60 minutes when using 15 mm gypsum plasterboard type F compared to 30 mm clay plaster system (fastening ensured by staples of 25 mm in length). This comparison shows that protection material should be chosen based on the primary objective (e. g., REI60) rather than the materials' basic protection time (Figure 5).

As described in Figure 2 and demonstrated in Figure 6a, the failure time of protection material has a significant impact on the charring of timber. Figure 6b compares FprEN1995-1-2:2024 calculations to furnace test results, showing the conservativeness of the proposed design equation, i. e. in the tests no failure of the plaster system occurred, while the design model considers the failure. This demonstrates clearly that if the failure time is postponed, the final charring depth is significantly smaller. Furthermore, in case of longer fires, the clay-based materials have great potential to outperform the gypsum plasterboards (e. g. compare the charring depths between the 20 mm clay plaster system and 15 mm Type F gypsum board at about 60 minutes, Figure 6c). Furthermore, Figure 6c includes further design options, i. e. clay plaster and reed board tested on a CLT wall preventing the charring of timber for 60 minutes [11]). An interpretation of test results is made for clay boards by introducing a start time of charring obtained from the fire tests [17], while calculating acc. to FprEN1995-1-2:2024 to demonstrate the charring behind the boards (length of fasteners is 25 mm in timber).

Exemplary applications

The following presents timber wall assemblies that comply with FprEN1995-1-2:2024. The assemblies are intended to illustrate the design possibilities of clay-based materials that satisfy the fire resistance requirements of REI30 and REI60. For this objective, the tabulated data provided in the LIGNUM [6] was used, which served as a base for a direct comparison between conventional wall layups (column A) and the introduced alternatives with clay-based materials (B and C). The design models and calculation methods [15] described earlier were used to derive the wall layups for clay-based protection systems. Table 1 and Table 2 present main design options with mineral wool as insulation layer for REI30 and REI60, respectively. Whereas in option B) clay boards are applied directly on the timber studs, in option C) a clay plaster system is applied on a plywood panelling (that also provides stiffness to the timber frame). Additionally, an alternative solution with wood fibre cavity insulation (WF) is given by indicating a minimum thickness required to reach the respective EI criteria.

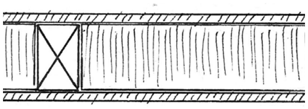
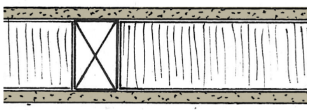
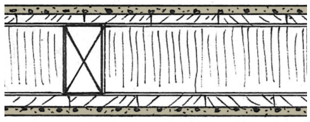
The design examples apply similarly to existing/historical timber wall structures, e. g. 'Fachwerk' type of buildings. The presented options further apply to solid wall structures, solely in case of CLT structures, the load-bearing capacity should be verified in accordance with its respective layer buildups in CLT.

Outlook

The design models and options based on the available design parameters for clay materials demonstrate useful insights for further potential applications. Currently, FprEN1995-1-2:2024 gives rather limited design options for ceiling applications with clay materials, i. e. maximum thickness of a plaster or board is limited to 20 mm. The main reason is an early fall-off compared to their application on walls. Innovative design solutions demonstrate how clay-based material can be constructively fixed into the floor structure to prevent its (early) fall-off in case of fire [1], yet such specific technical solutions require further research and improvements in design models with clay to wider the scope of calculation options in future. Another approach for intermediate floors could be the introduction of 'clay floor topping', substituting the commonly used floor screed [18]. When the present design equations in FprEN1995-1-2:2024 are to be applied to compare the performances of clay plaster and floor screed, the basic protection time of both materials is comparable, see Figure 6. Standard screed systems often feature a layer thickness of 5 cm or greater, mainly to provide sound insulation. Using a clay-based alternative providing similar fire resistance is unlikely to increase the floor thickness.

The design methods according to Eurocode 5-1-2 are also applicable for historic timber constructions which include panel infills such as earth and bricks. Meaning, for future design options, the design values for clay plaster present useful basis for estimating the protection effect provided by those historic type of infill materials as well as by their typical clay plaster coating. In some national design guidelines for historic build-

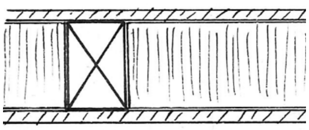
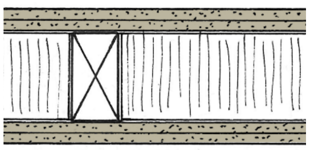
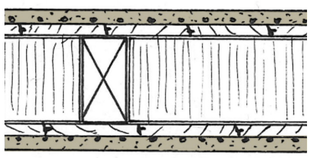
Table 1. Design options to fulfil the fire resistance of timber wall assemblies for 30 minutes (REI30).**

Design option*	**A) Conventional (gypsum plasterboard**)**		**B) Clay material as fire protection**		**C) Combination of materials as fire protection system**	
Wall layup						
Layers in assembly						
1	**Gypsum plasterboard Type F**	**10 mm**	**Clay board**	**18 mm**	**Clay plaster system**	**10 mm**
2	Mineral wool/Timber	120 mm	Mineral wool/Timber	120 mm	Plywood	15 mm
3	**Gypsum plasterboard Type F**	**10 mm**	**Clay board**	**18 mm**	Mineral wool/Timber	120 mm
4					Plywood	15 mm
5					**Clay plaster system**	**10 mm**
Option for WF cavity insulation material	WF cavity insulation 120 mm (only EI criteria)		WF cavity insulation 120 mm (only EI criteria)		WF cavity insulation 120 mm (only EI criteria)	

** Calculations and detailing according to FprEN1995-1-2:2024; layer thicknesses indicate the minimum required thickness of material to fulfil the requirements.*

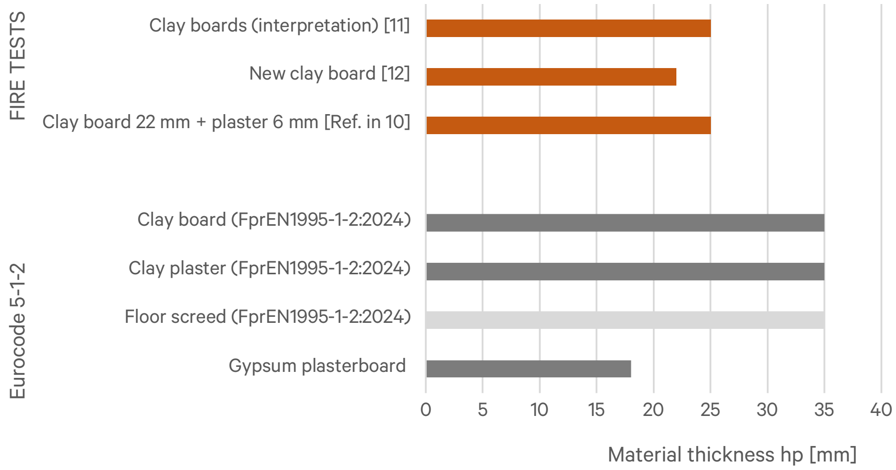
*** According to LIGNUM 4.1 (442-3): Applied load 20 kN/m; max wall height 3 m; stud distance ≤ 700 mm; timber C24, size 40 mm × 120 mm; mineral wool ≥ 26 kg/m³.*

Table 2. Design options to fulfil the fire resistance of timber wall assemblies for 60 minutes (REI60).**

Design option*	**A) Conventional (gypsum plasterboard**)**		**B) Clay material as fire protection**		**C) Combination of materials as fire protection system**	
Wall layup						
Layers in assembly						
1	**Gypsum plasterboard Type F**	**15 mm**	**Clay board**	**35 mm**	**Clay plaster system**	**22 mm**
2	Mineral wool/Timber	140 mm	Mineral wool/Timber	140 mm	Plywood	18 mm
3	**Gypsum plasterboard Type F**	**15 mm**	**Clay board**	**35 mm**	Mineral wool/Timber	140 mm
4					Plywood	18 mm
5					**Clay plaster system**	**22 mm**
Option for WF cavity insulation material	WF cavity insulation	140 mm (only EI criteria)	WF cavity insulation	140 mm (only EI criteria)	WF cavity insulation	140 mm (only EI criteria)

** Calculations and detailing according to FprEN1995-1-2:2024; layer thicknesses indicate the minimum required thickness of material to fulfil the requirements.*

*** According to LIGNUM 4.1 (442-4): Applied load 50 kN/m; max wall height 3 m; stud distance ≤ 700 mm; timber C24, size 80 mm × 140 mm; mineral wool ≥ 26 kg/m³.*



07 Options for fire protection materials that can prevent timber from charring for 30 minutes; Comparison of required protection material thicknesses determined by the calculations and the (interpreted) results obtained from fire tests.

ings (e.g. in Germany) predefined historic timber assemblies are presented with straw-clay panel infill to reach REI30 [20]. As an outlook, these historic material combinations present great potential to be further investigated in case of fire to increase the authentic design options for upgrading existing structures while preserving the traditional material use and building technologies. This traditionally proven principle of filling timber frame with earthen materials might again become interesting in the case of preassembled interior wall elements filled with clay from the site [4]. If this in-fill material could be considered as a protection layer in the design model (as outlined earlier), even with very conservative parameters, it might replace common mineral wool insulation, which it can outperform easily in other domains such as thermal mass and hygroscopic comfort.

An additional future option lies in the further improvement of the clay-based plasters and boards (i.e. enhancing the material specific thermal properties at elevated temperatures). In order to illustrate this potential, Figure 7 presents a comparison between the design options according to FprEN1995-1-2:2024 and the results obtained from the fire tests with clay boards. For example, a 22 mm thick clay board (i.e. development of a clay-hemp board in Finland [20]) could potentially provide similar fire protection effect as 35 mm of clay plaster system. This result could be interpreted in relation to the design options demonstrated in Table 1 and Table 2, which suggest that the clay material thickness could be potentially reduced.

Discussion

This paper has shown that clay-based materials as panelling for timber present practical design alternatives. Especially if further requirements beyond fire protection are also considered such as sound insulation, room acoustics, thermal mass in light-weight timber assemblies etc. (which in practice often leads to layer thicknesses higher than the minimum required for fire safety). Thus, assemblies with clay layers designed according to FprEN1995-1-2:2024 appear to be feasible alternatives to conventional solutions. This suggests a need towards a more holistic design approach. Experimental results have shown effective protection performance of clay plaster and boards particularly in longer fires. The delayed failure time (i.e. resulting in less reduction in the residual cross-section of the protected timber) plays an important role herein, which in turn highlights that the fastening system of clay materials into the substrate is a vital parameter. Further work on the failure times of clay materials could be studied to enhance design models for future applications. For clay boards, further research and fire testing would allow to propose an improved design model (see Figure 7), potentially introducing better parameters than those of clay plaster, which are applied equally to plaster and board systems in the current design model. Additional, investigations on clay-based materials' behaviour in natural fires would be highly valuable in view of performance-based design that is becoming more prevalent in case of large timber building designs.

The presented design options with clay-based materials are applicable if the design rules and detailing described in FprEN1995-1-2:2024 are followed. Further, to ensure the material quality of clay plaster and boards, compliance to their respective product standards and application design is crucial. It should be noted that clay-based materials would require European product standards to become "conventional" design solutions in various design guidelines (not only fire-related). In order to facilitate the use of clay for a wider range of designers, it is advisable to incorporate clay-based materials into the tabulated design data given in design guidelines, alongside other commonly used materials such as gypsum plasterboard. This inclusion could further promote the ease-of-use and accessibility in designing with clay.

Conclusion

Design parameters and detailing for clay plaster and boards are currently proposed for the revision of the fire part of Eurocode 5 dealing with the structural fire design of timber. Accordingly, this paper introduces the fire design models and performance of clay materials as fire protection, contributing to their wider use in new and existing buildings. Practical design options demonstrate an adequate alternative to conventional solutions used today, while indicating great potential for future applications. The overview indicates that advancements in both product development, design and legislation are crucial for the broader adoption of clay materials in timber construction.

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