

# Structural Fire Design with Aged Reclaimed Timber: Small-Scale Charring Performance Assessment

Authors: Johanna Liblik, Maria Pernits, Alar Just, Alar Konist

This paper investigates the fire performance of aged reclaimed structural timber. Using small-scale cone heater tests, the research compares charring performance between reclaimed and contemporary timber under standard fire exposure conditions.

This work was conducted as part of **Drastic's Nordic Demonstrator**, which focuses on validating reclaimed timber for structural and load-bearing applications in temporary commercial buildings. It contributes directly to Demonstrator objectives by improving understanding of material variability and supporting the safe integration of circular timber into modern design frameworks.

The work was conducted by researchers from **TalTech (Tallinn University of Technology)**, a Drastic project partner.

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## STRUCTURAL FIRE DESIGN WITH AGED RECLAIMED TIMBER: SMALL-SCALE CHARRING PERFORMANCE ASSESSMENT

Johanna Liblik<sup>1</sup>, Maria Pernits<sup>2</sup>, Alar Just<sup>3</sup>, Alar Konist<sup>4</sup>

**ABSTRACT:** Timber can play a vital role in the circular economy when reusing materials from deconstruction in new buildings, but modern design constraints hinder its widespread use. Despite efforts to promote reuse of reclaimed timber in construction, its fire performance is not well understood. Current Eurocode 5-1-2 guidelines do not specifically address aged timber of the same species, posing challenges for structural fire design. Limited research indicates that heritage timber chars faster than new timber, influenced by factors like radial cracks. This paper presents an assessment of reclaimed timber's charring performance compared to contemporary timber, using a systematic approach across different origins and age groups. Small-scale fire testing and thermogravimetric analysis evaluated the charring rates and thermal decomposition of wood species. The test results indicate that the age of timber does not show a clear correlation with its charring rate. However, older timber appears to exhibit a significantly greater degree of variability in charring rates within species when compared to new timber. It was observed that factors beyond age, such as the annual ring orientation in relation to heat exposure, may have a comparable or even more substantial influence on the charring characteristics of timber. By integrating results from previous studies, this research enhances the understanding of the charring behaviour of aged timber, thereby providing valuable data that can inform the design of structural applications involving aged timber.

**KEYWORDS:** reclaimed timber, heritage timber, fire performance, charring rate, structural fire design

### 1 – INTRODUCTION

Innovations and circular economy principles can address building sector challenges, improving quality of life and reducing environmental impact [1]. Timber supports the circular economy by being renewable, carbon-storing, and highly recyclable, reducing waste and promoting sustainability [2]. The material reuse and lifespan can be significantly prolonged by reusing deconstructed wood materials as part of the primary load-bearing element in new buildings. Despite their potential as structural elements, the reuse of timber is restricted by factors like the contemporary engineering design process and modern building codes, with fire safety being one of the key concerns. Emerging circular timber practices are now pushing for standardization efforts to overcome these barriers and enable industrial-scale implementation of

reclaimed timber. In addition, novel design solutions are introduced to the market, e.g. CLT made of up-cycled wood [3], which among other aspects necessitate a solid comprehension of their fire performance. Thus, despite ongoing efforts to scale up reclaimed timber reuse, the fire performance (i.e. design for fire safety) amongst other relevant performance criteria cannot be overlooked.

Timber is a combustible building material vulnerable to fire. In Europe, Eurocode 5-1-2 [4] outlines structural fire design for timber structures, but its use is limited to modern standardised timber products. Today, lack of data on the fire behaviour of aged, reclaimed wood presents a challenge to its (complete) re-entry into the market. There is currently no design code or available guidance for the charring performance of reclaimed timber, essential for adequate fire design purposes. Yet, charring is a critical

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<sup>1</sup> Johanna Liblik, Department of Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia, johanna.liblik@taltech.ee

<sup>2</sup> Maria Pernits, Department of Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia, maria.pernits@gmail.com

<sup>3</sup> Alar Just, Department of Engineering and Architecture, Tallinn University of Technology, Tallinn, Estonia, alar.just@taltech.ee

<sup>4</sup> Alar Konist, Department of Energy Technology, Tallinn University of Technology, Tallinn, Estonia, alar.konist@taltech.ee

factor when determining the fire resistance of timber structures since it reduces its load-bearing capacity and integrity [5]. The factors influencing the charring of timber are thoroughly examined in [6], including material density, moisture content, permeability, grain orientation, and species (chemical composition); in addition, the system properties under which timber is tested are also crucial factors, including thermal exposure, sample orientation and size, and test method.

The relevance of determining the fire performance of reclaimed timber has recently been addressed by a review study [7] on the applicability of non-destructive testing for evaluating the fire performance of reused structural timber. It was stated that while factors such as density, moisture content, permeability, and species influence charring, non-destructive testing cannot accurately predict fire performance based on any single parameter or their combination. On the other hand, experimental studies on the charring performance of heritage timber are scarce. One study [8] found heritage timber (> 100 years old) chars at a rate up to 20% faster than contemporary timber, while another study [9] noted radial cracks in heritage timber accelerate the charring. Similar conclusion has been stated by another study [10] that the charring of historical wood is significantly faster compared to new wood, wherein this conclusion was further confirmed by comparing the results of the medium-scale test for historical wood with the results of other authors for new wood [10]. Furthermore, a recent study [11] reported, based on an experimental test series with timber samples over 100 years old, that heritage hardwood generally chars at a higher rate than heritage softwood. It must be noted that these existing studies focus on materials obtained from single buildings and solely a few timber species were investigated. Thus, a systematic comparison across age groups of reclaimed timber versus new timber is lacking, highlighting a gap in understanding fire performance between new and reclaimed (aged) timber. As previous studies highlight the need for extended fire performance data on aged wood species, this study aims to further advance the understanding of charring behaviour of aged timber.

The aim of this paper was to determine the charring performance of reclaimed timber in relation to contemporary timber and to estimate if it is adequate to use contemporary procedures/design codes also for the aged timber in standard fire exposure conditions. A systematic assessment approach, i.e. different origins and age groups of reclaimed timber specimens were tested and analysed in view of their charring performance.

## 2 – EXPERIMENTAL WORK

The experimental work was conducted using the cone heater of a cone calorimeter [12], which is well recognised for its reliability and capacity to efficiently evaluate a large number of specimens for comparative purposes. This also allowed for a direct comparison with the results from previous studies cited. Furthermore, numerous previous studies have shown good correlation between the cone heater test and furnace test results on the charring rate of timber under standard fire exposure conditions (e.g. [14][15]). Consequently, the results obtained from cone tests could be used to estimate the potential performance of the timber specimens in a furnace. The cone heater test program was complemented by thermogravimetric analysis to aid in the interpretation of the cone test results.

### 2.1 MATERIALS

A total of 6 different wood species were collected for this study from Estonia and Norway, described in Table 1. Test sample EW0 served as a reference for comparing the performance of aged timber with both fresh timber and findings from previous research. The wood samples consist of Norway spruce, with ages ranging from approximately 120, 100, 30, 10, and 0 year. The wood species were collected from abandoned barns and other deconstructed (residential and sports hall) buildings in southeastern Norway and Estonia. All species were conditioned under test laboratory hall conditions at 20°C ± 2°C and 45% ± 5% RH for approximately five months prior to the preparation of the test specimens. The moisture content of the specimens was determined by an oven-dry procedure at 103°C. The average moisture content for the specimens was 9%, which is in an acceptable range considering the in-service timber and the similar previous studies. The preparation of the wood species for the testing was carried out based on the test method, see Section 2.3.

Table 1: Timber specimens used in this study.

Specimen ID	Age [years]	Place of collection	Origin
EW120	120	Residential building	Estonia
EW30	30	Sports hall	Estonia
EW100	100	Residential building	Estonia
EW0	Fresh	New wood (factory)	Estonia
NW100	100	Barn timber	Norway
NW10	10	Scaffolding material	Norway

## 2.2 THERMOGRAVIMETRIC ANALYSIS

TGA was used to determine the thermal degradation of wood species at elevated temperatures and to detect differences between the wood species. The analysis was conducted on a NETZSCH STA 449 F3 Jupiter TG-DSC. Test samples were crushed in a ball mill until analytical particle size was achieved and conditioned on a room temperature (23 °C) in a closed container before testing. The samples were tested under nitrogen atmosphere at a flow rate of 20 mL/min. A constant heating rate of 10 °C/min was applied for measurements of linear heating programme in a temperature range of 20°C to 700°C. The slow heating regime was chosen to provide a clearer view of mass loss changes, in contrast to higher heating rates. The results were primarily analysed to evaluate how temperature increase affects the mass loss of the wood species. The results were used to support the analysis of the cone heater results.

## 2.3 CONE HEATER TESTS

The cone heater of a cone calorimeter [12] was used that enabled to determine the following: i) charring depth; ii) charring rate for each test specimen. The dimensions of the full test specimen were about 45 mm x 100 mm x 100 mm (measuring precision: ± 0.1 mm). This specimen size and thickness was chosen as it enabled a direct comparison with respective previous studies [8][9][11]; it is known that the dimensions of a test sample affect the heat and mass transfer, and thus the pyrolysis behaviour [6]. Specimens were cut with the exposed face perpendicular to the grain to minimize variations in the charring performance caused by grain orientation [6]. Figure 1 presents cross-sectional examples of each test specimen. The side of specimen exposed to the cone heater was freshly cut as in [8] that also allows similar conditions for all specimens. Table 2 provides a list of prepared test specimens with their dimensions and mean densities.

Table 2. Description of test specimens.

Specimen ID	Dimensions of timber specimens [mm x mm x mm]	Density (mean) [kg/m <sup>3</sup> ]	Standard deviation SD
EW120	45 x 100 x 100	464	20
EW30	45 x 100 x 100	453	22
EW100	45 x 100 x 100	439	37
EW0	45 x 100 x 100	506	19
NW100	(2 x) 45 x 50 x 100	436	5
NW10	(2 x) 45 x 45 x 95	463	20



Figure 1. Example of the side view for each test specimen ID.

Due to limitations in the received raw material, it was not possible to cut the total required specimen size for NW100 and NW10. As a result, these test specimens were prepared by tightly fixing two halves together, thereby achieving a total volume highly comparable to that of the other test specimens. The EW30 specimens comprised two timber layers glued together, see Figure 1. Each specimen ID was subjected to three repeated tests, resulting in a total of 36 tests. Each specimen was wrapped into an aluminium tape to prevent heat losses and air flow within the specimen inside the specimen holder [12].

The setup and test method followed the general principles given in ISO 5660-1 [12]. The tests were conducted in a horizontal orientation with the test specimen in a retainer frame. The specimens were tested under a constant predetermined heat flux level of 50 kW/m<sup>2</sup>. Two test times were selected for each test specimen, 15 and 30 minutes. To prevent any additional charring after the fire test, the specimens were promptly immersed in water after test termination. The char depth was determined by carefully removing all the charcoal and measuring the residual cross-section of the timber specimen along its centre line. Charring rates were calculated from the char depth and the heat duration the material was exposed to.

## 3 – RESULTS AND ANALYSIS

### 3.1 THERMOGRAVIMETRIC ANALYSIS

Testing was conducted using two samples of each wood species to identify any discrepancies. Figure 2 presents the results on the relationship between the temperature increase and mass loss. Despite the differences between the wood species (see Table 1), the mass loss trend was closely comparable across all specimens. Table 3 summarizes the main results and mean values for the total mass at 700°C and the total mass and mass loss at 300°C, as this temperature is commonly recognised (e.g., acc. to EN 1995-1-2) as the start time of charring. Figure 3 offers

a close-up examination of the mass loss trend up to 300°C, where initial differences between species in mass loss are observed. However, after approximately 280°C, the mass loss patterns start to align across all samples. Considering all test species, the average mass loss at 300°C ranged from 21% to 26%. No clear trend was observed across the different age groups of the wood species. For instance, EW120 and EW0 (new wood) exhibited very similar mass losses of 26.0% and 25.0% at 300°C, respectively. In contrast, the mass loss at 300°C was slightly lower for the other specimens compared to EW120 and EW0. When comparing the residual mass at 700°C, EW120 showed 11.6%, while EW0 showed 14.7%, indicating that the new wood (EW0) experiences a slower rate of decomposition at elevated temperatures.

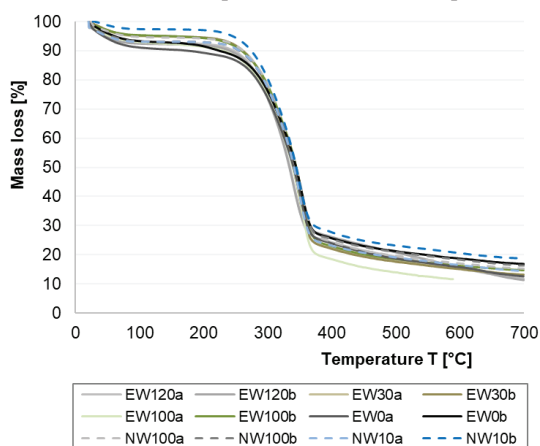


Figure 2. Test results on the effect of temperature on mass loss obtained from TG analysis.

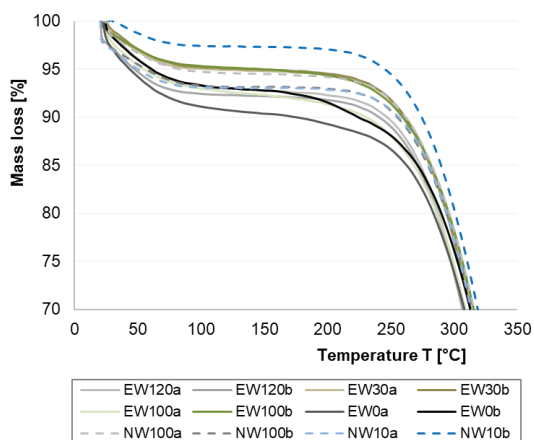


Figure 3. Test results on the mass loss in relation to the effect of temperature increase until 300°C.

When comparing the 100-year-old wood samples of different origins, EW100 and NW100, the total remaining mass at 700°C was 13.2% and 15.8%, respectively. In comparison, the remaining mass of new wood (EW0) was 14.7%. Thus, no significant difference

in the decomposition of the wood species at elevated temperatures was observed compared to new timber; however, some variations were noted, e.g. difference in the mass loss between total mass loss at 300°C and total mass at 700°C between the EW120 and NW100 was about 5%.

Table 3. Test specimens and mean test results from TG analysis.

Specimen ID	Initial mass [mg]	Total mass loss at 300°C [%]	Total mass at 300°C [%]	Total mass at 700°C [%]
EW120	5.0	26.0	74.0	11.6
EW30	5.0	22.8	77.2	13.1
EW100	4.9	23.6	76.4	13.2
EW0	5.0	25.0	75.0	14.7
NW100	5.0	22.1	77.9	15.8
NW10	5.0	21.3	78.8	16.6

### 3.2 CONE HEATER TESTS

Results are presented for the charring depths and charring rates, with respect to their test duration, age groups and densities. Test results are compared across different specimens, with references to existing research for comparison.

#### Charring depths

Test specimens were documented and an example of a timber specimen before and after a fire test is presented in Figure 4. The residual thickness of the wooden specimen was measured at the centreline of the specimen (marked with red arrow), after the mechanical removal of the charcoal. The char line along the exposed surface of the wooden specimens was roughly uniform, indicating that the rounded corners did not affect the accuracy of the measurements.

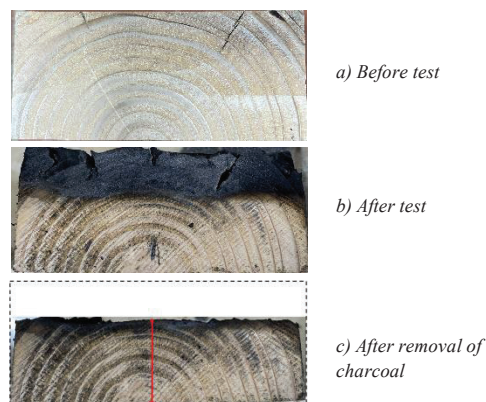


Figure 4. Documentation of a test specimen (EW120) before and after a 15-minute test.

Figure 5 presents the charring depths measured after the removal of charcoal. Notably, the charring depths show an increase with test duration, which was expected. The results indicated in red correspond to the new timber (EW0), which demonstrated a high degree of repeatability in charring depths across all three specimens. By excluding the single highest charring depth determined in the 15-minute test, the charring depths of aged timber were found to closely resemble those of new timber, with some specimens even showing less charring. However, it should be noted that the mean density values differ between new and aged timber, with values of 505 kg/m<sup>3</sup> and 451 kg/m<sup>3</sup>, respectively. Specimens of NW10 demonstrated the least charring, possibly due to prior exposure to mortars or similar materials during its use as a scaffolding material (Table 1), which may have an effect on its charring.

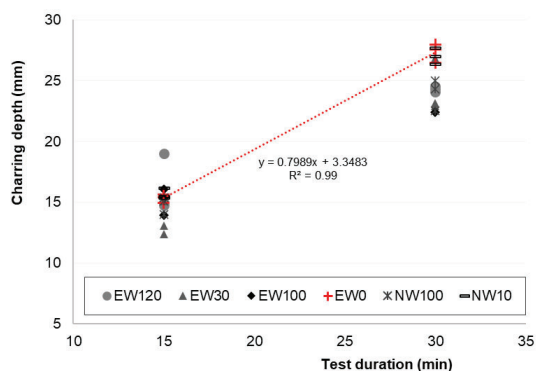


Figure 5. Charring depths obtained from cone heater tests in relation to test duration.

### Charring rates

Figure 6 presents the determined charring rates in relation to the test duration. A longer test duration results in a slower charring rate for timber that is related to the formation of charcoal and the stabilization of charring conditions. No clear trend is observed in the charring rates across different age groups and origins of timber. However, somewhat fastest charring rates were determined in specimens older than 100 years (EW120, EW100, NW100), suggesting that significantly older timber may char slightly faster than younger timber. The comparison between new and aged timber should also account for density, although the approximately 50 kg/m<sup>3</sup> difference between new and aged timber is not considered substantial to significantly impact the charring rates. It is important to highlight that greater variation in charring rates was observed within a single specimen ID of aged timber, see the individual values in Figure 6 that deviate from the others.

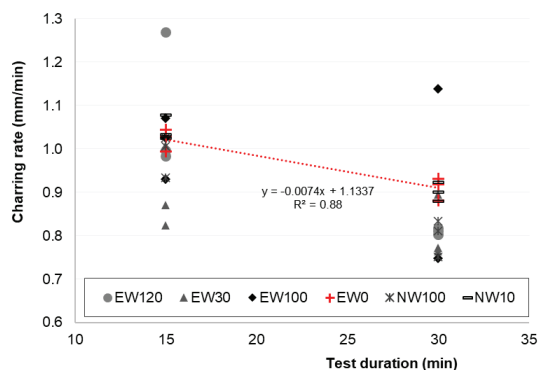


Figure 6. Charring rates of test specimens in relation to test duration.

Figure 8 illustrates the relationship between the charring rate and the age of timber for the specimens of Estonian origin (EW). While most specimens of aged timber have comparable density values (see Table 2), the results for the EW30 specimens show significant deviation, which could be foremost attributed the density variations (compare results of 412 kg/m<sup>3</sup> and 521 kg/m<sup>3</sup>), with denser timber indicating slower charring rate. Moreover, the EW30 samples consist of two bonded timber layers (Figure 1), potentially increasing the variation in charring rates within the specimen ID. The highest charring rate, indicated by a red asterisk in Figure 8, corresponds to a specimen from the batch of 120-year-old timber (EW120) that mainly differed from the other two samples in its visual characteristics, see Figure 7 left (i.e., width of the annual rings), despite having a very similar density to other two samples. This result indicates that, when comparing test outcomes, it is essential not only to evaluate factors such as the density of the samples but also to consider the structure of the annual rings, as well as any other defects or cracks that may affect the repeatability of the results (within one specimen ID). It was observed that a batch of aged timber from a specific collection site may exhibit significant variation in the characteristics and quality of the timber material. The variation in test results for new timber appears to be minimal when it (see EW0) was tested, reflecting a higher degree of homogeneity of the material and the lack of significant differences within the batch compared to aged timber.



Figure 7. EW120 test specimens: Left – Timber sample with a charring result indicated by a red asterisk in Figure 8; right – Timber specimen of the remaining two samples from the same specimen ID.

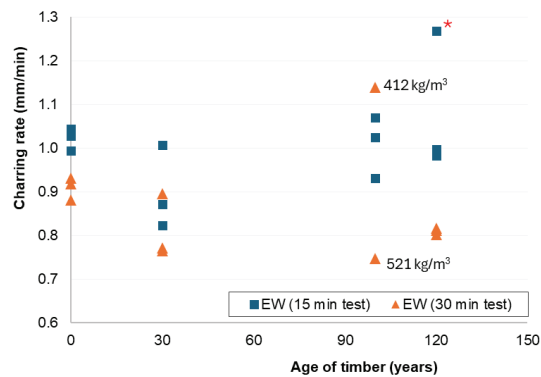


Figure 8. Charring rates in relation to the age of timber (EW).

Figure 9 presents results for the specimens of Norwegian origin, where some variation is also observed within a batch of NW100 in case of 15-minute testing, despite the specimens having very similar densities, see Table 2.

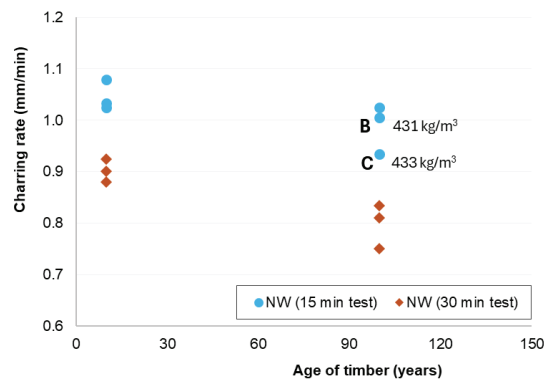


Figure 9. Charring rates in relation to the age of timber (NW), refer also to Figure 10.

When analysing the performance of specimens (NW100) based on their visual appearance, as shown in Figure 10, the faster charring rate observed in specimen B (Figure 9) could be attributed to the orientation of the annual growth rings being slightly more parallel to the heat exposure. Also, the width of the annual rings appears to have some influence. This may further suggest that the orientation and slope of annual rings in timber are important factors when comparing different test results (particularly within one specimen ID), highlighting that multiple variables can impact the charring results. Consequently, a comprehensive approach that simultaneously accounts for multiple factors affecting charring performance appears more effective in identifying the dominant influences on fire test outcomes. The NW100 specimens consisted of two halves fixed together. Test results showed uniform charring across the specimen, with negligible influence from this setup compared to other solid specimens.

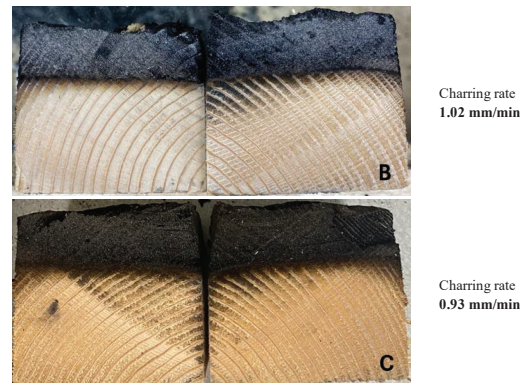


Figure 10. Comparison of NW100 test specimens after 15-minute fire test, refer also to Figure 9.

Figure 11 presents a comparison of all test results regarding the relationship between charring rate and the age of timber. The highest charring rates, marked by a red circle, have already been discussed above. When excluding these values from the overall data, the trend shows that charring rates for all timber ages are ranging between 0.75 and 1.1 mm/min. Tests with the oldest samples of timber (EW120, EW100 and NW100) show comparable performance, despite their differences in origins and place of collection (Table 2). Results show that it cannot be concluded that the age of timber has a significant impact on the charring rate, e.g., new timber (0 years) exhibits a charring rate similar to that of timber aged 120 years (compare results of 15-minute tests). The 30-minute tests indicate that older timber demonstrates even a slower charring rate compared to new timber. (Table 2).

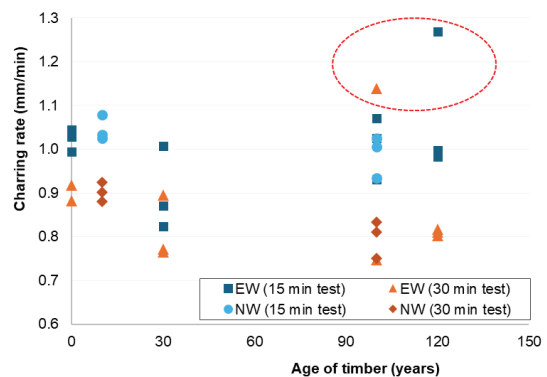


Figure 11. Comparison of charring rates to age of timber between EW and NW specimens in all tests.

It is widely recognized in the literature that the charring rate is strongly dependent on the density of the material, with several charring models incorporating density as a key variable [6][13]. This study aimed to reduce the density variation between selected specimens to gain clearer insight into how timber age affects charring (Table 2), although achieving identical density across all

specimens was not possible as one would expect with timber material. Figure 12 presents the results of charring rate versus densities of all specimens. The results indicate that, despite variations in the age and slight differences in densities of the aged timber specimens, the charring rates determined in a 15-minute test show larger scatter, whilst in case of 30-minute test, the deviation between charring results is reduced. No clear trend was observed between charring rate and density across the tests. However, in some specific instances, variations in density appeared to influence the charring rate, as previously discussed (see Figure 8).

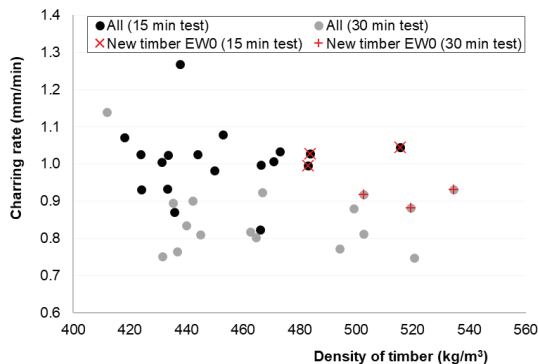


Figure 12. Charring rates in relation to density of timber.

Main observations and comments can be given based on the obtained experimental data:

- 1) The age of timber does not seem to be a primary factor in determining its charring performance; other well-known factors affecting the charring behaviour should also be considered.
- 2) The deviation in charring rates among all specimens reduces with a longer test duration, as shown by the comparison of the 15-minute and 30-minute test results. This trend suggests that prolonged heat exposure conditions lead to a more consistent charring behaviour (related to the formation of charcoal) and potentially resulting in a more reliable comparison of test results between different specimens.
- 3) In assessing the charring performance of timber specimens, it is important to account for characteristics such as the orientation of the annual growth rings of the test specimen in relation to heat exposure, as this appears to have an influence in interpreting, comparing and understanding the results.
- 4) A few discrepancies were observed when analysing the charring results of aged timber. In some cases, the results did not provide a clear understanding of the factors that ultimately influence the charring rate. Therefore, it is advisable that future research not

only perform cone heater tests but also include other tests to support the analysis, e.g. an assessment of specimen permeability, as permeability can have a significant role in the charring rate of timber, i.e. higher permeability refers to faster charring rate in case of timber with similar densities [6][13]. This is further discussed in Section 6.

### 3.3 COMPARISON OF TEST RESULTS TO PREVIOUS STUDIES

A comparative analysis between the obtained results and previous research [8][11][14] was carried out. Table 4 summarizes the results of previous studies conducted using a methodology comparable to that employed in this study. Two studies used specimens with a thickness of 45 mm, except the study by Xu et al [14]. Note that the results from previous studies presented here are approximate values, extracted from graphs and tables in the respective papers. For precise data and further details, please refer to the original sources.

Table 4. Previous studies with cone heater on heritage and new wood.

Reference	Age of wood specimen [years]	Density (mean) [kg/m <sup>3</sup> ]	Species	Moisture content [%]
Chorlton & Gales (2019) [8]	~120	418	Pine	7-8
	~180	395	Spruce	7-8
	New (glulam)	504	Spruce	7-8
Philion et al (2024) [11]	~140	566	Hardwood	8.7
	~190	356	Softwood	7
Xu et al (2015)* [14]	New	470	Douglas fir	14
	New	460	Scots pine	17.5

\*Test specimen height was 50 mm (1 mm tolerance) [14].

Figure 13 presents the comparison of results with regards to the age of timber and its respective charring rate. The results from [8][11] fall within the charring rate limits determined in this study, while the charring rates of Canadian heritage timber, around 1–1.1 mm/min, are consistent with those observed in 100-year-old and older timber from Estonia and Norway. On the other hand, the charring rates for new timber can vary significantly across tests, as seen in the results in [8] and [14]. In case of 15-minute tests, the charring rates of new timber observed in this current study (~1 mm/min) fall within the range reported in previous research for new timber (0.8 – 1.3 mm/min). This finding reinforces the earlier argument that additional factors (e.g., grain and annual ring orientation) should be carefully considered alongside primary given parameters (e.g. type of species

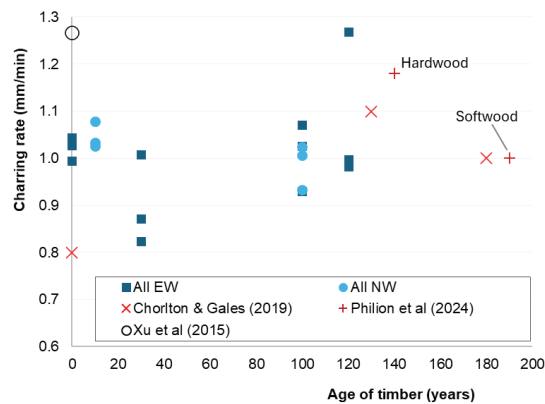


Figure 13. Comparison of charring rates in relation to the age of timber between different studies determined in a 15-minute test.

and density), as charring is highly dependent on several material properties [13].

The charring rate of approximately 0.8 mm/min reported by [8] aligns well with the results obtained by Mikkola [19], who tested new timber specimens of 38 mm thickness (490 kg/m<sup>3</sup> spruce and 560 kg/m<sup>3</sup> pine) at 10% moisture content. Given that the moisture content was somewhat higher in case of [19], lower moisture content should result in a slightly higher charring rate than 0.8 mm/min. In this current study, the results for new timber (EW0, moisture content 9%) were around 1.0 mm/min. This difference to other studies (compare 0.8 mm/min [8] and 1.3 mm/min [14]) likely arises from multiple influencing factors, despite similar testing methods and specimen sizes, raising questions about the comparability of these results, as discussed in the next section. Figure 14 presents the comparison of results in view of the density of timber. Results from the study by Chorlton & Gales [8] for the heritage timber agree well to the dataset of charring rates obtained in this current study with similar densities. A significant difference is observed between the results of new timber in this study and [8] which may be influenced by the orientation of annual growth rings relative to heat exposure, as the density and the moisture content are highly comparable.

#### 4 – DISCUSSION

A similar observation to this current study regarding the lack of a clear trend in the charring performance across different age groups of timber has been observed in a study that examined the impact of oak wood age (0, 10, 40, 80, and 120 years) and its chemical composition on the charring rate. The study concluded that, based on the charring rate results, no definitive conclusion could be drawn regarding the influence of sample age on the charring rate [16]. On the other hand, the conclusions from [8] suggest for softwood that heritage timber chars

faster than new timber. It was also noted in [8] that the older timber was less dense than the contemporary timber (Table 4), a factor that should be considered when interpreting the results. However, information on the orientation of annual rings of the timber specimens related to heat exposure was not provided, and only mean charring test results were reported. This suggests that more comprehensive data should be provided for these types of tests to enable reliable comparisons between studies worldwide, despite the use of similar test method and test specimens.

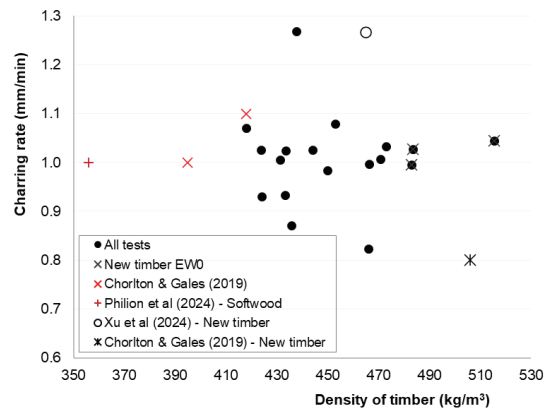


Figure 14. Comparison of charring rates in relation to the density of timber between different studies determined in a 15-minute test.

In this study, the grain and annual ring orientation in relation to the heat exposure was observed to influence the charring performance of timber specimens. Interestingly, in a study by [17], a strong correlation was observed between oxygen permeability perpendicular to the wood fibre direction and the charring rate, since oxygen plays a crucial role in influencing the charring process. In addition, it was observed [17] that the impact of annual ring orientation on density and charring rate appears to be specific to each wood type. In some cases, the variation was observed only in density, while in others, it was seen in the charring rate, making it difficult to identify an overall pattern. In [6], a reference is made that small changes in grain angle can result in large changes in moisture and oxygen movement, thus affecting the charring rate. Another study on Chinese wood tested in cone calorimeter [18] concluded that the significances of the effects of the ring width and the density were less than that of the gas permeability, while also stating that the relationship between density and charring rate was not found for all species. Similar observations to the studies described above were also made in this current study, which indicate that the studies with cone calorimeter should be complimented by other relevant tests to explicitly understand the differences in the charring performance of timber.

Given the complexity of wood's chemical and physical structure, its reaction to elevated temperatures is influenced by multiple material properties, including density, moisture content, chemical composition, grain orientation, permeability, scale effect, char contraction, and char oxidation [13]. The inclusion of timber age as an additional factor complicates the accurate assessment of charring performance, as multiple factors can simultaneously influence the results. Due to the observed variability in charring rates for aged timber, it is recommended that a higher number of tests should be performed within the same material batch to obtain a statistically representative estimate of the expected charring performance.

Studies conducted in the past [19] [20] [21] have found that charring rates from cone calorimeter tests with a test duration of about 30 to 40 minutes are similar or even somewhat higher to those obtained from furnace tests (ISO 834 [12]). This difference could be related to the oxygen concentration in each test as described in [20]. While cone calorimeter tests are conducted under ambient room conditions with 21% oxygen, furnace tests are performed with oxygen levels below 10%. Whilst the cone test results tend to yield somewhat conservative charring rates, [19] suggests that a more accurate estimation of timber's charring rate can be obtained by considering not only the heat flux and charring rate but also the influence of oxygen concentration. Xu et al. [14] have further demonstrated how the cone test results can be transformed to equivalent charring rates for standard furnace tests. Considering both the existing literature and the results obtained in the present study, it could be stated that the cone testing is a useful tool for initial analysis of charring of aged timber, offering a sufficient basis to predict and compare charring behaviour in similar species when furnace testing is not feasible. Results reported from [14] indicated that the charring rate tended to be essentially constant when the fire exposure time exceeded 30 min, whilst being significantly higher with shorter test durations. This present study showed less scatter in the charring across all specimens in case of 30-minute tests (Figure 11), thus it would be recommended to test 30 minutes to compare the charring performance of different specimens with each other. This time frame aligns with previous studies with cone calorimeter [14] [19] [20], providing a solid basis for estimating charring in a furnace.

To enable a meaningful comparison and draw valid conclusions regarding the charring behaviour of different aged timber specimens, it is essential that the basis of comparison is as comparable as possible. Otherwise, variations in material properties such as density, grain

and annual ring orientation, species and moisture content could significantly influence the results, potentially obscuring the underlying differences in charring behaviour between old and new timber. Without controlling for these variables, it would be difficult to obtain reliable insights into the factors contributing to charring variations across the specimens. When testing wood samples of different origins and ages, inherent variations between the specimens are inevitable, making it challenging to consistently match specific characteristics such as the density and annual ring orientation. These differences complicate the ability to draw definitive comparisons between the test samples and their corresponding outcomes. As such, it is important to account for these factors when drawing broader conclusions also from this study.

Future research on the charring performance of timber should provide more detailed information and comparable test samples regarding grain and annual ring orientation, as well as density since these factors have been shown to significantly influence charring. This would enable more accurate comparisons and interpretation between different studies when other factors are in focus such as the age of timber.

## 5 – CONCLUSION

The aim of this paper was to determine the charring performance of reclaimed timber in relation to contemporary timber and to estimate if it is adequate to use contemporary procedures/design codes also for the aged timber in standard fire exposure conditions. Results from cone heater tests indicate that there is no clear trend between the charring rate and the age of timber. However, the charring rate of aged timber exhibits greater variation within a single material batch compared to new timber, which appears more homogeneous. Therefore, while additional tests and analyses are highly recommended to fully understand the variability in charring rates for aged timber, the current study suggests that the charring rate values provided in design codes such as Eurocode 5 are likely applicable to aged timber. In the future, cone heater tests should be complemented by additional material testing, such as permeability, to provide a more comprehensive understanding on the main influencing factors on charring and improve the interpretation and comparison of test results among other research studies.

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