Gypsum plasterboards under natural fire—Experimental investigations of thermal properties

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Abstract
The use of fire protection materials is a common approach to ensure the fire resistance of steel elements exposed to fire. In this article, experimental investigations regarding the thermal behavior of gypsum plasterboards for steel elements exposed to natural fires are presented. Material properties, such as the specific heat, the thermal conductivity, and the density of gypsum plasterboards, have been investigated yet, but not especially for natural fire scenarios with different heating rates and cooling phases. For this purpose, experimental investigations of gypsum plasterboards under natural fire exposure are presented. Based on our own experimental investigations, the thermal properties of the investigated gypsum plasterboard for both the heating and cooling phases are demonstrated. Additionally, results from a large-scale fire test on loaded steel beams as well as unloaded steel columns protected with gypsum plasterboards are presented. The test results show a clear dependency on the heating and cooling rate. Furthermore, the thermal material properties change within the heating and cooling phase. So, the main objective of this article is to provide the thermal properties of selected gypsum plasterboard exposed to natural fires in the heating and cooling phases.

KEYWORDS
cooling phase, fire protection, gypsum plasterboards, heating phase, material properties, natural fire

1 | INTRODUCTION

1.1 | Passive fire protection materials under natural fire

To meet a fire resistance steel components usually have to be protected for a severe fire exposure. In addition to reactive systems passive fire protection materials (FPM), such as gypsum plasterboards according to EN 520 (2009)\(^1\) are commonly used for theses purpose. The fire protection behavior of FPM leads to a delayed heating of the protected steel element and thus guarantees a sufficiently long fire resistance. If the calculation methods of the Eurocodes are to be used for the design of steel elements under fire exposure, for the thermal material properties of the FPM values must be known.

The fire protection behavior of FPM is typically derived by fire tests (EN 1363-1\(^2\)) according to the ISO 834 standard fire curve.\(^3\) Therefore, the assessment of the fire protection behavior of FPM is solely related to this fire scenario. Depending on the thickness of the FPM and the section factor of the steel element, fire resistances of R 30 to R 180 can be achieved. Based on the desired fire resistance class, some product manufacturers give values for the thickness of FPM depending on the steel section factor. In addition to the standard
fire curve, the centralized European rules for the fire design of structural elements in fire (EN 1993-1-2) also allow fire safety design with natural fire scenarios. A natural fire scenario is a more realistic and often more economical way of design that deviates from the standard fire curve. In contrast to the standard fire curve, which assumes a rapid and continuous rise in temperature, a natural fire curve consists of realistic heating and cooling phases. Natural fire curves depend on various parameters such as ventilation, room configuration and fire load (quantity and quality). Therefore, the heating and cooling rate can vary widely. As such, it is of great importance to know the fire protection behavior and likewise the thermal material properties of FPM in the case of natural fire.

In the German national annex of EN 1993-1-2 (2010), only constant temperature-independent material properties for selected FPM are provided, determined on the basis of component tests using the ISO 834 standard fire curve. The draft of EN 1995-1-2 contains temperature-dependent thermal properties of gypsum plasterboards in the heating phase, based on the investigation of protected wooden components under ISO 834 standard fire curve (cf. Schleifer). Additionally, the product manufacturers of FPM mainly provide constant material parameters. The thermal properties of FPM for natural fire scenarios cannot be obtained from the standard fire tests. In consequence, the thermal properties of FPM for different heating rates and cooling phases are required. Especially for the cooling phase, which distinguishes a natural fire from the ISO 834 standard fire curve, the thermal properties are unidentified yet.

Recent experimental studies show the temperature dependency of the thermal material properties of FPM. For a detailed investigation of the fire protection behavior of gypsum plasterboards, experimental small-scales test on gypsum plasterboard and a large-scale fire test with protected steel elements under natural fire were carried out. The article describes the basic idea of the experimental procedure and presents the main test results. For simulation purpose, temperature-dependent functions for the thermal material properties of gypsum plasterboards are presented. The results enlarge the knowledge of fire protection behavior of gypsum plasterboard and the application of temperature-dependent thermal properties under natural fire especially for the cooling phase.

2 | STATE OF THE ART

2.1 | Thermal decomposition of gypsum plasterboards

In general, gypsum plasterboards consist of a porous solid core of primarily calcium sulfate dihydrate CaSO\(_4\)·2H\(_2\)O between two layers of paper. During fire exposure, the chemically bounded water evaporate and a reversible decomposition process of the core material takes place. Up to 80°C, the reversible dehydration process of calcium sulfate dihydrate to calcium sulfate hemihydrate and then to calcium sulfate anhydrite occurs at 125°C and 150 to 225°C, respectively. The first and second dehydration process is given as a chemical Equations (1) and (2):

\[
\text{CaSO}_4 \cdot 2\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + \frac{3}{2}\text{H}_2\text{O} \quad (1)
\]

\[
\text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} \rightarrow \text{CaSO}_4 \cdot \frac{1}{2}\text{H}_2\text{O} + \frac{1}{2}\text{H}_2\text{O} \quad (2)
\]

Both dehydration processes are endothermic. At 375°C to 400°C, there is a third exothermic reaction from CaSO\(_4\) (III) to CaSO\(_4\) (II) (Equation (3)). The crystalline structure of gypsum transforms from a soluble to an insoluble anhydrite CaSO\(_4\), where energy Q released. Above 700°C calcium carbonate changes to calcium oxide and carbon dioxide. The exothermic reaction is given in Equation (4):

\[
\text{CaSO}_4(\text{III}) \rightarrow \text{CaSO}_4(\text{II}) + Q \quad (3)
\]

\[
\text{CaCO}_3 \rightarrow \text{CaO} + \text{CO}_2 + Q \quad (4)
\]

The dehydration processes and the chemical reactions characterize the temperature-depended thermal properties of gypsum plasterboards.

2.2 | Thermal properties of gypsum plasterboards—Literature data

The temperature distribution of a protected steel element under natural fire can calculated with the Fourier Equation (5):

\[
\frac{\partial}{\partial x} \left( \lambda \frac{\partial T}{\partial x} \right) + \frac{\partial}{\partial y} \left( \lambda \frac{\partial T}{\partial y} \right) + \frac{\partial}{\partial z} \left( \lambda \frac{\partial T}{\partial z} \right) - \rho c_p \frac{\partial T}{\partial t} = -\dot{q} \quad (5)
\]

Therefore, the thermal conductivity \(\lambda\), the specific heat capacity \(c_p\) and the density \(\rho\) must be known. In the literature, the thermal material properties for gypsum plasterboards are mostly given for the heating phase with different heating rates. The temperature-dependent material properties are determined experimentally, calibrated on fire tests with ISO 834 standard fire curve or usually modified or optimized with numerical simulations. In addition, various gypsum plasterboards (like Type F or Type X) are examined using various testing methods and procedures. According to chemical formulation of gypsum plasterboards, the thermal properties vary. This results in different courses of the thermal properties, which leads to a limited comparability. In Figure 1, the functions for the temperature-dependent thermal properties in the heating phase derived from literature data are shown. Furthermore, the own results are shown, which are explained further in detail.

For measuring the thermal conductivity \(\lambda\), for example, a thermal conductivity meter, TPS or a Laser flash apparatus (LFA) were used. Depending on the temperature, \(\lambda\) differs from 0.15 to 2.0 W/(m·K) in the heating phase. The literature data shows, that the temperature-dependent \(\lambda\) can be divided into four phases affected by several factors such as temperature, moisture content, porosity and appearance of cracks. First, \(\lambda\) shows a constant value up to 100°C, followed by a linear decrease to 200°C, again a constant value between 200°C and 600°C and a linear increase from 600°C. The
transformation processes of calcium sulfate dehydrate are reflected in the course of $\lambda$. At 100°C, the chemically bounded water in the gypsum plasterboard evaporate. Then, the reversible dehydration processes occur at 125°C and 150 to 225°C, respectively. This reduction of $\lambda$ occurs with increase of air pores between particles in the gypsum plasterboard with material expansion. After material transformation of CaSO$_4$ at 375°C to 400°C, $\lambda$ gradually increases again. At a temperature around 600°C, decarbonation generally occurs. The thermal conductivity increases due to crack development processes in the gypsum plasterboard. Details information of the phase transformation of gypsum plasterboards are clearly explained in References 9, 14, 15. Mehaffey$^{11}$ simplifies the variation of $\lambda$ into a bilinear course, with a linear decrease up to 200°C and a linear increase up to 0.12 W/(m·K) at 1100°C. However, the results of Lázaro$^9$ based on experimental and numerical investigations enable a sub-division of $\lambda$ into four phases in the range of 0.04 to 0.61 W/(m·K), which is slightly smaller compared to the other literature data. From 600°C, they only show a steeper increase of $\lambda$ up to 2.5 W/(m·K) to model the fire protection behavior of wooden components and Light gauge Steel Frames protected with gypsum plasterboards.

Furthermore, thermogravimetric analysis (TGA) measurements with heating rates of 10°C and 20°C/min were performed to determine the mass loss.$^7,11,16$ The literature data shows a decrease of mass at 200°C and 600°C, which is mainly caused by evaporation of chemically bounded water and the dehydration process. Depending on moisture content and temperature, mass loss up to 29% was
determined. Another mass reduction up to 6% occurs after 650°C following the decompositions of impurities of gypsum.\textsuperscript{17} At 1000°C, gypsum plasterboard density \( \rho \) is 71% to 90% of their value at ambient temperature. So, the literature data shows the correlation between mass loss and moisture content. While Hollmann et al\textsuperscript{a} and Mazello et al\textsuperscript{10} determined mass loss up in three phase up to 18% to -23%, Keerthan et al\textsuperscript{18} simplifies the mass loss as a shortly decrease up to 200°C following by a constant value.

The simultaneous thermal analysis (STA) was also used by References 8 and 9 to determine mass loss and specific heat capacity \( c_p \) simultaneously. In addition to STA, DSC was used with different heating rates (2, 5, 10, 20 K/min) to determine \( c_p \). The literature data of \( c_p \) shows a peak at 150°C to 200°C up to 30 000 J/(kg K), which results from the phase transformation (endothermic reaction).\textsuperscript{10} The higher the moisture content of the gypsum plasterboard, the higher the latent heat and the energy required for the evaporation process. The evaporation of the chemically bounded water withdraws energy, which is expressed in an increase of \( c_p \). According to König,\textsuperscript{12} the dehydration processes can be determined more precisely by using DSC with a heating rate of \(<5\text{ K/min.}\) Schleifer\textsuperscript{7} determines \( c_p \) with a heating rate of 20 K/Min, so the first peak of approx. 25 000 J/(kg K) occurs later then the peak of 30 000 J/(kg K), which was determined with a heating rate of 5 K/min (cf. König\textsuperscript{23}). Furthermore, the percentage of calcium sulfate dehydrate, can vary for different plasterboards depending on the manufacturer and affects the peak. The larger calcium sulfate dehydrate content, the higher the \( c_p \) peak at 150°C to 200°C.\textsuperscript{15}

In the temperature range from 200°C to 400°C, \( c_p \) is almost constant. At a temperature of 400°C, a short-term increase of \( c_p \) is due to the transition of the crystalline structure of CaSO\textsubscript{4}.\textsuperscript{9} Above 600°C, a further peak appears, which can be explained by the decomposition of calcium carbonate (CaCO\textsubscript{3}) with release of carbon dioxide. Depending on the temperature, \( c_p \) differs from 750 to 30 000 J/(kg K).

In total, the literature data shows the characteristic functions of the temperature-dependent thermal properties only in the heating phase. Accordingly, there is a lack of information, how the thermal properties of gypsum plasterboards behave in the cooling phase.

3 | EXPERIMENTAL INVESTIGATIONS

3.1 | Specimens and experimental test procedures

To determine the fire protection behavior of protected steel elements under natural fire curve, it is necessary to know the temperature-dependent material properties for both the heating and cooling phases, since the thermal material properties deviate according to the temperature. Using thermo-analytical measurement methods and procedures, \( \lambda \), \( c_p \), and \( \rho \) are determined as a function of temperature.

For the experimental investigations gypsum plasterboards (Typ F, \( \lambda_{20\text{C}} = 0.23 \text{ W/}[\text{m-K}], \rho_{20\text{C}} = 780 \text{ kg/m}^3 \)) were used. The \( \lambda \) was measured with the Transient Plane Source (TPS) method according to DIN EN ISO 22007-2 (2015).\textsuperscript{13} The differential scanning calorimetry (DSC) analyses in accordance with DIN 51007 (1994)\textsuperscript{19} are performed in order to determine \( c_p \). Additionally, the temperature-dependent mass loss of the gypsum plasterboards are determined by TGA according to DIN 51006 (2005).\textsuperscript{20}

Previously, fire simulations with computational fluid dynamics-models and zone models were carried out to determine the heating and cooling rates in different room and use configurations.\textsuperscript{21} The results were evaluated statistically. The mean values of the heating rate (20 K/min) and cooling rates (6 K/min) were selected from a static distribution. Due to the thermo-analytical measuring methods and procedures, the heating rate of 10 K/min, 40 K/min and the cooling rate of 10 K/min were additionally selected. The experimental results from the thermo-analytical measuring methods and procedures are provided in the following.

3.2 | Temperature-dependent thermal conductivity

For measuring \( \lambda \) a sensor, which works as a thermocouple (TC) and plane heat source at the same time, was placed between two identical samples of gypsum plasterboards. The samples including the sensor were clamped in a sample holder and positioned in a furnace. A muffle furnace VECSTAR Ltd. LF 2 SP, a Kapton 8563 sensor and a Mica 4921 sensor were used for the experimental setup (see Figure 2).

Due to the measuring equipment, the measuring boundary conditions were limited to temperatures of up to 400 to 500°C and heating rates of \(-10\text{ K/min.}\) For comparability of results, the samples were preconditioned. The 80 x 80 mm\textsuperscript{2} samples of gypsum plasterboard were previously dried for 24 hours at 40°C before the thermal conductivity measurement was performed. Due to the sample holder the thickness of the samples was limited to \( t = 20 \text{ mm.}\) The results can be transferred to comparable thicknesses. The samples were characterized both at room temperature and at elevated temperature. Figure 3 displays the results of \( \lambda \) for the heating and cooling phases. For comparison, the constant value \( \lambda \) for gypsum plasterboards according to the National German Annex of EN 1993-1-2 (2010)\textsuperscript{5} is also given. The measurement results of \( \lambda \) for the heating and cooling phase are shown, along with the statistical distribution of 24 measurement values per temperature step.

The temperature-dependent thermal conductivity was measured during constant heating and cooling (at a rate of \(-10\text{ K/min.}\) until 500°C. The thermal conductivity shows a range of variation. At 100°C in particular, a large scattering of \( \lambda \) was observed SD >0.1), which correlated to the moisture content and the evaporation of the free and chemically bound water of the gypsum plasterboard. In addition, the range of variation can be caused by the pore content/structure and the chemical transformation processes in the gypsum plasterboard (cf. Zehfuß et al\textsuperscript{21}). Besides, \( \lambda_{26\text{C}} \) is slightly higher than the manufacturer value of \( \lambda_{26\text{C}} = 0.23 \text{ W/(m-K)}.\)

The experimental results clearly show that \( \lambda \) is temperature dependent. In comparison to the simplified constant value for \( \lambda \) according to German National Annex of DIN EN 1993-1-2 (2010),\textsuperscript{5} the measured thermal conductivity differs with temperature and in the heating and
cooling phases. In addition, chemical and physical processes can be clearly identified in the temperature-dependent curve of $\lambda$. The measurement results of the gypsum plasterboard in the heating phase were noticeably characterized by the first and second dehydration.

In the cooling phase, the measured values for the thermal conductivity are lower (see Figure 3). It can be assumed that the gypsum plasterboards were subjected to irreversible material changes due to temperature exposure during the heating phase.
3.3 | Temperature-dependent specific heat capacity

In order to measure the specific heat capacity of the investigated gypsum plasterboard, DSC analyses were performed according to DIN 51007 (1994)" and ISO 11357-1 (2016)." For the determination of \( c_p \), a Mettler Toledo DSC 822e with a temperature sensor of \(-180^\circ C\) to \(700^\circ C\) was used. The samples were placed in the sample holder with small quantities in the mg range (9.6-11.22 mg, total three samples). Therefore, the gypsum plasterboards were crushed and pulverized. The samples were placed inside aluminum crucibles and a sapphire reference sample of \( \alpha - Al_2O_3 \) was used. The DSC analyses were performed under nitrogen atmosphere (flow rate 35 mL/min). Both samples (gypsum plasterboard and sapphire reference) were subjected to the same temperature program, whereby the heat flow differences between the sample and the reference sample were measured. The heat flow differences give information about the reaction and evaporation enthalpy of the investigated gypsum plasterboard.

During the heating phase (up to \(600^\circ C\)), the DSC analyses were carried out for heating rates of 10 K/min and 20 K/min. The heat capacities for the cooling phase were calculated for cooling rates of 6 K/min and 10 K/min. The temperature-dependent specific heat capacity (a mean value of three tests) are shown in Figure 4. The left figure shows the entire measurement data and the right figure a selection in the range of 0 to 5 kJ/(kg.K).

Based on the results, it can be seen that \( c_p \) is temperature- and heating-rate dependent. Additionally, \( c_p \) diverges in the heating and cooling phases. Accordingly, the assumption of a constant value does not justify the temperature-dependent \( c_p \).

For the gypsum plasterboard (see Figure 3), a high increase in heat capacity occurs at 100-200°C, resulting in maximum values of 21 kJ/(kg.K) at 140°C for 10 K/min and of 18 kJ/(kg.K) at 150°C for 20 K/min, respectively. The high double peak is caused by the two dehydration processes of the gypsum. The higher the heating rate, the later the peaks occur. With a further temperature increase, the heat capacity remained nearly constant. After 400°C, \( c_p \) increased a second time up to 5 kJ/(kg.K) due to the decarbonation. The influence of the heating rate can be seen in the measurement data. However, the qualitative course of \( c_p \) is the same. After the heating phase (heating rate 20 K/min), the cooling phase (cooling rate 6 K/min) was tested, at 10 K/min for the heating and following cooling phases. The discontinuity of \( c_p \) from the heating into the cooling phase can be attributed to the changeover point from the heating phase to the cooling phase. Due to the DSC measurement equipment, there is a short time period between the heating and cooling phases. Therefore, there is a gap in the experimental data between the heating and cooling phases in Figure 4. The lower the maximum temperature, the lower the gap.

During the cooling phase, \( c_p \) was nearly constant between 0.45 and 0.9 kJ/(kg.K). The measurement results in the cooling phase demonstrated that the cooling rate affected \( c_p \). In the cooling phase, the measured values for \( c_p \) are lower at a cooling rate of 10 K/min than at a cooling rate of 6 K/min. However, the direct influence of the cooling rate on the measured \( c_p \) cannot be clearly derived from these data, because \( c_p \) had been previously determined at different heating rates. Overall, the test results of the cooling phase depend on the maximum temperature and heating rate of the heating phase and the cooling rate itself. Nevertheless, the values can be used to show that the \( c_p \) decreases or stays nearly constant as the temperature is reduced. At ambient temperature, the temperature and heating rates dependent on \( c_p \) are scattered between 0.40 and 0.78 kJ/(kg.K).

3.4 | Mass loss and temperature-dependent density

A total of 24 samples were measured at ambient temperature to determine the density of the investigated gypsum plasterboard. The initial \( \rho \) of the investigated gypsum plasterboard was determined to be 807 kg/m³ (moisture content 2.63%). As the initial \( \rho \) of the investigated gypsum plasterboard changes due to mass loss and is affected by the moisture content, the curves given in Figure 5 show a dependency on the heating rates. In order to calculate the temperature dependent density, TGA according to DIN 51006 (2005)" were performed in a temperature range of 20°C to 1000°C for samples of 9.59 mg to 10.33 mg using a TGA/DSC 1 from Mettler Toledo. The analyses were carried out under oxygen (flow rate 50 mL/min) for
Temperature- and heating-rate dependent mass loss of a gypsum plasterboard

10 K/min, 20 K/min and 40 K/min in the heating phase as well as for 6 K/min and 10 K/min in the cooling phase. The samples were taken in a ceramic crucible, which was then placed on the thermal balance of the TGA equipment. Briefly, the TGA/DSC recorded and plotted mass loss at various temperatures. Assuming that the volume change of the samples was negligible (thermal expansion of gypsum 1.2·10^{-4} mm/K) as the temperature increased, the temperature-dependent density is based on the measurement results of mass loss.

The temperature-dependent mass loss and the density decreased during the heating phase. The irreversible maximum mass loss was determined to be 23% at 1000°C for 10 K/min, 20 K/min and 40 K/min, respectively. Therefore, \( \rho \) was reduced to 621 kg/m³ at 1000°C. The lower the heating rate, the earlier the mass loss occurred. The mass loss correlated to the chemical and physical processes in the gypsum plasterboard. The chemical and physical processes were shown in the course of the mass loss. Therefore, the two dehydration reactions in the gypsum plasterboard, which took place with the increase in temperature, were shown as a mass loss of 18% at 100 and 200°C (see Figure 5).

In the cooling phase, the results showed that the cooling rate is irrelevant. After the mass loss occurs in the heating phase, a constant value of the mass and the density can be assumed. The lower the temperature of the heating rate, the lower the mass loss and the higher \( \rho \) in the cooling phase.

4 | LARGE-SCALE FIRE TEST

4.1 | Test specimens and the test procedure

In order to investigate the influence of a natural fire scenario on the fire protection behavior of gypsum plasterboards, a large-scale fire test was performed at the testing facility of the Institute of Building Materials, Concrete Construction and Fire Safety (iBMB) at TU Brunswick (Germany). The natural fire curve was selected as a representative fire curve from a large number of simulations.14 The large-scale fire test was intended to test the application of the thermal material properties. In addition, scaled effects were investigated more closely since they were not taken into account by the thermo-analytical tests. In particular, the crack behavior, the joint formation and the fire protection behavior of the gypsum plasterboard with and without loads were investigated. One unloaded I-section columns (HEA 240) with a length of 1000 mm was used as test specimens as well as one loaded I-section beam (HEA 240, length 4900 mm). Gypsum plasterboard was applied to protect the steel elements. In the following the results of the unloaded and loaded specimens with gypsum plasterboard will be presented.

To estimate the fire protection behavior of the gypsum plasterboard, the test specimens were boxed with a single-layer of gypsum plasterboard (20 mm thickness). Other thicknesses were not investigated. To ensure a three-sided fire exposure, the beam was dispersed under the furnace ceiling, which consisted of cover panels made from aerated concrete. The column was placed on the bottom of the furnace, thus ensuring a four-sided fire exposure. The free ends of the test specimen were covered by 20 mm thick insulation boards made from vermiculite. In order to avoid heat transfer into the test specimen, the protected steel column was additionally placed on 20 mm of thick rock wool and plaster.

The loaded steel beam with gypsum plasterboard was designed as a single-span beam with a length of 4.90 m. Additionally, the loaded steel beam had two load bearing points at the third points of the length, which were applied with a constant load of 40 kN to achieve a 30% utilization of the steel beam. In order to prevent the gypsum plasterboard from falling off, the protected steel beam was loaded less. However, for the loaded specimen, the load was applied according to a two-point bending test (see Figure 6).

The target parameters in the large-scale fire test were the temperatures and the deformations of the specimens. The temperature of the test specimens was measured by TCs type K, which were welded to the flanges and webs. Temperatures were measured at two positions (1/2 · length, 4/5 · length) on the column. In the case of the loaded beam, the steel temperatures were measured at four positions across the length. The locations of the TCs are shown in Figure 7 for each test specimen.

In order to control and to record the temperature inside the furnace, plate TCs were installed near the test specimens. The natural fire curve shown in Figure 8 could, therefore, be implemented using the gas burners. Further information on the determination of the natural fire curve is given in References 14 and 21. The deformation of the loaded steel beam was measured with potentiometers at the load bearing points (in the x and y axis of the beam). The development of the mechanical load during the fire test is shown in Figure 8. Initially, the load was increased to the desired load level of 40 kN. After a preload time of 15 minutes. The fire test was started and the load was kept constant.

The natural fire curve is characterized by a non-linear heating phase (heating rate ~ 20 K/min) that reaches its maximum temperature of 852°C after 31 minutes. At this point the temperature exceeds the standard time-temperature curve for a short period of time (see Figure 8). The cooling phase of the natural fire curve shows an approximately bilinear behavior with a change in the cooling rate after
50 minutes. Before 50 minutes, the furnace temperature was controlled by the gas burner, and afterwards a natural, uncontrolled cooling phase in the furnace took place (see Figure 8). At this point, the load was removed to avoid the fall off of the gypsum plasterboard.

### 4.2 Test results

The measured temperatures of the steel profiles of the beam (1/2 length) and column (1/2 length) with gypsum plasterboard (20 mm thickness) are shown in Figure 9.

During the heating phase, the furnace temperature and the steel temperature rose continuously. Due to the thermal fire protection behavior of gypsum plasterboard, the steel temperatures were below the furnace temperature. The natural fire scenario reached its maximum temperature of 852°C after 31 minutes. The temperature development inside the column was more homogeneous than the beam due to the four-side fire exposure.

In the cooling phase, all test specimens showed lower cooling rates when compared to the furnace temperature, resulting in a
temperature difference of 110 °C to 300 °C. This temperature difference between the test specimens and the gas temperature in the furnace was due to the inverted insulation effect of the gypsum plasterboard and the thermal inertia of the steel profiles HEA 240. Further details are shown in Reference 14.

5 | PROPOSAL FOR TEMPERATURE-DEPENDENT FUNCTIONS FOR THERMAL PROPERTIES

For modeling the thermal behavior of the gypsum plasterboard, temperature-dependent functions for the thermal properties have to be defined. So, based on the experimentally gained data a proposal for temperature-dependent functions is formulated. The thermal properties \( \lambda \), \( c_p \), and \( \rho \) were determined up to 600 °C with different heating and cooling rates. Thus, the authors had to make assumptions about the temperature-dependent functions of the thermal properties for >600 °C, due to the missing measurement data. Figure 10 shows the proposal for temperature-dependent functions of the thermal properties for gypsum plaster board.

For the derivation of the proposed functions in a first step the measured values were used and secondly calibrated with the temperature results of the large-scale fire test to ensure the application for fire design of real structures. Therefore the functions of \( \lambda \), \( c_p \) and \( \rho \) were optimized until the best temperature-dependent curve was obtained.

Due to the irreversible material behavior of gypsum plasterboard, the temperature-dependent function for the heating phase could not be used for the cooling phase. Different maximum temperatures, heating and cooling rates are possible, depending on the natural fire scenario. The temperature-dependent functions presented were designed for one natural fire scenario. The change from the heating phase to the cooling phase, as shown in Figure 10, must be taken into account by \( \Theta_x < \Theta_{x-1} \) (with \( x \): Time [min]). This raises the question of whether the cooling phase has an effect at all. The transition criterion from heating to cooling phase were designed for the investigated natural fire. Applicability to other natural fires with different heating and cooling phases as investigated here have to be proofed carefully.

![Figure 10: Temperature-dependent functions of the investigated gypsum plasterboard](image_url)
The temperature-dependent functions for the investigated gypsum plasterboard under natural fire of up to 1000°C are also given in Figure 10. For λ, the mean values of the TPS measurement for both the heating phase and the cooling phase have been reduced by an average of ~30% due to high variation in the measured values and the fact that the TPS achieves slightly higher measured values (see Figure 3). The λ values were modified until the best temperature-dependent curve was achieved. The thermally induced crack formations, which were also detected in the large-scale fire test, were simplified by increasing λ from temperatures of 500°C upwards (cf. References 8 and 9). Further, shrinkage, cracks and ablation of gypsum plasterboards is simplified modeled by increasing λ starting from 600°C. The temperature-dependent curve of \( c_p \) was derived from the DSC data (up to 600°C), with a heating rate of 20 K/min (see Figure 4). No experimental data was available for temperatures >600°C, so a constant value of \( c_p = 2.2\, \text{kJ/(kg·K)} \) up to 1000°C was assumed. A constant value of \( c_p = 2.2\, \text{kJ/(kg·K)} \) was also used for the cooling phase. The density was specified in the heating phase according to the TGA measurements of up to 1000°C and a heating rate of 20 K/min depending on the temperature (see Figure 5). During the cooling phase, the density was set at \( \rho = 702.09\, \text{kg/m}^3 \) (0.71 · \( \rho_{20°C} = 807\, \text{kg/m}^3 \)).

6 | CONCLUSIONS

The main objective of this article is to show the difference in the thermal properties of selected gypsum plasterboard in the heating and subsequent cooling phase. Furthermore, the fire protection performance of gypsum plasterboards under natural fire was investigated. This was achieved by experimental fire tests at both small and large scale. The temperature and heating-rate-dependent material properties of the gypsum plasterboard, such as \( \lambda, c_p, \) and \( \rho \), were determined experimentally. The investigated gypsum plasterboard reveals a clear dependency on heating and cooling rates. However, currently only constant values of thermal properties for the cooling phase exist. This is due to the fact that the fire protection behavior of gypsum plasterboards is solely assessed for fire exposure according to the standard fire curve. As the temperature regime of a natural fire scenario can deviate significantly from the standard fire curve, it is highly recommended to assess the influence of varying heating and cooling conditions on the thermal behavior of the investigated gypsum plasterboard.

The fire protection behavior was tested in a large-scale fire test under a natural fire curve, both with and without mechanical load. The influence of the mechanical load on the thermal behavior of the gypsum plasterboard seems to be small, as an effect on the fire protection behavior of the gypsum plasterboard was not evident (see Figure 9). Only an increased number of cracks (temperature and load induced) and the temperature dependence of the material properties was determined. But the beam utilization (30%) was comparatively low, so further research is needed to investigate possible correlation between fire protection behavior and load utilization.

The results of the large-scale fire test were used to calibrate the thermal material properties. Based on these thermal material properties, temperature-dependent functions of gypsum plasterboard for the heating phase and especially for the cooling phase were derived. Due to the wide range of fire protection boards and natural fires, the experimental procedures and boundary conditions presented in this article can only be applied when the required material properties of the investigated gypsum plasterboard and the natural fire (heating and cooling rate) are comparable.

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DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

1. European Committee for Standardisation. EN 520:2009-12. Gypsum plasterboards - Definitions, requirements and test methods.
2. European Committee for Standardisation. EN 1363-1:2012-10. Fire resistance tests—Part 1: General Requirements.
3. International Organisation for Standardisation. ISO 834-11:2014. Fire resistance tests—Elements of building construction—Part 11: Specific requirements for the assessment of fire protection to structural steel elements.
4. European Committee for Standardisation. EN 1993-1-2:2010-12. Eurocode 3: Design of steel structures—Part 1-2: General rules—Structural fire design. German version.
5. German Institute for Standardisation. DIN EN 1993-1-2/NA: 2010-12. National Annex - Nationally determined parameters—Eurocode 3: Design of steel structures—Part 1-2: General rules—Structural fire design.
6. European Committee for Standardisation. EN 1995-1-2. Eurocode 5: Design of timber structures—Part 1-2: General—Structural fire design; German version, 2010.
7. Schleifer, V. Zum Verhalten von raumabschließenden mehrschichtigen Holzbauteilen im Brandfall [Dissertation] ETH Zürich. https://doi.org/10.3929/ethz-a005771863, 2009.
8. Hollmann D, Schnetgöke R. Thermische Materialkennwerte von plattenförmigen Bekleidungsmaterialien für den Nachweis brandbeanspruchter Stahltragwerke. 3rd Workshop Structural Fire Engineering 2016, Technische Universität Braunschweig, paper 6, p. 1–16.
9. Lázaro D, Puente E, Lázaro M, Lázaro PG, Peija J. Thermal modelling of gypsum plasterboards assemblies exposed to standard fire tests. Wiley Fire Mater. 2016;40:568–585. https://doi.org/10.1002/fam.2311.
10. Manzello SL, Gann RG, Kuckuk SR, Lenhert DB. Influence of gypsum board type (X or C) on real fire performance of partition assemblies. Fire Mater. 2007;31:420–442. https://doi.org/10.1002/fam.940.
11. Mehaffey JR, Cuerrier P, Carisse G. A model for predicting heat transfer through gypsum-board/wood-stud walls exposed to fire. Fire Mater 18, Seite 297–305, 1994.

12. König J. Fire exposed simply supported wooden I-joists in floor assemblies, SP Swedish National Testing and Research Institute, SP Report 2006: 44, Stockholm, 2006.

13. European Committee for Standardisation. EN ISO 22007-2:2015-12. Plastics—Determination of thermal conductivity and thermal diffusivity—Part 2: Transient plane heat source (hot disc) method (ISO 22007-2:2015); German version.

14. Zehfuß J, Schaumann P, Sander L, Weisheim W. Prüfverfahren für thermische Materialkennwerte von Brandschutzbekleidungen und reaktiven Brandschutzsystemen für die Bemessung von Stahltragwerken bei Naturbränden. Schlussbericht zu IGF-Vorhaben Nr. AIF 19176. Deutscher Ausschuss für Stahlbau (DAST), 2018.

15. Dodangoda MT, Mahendran M, Keerthan P, Frost RL. Developing a performance factor for fire rated boards used in LSF wall systems. Fire Safety J. 2019;109:102872.

16. Ghazi Wakili K, Hugi E, Wullschleger L, Frank Th. Gypsum board in fire—Modeling and experimental validation. J Fire Sci 25, Seite 267–282, DOI: https://doi.org/10.1177/0734904107072883, 2007.

17. Sultan MA, Lougheed GD. Results of fire resistance tests on full-scale gypsum board wall assemblies. IR-833, Institute for Research in Construction, National Research Council of Canada, January 2002.

18. Keerthan P, Mahendran M. Numerical studies of gypsum plasterboard panels under standard fire conditions. Fire Safety J. 2012;53:105–119.

19. German Institute for Standardisation. DIN 51007:1994-06. Thermal analysis; differential thermal analysis; principles.

20. German Institute for Standardisation. DIN 51006:2005-07. Thermal analysis (TA)—Thermogravimetry (TG)—Principles.

21. Zehfuß J, Sander L, Schaumann P, Weisheim W. Thermische Materialeigenschaften von Brandschutzmaterialien für Naturbrandbeanspruchung. Ernst Sohn, 2018, Bautechnik;95(8):535–546. https://doi.org/10.1002/bate.201800033.

22. International Organisation for Standardisation. DIN ISO 11357–1:2017-02. Plastics - Differential scanning calorimetry (DSC) - Part 1: General principles (ISO 11357-1:2016); German version.

23. Jansson R. Measurement of thermal properties at elevated temperatures – Brandforsk project 328–031. SP Swedisch National Testing and Research Institute 2004, SP Report 2004: 46.

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