

# Thermal properties of reinforced concrete for containment pressurisation studies: state of the art and proposals for best estimate and conservative values

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**Abstract.** In case of loss of coolant accident or severe accident in a nuclear pressurised water reactor, the containment pressure must remain below the design pressure to prevent radioactive releases. The evolution of containment pressure can be estimated by computer codes such as ASTEC or MAAP. However, especially for severe accident, the pressurisation kinetics during the first 24 hours is very sensitive to the thermal properties of the containment concrete, which stores most of the decay heat. A wide range of thermal properties (thermal conductivity, specific heat and density) of concrete and reinforced concrete can be found in the literature, depending on the concrete temperature, composition and relative humidity. This paper presents a review of available thermal properties for concrete and reinforced concrete and makes some proposals for best estimate and conservative properties to calculate the evolution of the containment pressure during the first 24 hours after the accident initiator.

## 1 Introduction and context

During a loss of coolant accident in a nuclear Pressurised Water Reactor, due to steam condensation on the walls and thermal heat exchange between the gas phase and the walls, most of the decay heat is transferred and stored in the containment concrete. This is particularly crucial in the event of a severe accident, such as one involving a core meltdown, where the decay heat builds up in the containment concrete over tens of hours. This transfer is still stronger in case of corium flooding in the ex-vessel phase, implying a massive steam production and condensation on the walls, together with a fast pressurisation of the containment. Such ex-vessel corium flooding is implemented in the severe accident management strategy for EPR reactors and currently deployed for the French operating plants [1]. During the first 24 hours of some specific severe accident<sup>1</sup>, it is the main part of the decay heat which is transferred and stored in the concrete. Consequently, the evaluation of containment pressure is very sensitive to the thermal properties of the containment con-

crete. For this type of scenario, ASTEC V2.0 simulation shows impact on the containment pressure at 24 hours of:

- 0,5 bar decrease for a thermal conductivity ( $\lambda$ ) increase from 1,7 W/m.K to 2 W/m.K;
- 0,75 bar decrease for a specific heat ( $C_p$ ) increase from 750 J/kg.K to 900 J/kg.K.

The sum of these two contributions, due to sensitivity of pressure calculations to concrete properties is above 1 bar, which represents an excessive uncertainty, considering the objective to not exceed the design containment pressure of 5 bars.

That is why relatively precise thermal properties – thermal conductivity ( $\lambda$ ), specific heat ( $C_p$ ) and density ( $\rho$ ) – of concrete are required, in the temperature range of 20°C to 150°C, for such safety evaluations. However, a wide range of thermal properties of concrete can be found in the literature. For example, in the considered bibliography, the thermal conductivity of concrete, based on experiments, varies from 1,0 W/m.K to 2,6 W/m.K (a discrepancy far above the 0,3 W/m.K variation considered in the previously mentioned sensitivity). Such uncertainty precludes any reliable assessment of the containment pressure.

The Eurocode [2] provides proposals for concrete thermal properties, but these have been established with a different objective (mechanical stability, fire conditions,

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<sup>1</sup> 4' Cold leg break Loss Of Coolant Accident (LOCA) on a French 900 MWe, with limestone concrete, assuming the failure of recirculation and associated loss of safety injection and containment spray system.

conservative values,...), and are not suited for the pressure containment issue. In our case, a different approach is required to establish:

- best-estimate values;
- conservative values, but not too penalizing, minimising the thermal properties to maximise the pressure containment.

In this paper, a comprehensive review of experimental data available in the literature is conducted to provide proposals for both best estimate and conservative values. It is noteworthy that, for well-characterized concrete compositions, alternative theoretical approaches may be employed. The thermal properties of concrete can be inferred from the thermal properties of its constituents, including aggregate particles, cement, pores, and steel, as well as their relative proportions and distribution. Instances of this methodology are documented in [3,4] for concrete, and [5] for reinforced concrete. The specific heat could also be theoretically assessed based on thermodynamic equilibrium solvers. Nevertheless, this approach is only applicable to well-defined concrete. Such detailed information regarding the constituents of reactor containment concrete is usually not available.

In severe accident case, with molten corium concrete interaction, due to their properties (higher gas content and ablation temperature) limestone or limestone common-sand concrete are more efficient to cool the corium, protect the containment basement and transfer the decay heat to the water, compared to siliceous ones. But the drawback is that they lead to larger steam production and higher pressurisation of the containment. The risk to exceed the containment design pressure is higher for reactors with limestone and limestone common-sand concretes. Consequently, the need of accurate thermal properties for containment pressurisation studies are more important for these types of concretes. However, all the various concrete composition (limestone and siliceous) will be considered to present the most complete analysis.

The review of literature is performed in Sections 2–6, which also present the analysis leading to critically assessed values for respectively thermal conductivity, specific heat, density and thermal diffusivity. Section 7 focuses on the way to extend recommended values to reinforced concrete, such as those of the reactor containments. The synthesis in Section 8 suggests operational values for the safety analysis calculations.

## 2 Literature review

The references analysed in the present study are reported in Table 1. Most of the references come from the US NRC NUREG [6] compilation of concrete properties data. It has been completed with additional references, mainly from French PHD reports.

Only normal-strength concretes have been considered while high-strength concretes have been not considered. It must be stressed that, only references providing experimental results or relation between the thermal properties and the temperature have been included in the analysis.

Some references estimating the thermal conductivity of the concrete by calculation from the thermal conductivity of the aggregate and the cement have not been considered anymore in this paper ([4] for example).

## 3 Thermal conductivity of concrete

On Figure A1, in annex, are reported all the thermal conductivity measurements as a function of temperature. For Kallel [7] and Zhang [3], the thermal conductivity is given as a function of temperature but also of the relative humidity. Consequently, for these two authors, they cannot be directly plotted on such graph as one unique curve. For sake of simplicity, only two Kallel's curves (with associated data) are included those with 40% and 100% of relative humidity. For Zhang [3] the range of variation for the whole relative humidity range is drawn.

### 3.1 Concrete composition influence

Most of the authors characterise the thermal conductivity as a function of the temperature, for each studied concrete composition (limestone, siliceous, ...) ([5,8–11,13–18]). Some authors indicated that siliceous concretes have a higher thermal conductivity than limestone ones [10,11,19]. However, Figure A1, and Figure 1 below do not evidence a strong impact of the concrete composition. In the low conductivity value range, it can be noticed that both siliceous and limestone concretes of Noh [5], have comparable values. In the high conductivity value range, at room temperature, there is 0,6 W/m.K of discrepancy between the Nguyen [11] and Mindeguia [10] conductivity, despite the fact they have similar composition, indicating that other factors than composition possibly play a key role in the variation of thermal property. In the same way, at higher temperature (100°C), for siliceous (Kallel [7]), limestone-common sand (Vodak [9]) and limestone (Nguyen [11]) concrete, similar values are reported. Moreover, the conductivity at room temperature, for various relative humidity, of Kallel [7] (siliceous) and Zhang [3] (limestone) are consistent, despite the difference of composition<sup>2</sup>. From these data, it cannot be assessed that the concrete composition can be considered to have a first-order impact on thermal conductivity.

### 3.2 Relative humidity influence

It can be noted in Figure 1, that the low conductivity values ( $\lambda < 1,7$  W/m.K) refer mainly to dried concrete, or experimental data without any indication of the relative humidity. On the opposite the high conductivity values ( $\lambda > 1,9$  W/m.K) are mainly associated to moist concrete, or data without any indication about the relative

<sup>2</sup> This comparison is not drawn in the present paper. Please refer to their publication.

**Table 1.** Literature review.

Reference	SiO <sub>2</sub> /CaO Content	$\lambda$	$C_p$	D	$\rho$	Comment
Kallel (2016) [7]	72%/13%	X	X	X		PHD report (French) <i>Measurements</i> at 30°C and 90°C for various relative humidity
Shin (2002) Yonggwang 3 & 4 [8]	56%/16%	X	X	X	X	<i>Measurements and temperature-dependent function</i> Undried concrete at low temperature (20°C) and high temperature (500°C, 700°C and 900°C)
Vodak (1997) [9]	48%/25%	X	X	X		Undried concrete at 50°C, 100°C, 150°C and 200°C
Mindeguia B40SC (2009) [10]	29%/38%	X	X	X	X	PHD report (French) – <i>Measurements</i> of undried concrete at 20°C, 150°C, 300°C and 600°C
Mindeguia B40 (2009) [10]	19%/63%	X	X	X	X	
Nguyen (2013) [11]	20%/64%	X	X	X	X	PHD report (French) – <i>Measurements</i> of undried concrete at 80°C, 150°C, 300°C and 450°C
Zhang (2015) [3]	Unknown – Limestone	X				<i>Measurements</i> at various relative humidity at 35°C
Noh (2017) Fire protection [5]	Unknown – Limestone & Siliceous	X				<i>Temperature-dependent function</i> high temperature (> 800°C) concrete/dry concrete
Kalifa (2000) (quoted by [7])	Unknown – Limestone	X				Dry concrete 100°C, 200°C, 300°C and 400°C
Crispino (1972) [14] (quoted by [12])	Unknown – Limestone	X				<i>Measurements</i> between 0°C and 200°C
Hundt (1975) [17] (quoted by [12])	Unknown – Limestone	X				<i>Measurements</i> at room temperature for one concrete and 20°C, 50°C and 100°C for another one
Muir (1977) [18] (quoted by [12])	Unknown – Limestone	X				<i>Measurements</i> at 100°C, 200°C, 400°C, 1000°C
Harmathy (1970) [15] (quoted by [12])	Siliceous gravel & limestone	X		X	X	<i>Measurements</i> at 20°C, 100°C, 200°C, 300°C, and 500°C, 600°C, 700°C, 1000°C for one concrete
Schneider (1976) [16] (quoted by [12])	Basalt (full scale test, dried and moist)	X				<i>Measurements</i> at room temperature for two concretes, and 20°C, 70°C, 100°C, 250°C, 400°C for another one
Harada (1970) [13] (quoted by [12])	Siliceous gravel for two compositions	X		X		<i>Measurements</i> at 20°C, 100°C, 350°C, 550°C and 750°C
Bazant (1996) [23] (quoted by [6])	Unknown – Limestone & Siliceous		X			<i>Measurements</i> for 3 limestone concrete and 2 siliceous globally every 100°C between 0°C and 700°C (with exceptions)
Granger (1995) [24]	Various French NPP concrete				X	<i>Measurements</i> at room temperature
EUROCODE [2]	Unknown	X	X		X	<i>Relation function of temperature</i>

humidity. This increase is also coherent with the results of Kallel [7] and Zhang [3], which show a variation of 0,6 W/m.K from 40% to 100% of relative humidity. This will appear to be the main parameter that influences thermal conductivity.

This variation raises the question of the relative humidity of the reactor containment concretes. Courtois [20], based on Oxfall work [21] reported the measurements and estimates of the relative humidity of various places in the containment wall of the Ringhals Nuclear Power Plant. The relative humidity decreases with ageing of the containment and is higher inside the wall compared to the

edges. The results indicate that the main part of the concrete, after 60 years of ageing, is in the range of 65% to 70% of relative humidity. In case of a severe accident, this initial moisture content will evolve according to two opposite phenomena:

- on one hand, heating of the containment may dry the concrete, decreasing the thermal conductivity. But, considering the great thickness of the wall, during the first 24 hours of an accident, this phenomenon is assumed to be negligible.
- On the other hand, the concrete may become wet due to the condensation on the interior surface of the contain-

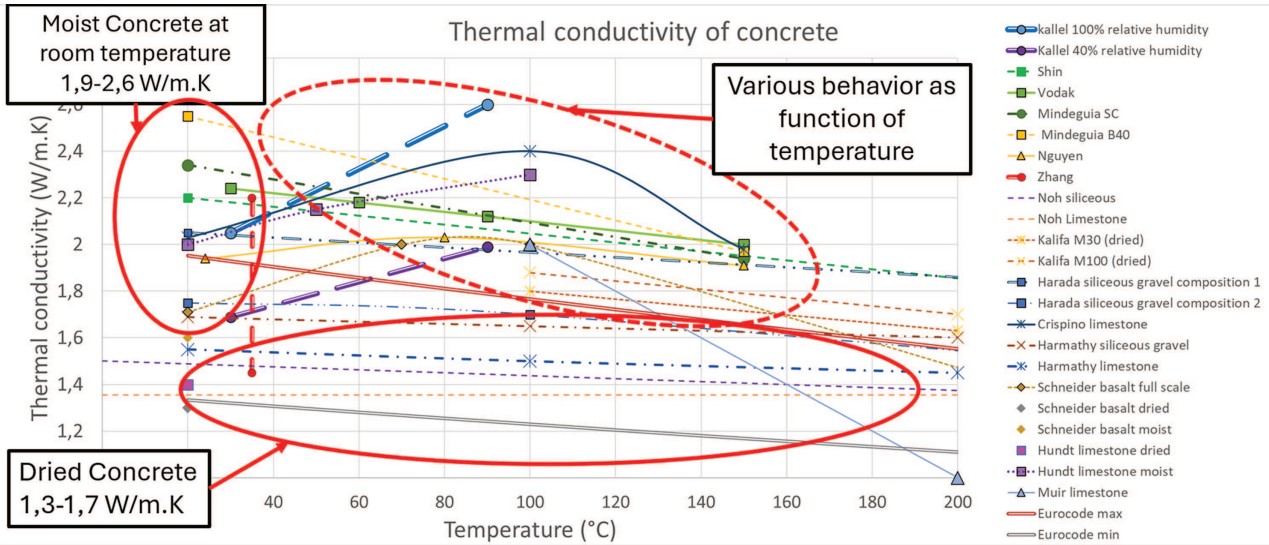


Fig. 1. Main thermal conductivity variation ranges.

ment. For containment with a metallic liner, this phenomenon should be absent. For the containment without liner, it should lead to an increase of the conductivity. By considering the wall thickness, it is also assumed to be negligible, during the first 24 hours.

Globally, a range of 65% to 70% of relative humidity is retained thereafter.

### 3.3 Variation with temperature

Two main behaviours can be identified for the temperature-dependence of thermal conductivity:

- according to Shin [8], Vodak [9], Mindeguia [10], Noh [5], Harada [13], Eurocode [2], Kalifa [7], Muir [18], and Harmathy [15], the thermal conductivity monotonously decreases with temperature;
- in contrast some paper reported an increase of thermal conductivity from room temperature up to 100°C. This is the case of Kallel [7], Hundt [17], Crispino [14], Nguyen [11], Schneider [16]. Furthermore Crispino [14], Nguyen [11], Schneider [16] measured a decrease above 100°C.

This apparent contradiction is interpreted, by Kallel [7], as a progressive drying of the concrete when temperature increases. In most of the experiments, the relative humidity is not controlled, and the drying at higher temperatures can overcome the associated increase of conductivity at constant relative humidity. This interpretation is supported by the results of Kallel [7], where relative humidity was controlled. Other authors, for example FIB [22], and others references within Kallel [7], indicate an increase of conductivity from room temperature, to a maximum value, followed by a decrease. For these uncontrolled relative humidity experiments, the temperature at which the change in trend is observed ranges from 50°C to 100°C. Due to the ebullition phenomenon at 100°C,

and according to the Kallel's [7] results, this temperature, for constant relative humidity, is assumed to be around 100°C. Moreover, above 100°C, all the available data indicate a decrease in the thermal conductivity.

### 3.4 Conservative and best-estimate value

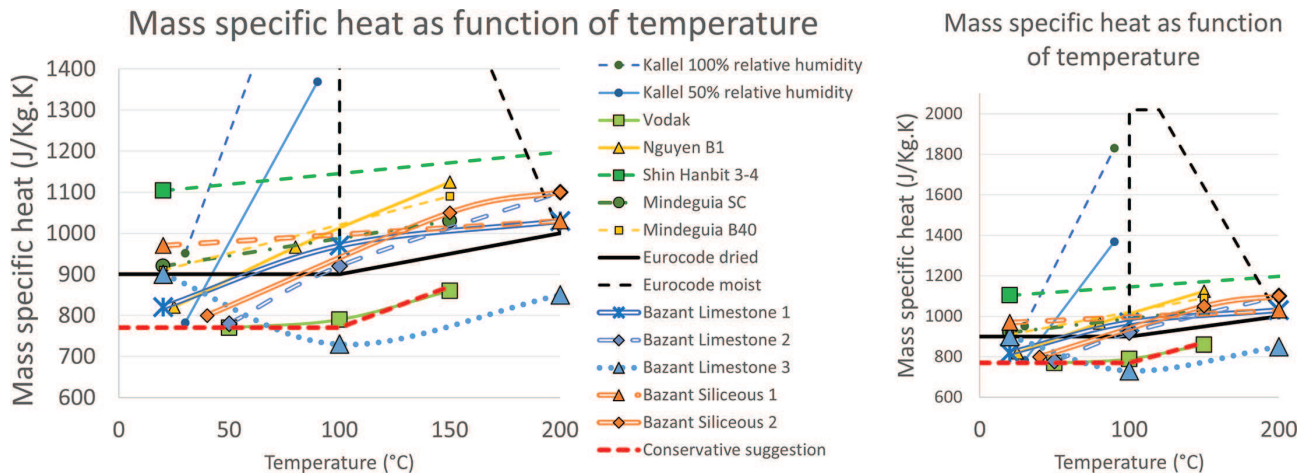
#### 3.4.1 Conservative value

At room temperature, the thermal conductivity of Kallel [7] for the selected relative humidity (i.e. 65–70%) is 1,9 W/m.K. The Zhang's measurements [3] obtained in the same conditions are in agreement with this value. Excluding all the measurements performed on dried concrete, and some measurements without information about their moisture content which are in the same range of conductivity (Harmathy [15], Schneider [16], Harada [13]), 1,9 W/m.K is the lowest value for "moist concrete" (Nguyen [11]). Considering a normal distribution with the student law, the 1,9 W/m.K value covers a quantile of 65% to 80% of the value at room temperature, depending on the inclusion or not of the low value of conductivity from the measurements without moisture content control (Harmathy, Schneider and Harada). This value is therefore considered as conservative, but not too penalizing.

Moreover, as explained previously, for constant relative humidity, the thermal conductivity is considered to increase with temperature up to 100°C and decrease beyond that. For the conservative approach, this increase is not taken into account, and the thermal conductivity is considered to remain constant at 1,9 W/m.K up to 150°C. Moreover, at 150°C, as shown in Figure 1, all the available data are between 1,9 and 2,0 W/m.K, reinforcing the rationale for this value.

#### 3.4.2 Best-estimate value

To determine "best-estimate values", at least two approaches can be followed:



**Fig. 2.** Mass specific heat measurements and recommendations (literature data) and proposals, zoom in the range of interest (left) and full scale (right) – limestone concretes are in cold colours (blue, violet), and siliceous in warm colours (red, yellow, orange).

- the first one would consist to take the mean value of conductivity of moist concrete at room temperature (2,1 W/m.K). For higher temperatures, the evolution of the conductivity to consider is not obvious. Indeed, due to the concrete drying during heating without moisture content control, some measurements exhibit an increase of conductivity while others a decrease. To be not too favorable or too conservative for the containment pressure, a reasonable approach could be to consider a constant value (no variation), of 2,1 W/m.K. This approach is the simplest one but is not in agreement with the data at 150°C (between 1,9 and 2,0 W/m.K).
- In the second one, which is considered in the present paper, one assumes an increase of conductivity up to 2,3–2,6 W/m.K at 100°C (Kallel [7], Hundt [17], Crispino [14]). But, in return, the conductivity at room temperature should not be too favorable. That is why, for the proposed best-estimate value, a conductivity of 1,9 W/m.K is chosen at room temperature, with an increase up to 2,4 W/m.K at 100°C, and a decrease to 1,9 W/m.K at 150°C (consistent with the data). This variation is considered to be “best-estimate” one and to better reproduce the involved physical phenomena and the variation of conductivity with temperature.

## 4 Specific heat

Figure 2 summarizes the available data for mass specific heat as a function of temperature.

As for the conductivity, the relative humidity of the concrete has an impact on its specific heat. Kallel [7] and the Eurocode [2], provide different values as a function of temperature and relative humidity. Due to the drying and evaporation phenomenon, moist concrete has higher specific heat than the dry ones. But, considering the case of a containment wall during the first day of a severe accident, due to the wall thickness and the global pressurisation, it cannot be assumed that the water could effectively evaporate.

In a conservative way, this effect will be not considered thereafter.

As for conductivity, the impact of the concrete composition cannot be really assessed since one does not observe any general trend.

In all measurements, except Bazant Limestone 3 which is not considered thereafter<sup>3</sup>, the specific heat increases with temperature. This is interpreted by several authors (for example Kallel [7]) as a consequence of endothermic chemical reactions. However, that increase from room temperature to 150°C is highly variable, from 100 J/Kg.K for Vodak [9], 300 J/Kg.K for Nguyen [11], or around 1000 J/Kg.K for Kallel [7] or Eurocode [2].

### 4.1 Conservative value

At low temperature, the minimal value of specific heat is 770 J/Kg.K (Vodak [9] at 50°C). With the previous hypotheses, this value covers a quantile of 85% of uncertainties. It is retained for the conservative assumption.

For higher temperatures, the Vodak’s [9] measurements are considered which correspond to the lowest specific heat value. A constant value of 770 J/Kg.K is retained up to 100°C, followed by an increase of 100 J/Kg.K to 870 J/Kg.K at 150°C. According to the previous section, all the authors observed an increase of at least 100 J/Kg.K between room temperature and 150°C.

### 4.2 Best estimate value

In a best estimate approach, it is observed that the Eurocode value for dried concrete is close to the average value of all data at each temperature (slightly above

<sup>3</sup> The unique behavior of the Bazant Limestone 3 concrete (decrease of specific heat at 100°C), raise the question of measure uncertainties of that value. It is not considered in the analysis.

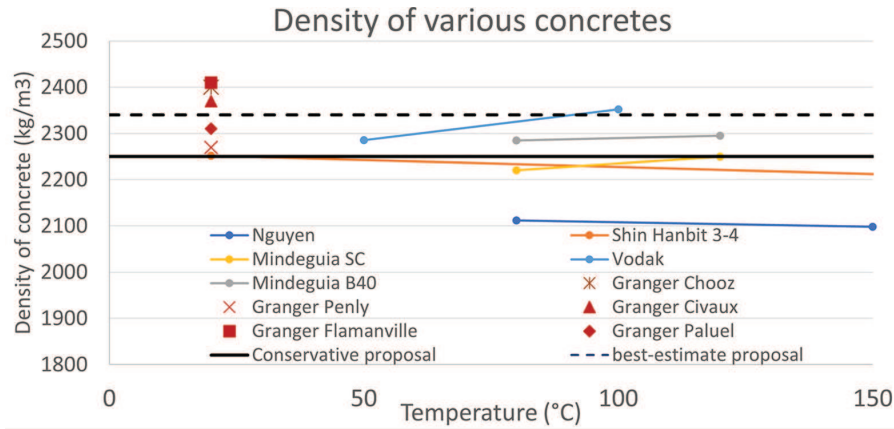


Fig. 3. Density of various concretes.

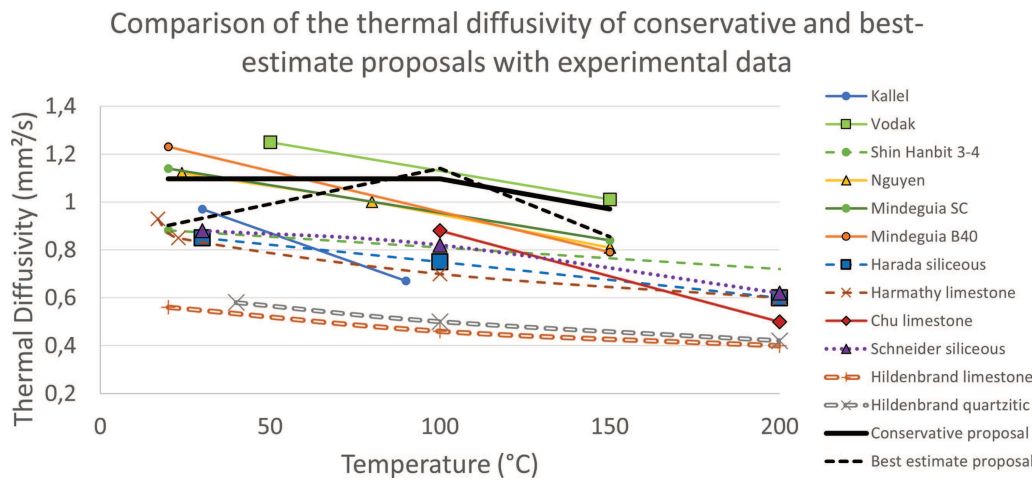


Fig. 4. Thermal diffusivity: available data and conservative/best-estimate proposals.

at room temperature, and below at 100°C and 150°C). This slight difference does not justify proposing a different interpolation from Eurocode (i.e. 900 J/Kg.K up to 100°C and 950 J/Kg.K at 150°C).

## 5 Density

Figure 3 summarizes the density available data as a function of temperature. Granger [24] provides density for the concrete of some French Nuclear Power Plant (NPP). Vodak [9] does not report data for density, but it has been estimated from the values of conductivity, specific heat and thermal diffusivity. First, it must be noted that the dispersion of the values is much lower than for the conductivity or the specific heat: all the data are within a 15% variation range, and most of them in a 5% variation range.

By definition, the density is also supposed to be a function of the concrete composition (type of aggregates and relative humidity). But, given the limited amount of data available, and the narrow range of variation, as for the conductivity and specific heat, the impact of composition will be not taken into account. Additionally, as most of the thermo-hydraulic containment code (such as ASTEC [25] or MAAP

[26]) uses constant concrete density (the thermal dilatation of the containment is not modelled), and the data show very little variation in the range of 20°C to 150°C, a constant density temperature-independent is assumed.

Excluding the results of Nguyen [11], which are very different from the others, the minimal value of density is 2250 Kg/m<sup>3</sup>. This value is retained for the conservative approach.

In the best estimate approach, the average value of all data, 2340 kg/m<sup>3</sup> is considered.

## 6 Thermal diffusivity

Some values for thermal diffusivity are also available in the literature. This parameter is directly linked to the others with the equation  $D = \lambda/\rho.C_p$ . Therefore, the available data can be used to check the consistency of the values retained previously for the best estimate and conservative approach. For that purpose, the data of thermal diffusivity of Kallel [7], Shin [8], Vodak [9], Mindeguia [10], Nguyen [11], Harada [13] and Harmathy [15], with the additions of Chu [27], Schneider [28] and Hildenbrand [29] extracted in Schneider [12] (not included in the Tab. 1),

**Table 2.** Suggested thermal properties for concrete<sup>§</sup>.

		Conservative values	Best estimate values
Density (kg/m <sup>3</sup> )		$\rho = 2250 \text{ kg/m}^3$	$\rho = 2340 \text{ kg/m}^3$
Specific heat (J/Kg.K)	$T < 100^\circ\text{C}$	$C_p = 770 \text{ J/Kg.K}$	$C_p = 900 \text{ J/Kg.K}$
	$100^\circ\text{C} < T < 150^\circ\text{C}$	$C_p = 770 + 2 \times (T - 100)$	$C_p = 800 + 1 \times T$
Thermal conductivity (W/m.K)	$T < 100^\circ\text{C}$	$\lambda = 1,9 \text{ W/m.K}$	$\lambda = 1,775 + 0,00625 \times T$
	$100^\circ\text{C} < T < 150^\circ\text{C}$		$\lambda = 3,4 - 0,01 \times T$

<sup>§</sup>In the equations, the temperature T is in °C.

**Table 3.** Suggested thermal properties for reinforced concrete.

		Conservative values	Best estimate values
Density (kg/m <sup>3</sup> )		$\rho = 2400 \text{ kg/m}^3$	$\rho = 2485 \text{ kg/m}^3$
Specific heat (J/Kg.K)	$T < 100^\circ\text{C}$	$C_p = 750 \text{ J/Kg.K}$	$C_p = 865 \text{ J/Kg.K}$
	$100^\circ\text{C} < T < 150^\circ\text{C}$	$C_p = 570 + 1,8 \times T$	$C_p = 775 + 0,9 \times T$
Thermal conductivity (W/m.K)	$T < 100^\circ\text{C}$	$\lambda = 2,0 \text{ W/m.K}$	$\lambda = 1,875 + 0,00625 \times T$
	$100^\circ\text{C} < T < 150^\circ\text{C}$		$\lambda = 3,5 - 0,01 \times T$

are reported in Figure 4. Especially, the low values of Hildenbrand measures [29,30], with no associated moisture content in [12], may be interpreted as linked to dry concretes.

As a result, both conservative and best estimate proposals proposed in this paper are within the range of variation of the experimental data.

## 7 Reinforced concrete

The containment walls of nuclear power plants are made of reinforced concrete. The presence of steel changes the thermal properties of the reinforced concrete compared to the concrete. A description of the amount of steel in the containment wall of French NPP, in the various directions of the wall, can be found in Granger (1995) [24]. Additionally, Noh [5] gives a complete description of how evaluate the thermal properties of a reinforced concrete, especially the thermal conductivity, taking into account the steel fraction in the various directions (in the direction of the thermal gradient or not). The equations of Noh [5] have been used thereafter.

To evaluate the properties of reinforced concrete, the thermal properties of steel are also required. These properties are less uncertain than the concrete ones. Moreover, due to the low fraction of steel, their uncertainty has a negligible effect on the reinforced concrete properties. For simplification, the steel properties considered by Noh [5] have been used.

The results are presented in Tables 2 and 3 in the synthesis part.

## 8 Synthesis

Based on the considered literature, best estimate and conservative thermal properties of concrete and reinforced concrete are proposed. These values are applicable from 20°C up to 150°C, for NPP up to 60 years, for the study of the first 24 hours of containment thermal hydraulics (pressurization especially) in design basis and severe accidents in NPP. They are not applicable to other applica-

tions (thermo-mechanics studies, long term severe accident studies,...). They could be used as default value, if little information is available about the concrete composition. In case of well-known concrete composition (chemical composition, thermal properties of the concrete constituents, relative humidity, etc.), alternative approaches could be used.

One of the main outcomes of this analysis is the dependence of concrete properties on the relative humidity (especially for thermal conductivity and specific heat). In perspective, additional experiments would be required to better characterize the concrete thermal properties for various relative humidity, temperature and concrete composition. A better characterization of the relative humidity of existing NPP (without or without internal steel liner, as a function of the NPP age), and their potential variation in case of severe accident, would also contribute to reduce uncertainties.

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### Conflicts of interest

The author declares that he has no competing interest to report.

### Data availability statement

This article has no associated data generated.

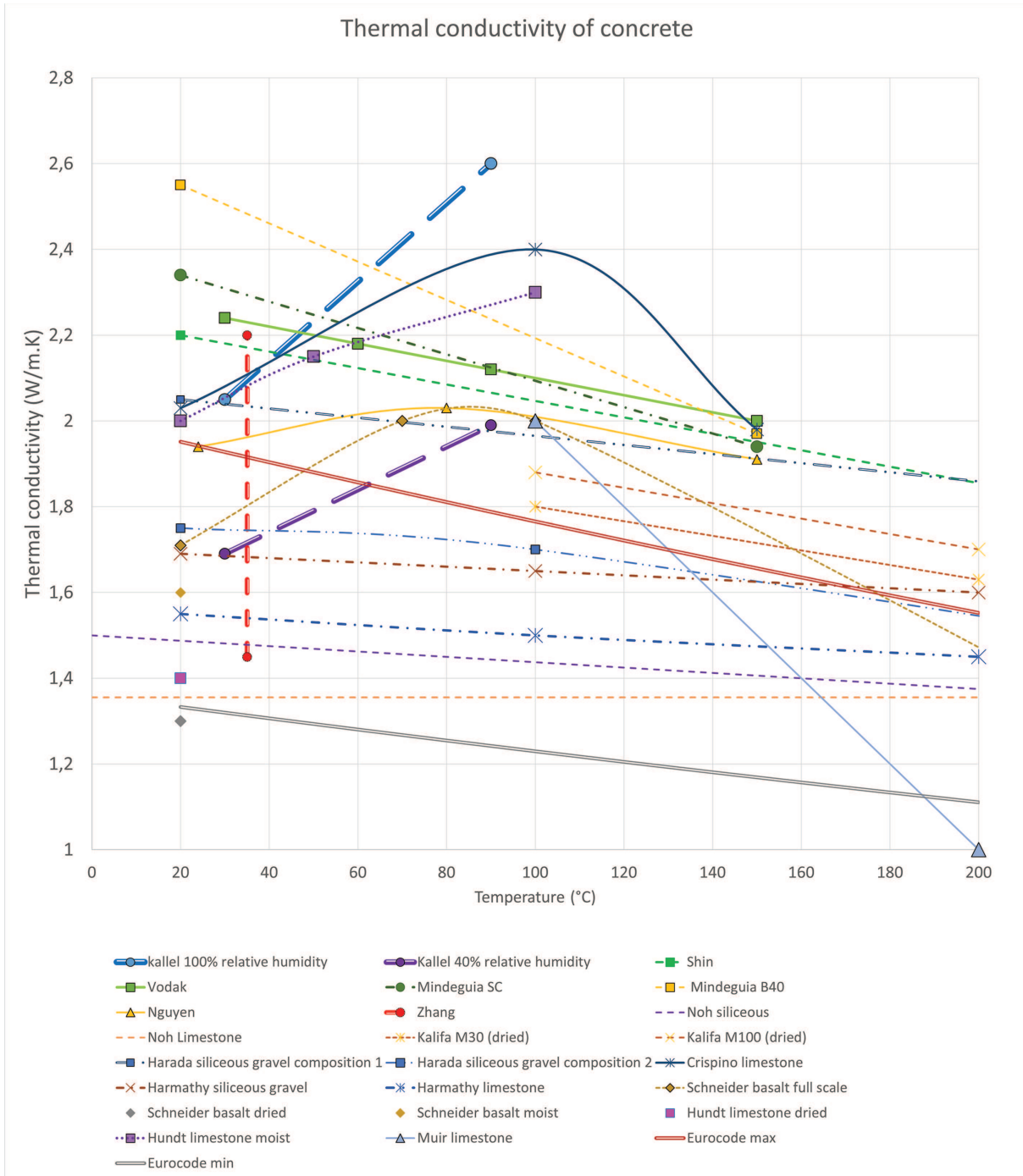
### Author contribution statement

The author confirms sole responsibility for the following: Study conception and design, data collection, analysis and interpretation of results, and manuscript preparation.

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Annex



**Fig. A1.** Thermal conductivity values available in the literature – limestone concretes are in cold colours (blue, violet), and siliceous in warm colours (red, yellow, orange).