Novel borehole method for measuring vapour pressure in concrete exposed to high temperatures

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Abstract

Understanding the behaviour of concrete during fire is essential to ensuring the safety of concrete structures. One of the most critical phenomena affecting concrete during fire is spalling, which is closely linked with the development of pore vapour pressure. Though the development of vapour pressure is widely recognised as a major driver of spalling, there is no standardised method of measurement and researchers employ various methods with various confounding factors. This lack of consistency significantly complicates the comparability of results across studies and limits progress toward better understanding of pressure development and its influence on spalling. Currently, there is no simple, well-documented, and easily-reproducible measurement method with a low amount of confounding factors.

This paper addresses the problem by examining the limitations of the existing methods and subsequently developing a novel "Borehole Method". The developed method significantly reduces the amount of the confounding factors by using drilled boreholes as the pressure collection zone and by entirely eliminating the transmission path and medium. Moreover, the method reduces the complexity of the measurements as the setup is straightforward and employs standard widely-available equipment.

The application of the method is illustrated on concrete specimens of different strengths and fibre contents, and the method yields reliable results that are consistent with known physical behaviour of concrete.

Overall, the novel Borehole Method offers a practical and easily-reproducible approach for vapour-pressure measurement and is, thus, suitable for wide usage. This will, hopefully, ensure its wide adoption and thus enable more transparent comparisons across future studies.

Keywords: Concrete, Pore vapour pressure, Measurement method, Borehole method, Fire, Spalling

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1. Introduction

Understanding the behaviour of concrete at high temperatures is essential to ensuring the safety and stability of reinforced-concrete structures exposed to fire. One of the most critical phenomena affecting the mechanical response of concrete during heating is concrete spalling, which is closely linked with the development of high pore pressure. According to many researchers, the vapour pressure is either the main factor inducing spalling (see, e.g., [1–3]) or an major factor contributing to spalling (see, e.g., [4–18]). Thus, the prediction of pore pressure in concrete during fire through measurements on representative specimens is of high importance when investigating the fire resistance of reinforced-concrete structures. However, despite growing scientific interest in the investigation of pore pressure, there are no standardised rules for measuring water vapour pressure, and most importantly, there no single standardised method of measurement.

The absence of standardisation in the field of vapour pressure measurement presents a significant problem which complicates the reproducibility of the measurements and the comparability of results across different studies. This problem originates from the fact that there are many factors which affect the vapour pressure and its measurement. The factors affecting the final measured pressure values can be broadly categorized into two categories: (a) material-related factors, (b) technological factors.

Material-related factors are linked with the properties of the material itself (e.g., concrete age, moisture content, concrete permeability, compressive and tensile strength, etc.). These properties will always be dependent on the mixture of the specific concrete being tested, and thus, can never be fully standardised. However, some standardisation is possible – e.g., the concrete age and moisture content during testing.

Technological factors are linked with the characteristics of the measurement process itself. These factors can be further divided into the measurement method (i.e., the experimental setup) and the boundary conditions (e.g., the selected thermal gradient, specimen size, or preloading applied to the specimen). Unlike in the case of the material-related factors, the technological factors can be fully standardised. Moreover, since these factors are external, it might be possible to reduce their number (e.g., by simplifying the experimental setup).

Since the final measured pressure values are dependent on various technological factors, it is essential to reduce the number of these factors as much as possible and standardise the remaining factors. This standardisation of technological factors would ensure that the differences in values obtained in various researches could always be attributed solely to the properties of the tested materials.

Unfortunately, there is currently no standardisation in the field of vapour measurement, and various researchers employ various methods.

Moreover, the methods used by various researchers are significantly different and often inadequately described – both in the sense of the measurement method as well as the measurement process itself. This significantly complicates the reproducibility of the measurements and the comparability of results across different studies.

One critical aspect linked with the technological factors is that none of the existing methods directly measure the pore pressure; instead, the water vapour pressure in a "collection zone" is measured. As many existing measurement setups use different collection zones, this further complicates the comparability of results across different studies. This topic is further discussed in detail in this paper in Section 3. It is also worth noting that the term "water vapour pressure" (hereafter also referred to simply as "vapour pressure" or "pressure") will be used in this paper instead of the often-used term "pore pressure" for the reasons presented in Section 3.

For the reasons explained above, the authors of this paper feel that to advance the knowledge in the field of vapour pressure measurement in concrete, it is crucial to introduce a simple, well documented, and easily reproducible method. Introducing such method could promote the use of a single method across various researches, which would allow comparisons of results across these various researches. Although the need for this simple and easily reproducible method is highlighted by various authors (see, e.g., [3] and [18]), no such method has yet been proposed to the best of our knowledge.

This paper focuses on the technological factors affecting the measurements and on the development of a novel measurement method. First, an overview of existing methods and their advantages and disadvantages from the point of view of the technological factors is presented. Subsequently, a novel, simple, well-documented, and easily-reproducible measurement method developed by the authors is presented. This novel method is easy to implement and resolves most of the disadvantages of existing methods linked with the technological factors. Moreover, this paper also presents an illustration of the application of novel method on specimens made from various concrete mixtures. Thus, this paper provides a systematic description of a method which enables reproducible measurements of vapour pressure in concrete exposed to high temperatures.

The presented method is the culmination of extensive work focused on investigating various existing setups and novel modified setups conducted by the authors of this paper, see the authors' previous work [19–24].

2. Existing methods for measuring water vapour pressure in concrete exposed to high temperatures

2.1. Overview of past measurements of water vapour pressure in concrete

The pressure of water vapour in concrete exposed to high temperatures was already investigated by many researchers in the past. The most notable experimental investigations will be briefly presented in this section. More extensive reviews of the pressure measurement methods can be found in, e.g., [3, 15].

Schneider and Herbst [25] measured vapour pressure in various types of concrete (varying in the type of aggregate). The pressure was collected in a cavity (a hollow cave-like free space) and transmitted to the pressure transducer using a metal tube containing air. A metal rod was placed in the metal tube to minimise the amount of the transmission medium (air). The tube was placed perpendicular to the heated surface, and the measurement setup was placed at the top of the specimens. For the heating of the specimens, two heating regimes were used – a gradual linear increase and a stepwise-incremental increase. The thermocouples were placed at various depths of the specimen in the direction of heating. Schneider and Herbst [25] reported vapour pressure of 0.18 to 0.76 MPa.

Jansson and Boström [26] measured vapour pressure in concrete containing poly-propylene (PP) fibres. The pressure was collected directly at the plain opened end of a metal tube without any special adjustment – i.e., the collection zone was only the opened end of the tube. The tube was protected against inflow of concrete during casting by placing a metal rod inside the tube during casting. After hardening of the concrete, the metal rod taken out and replaced with silicone oil. During heating, the pressure was transmitted through the silicone oil to a pressure gauge (type P8AP/100). The tube was placed perpendicular to the heated surface, and the measurement setup was placed at the top of the specimens. For the heating, three heating regimes corresponding to three standardised fire curves (RWS, ISO834, and hydrocarbon) were used. The location of the thermocouples was not specified. Jansson and Boström [26] reported vapour pressure of 0.1 to 0.7 MPa.

Bangi and Horiguchi [27] conducted an extensive study aimed at measuring vapour pressure in high-performance concrete (HPC). These authors analysed the effect of the collection zone, the transmission medium, and the heating regime on the measured values of the vapour pressure. They concluded that a sintered metal collection cup and silicon oil transmission medium were the most effective for the pressure measurement. The silicon oil was transmitted using a tube with the inner diameter of 1.5 mm. The tube was placed perpendicular to the heated surface, and the measurement setup was placed below the specimens in order to prevent leakage of the silicone oil into the concrete – see Figure 1. For the heating, three heating regimes were used – a slow, mid, and fast heating. The thermocouple was placed on the sintered metal collection cup. Bangi and Horiguchi [27] reported vapour pressure of 0.1 to 4 MPa and concluded that at higher speeds of heating, the pressure is greater in the inner parts of the concrete.

Ko et al. [11] conducted an experimental research on the effects of heat and moisture transfer on the causes of vapour pressure surges and spalling. The pressure was collected directly at the plain opened end of a metal tube – i.e., in the same way as in [26]. The transmission medium was air, and the air was transmitted using a metal tube with the inner diameter of 4 mm. The tube was placed parallel to the heated surface in order to minimize the thermal gradient along the tube, and the measurement setup was placed on the side of the specimen. For the heating, the ISO834 fire curve was used. The thermocouple was

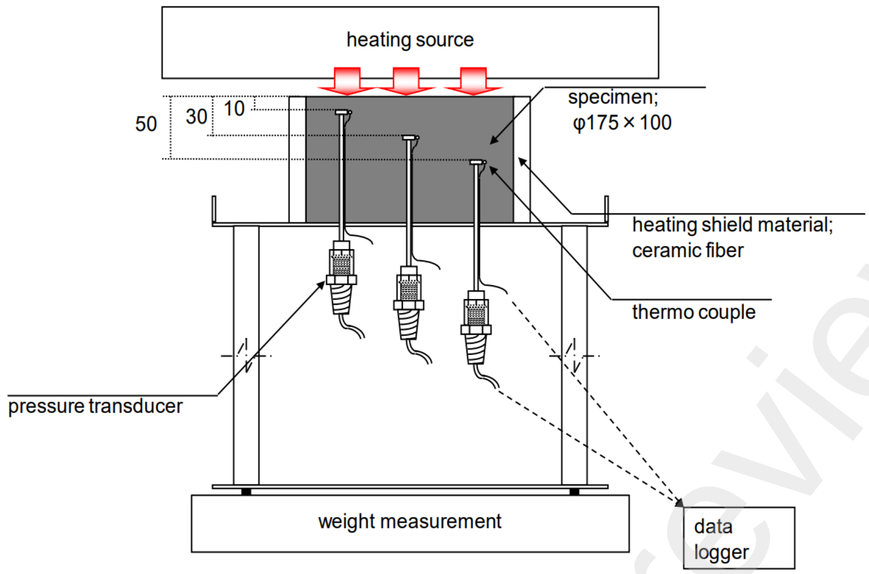


Figure 1: Measurement setup used by Bangi and Horiguchi [27] (taken from [27, Fig. 2].

placed near the collection zone (tube end). Ko et al. [11] reported vapour pressure of 0.1 to 0.45 MPa.

Debicki et al. [2] conducted an study aimed at measuring vapour pressure in HPC with PP fibres. Unlike in the other researches described in this section where the specimens were slab-shaped, Debicki et al. used spherical specimens in order to heat the specimen uniformly on its whole surface, and thus, concentrate the vapour pressure in the centre of the specimen. The pressure was collected directly at the plain opened end of a metal tube, as in [11, 26]. The transmission medium was air, and the air was transmitted using a metal tube with the inner diameter of 2 mm. The metal tube was filled with a metal rod with the diameter of 1.5 mm, as in [25]. The tube was placed perpendicular to the heated surface, and the measurement setup was placed at the top of the specimens. For the heating, a gradual linear increase of 5°C/min was used. The thermocouple was placed in the collection zone (tube end). Debicki et al. [2] reported vapour pressure of 1.4 to 3.5 MPa.

Ozawa and Morimoto [28] investigated the effect of jute fibres, Water-soluble polyvinyl alcohol (WSPVA) fibres, and PP fibres on the vapour pressure in HPC. The pressure was collected directly at the plain opened end of a metal tube, as in [2, 11, 26]. The transmission medium was mineral (hydraulic) oil, and the oil was transmitted using a metal tube with the inner diameter of 2 mm. The tube was placed parallel to the heated surface, and the measurement setup was placed on the side of the specimen. For the heating, the RABT30 fire curve was used. Multiple thermocouples were placed at various depths in the direction of heating. The thermocouples were placed near the collection zone (tube end). Ozawa and Morimoto [28] reported vapour pressure of 0.3 to 4.7 MPa.

Ding et al. [29] investigated the effect of different polypropylene and metal fibres on the vapour pressure in fibre-reinforced self-compacting concrete (FRSCC) during fire. The pressure was collected using a sintered metal collection cup at the end of a metal tube, as in [27]. The transmission medium was silicone oil, as in [27], and the oil was transmitted using a metal tube with the inner diameter of 2 mm. The tube was placed perpendicular to the heated surface, and the measurement setup was placed at the top of the specimens. For the heating, the ISO834 fire curve was used until 600°C, and then, the temperature was held constant at 600°C. The thermocouple was placed on the sintered metal collection cup. Ding et al. [29] reported vapour pressure of 0.31 to 1.19 MPa. Ding et al. [29] also proposed an empirical formula based on the regression analysis of the results of measured pressure development in the investigated FRSCC.

Ozawa et al. [30] evaluated the behaviour of high-performance concrete in response to the extreme heating while also measuring the vapour pressure in the concrete. The pressure was collected directly at the plain opened end of a metal tube, as in [2, 11, 26, 28]. The transmission medium was mineral (hydraulic) oil, and the oil was transmitted using a metal tube with the inner diameter of 2 mm. The tube was placed parallel to the heated surface, and the measurement setup was placed on the side of the specimen. For the heating, the RABT30 fire curve was used. Multiple thermocouples were placed at various depths in the direction of heating. The thermocouples were placed near the collection zone (tube end) – see Figure 2. Ozawa et al. [30] reported vapour pressure of 0.2 to 6.2 MPa.

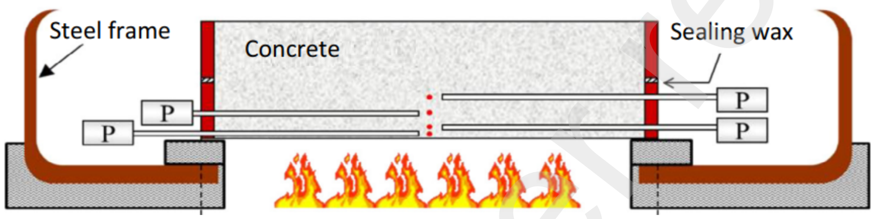


Figure 2: Measurement setup used by Ozawa et al. [30] (taken from [30, Fig. 4]).

Choe et al. [14] investigated the effect of water vapour pressure build-up on spalling of high-strength concrete (HSC). The pressure was collected directly at the plain opened end of a metal tube, as in [2, 11, 26, 28, 30]. In order to prevent clogging of the tubes opened end due to the inflow of concrete during casting, the tube end was sealed with a paraffin with a melting point of 62°C. The transmission medium was air, and the air was transmitted using a metal tube with the inner diameter of 2 mm. The tube was placed parallel to the heated surface, and the measurement setup was placed on the side of the specimen. For the heating, two regimes were used – fast heating according to the ISO834 fire curve and slow heating of 1°C/min. The thermocouple was placed in the collection zone (tube end). Choe et al. [14] reported vapour pressure of 0.25 to 3.1 MPa and concluded that "*the moisture migration and water vapour pressure formation (...) are significantly affected by the heating rate*".

Gil et al. [18] investigated material-related factors influencing vapour pressure measurements in concrete and its influence on spalling. The pressure was collected using a sintered metal porous head of 5 mm in length at the end of a metal tube. The transmission medium was silicone oil, as in [27, 29], and the oil was transmitted using a metal tube with the diameter of 2 mm. The tube was always placed either perpendicular to the heated surface (single-directional heating) or perpendicular and parallel to the heated surface (multi-directional heating). The measurement setups were placed on the faces of the specimens. The thermocouple were not used in the specimens in which the pressure was measured as this "*could lead to some pressure leakage and compromise accuracy of measurements*" according to Gil et al. [18]. The temperatures inside the concrete specimens were obtained through a second set of tests which were conducted on replicate specimens with thermocouples placed at the same location as the pressure probes in the first set of specimens [18]. Gil et al. [18] reported peak vapour pressure of 0.10 to 4.00 MPa and concluded that "*the specimen geometry and* *test conditions have significant influence on the pore pressure trends*".

2.2. Identification and description of the important parameters of the existing methods

As can be readily seen by comparing the past measurements of vapour pressure conducted by various researches (see Section 2.1), each researcher uses a different measurement method, and the measurement methods often vary significantly (compare Figures 1 and 2). However, the most important parameters of the existing methods can be summarised into the following three categories (cf. [3, 15]):

- direction of tube with respect to the heating:
  - parallel to heated surface,
  - perpendicular to heated surface,
- transmission medium:
  - air,
  - air + rod,
  - oil,
  - oil + rod,
- collection zone type:
  - plain open-ended tube,
  - collection cup attached to a tube,
  - sintered head attached to a tube,
  - cavity connected to a tube.

Note that Li et al. [3, 15] differentiate the measurement methods in a similar way but using slightly different naming. Li et al. [3, 15] additionally differentiate the measurement methods based on the location of thermocouples. This differentiation is omitted in this paper as the location of thermocouples does not affect the vapour pressure.

2.2.1. Direction of the tube with respect to the heating

The direction of the tube with respect to the heating is important due to the fact that it determines whether the tube lies in an isothermal layer or not. This is important because the tube acts as a transmission path for the transmission medium, and an improper orientation, especially in combination with an unsuitable transmission medium, can lead to significant inaccuracies in the measured data (i.e, the value of the pressure).

If the tube is parallel to the heated surface, it can be assumed that the entire tube lies within an isothermal layer – i.e., the tube has a uniform temperature along its length. Moreover, the temperature of the tube is equal to the temperature at the collection zone as this zone is at the end of the tube. The transmission medium (such as air or oil) is then expected to exhibit a uniform temperature along the entire length of the transmission path.

If the tube is perpendicular to the heated surface, then the temperature of a tube (i.e., the transmission path) varies along its length, and the temperature of the tube is different from the temperature of the collection zone. This can introduce effects adversely affecting the accuracy of the measurements. In the case of liquid transmission mediums such as oil, the thermal expansion or contraction of the medium can distort the pressure measurements. In the case of gas transmission mediums such as air, the condensation of the vapour in cooler parts of the tube can reduce the measured values of pressure.

It can be readily seen that the parallel orientation of the tube to the heated surface is much more suitable with regards to the accuracy of the measurements.

2.2.2. Transmission medium

Direct installation of pressure sensors (e.g., pressure gauges or pressure transducers) inside concrete specimens is generally unfeasible due to the significant size of the sensors and the high temperatures during heating. Instead, the pressure collected in the collection zone is typically transferred from inside the specimen to an external pressure sensor via a dedicated transmission path [3, 15].

This transmission path is usually a metal open-ended tube (with an inner diameter of 2 mm), filled with a transmission medium, see, e.g., [3] and references therein. Typical transmission media used in previous researches include air (see, e.g., [2, 11, 14, 25]), silicone oil (see, e.g., [3, 15, 26, 27, 29], or mineral oil (see, e.g., [28, 30]).

According to [3], the transmission medium has very high effect on the maximum value of the measured pressure, while the collection zone type has much smaller effect.

Using air as the transmission medium introduces a large free volume [3, 11, 14, 15] which delays the build-up of vapour pressure [3, 15]. Thus, it would seem more prudent to use oil as the medium. However, using oil as the medium also has its disadvantage as the "*thermal expansion of oil may cause additional hydraulic pressure, which may significantly increase the test results*" [3]. This statement is supported by the fact that highest values of pressure are obtained when oil is used as the transmission medium, see, e.g., [3, 15].

To reduce the extent of the adverse effects of the transmission medium on the measured pressure, in previous researches, solid elements were inserted into the metal tubes in order to minimize the volume of the transmission medium [3, 15]. As the solid elements, loosely-fitted metal rods (see, e.g., [2, 25]) or thermocouples (see, e.g., [3, 15] and references therein) were used. However, the complexities associated with the installation of the solid elements may cause additional uncertainties and hinder wide adoption of the methods employing these elements [3, 15]. Moreover, in the case of air, the presence of a metal rod impairs the build-up of the vapour pressure [15].

Thus, it can be concluded that from the presented option, the most advantageous option from the accuracy point of view seems to be the oil transmission medium with a solid insert. With this option, there is no delay of the build-up of vapour pressure, and the volume of the oil is low and thus the effect of its thermal expansion is smaller. However, this option is least advantageous from the practical-applicability point of view. The best option would be to omit the transmission medium altogether if possible – see Section 4.

2.2.3. Collection zone

The "collection zone" refers to the region inside the concrete in which the vapour pressure is collected. This zone is connected with the transmission path in order to transmit the vapour pressure from the collection zone to the measurement device outside the concrete. In the existing previous researches, the following types of collection zone were used. For a more detailed comparison of these collection zones and their effects on the measurements see [3, 15].

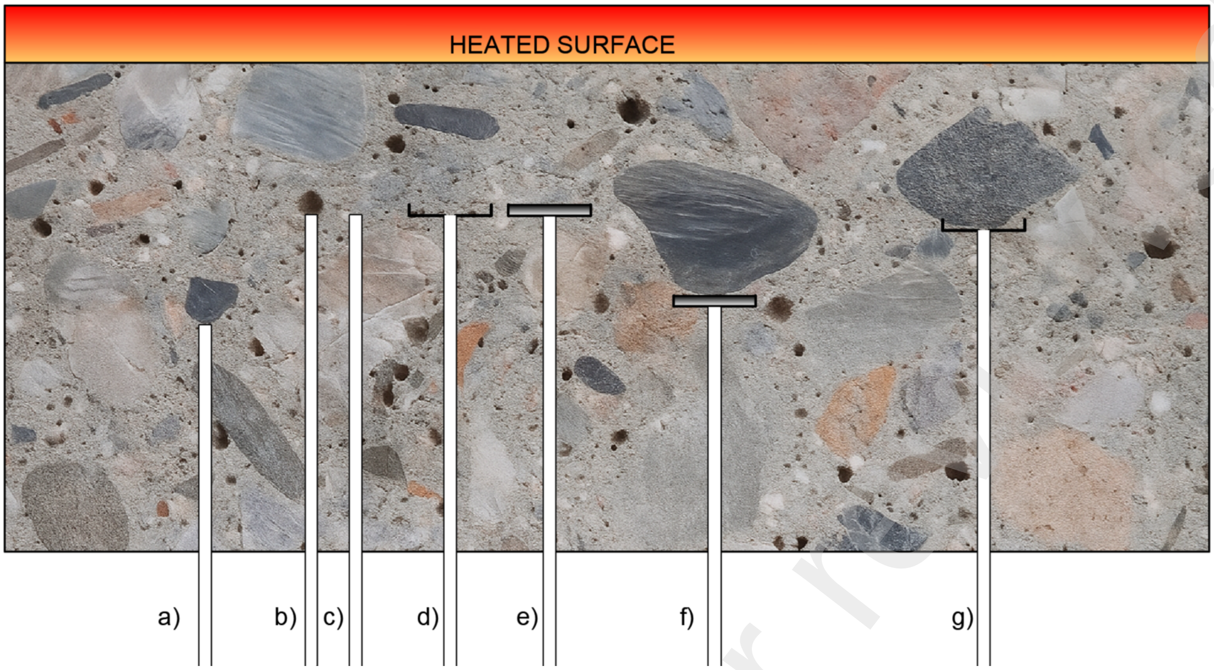


Figure 3: Free, blocked, and partially blocked collection zones.

A common collection zone type (CZT) is a plain opened end of a metal tube (used for pressure transmission) without any special adjustment – see Figure 4(a) and [2, 3, 11, 14, 15, 26, 28, 30]. In this case, only the opened end of the tube is the collection zone. In some cases (see, e.g., [14]), the end of the tube is sealed with a paraffin before concrete casting to prevent the fresh concrete from entering the tube during the casting. The advantage of this CZT is that it is easy to set up. However, a significant disadvantage is that the pressure is collected in a very small localised area, which can adversely affect the measurement for three reasons. Firstly, the local properties of the concrete matrix in this area might differ from the overall average properties, and thus, the measured pressure might fail to accurately represent the overall pressure in the concrete. Secondly, due to the small size of the collection zone (a circle with the diameter of 2 mm), the whole collection zone may become blocked by a large aggregate particle, see Figure 3. As a result, water vapour migrating from the heated surface towards the cooler interior may be prevented from entering the collection zone, thereby compromising the accuracy and representativeness of the measured pressure values. Thirdly, a naturally occurring macro pore may develop near the tube end, see Figure 3. This macro pore would significantly increase the area of the collection zone, which would increase the amount of vapour and thus pressure values. Though this may seem as a beneficial effect, in reality, it is an adverse effect as the measurements would not be comparable with other standard ("no-pore") plain open-ended measurements. Apart from the disadvantages related to the small size, additional disadvantage stems from the fact that the collection zone (an end of a metal tube) is a foreign object in the concrete. Since the tube is a foreign object, an interfacial transition zone (ITZ) forms around the tube and its opening [31–33]. This ITZ layer affects the transport of vapour [31, 34, 35], which might distort the measurements even further.

Another common type of a collection zone is a metal collection cup – see Figure 4(b) and, e.g., [3, 15, 27, 29]. Though, the collection cup can be used as-is (see. e.g., [27]), the cup is usually complemented by a porous sintered metal disk acting as a lid. The disk is made of a porous sintered metal with evenly distributed pores with a diameter of 2 or 4 µm. This porous sintered metal enables the collection of the vapour in an evenly manner due to its evenly distributed pores, and this, in turn, leads to stable pressure measurements [27]. The advantage of this CZT is that it collects the vapour from a larger area, and thus, enables more stable and representative pressure measurements. The disadvantage is that this CZT is more complicated to set up, and that it introduces additional factors which might affect the measurements. Specifically, in the setup without the porous lid, a backflow of concrete into the cup can occur, and this might affect the measurements. On the other hand, in the setup with the porous lid, the lid may alter local properties of the concrete matrix [3], which might affect the transport of vapour and thus affect the measurements. Moreover, in both cases the cup introduces free volume of air into the concrete which facilitates vaporization of condensed moisture and delays build-up of the pressure [3]. Additionally, the disadvantages regarding the ITZ and the aggregate-induced blockage described for the previous type (the plain open-ended tube) are also true for the collection cup. However, it should be noted that the risk of full blockage by aggregate particles is lower for the collection cup due to the larger size of the collection zone. This is especially true for the collection cup with a lid, see Figure 3.

Similarly to the collection cup with a sintered-metal disk, a sintered-metal porous head with a diameter of approximately 5 mm was also employed by some researchers for collecting the pressure – see Figure 4(c) and [3, 13, 18]. The advantage of this CZT is that it collects the vapour from a larger area and from multiple directions. Additional advantage over the previous types is that it cannot be fully blocked by aggregate particles thanks to its elliptical shape. However, a significant disadvantage is that the porous head is a highly-specialised product which is not easily available. Moreover, similarly to the collection cup, the porous head may alter local properties of the concrete matrix, which might affect the measurements, and has the same disadvantage regarding the ITZ.

Schneider and Herbst [25] used a specific type of a collection zone where they created a cavity (a hollow cave-like free space) containing air inside the concrete around the end of the metal tube – see Figure 4(d). The advantage of this CZT is that the pressure is collected from a larger area rather than from a small localized region, which might provide more representative pressure measurements (cf. the plain open-ended tube). Additional advantage is that the collection zone cannot be fully blocked by aggregate particles thanks to its circular shape. The disadvantage is that the cavity has to be create in a clear and controlled manner which might be complicated, and even the authors of this approach do not describe how to create this cavity. Moreover, similarly to the previous types, an ITZ can form on the surface of the cavity, which might distort the measurements.

In summary, 4 distinct types of collection zones were previously employed by researchers: (a) plain open-ended tube, (b) collection cup attached to a tube, (c) sintered head attached to a tube, (d) cavity connected to a tube. Each of these collection zone types have their own advantages and disadvantages. The disadvantages are: (i) small localised collection/measurement area, (ii) risk of blockage, (iii) complicated setup or complicated availability of specific parts, (iv) effect of the setup on the measurements, (v) formation of an ITZ, which might distort the measurements. It is worth noting that the last disadvantage is shared by all of the collection zone types.

Due to the large number of advantages and disadvantages of the various CZTs, no one type can be selected as optimal. Based on the research presented by Li et al. [3, 15], the

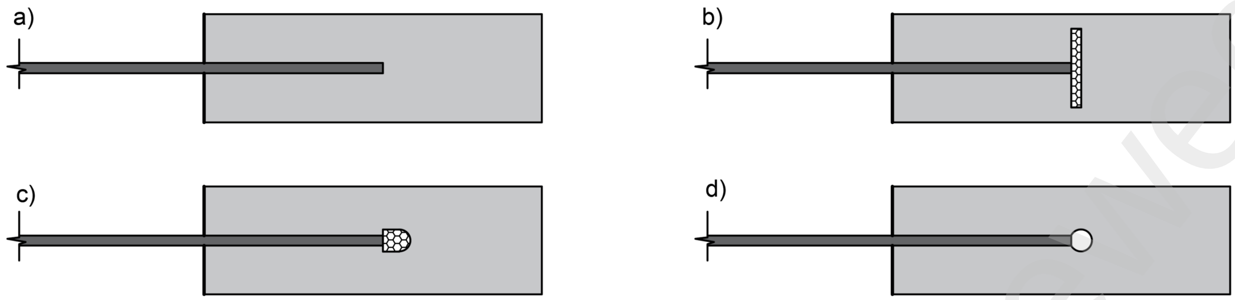


Figure 4: Collection zone types (cf. [15, Table 1]).

collection cup with a sintered metal disk seems to provide most accurate and stable results; however, this CZT is quite complicated to use.

In this paper, an entirely new type of collection zone, which bears none of the above-mentioned disadvantages, will be introduced – see Section 4.

2.3. Summary of existing methods

In this section, various existing methods for vapour pressure measurement were introduced, analysed and compared. The analyses and comparisons were focused mainly on the: (a) direction of the transmission tube with respect to the heating, (b) transmission medium, and (c) collection zone type.

Based on the combination of all of the presented options regarding the direction of the tube, transmission media, and collection zone types, it can be concluded that there are at least 32 ($1 \times 4 \times 4$) possible setup variations. The indicated number of possible combinations is only the lower-bound estimate as further options and combinations are theoretically feasible. This significantly complicates the interpretation of experimental results across various researches and calls for a need to develop a standardised test method for measuring vapour pressure. This need is also highlighted by Li et al. [3] and Gil et al. [18]. In the paragraphs below, the most suitable options (or at leat the least-disadvantageous options) are presented with the aim to point to a most suitable test method (i.e., a combination of options).

The parallel orientation of the tube to the heated surface was identified as optimal with regards to the accuracy of the measurements.

Out of the existing transmission medium options, the most suitable medium seemed to be oil with a solid insert; however, this option is least advantageous from the practical-applicability point of view, and an optimal option would be to omit the transmission medium altogether.

The collection zone types have various advantages and disadvantages and none can be selected as optimal. Though the collection cup with a sintered metal disk seems to provide most accurate and stable results [3, 15], this CZT is quite complicated to use.

As the existing options regarding the transmission medium and the CZT have significant disadvantages, they do not provide a sufficient base for the development of a simple and accurate test method. Thus, a novel method introducing entirely new approach to the transmission medium and collection zone, which solves all of the disadvantages of the existing methods, will be introduced in this paper – see Section 4.

3. Pore pressure versus measured pressure

Before moving to the next section, which will present a novel method for vapour pressure measurement, one important issue needs to be discussed first – the fundamental essence of the measured pressure values.

Li et al. [15], Gil et al. [18], and other researchers state that pore pressure measurements reported by different researchers are generally inconsistent and not in agreement with each other. This fact can also be readily seen when comparing the pressure values reported by various researchers, see Section 2.1. As Li et al. [15] report, these inconsistencies are due to the fact that the measuring instruments, especially in the case of the collection cup with the sintered metal disk, alter the properties of the concrete near the measuring instruments and introduce free volume of air into the concrete. Li et al. [15] further state that, in the collection zone, the "*large free volume facilitates vaporization of condensed moisture and delays build-up of pressure*". Mugume and Horiguchi [36] also specifically state that the pressure measurement method has a "*significant effect on the pore pressures measured*". Similarly, Gil et al. [18] state that most studies have differences in test parameters, and these differences cause a "*significant variation on the measured pressure values*". Thus, it can be summarized that the measured pressure greatly depends on the measurement setup, mainly on the pressure collection zone (e.g., cavity, porous metal cup, end of a tube, etc.).

The fact that the measured pressure depends on the measurement setup suggests that the measured pressure is not the real pore pressure but rather the pressure in the collection zone, which will further be denoted as the "collection zone pressure" (CZP) in this paper. Moreover, due to the reasons presented above, especially the fact that the measurement instruments alter the local properties of the concrete, the authors of this paper propose that the CZP can be substantially different from the real pore pressure.

Surprisingly, the claim that the CZP, rather than the real pore pressure, is being measured is not mentioned by other researchers as far as the authors of this paper were able to ascertain. Nonetheless, apart from the reasons presented above, this claim is supported by various statements by other authors. For example, Li et al. [15] state that the measured pressure is "a mean pressure in front of the pressure gauge", which indicates that it is the CZP rather than a real pore pressure. Moreover, according to Ju et al. [12], the concrete porosity and pore connectivity affect vapour transport and accumulation in concrete. Since concrete porosity affects vapour transport and accumulation, the authors of this paper argue that the collection zone, which is much greater in size than concrete pores, will most certainly greatly affect the vapour accumulation, and thus, the nearby vapour pressure – i.e., the CZP. Åhs [37], who focuses on moisture and drying in general, states that the RH-probe causes disturbance to the drying process and the moisture field. In the case of concrete vapour pressure, the measurement system is a disturbing factor in the same sense as the RH-probe, and thus, the measurement system will significantly affect the pressure in its vicinity.

Based on the discussion presented above, the following conclusion is proposed by the authors of this paper. When measuring the pressure of water vapour in concrete during heating, the real pore pressure is not measured. In reality, the vapour pressure in the collection zone of the measurement system (i.e., the CZP) is measured. The data obtained by measuring the CZP can be viewed as proxy data representing the vapour pressure in the concrete; however, they should never be interpreted as true pore pressure. Unfortunately, a generally applicable conversion ratio between the CZP and the real pore pressure cannot be determined as this relationship will always be dependent on the measurement setup being used. Moreover, even the specific relationship for a given measurement setup cannot be determined as the real pore pressure is impossible to measure due to the measurement disturbance effect – i.e., any measurement instrument penetrating the pore would obscure the results. Moreover, the true pore pressure originates in the microstructure of concrete [12] – i.e., in the pores with diameters ranging from less than 10 nm [12] to 911 µm [38]. Given these small diameters, it is impossible to measure the pressure directly in the individual pores.

As real pore pressure cannot be measured and the CZP is always dependent on the measurement method, for mutual comparability of results across different studies, the CZP should always be measured using the same measurement method. Unfortunately, there is no unified or standardised testing method for measuring the CZP in heated concrete, and various researchers have developed various measurement methods which resulted in non-consistent test set-up and procedures [18]. As Gil et al. [18] point out, the development of a standardised method for measuring vapour pressure would enable comparability among different studies.

In the next section, a novel measurement method developed by the authors of this paper will be presented. This measurement method is not only easily implementable but also solves all of the disadvantages of the existing methods (see Section 2.3). The aim of the authors of this paper is to provide an easily reproducible measurement method for other researchers and thus promote the use of a single measurement method among various researchers.

4. Novel Borehole Method

Due to the absence of a standardised vapour pressure measurement method and significant disadvantages of existing methods, the authors of this paper have developed a novel measurement method referred to as the "Borehole Method".

In this method, a borehole is created in a concrete specimen after its casting and hardening, and this borehole is used as the collection zone – see Figure 5. The collection zone (i.e., the borehole) is oriented parallel to the heated surface – i.e., at a uniform distance (depth, see Figure 5) from the heated surface. Thus, the borehole lies in an almost-perfect isothermal layer and, theoretically, also in an isobaric layer. This enables the collection of the vapour in an evenly manner from a larger yet isobaric area, and thus, enables more stable and representative pressure measurements. Moreover, the borehole is directly connected to a pressure gauge, and thus, the transmission path and transmission medium are altogether omitted, which solves the disadvantages linked with the transmission medium.

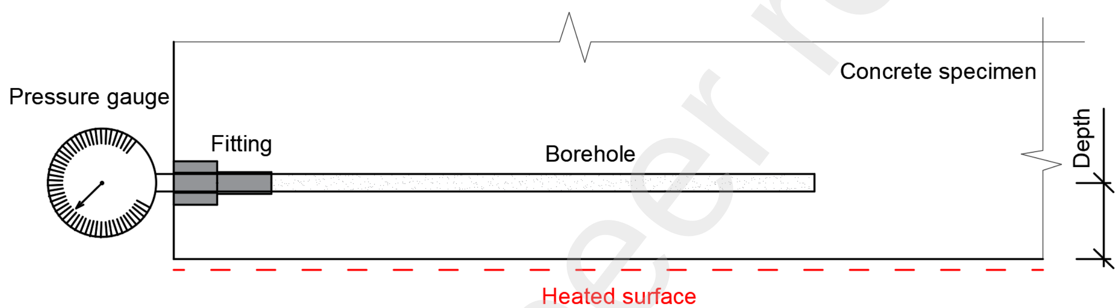
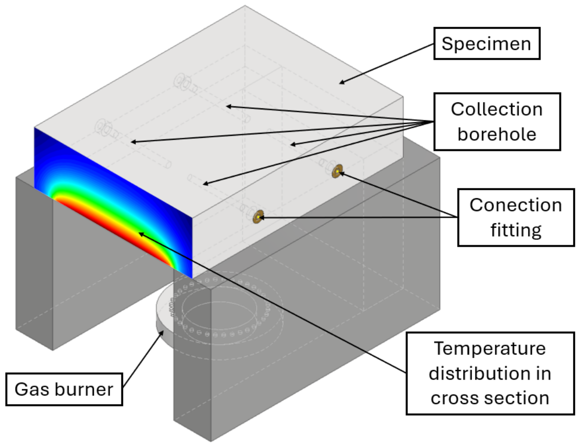


Figure 5: Simplified diagram of the borehole method (cross-section).

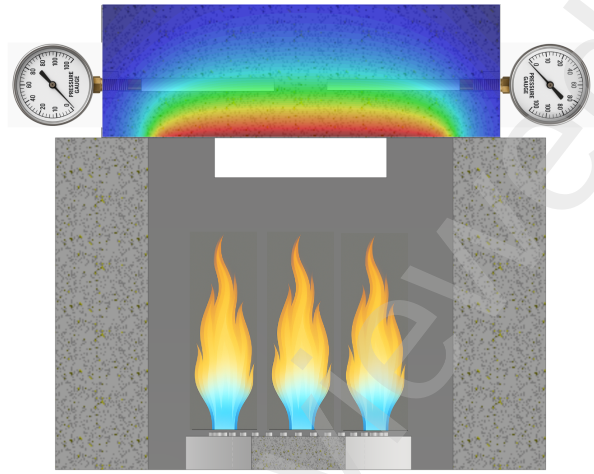
The main novelty and benefits of the Borehole Method lie in two points. Firstly, there is no transmission path nor medium in the Borehole Method, whereas in all researches found by the authors, a transmission path and medium were used. By omitting the transmission medium, the disadvantages linked with the transmission media are resolved, see Sec. 4.1.2. Secondly, the collection zone (the borehole) is created after casting and hardening of concrete by drilling. The authors of this paper have not found any studies aimed at vapour pressure in concrete during heating that would measure the vapour pressure via holes drilled after hardening. All of the documented methods use instruments inserted during casting, see Section 2. Some drilled-hole or borehole methods (see, e.g., [39], [40, Sec. 2.1], [37]) do exist for permeability, RH or moisture measurements, but these are not designed for measuring vapour pressure. This novel type of collection zone has great benefits over the existing collection zones, e.g., no ITZ layer nor risk of blockage, see Sec. 4.1.1.

The Borehole Method and its advantages will be further described in detail in this section. Note that the presented method is the culmination of extensive work focused on investigating various existing setups and novel modified setups conducted by the authors of this paper, see the authors' previous work [19–24]; however, for conciseness, the development of the method is not presented in this paper, and only the final, most suitable method is presented.

The overall experimental setup used in the Borehole Method is shown in Figures 6 and 7.



(a) 3D view



(b) Cross section

Figure 6: Setup of the Borehole Method.

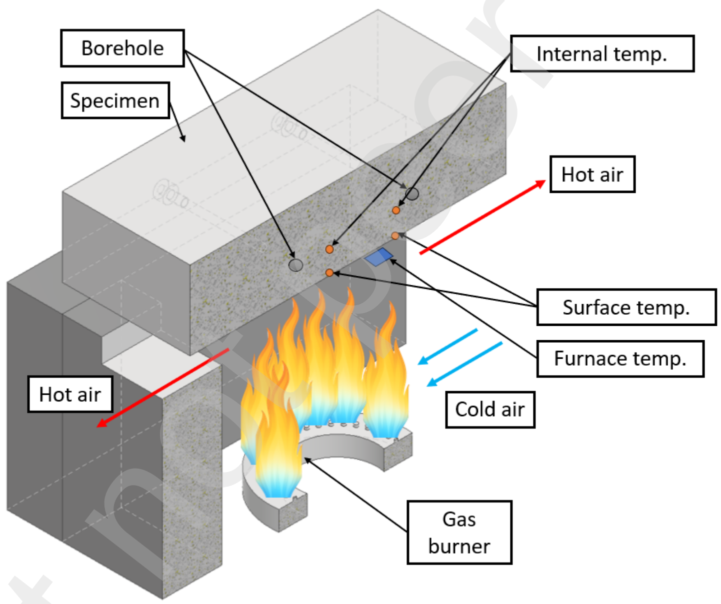


Figure 7: Cross section of the furnace and the test specimen

4.1. Most important parameters of the method

In this section, the most important parameters (as defined in Section 2.2) of the novel Borehole Method are discussed.

4.1.1. Collection zone

The collection zone is the entire borehole from its inner end to the connection fitting (outer end). Since the borehole is oriented parallel to the heated surface, the entire borehole lies within an isothermal layer and thus theoretically also in an isobaric layer. This reduces the risk of effects which might adversely affect the accuracy of the measurements such as the condensation of the vapour in cooler parts. This novel type of collection zone has none of the disadvantages of the existing collection zones (see Section 2.2.3) – specifically: (i) the collection area is large and not localised, (ii) there is no risk of blockage, (iii) the

Figure 8: A borehole in a specimen split during a transverse-tensile test.

setup is straightforward and employs standard widely-available equipment, (iv) there are no instruments which might affect the vapour transport and thus affect the measurements, (v) there is no ITZ layer which could affect the measurements. Moreover, the borehole passes through all of the components of the concrete (i.e., cement matrix as well as the aggregates), and thus, the borehole provides results representative for the concrete as a whole and not any specific component, e.g., the cement matrix – see Figure 8.

4.1.2. Transmission medium

When using the Borehole Method, the there is no "metal tube" connecting the collection zone and the pressure gauge, and thus, there is no transmission system or transmission medium. The only part of the setup, which might be considered as the transmission system, is the small connection fitting embedded into the side of the specimen, see the highlighted area in Figure 8. However, as this fitting is quite short compared to the borehole length, it can be omitted from the considerations, and it can be assumed that the pressure gauge is connected directly to the collection zone.

Since there is no transmission system nor transmission medium, all of the disadvantages linked with the transmission media (see Section 2.2.2) are resolved.

4.1.3. Direction of the tube with respect to the heating

As mentioned in Section 4.1.2, there is no metal tube (transmission system) in the setup of the Borehole Method. However, the same advantages and disadvantages of tube orientation (see Section 2.2.1) also hold true for the borehole orientation. As the perpendicular orientation has many disadvantage while the parallel has none, the parallel orientation of the boreholes is used in the Borehole Method setup, see, e.g., Figure 6.

4.2. Specimen description

The Borehole Method is intended to be used with slab specimens uniformly exposed to heating on their bottom face, see Figure 6. The slabs should be as large as possible to mitigate the inaccuracy due to the size-effect – i.e., the difference between the measured pressure in the specimens and pressure in real structures. However, it is significantly impractical to create full-scale specimens. Thus, the authors of this paper propose the dimensions of

400 mm × 400 mm × 100 mm to be used (cf., e.g., [41, 42]). These dimensions lead to a total weight of the specimen around 40 kg, and thus, the specimens can be manipulated with without the need for heavy machinery.

In the specimens, multiple boreholes at the same isothermal depth should be used, see Figure 6. As these boreholes are at an isothermal depth, they should theoretically provide identical pressure measurements. However, due to the non-homogeneous nature of concrete, the pressures will most probably be slightly different in the various boreholes. By measuring the pressure in multiple boreholes at various locations within the same isothermal layer, more accurate information regarding the pressure in the specimen are obtained – both in terms of the average pressure as well as the maximal pressure. In the 400 mm × 400 mm × 100 mm specimens, two sets of two opposing boreholes should be used (i.e. four boreholes for each specimen in total), see Figure 6.

4.3. Specimen preparation

4.3.1. Preparation prior to casting

For the measurement of vapour pressure using the Borehole Method, only very little preparation is needed prior to casting of the concrete. This is a significant benefit over the existing methods which require the instalment of various instruments prior to the casting – e.g., metal tubes, collection cups, sintered metal heads, etc.

When using the Borehole Method, the only required instrument which must be installed in the formwork is a metal connection fitting (see Figures 5 and 9), to which the pressure gauge will later be connected (see Figure 5). The fitting must have the same thread diameter as the pressure gauge. Moreover, the inner diameter if the fitting must be greater than the planned borehole diameter because the borehole will be drilled through the fitting. The fitting must be located on the side of the specimen so that the borehole, which will be drilled later, will be parallel to the heating side. The fitting must be sealed at its inner end to prevent the backflow of concrete into it and to prevent excessive drying of the concrete near the inner end of the fitting. Paraffin with a low melting point can be used a suitable sealant.

Additionally, it is recommended (but not required) to place thermocouples in the formwork at predetermined depths from the heated surface (see Figure 9) so that the evolution of the temperature distribution can be observed during the heating and the pressure measurements.

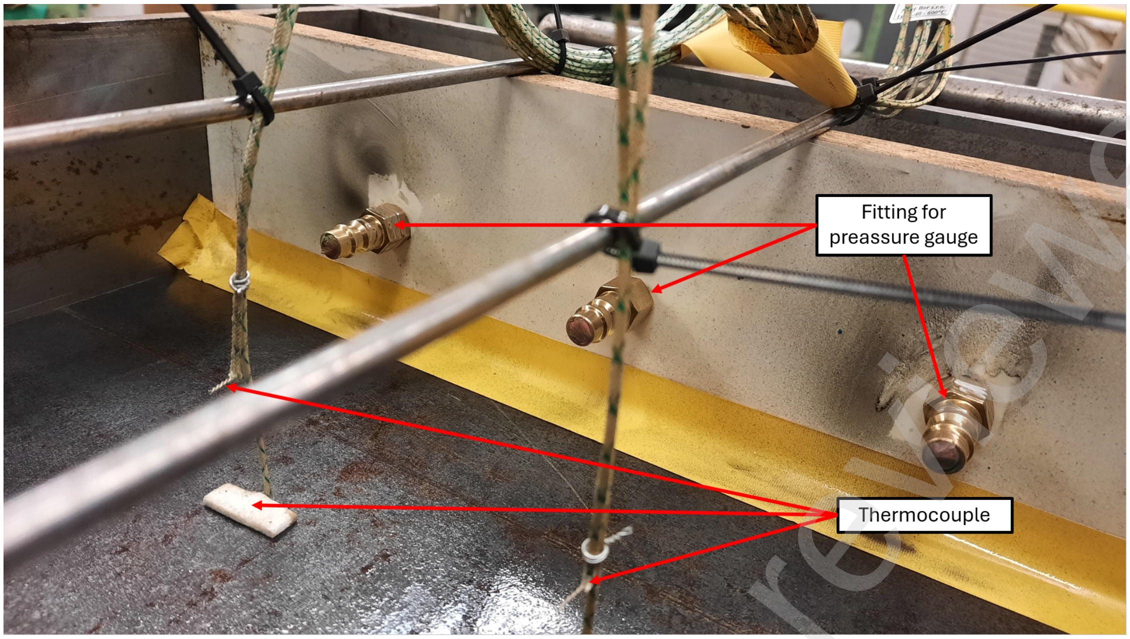


Figure 9: Preparation and instrumentation of concrete specimen before casting.

4.3.2. Casting of concrete

Prior to the casting of the concrete, a release agent should be applied to the formwork. After the casting, the specimen should be covered to prevent moisture loss, or the specimen should be placed in a moisture-controlled chamber.

4.3.3. Preparation after casting

After the casting and hardening of the concrete, the specimen needs to be demoulded and the boreholes need to be drilled. Each borehole is drilled through the corresponding connection fitting embedded into the side of the specimen. Each borehole must be drilled parallel to the heated surface and as straight as possible. The borehole should be drilled using a drill press, drill jig, or some similar device which ensures straight and accurate drilling at the correct angle.

The boreholes should be drilled only after the concrete reaches a sufficient strength to ensure that during drilling, the aggregates will be drilled out and not ripped out, see Figure 8. The recommended age for earliest drilling is 7 days. Moreover, the drilling of the boreholes should be planed close to the heating of the specimens. Ideally, the boreholes should be drilled right before the heating to prevent drying of the concrete through the borehole. If this cannot be ensured, the borehole must be sealed from the outside to prevent the drying. A rubber cap or plug can be used as the sealant. This sealant should be removed right before the heating and should be immediately replaced by the pressure gauge.

After the drilling of the boreholes, the boreholes must be cleaned of any residual debris before attaching the sealant or the pressure gauge.

4.4. Borehole diameter

It must be noted that this Borehole Method, like all of the other existing methods, does not measure the real pore pressure but rather the collection zone pressure (see Section 3), and the pressure will depend on the diameter of the borehole, see the explanation below.

The collection zone pressure is the pressure of the vapour in the borehole, and this pressure will depend on two main factors: (a) the amount of vapour released into the borehole, and (b) the volume of the borehole. With increasing amount of vapour released into the borehole, the pressure increases. In contrast, with increasing volume of the borehole, the pressure decreases. These two factors are linked with the borehole diameter in the following ways. The amount of vapour released into the borehole increases with the surface area of the borehole, and thus, it increases with the borehole diameter. The volume of the borehole also increases with the borehole diameter. Since both factors increase with the borehole diameter, and the factors affect the pressure in opposing ways, one might conclude that the pressure is not dependent on the borehole diameter. However, the factors do not depend on the diameter in the same way. With increasing diameter, the surface area (and thus the amount of vapour) increases linearly but the volume of the borehole increases quadratically. This means that for each diameter, the ratio between amount of vapour and the volume will be different – see Figure 10. Thus, the measured pressure does indeed depend on the borehole diameter, and for mutual comparability of results from various measurement, the borehole diameter must always be the same in all specimens.

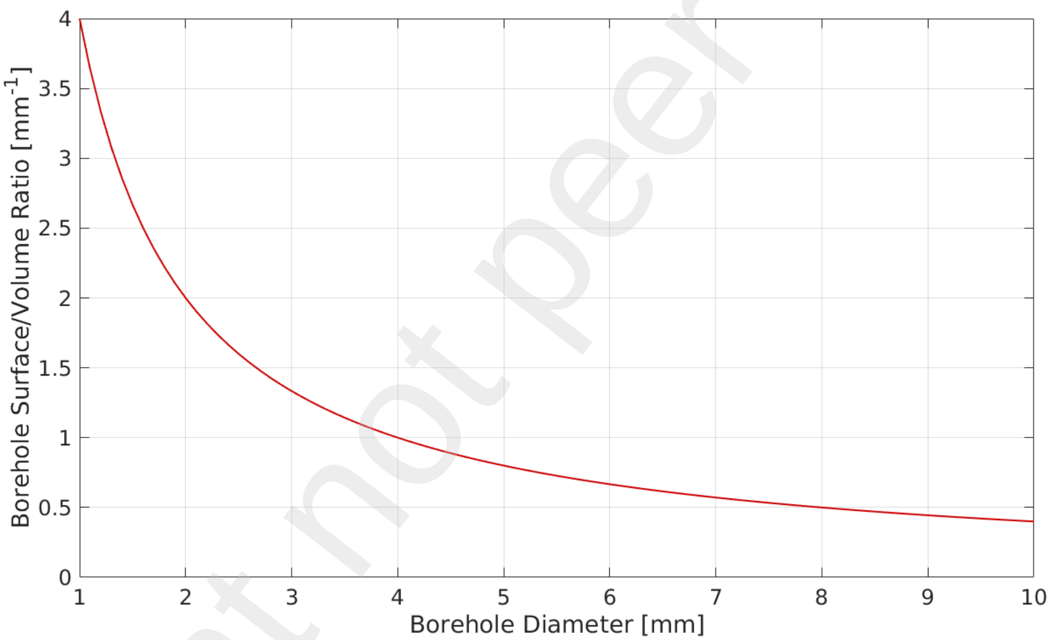


Figure 10: Borehole surface area to borehole volume ratio.

The authors of this paper have selected the diameter of 6 mm as the optimal diameter which should be used when using this method. This diameter is large enough for practical usage (the corresponding drill bit is strong enough to drill though the concrete) while small enough to not significantly affect the properties of the concrete specimen.

4.5. Heating regime

The most suitable heating regime cannot be generally stated as the heating regime depends on the goals of an individual research.

If the real behaviour of concrete during fire is to be determined, the appropriate heating regime (fire scenario) must be used – e.g., ISO-834 fire curve, hydrogen fire curve, problem-specific fire cure, etc.

If the behaviour of concrete during heating – i.e., vapour pressure evolution and possible spalling – is to be investigated, an arbitrary heating regime can be used. The only condition is that the same heating regime must be used for all specimens which are to be compared.

If only the comparison of vapour pressure in various types of concrete is to be conducted, without the need for determining the spalling behaviour, the authors of this paper do not recommend the use the typical fire scenarios for heating. These typical fire scenarios reach very high temperatures quickly, which may lead to concrete spalling, which is undesirable in vapour pressure comparisons as it greatly affects the vapour pressure distribution and measurements.

Regardless of the heating regime used, the specimen must be heated as uniformly as possible – i.e., the temperature of the heated surface should be as uniform as possible at all times. This can be achieved by various means. The authors of this paper propose a simple experimental setup where a small-scale furnace is built around a gas burner (using, e.g., aerated concrete blocks) with the specimen acting a roof of the furnace – see Figures 6 and 7.

5. Illustration of the novel Borehole Method application

In this section, the application of the novel Borehole Method is illustrated. Specifically, a study aimed at the measurement of vapour pressure in concrete using the novel method is presented. In this study, two types of concrete are used – normal-strength concrete (NSC) and high-performance concrete (HPC).

5.1. Specimens

In accordance with the method guidelines, specimens with the dimensions of 400 mm × 400 mm × 100 mm were used. All other specifications of the specimens (e.g., number of boreholes, diameter of boreholes, etc.) were also in accordance with the method guidelines – see Sections 4.2 and 4.3.

The normal-strength concrete (NSC) series contained four different concrete mixtures which varied only in the polypropylene (PP) fibre content – specifically:

- NSC-REF: three specimens with no fibres,
- NSC-PP6: two specimens with 1 kg/m^3 of 6 mm long PP fibres,
- NSC-PP12: two specimens with 1 kg/m^3 of 12 mm long PP fibres,
- NSC-PP18: one specimen with 1 kg/m^3 of 18 mm long PP fibres.

The high-performance concrete (HPC) series contained three different concrete mixtures which varied only in the polypropylene (PP) fibre content and the steel fibre (SF) content – specifically:

- HPC-REF: three specimens with no fibres,
- HPC-SF13-PP6: two specimens with 40 kg/m^3 of 13 mm long SF fibres and 1 kg/m^3 of 6 mm long PP fibres,
- HPC-SF13: two specimens with 40 kg/m^3 of 13 mm long SF fibres.

The PP fibres were dry-dosed directly into the solid components of the mixture and homogenized prior to the addition of water and admixtures. Steel fibres were added after the wet mixing stage to minimize fibre clustering and ensure uniform distribution.

5.2. Compressive strength

In order to enable the comparison of measured pressure values with respect to the strength of concrete, compressive strength was measured for each mixture on cubic specimens. Each cubic specimen had an edge length of 150 mm, in accordance with the standard EN 12390-3 [43]. The number of specimens was 6 for NSC-PP12, NSC-PP18, and HPC-SF13-PP6 mixtures; for all the other mixtures, the number of specimens was 9. The obtained compressive strengths and their standard deviations are presented in Tables 1 and 2.

Table 1: Compressive strength results of the NSC series.

Mixture type	f_{cm} [MPa]	Standard deviation [MPa]
NSC-REF	45.6	0.9
NSC-PP6	34.2	2.5
NSC-PP12	37.2	4.2
NSC-PP18	40.1	2.3

Table 2: Compressive strength results of the HPC series.

Mixture type	f_{cm} [MPa]	Standard deviation [MPa]
HPC-REF	135.1	8.0
HPC-SF13-PP6	99.3	0.5
HPC-SF13	109.0	4.8

5.3. Permeability

As vapour migration and vapour pressure in concrete exposed to high temperatures is strongly governed by the permeability of concrete (see, e.g., [8, Sec. 3.4.9]), an indicative permeability testing was performed to enable the comparison of measured pressure values with respect to the permeability of the material. Permeability was measured using the Proceq Torrent permeability tester [40]. The method was chosen for its simplicity and in-house availability. It should be emphasised that this testing method is primarily intended for assessment of durability of concrete cover [40]. Thus, the measured permeability values should be interpreted as an indicative parameter to compare the investigated materials relative to each other rather than to assess exact permeability values.

5.4. Heating regime and data collection

The test specimens were heated in a small-scale gas-fired furnace, as described in Section 4.5, see also Figures 6 and 7.

An example of the furnace temperature evolution (temperature-time curve) used in the experiment is shown in Figure 11 by the bold black solid line. A nearly identical temperature evolution was applied to all specimens in both the NSC and HPC series.

The furnace temperature was monitored and controlled using a plate thermometer. For each specimen, two K-type thermocouples measured the surface temperature, and two additional K-type thermocouples measured the internal temperature at a depth of 40 mm from the heated surface. Temperatures were recorded automatically by a computer-connected data logger. Boreholes for vapour-pressure measurements were located at the same depth (40 mm). Vapour pressure was measured with analogue dial gauges; pressure readings were taken manually at regular 5-minute intervals.

5.5. Detailed illustration of the measurements

As this paper focuses primarily on the presentation of a novel Borehole Method, only some illustrative examples of measurements are presented in this paper. Fore more detailed results, see our previous work [22].

5.5.1. HPC-REF panel

In this subsection, the evolutions of temperatures and vapour pressures in one of the HPC-REF panels (HPC-REF panel 3, futher denoted as HPC-REF_3) are presented – see Figure 11.

As can be readily seen in Figure 11, the evolution of vapour pressure is similar in all boreholes in most time steps. Moreover, in most boreholes, the maximal pressure was observed at $t = 110\,\text{min}$ during which the temperatures of the boreholes were 255 °C. The values of the maximal pressures were 2.6 MPa, 2.5 MPa, and 1.8 MPa.

As can also be seen in Figure 11, though the pressure in most boreholes peaked at $t = 110\,\text{min}$, in one borehole (the P3 borehole), the pressure continued to increase up to

$t = 150$ min (borehole temperature of 300 °C). Thus, in this borehole a significantly higher maximal pressure was observed. This highlights one of the advantages of this method, which is that it collects the pressure from various places inside the specimen, which increases the chance of finding and measuring local vapour pressure extremes. The value of the maximal pressure in this borehole was 3.65 MPa.

It is also worth noting that an issue with the heat source occurred in the first minutes of the heating; however, was can be seen in Figure 11, issues with the heat source during this time affect the temperature of the boreholes only very slightly and do not affect the pressure measurements at all as moisture is not vaporising yet.

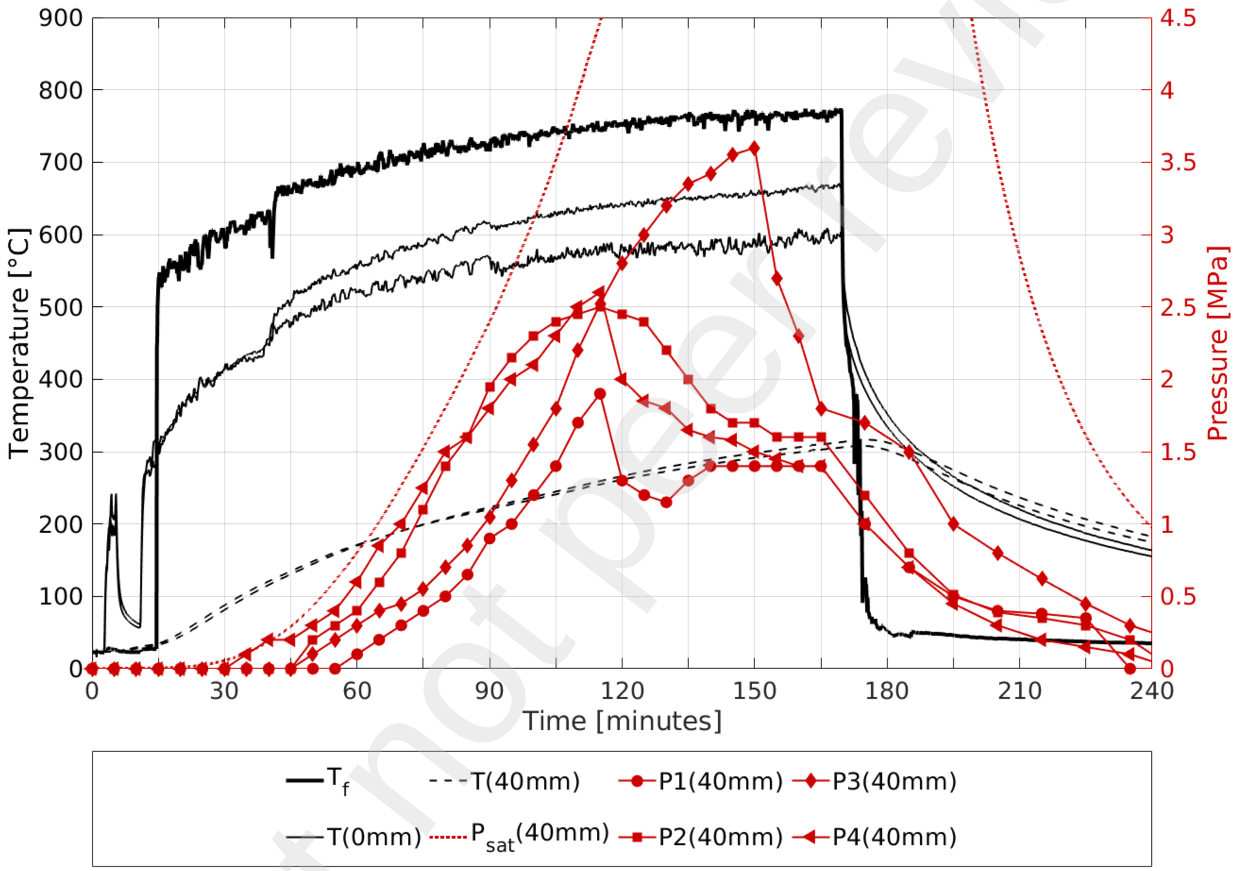


Figure 11: Evolutions of temperature and vapour pressure for HPC-REF panel 3 (HPC-REF_3 specimen). T_f is the measured furnace temperature. T(0mm) is the measured surface temperature (two thermocouples). T(40mm) is the measured internal temperature at a depth of 40 mm from the heated surface (two thermocouples). P_{sat}(40mm) is the saturation pressure at a depth of 40 mm from the heated surface, calculated from the mean values of T(40mm). P1–P4 are the measured vapour pressure evolutions at a depth of 40 mm from the heated surface for boreholes 1–4, see Figure 6.

5.5.2. Agreement of the measured pressure with the theoretical fully-saturated pressure

In most specimens, the vapour-pressure histories exhibit a time evolution similar to the theoretical saturation-pressure curve, see Figure 11, particularly in the NSC and HPC-REF series. However, the measured pressures remained systematically below the saturation pressure throughout the experiments, including the cooling phase, which corresponds to the fact that the specimens were not fully saturated.

5.6. Overview of all results

5.6.1. NSC series

A total of eight specimens were tested within the NSC series. All tests were carried out at the specimen age of 28 days, and no spalling was observed during the testing of the NSC specimens. The results are summarized in Table 3, where:

- T1 denotes the temperature T(40mm) at the initial occurrence of the pressure,
- T2 denotes the temperature T(40mm) at the time of the peak pressure,
- $P_{max,avg}$ denotes the arithmetic mean of the per-borehole maximum pressures,
- P_{max} denotes the overall maximum pressure recorded in any single borehole.

Note that the standard deviations of the measured maximum pressure are given in Section 5.6.3.

Table 3: Summary of NSC series results.

Specimen	Permeability [$\times10^{-16}$ m^2]	T1 [°C]	T2 [°C]	$P_{max,avg}$ [MPa]	P_{max} [MPa]
NSC-REF_1	0.033–0.051	120	280	0.63	0.66
NSC-REF_2	0.033–0.051	100	230	0.36	0.52
NSC-REF_3	0.033–0.051	160	260	0.33	0.42
NSC-PP6_1	0.197–0.255	110–140	200	0.11	0.17
NSC-PP6_2	0.197–0.255	100–130	190	0.09	0.10
NSC-PP12_1	0.065	110	190	0.42	0.75
NSC-PP12_2	0.112	90	200	0.26	0.42
NSC-PP18_1	0.100	90–130	180–260	0.29	0.37

Table 3 reveals a clear correlation between the increased permeability (due to the fibres) and the measured pressure. The lowest pressure values were recorded in the specimens with the highest permeability, i.e., the NSC-PP6 series, whereas the highest (based on the average pressure from all boreholes) pressures were observed in the NSC-REF specimens.

One seemingly notable exception is the specimen NSC-PP12_1 which exhibited the highest individual pressure value within the NSC series; however, the average pressure in NSC-PP-12_1 specimen was 0.42 MPa, which is comparable to the average values measured in the NSC-REF specimens. Moreover, during permeability tests, the specimen showed significantly lower permeability compared to the other PP-fibre-reinforced specimens. This may be attributed to technological inconsistencies during the mixing process, such as uneven or insufficient dispersion of the PP fibres within the dry components of the concrete mixture.

5.6.2. HPC series

A total of seven specimens were tested within the HPC series. The tests were carried out at specimen ages ranging from 28 to 250 days.

Spalling occurred in two of the specimens during testing. In the case of HPC-REF_1 specimen, continuous spalling of small concrete fragments was observed. Due to the explosive nature of the spalling, these fragments disintegrated into fine particles and dust. For safety reasons, the test was preliminarily terminated. The spalling and test termination occurred before the vapour formation, and thus, no pressure was measured. The HPC-FC_1 specimen also experienced spalling during pressure measurement. In contrast to the HPC-REF_1 specimen, two distinct explosive spalling events occurred, resulting in significant cracks across the specimen. These events took place at the 25th and 40th minute after the initiation of heating.

A summary of the measurements is presented in Table 4. For the explanation of the notation, see Section 5.6.1. Regarding permeability, the HPC series could not be meaningfully analysed by the Torrent method – all specimens returned essentially identical, lower-bound readings in the range (0.005–0.01) $\times 10^{-16}$ m^2, i.e. at or near the instrument's resolution. Because these identical values were obtained for all HPC specimens, the permeability data are not given in Table 4.

Table 4: Summary of HPC series results.

Specimen	Age [days]	Spalling	T1 [°C]	T2 [°C]	$P_{max,avg}$ [MPa]	P_{max} [MPa]
HPC-REF_1	28	Yes (significant)	–	–	–	–
HPC-REF_2	250	No	120	200–260	1.55	1.9
HPC-REF_3	250	No	120	260–300	2.7	3.65
HPC-SF13-PP6_1	30	No	100–140	250	1.13	1.35
HPC-SF13-PP6_2	30	No	120–180	300	2.1	2.7
HPC-SF13_1	40	Yes	160	440	2.0	2.3
HPC-SF13_2	50	No	160–180	340	1.5	3.7

From Table 4, it can be readily seen that the maximum pressure values were observed in the HPC-FC_2 specimen (3.70 MPa) and the HPC-REF_3 specimen (3.65 MPa). The HPC-REF_3 specimen also showed the highest average pressure (2.7 MPa).

Compared to the NSC series, the emergence of the vapour pressure in the HPC specimens occurred at later times after the initiation of heating, and thus, at higher temperatures. This was primarily attributed to the lower water-to-cement ratio, resulting in a lower amount of free water within the cement matrix. With lower amount of free water, the amount of vapour was also lower, and more time was needed for the pressure to rise. In addition, the low permeability of HPC leads to slower migration of water vapour and delayed formation of a moisture clog.

The maximum pressure was also reached at later time and higher temperatures than in the NSC series. This was observed in all specimens across the HPC series.

5.6.3. All series

Figure 12 presents a comprehensive overview of the measured vapour pressures in the panel specimens and the corresponding compressive strengths obtained on the cubic specimens. The centre of each ellipse corresponds to the mean value of the measured pressure and compressive strength. The lengths of the semi-axes represent the respective standard deviations of the measured values.

The number of specimens used for compressive strength testing was 6 or 9 for each mixture, see Section 5.2. The number of specimens used for vapour-pressure measurements is specified in Section 5.1. Each specimen contained four boreholes (see Section 4.2); therefore, the total number of vapour-pressure measurements for each material was as follows: 12 for NSC-REF, 8 for NSC-PP6, 8 for NSC-PP12, 4 for NSC-PP18, 12 for HPC-REF, 8 for HPC-SF13-PP6, and 8 for HPC-SF13.

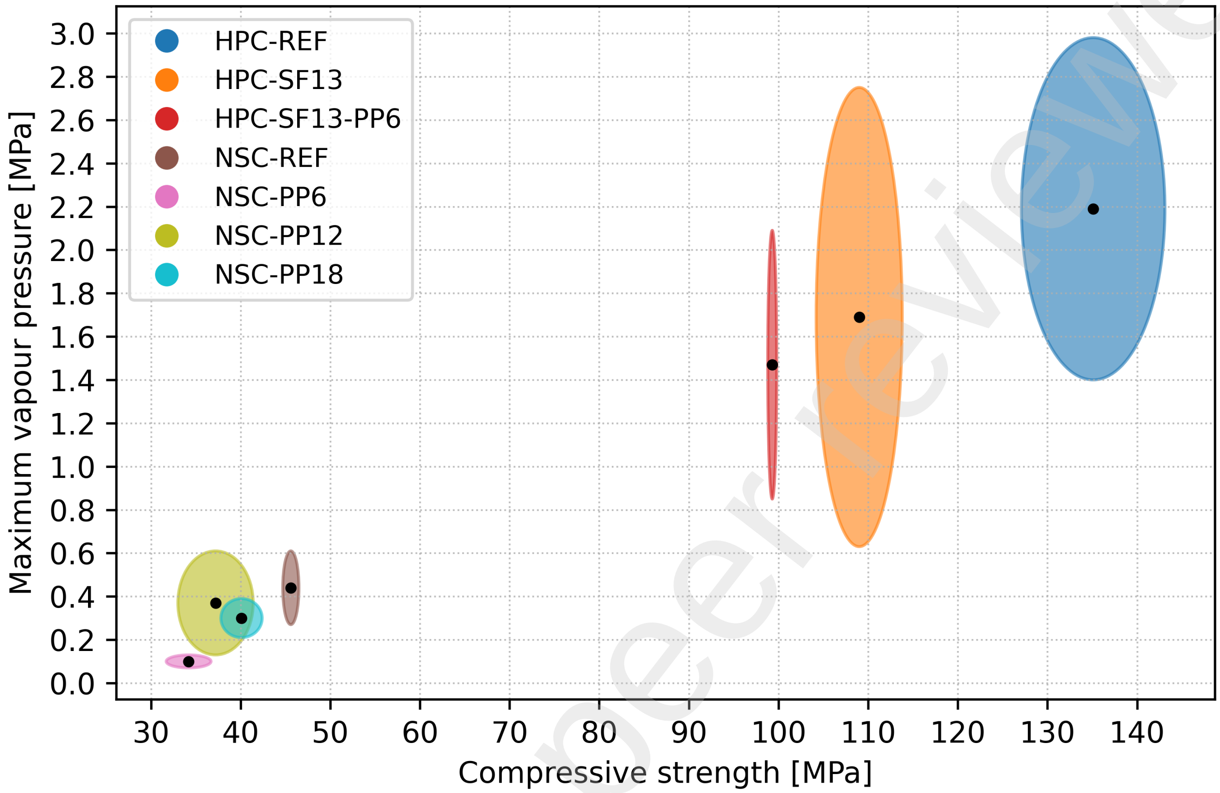


Figure 12: Graphical representation of the maximum vapour pressure and compressive strength for each concrete mixture – mean values (black dots) and standard deviations (ellipses semi-axes).

As can be readily seen in Figure 12, a logical trend can be observed – with increasing compressive strength, the vapour pressure also increases. This can be primarily attributed to the fact that increased compressive strength is linked with decreased aeration and permeability. Though this is a generally know fact (see, e.g., [8]), it is worth highlighting as it shows that the novel Borehole Method produces results conforming to this general rule.

Additionally, it can also be observed in Figure 12 that in both the NSC and HPC series, the addition of fibres decreases the compressive strength as well as the vapour pressure. This is, again, a generally know fact (see, e.g., [8]), and shows that the novel Borehole Method produces logical results.

6. Conclusions

As already highlighted in the introduction, investigating the development of vapour pressure in concrete at high temperatures is essential to ensuring the safety and stability of reinforced-concrete structures during fire.

One of the most pressing problems in the field of vapour pressure measurement is the absence of a widely-used, well-documented, and easily-reproducible method for measurements. As pointed out in this paper, the measured pressure is never the true pore pressure, and the measured values depend heavily on the measurement method making the measurement obtained by various methods incomparable. This further highlights the need for a single widely-used method. The solution to this problem presented in this paper consisted of two main steps.

In the first step, an extensive overview of the existing methods and their advantages and disadvantages was presented. In this overview, it was found that each existing method had significant disadvantages. Thus, in the second step, a novel method developed by the authors was presented. This novel method resolves many of the disadvantages of the existing methods and is easily reproducible. The main advantages of the proposed method over the existing methods are the following.

- The entire collection zone lies within an isothermal layer.
- The collection zone is large and not localised.
- There is no risk of blockage of the collection zone.
- The setup is straightforward and employs standard widely-available equipment.
- There are no instruments which might affect the vapour transport and thus affect the measurements.
- These is no ITZ layer which might affect the vapour transport and thus affect the measurements.
- The collection zone passes through all of the components of the concrete, and thus, the results are representative for the concrete as a whole and not any specific component.
- There is no transmission system nor transmission medium, and thus, all of the disadvantages linked with the transmission media are resolved.

Additionally, a practical application of the novel method was presented through an experimental investigation of vapour pressure measurements in NSC and HPC slab specimens. The experimental investigation, conducted using the novel method, has confirmed that the proposed measurement method is functional, repeatable, and suitable for measuring pressure in concrete exposed to high temperatures. The measured values followed the expected trends based on known material characteristics and were consistent with theoretical assumptions related to the behaviour of fully saturated materials. Moreover, selected measurements confirmed the ability of the method to capture the differences in the behaviour of various types of concrete.

Though a novel method for vapour pressure measurement, which resolves many disadvantages of the existing methods, has been proposed in this paper, additional recommendations for further development in this field can be formulated. These recommendations are linked with the urgent need to standardise the methodology for vapour pressure measurement in concrete exposed to high temperatures, as has recently been done for spalling experiments through RILEM recommendations on standardised test methods [41, 42].

For better mutual comparability of results from various studies, the following parameters should be standardised (cf. [8, 41, 42, 44]):

- Gravimetric moisture content of the specimens prior to testing, ideally determined through oven-drying of companion specimens at 105 °C until constant mass.
- Specimen age at the time of testing, e.g., 90 days.
- Heating protocol, including initial temperature, heating rate (for example, 2 K/min), and possible holding periods at target temperatures.
- Dimensions of the test specimens, including the mould type.
- Stress-strain boundary conditions, e.g., should the specimens be pre-loaded or not, and should the specimens be free to expand or not.
- Sensor configuration, detailing the type, number, depth, and location of thermocouples and pressure transducers.

Moreover, the standardisation should also focus on specifying the parameters which should be reported in experimental studies. The authors of this paper recommend that the following parameters should be reported for more meaningful interpretation and better mutual comparability of results.

- Material permeability, which plays a critical role in vapour migration and the formation of moisture clogging. The absolute value should be reported along with the method of its determination.
- Compressive strength of the tested concrete, serving as an indicator of material maturity and mix consistency.
- Temperatures at the onset of pressure and at the maximum of pressure, which are key factors for assessing spalling risk and comparative material performance.
- Occurrence of spalling, including the approximate time and temperature of its onset, as this may significantly affect the internal temperature and pressure distribution.

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References

[1] Y. Ichikawa, G. England, Prediction of moisture migration and pore pressure build-up in concrete at high temperatures, Nuclear Engineering and Design 228 (1) (2004) 245–259. `doi:10.1016/j.nucengdes.2003.06.011`.

[2] G. Debicki, R. Haniche, F. Delhomme, An experimental method for assessing the spalling sensitivity of concrete mixture submitted to high temperature, Cement and Concrete Composites 34 (8) (2012) 958–963. `doi:10.1016/j.cemconcomp.2012.04.002`.

[3] Y. Li, E.-H. Yang, A. Zhou, T. Liu, Pore pressure build-up and explosive spalling in concrete at elevated temperature: A review, Construction and Building Materials 284 (2021) 122818. `doi:10.1016/j.conbuildmat.2021.122818`.

[4] T. Z. Harmathy, Effect of moisture on the fire endurance of building elements, Moisture in Materials in Relation to Fire Tests, ASTM Special Technical Publication No. 385, pp. 74–95 (1965). `doi:10.4224/40001466`.

[5] Z. P. Bažant, W. Thonguthai, Pore Pressure in Heated Concrete Walls: Theoretical Prediction, Magazine of Concrete Research 31 (107) (1979) 67–76. `doi:10.1680/MACR.1979.31.107.67`.

[6] Z. P. Bažant, Analysis of Pore Pressure, Thermal Stress and Fracture in Rapidly Heated Concrete, in: International Workshop on Fire Performance of High-Strength Concrete. Proceedings. Appendix B: Workshop Papers. B10, Gaithersburg, MD, 1997.
URL `https://tsapps.nist.gov/publication/get_pdf.cfm?pub_id=916655`

[7] F.-J. Ulm, O. Coussy, Z. P. Bažant, The "Chunnel" Fire. I: Chemoplastic Softening in Rapidly Heated Concrete, Journal of Engineering Mechanics 125 (3) (1999) 272–282. `doi:10.1061/(ASCE)0733-9399(1999)125:3(272)`.

[8] A. Khoury, Y. Anderberg, Fire safety design – Concrete spalling review, Swedish National Road Administration, 2000.

[9] P. Kalifa, F.-D. Menneteau, D. Quenard, Spalling and pore pressure in HPC at high temperatures, Cement and Concrete Research 30 (12) (2000) 1915–1927. `doi:10.1016/S0008-8846(00)00384-7`.

[10] K. Hertz, Limits of spalling of fire-exposed concrete, Fire Safety Journal 28 (2) (2003) 103–116. `doi:10.1016/S0379-7112(02)00051-6`.

[11] J. Ko, D. Ryu, T. Noguchi, The spalling mechanism of high-strength concrete under fire, Magazine of Concrete Research 63 (5) (2011) 357–370. `doi:10.1680/macr.10.00002`.

[12] Y. Ju, H. Liu, K. Tian, J. Liu, L. Wang, Z. Ge, An investigation on micro pore structures and the vapor pressure mechanism of explosive spalling of RPC exposed to high temperature, Science China Technological Sciences 56 (2) (2013) 458–470. doi:10.1007/s11431-012-5110-4.

[13] R. Felicetti, F. Lo Monte, P. Pimienta, A new test method to study the influence of pore pressure on fracture behaviour of concrete during heating, Cement and Concrete Research 94 (2017) 13–23. doi:10.1016/j.cemconres.2017.01.002.

[14] G. Choe, G. Kim, M. Yoon, E. Hwang, J. Nam, N. Guncunski, Effect of moisture migration and water vapor pressure build-up with the heating rate on concrete spalling type, Cement and Concrete Research 116 (2019) 1–10. doi:10.1016/j.cemconres.2018.10.021.

[15] Y. Li, D. Zhang, K. H. Tan, On measuring techniques of pore pressure in concrete at elevated temperature, Cement and Concrete Composites 114 (2020) 103737. doi:10.1016/j.cemconcomp.2020.103737.

[16] D. Zhang, K. H. Tan, Effect of various polymer fibers on spalling mitigation of ultra-high performance concrete at high temperature, Cement and Concrete Composites 114 (2020) 103815. doi:10.1016/j.cemconcomp.2020.103815.

[17] T. Kannangara, P. Joseph, S. Fragomeni, M. Guerrieri, Existing theories of concrete spalling and test methods relating to moisture migration patterns upon exposure to elevated temperatures – A review, Case Studies in Construction Materials 16 (2022) e01111. doi:10.1016/j.cscm.2022.e01111.

[18] A. Gil, S. Banerji, V. Kodur, Factors influencing pore pressure measurements in concrete during heating and its influence on fire-induced spalling, Cement and Concrete Composites 142 (2023) 105228. doi:10.1016/j.cemconcomp.2023.105228.

[19] R. Chylík, Measurement of pore pressure in concrete at high temperatures: Lessons from initial failure, in: Proceedings of PhD Workshop, Department of Concrete and Masonry Structures 2021, FCE CTU, Prague, Czech Republic, 2021, (In Czech). URL https://concrete.fsv.cvut.cz/phdworkshop/proceedings/2021/pdf/Chylik_Roman.pdf

[20] R. Chylík, Measurement of pore pressure in concrete at high temperatures, in: Proceedings of PhD Workshop, Department of Concrete and Masonry Structures 2022, FCE CTU, Prague, Czech Republic, 2022, (In Czech). URL https://concrete.fsv.cvut.cz/phdworkshop/proceedings/2022/pdf/Chylik_Roman.pdf

[21] R. Chylík, Pore pressure and spalling of concrete exposed to high temperature: From history to the present, in: Proceedings of PhD Workshop, Department of Concrete and Masonry Structures 2023, FCE CTU, Prague, Czech Republic, 2023, (In Czech). URL https://concrete.fsv.cvut.cz/phdworkshop/proceedings/2023/pdf/Chylik_Roman.pdf

[22] R. Chylík, Experimental Measurement of Pore Pressure in Concrete Exposed to High Temperatures, PhD Thesis, CTU in Prague, (In Czech) (2024).
URL https://dspace.cvut.cz/handle/10467/118562

[23] J. Tomáš, Methods of measurement of pore pressure in concrete exposed to high temperatures, Master's Thesis. Supervisors: R. Štefan, R. Chylík, CTU in Prague, (In Czech) (2021).
URL https://dspace.cvut.cz/handle/10467/93042

[24] M. Macháč, Experimental and numerical analysis of pore pressure in concrete exposed to high temperatures, Master's Thesis. Supervisors: R. Štefan, R. Chylík, CTU in Prague, (In Czech) (2022).
URL https://dspace.cvut.cz/handle/10467/99525

[25] U. Schneider, H. J. Herbst, Pressure development in heated concrete members, in: Concrete Structures, Behavior of Structural Concrete, SMiRT 10, H – Concrete Structures, IASMiRT, Anaheim, CA, USA, 1989, pp. 113–118.
URL http://www.lib.ncsu.edu/resolver/1840.20/29477

[26] R. Jansson, L. Boström, The influence of pressure in the pore system on fire spalling of concrete, Fire Technology 46 (2010) 217–230. doi:10.1007/s10694-009-0093-9.

[27] M. R. Bangi, T. Horiguchi, Pore pressure development in hybrid fibre-reinforced high strength concrete at elevated temperatures, Cement and Concrete Research 41 (11) (2011) 1150–1156. doi:10.1016/j.cemconres.2011.07.001.

[28] M. Ozawa, H. Morimoto, Effects of various fibres on high-temperature spalling in high-performance concrete, Construction and Building Materials 71 (2014) 83–92. doi:10.1016/j.conbuildmat.2014.07.068.

[29] Y. Ding, C. Zhang, M. Cao, Y. Zhang, C. Azevedo, Influence of different fibers on the change of pore pressure of self-consolidating concrete exposed to fire, Construction and Building Materials 113 (2016) 456–469. doi:10.1016/j.conbuildmat.2016.03.070.

[30] M. Ozawa, T. Tanibe, R. Kamata, Y. Uchida, K. Rokugo, S. S. Parajuli, Behavior of ring-restrained high-performance concrete under extreme heating and development of screening test, Construction and Building Materials 162 (2018) 215–228. doi:10.1016/j.conbuildmat.2017.11.144.

[31] M. P. Lutz, P. J. Monteiro, R. W. Zimmerman, Inhomogeneous interfacial transition zone model for the bulk modulus of mortar, Cement and Concrete Research 27 (7) (1997) 1113–1122. doi:10.1016/S0008-8846(97)00086-0.

[32] U. M. Angst, M. R. Geiker, A. Michel, C. Gehlen, H. Wong, O. B. Isgor, B. Elsener, C. M. Hansson, R. François, K. Hornbostel, R. Polder, M. C. Alonso, M. Sanchez, M. J. Correia, M. Criado, A. Sagüés, N. Buenfeld, The steel–concrete interface, Materials and Structures 50 (2) (2017) 143. doi:10.1617/s11527-017-1010-1.

[33] J. A. Larbi, Microstructure of the interfacial zone around aggregate particles in concrete, Heron 38 (1) (1993) 1–69.
URL https://heronjournal.nl/38-1/1.pdf

[34] H. Wong, M. Zobel, N. Buenfeld, R. Zimmerman, Influence of the interfacial transition zone and microcracking on the diffusivity, permeability and sorptivity of cement-based materials after drying, Magazine of Concrete Research 61 (8) (2009) 571–589. doi:10.1680/macr.2008.61.8.571.

[35] K. Wu, H. Shi, L. Xu, G. Ye, G. De Schutter, Microstructural characterization of itz in blended cement concretes and its relation to transport properties, Cement and Concrete Research 79 (2016) 243–256. doi:10.1016/j.cemconres.2015.09.018.

[36] R. B. Mugume, T. Horiguchi, Effect of the measurement technique on the amount of maximum pore pressures measured inside concrete subjected to high temperatures, in: 2nd International RILEM Workshop on Concrete Spalling Due to Fire Exposure, RILEM, Delft, Netherlands, 2011, pp. 87–94.
URL https://www.rilem.net/images/publis/6c753d1a4632a11ebce69c0862028dbd.pdf

[37] M. Åhs, Evaluation of an Embedded Wireless Relative Humidity Probe for Monitoring Concrete Drying, (TVBM; No. 3191). Division of Building Materials, LTH, Lund University (2024).
URL https://lucris.lub.lu.se/ws/portalfiles/portal/200750141/Evaluation_of_an_Embedded_Wireless_Relative_Humidity_Probe_for_Monitoring_Concrete_Drying_TVBM-3191_final_draft.pdf

[38] L. Bao, G. Xu, H. Li, C. Xin, H. Li, M. He, C. Liu, The Study of the Three-Parameter Normal Distribution Characteristics of the Pore Structure in C80 High-Performance Self-Compacting Concrete (HPSCC), Journal of Composites Science 8 (12) (2024) 510. doi:10.3390/jcs8120510.

[39] J. W. Figg, Methods of measuring the air and water permeability of concrete, Magazine of Concrete Research 25 (85) (1973) 213–219. doi:10.1680/macr.1973.25.85.213.

[40] R. J. Torrent, A two-chamber vacuum cell for measuring the coefficient of permeability to air of the concrete cover on site, Materials and Structures 25 (1992) 358–365. doi:10.1007/BF02472595.

[41] P. Pimienta, R. McNamee, I. Hager, K. Mróz, L. Boström, S. Mohaine, S.-S. Huang, J.-C. Mindeguia, F. Robert, C. Davie, R. Felicetti, M. J. Miah, M. Lion, F. Lo Monte, M. Ozawa, I. Rickard, K. Sideris, M. C. Alonso, A. Millard, U.-M. Jumppanen, L. Bodnarova, J. Bosnjak, S. Dal Pont, V. Dao, D. Dauti, F. Dehn, R. Hela, T. Hozjan, M. Juknat, J. Kirnbauer, J. Kolsek, M. Korzen, H. Lakhani, C. Maluk, F. Meftah, B. Moreau, F. Pesavento, D. T. Pham, K. Pistol, J. P. Correia Rodrigues, M. Roosefid, M. Schneider, U. K. Sharma, L. Stelzner, B. Weber, F. Weise, Recommendation of RILEM TC 256-SPF on the method of testing concrete spalling due to fire: material screening test, Materials and Structures 56 (164) (2023). doi:10.1617/s11527-023-02202-z.

[42] P. Pimienta, R. McNamee, F. Robert, L. Boström, S.-S. Huang, K. Mróz, C. Davie, S. Mohaine, M. C. Alonso, L. Bodnarova, J. Bosnjak, S. Dal Pont, V. Dao, D. Dauti, F. Dehn, R. Felicetti, I. Hager, R. Hela, T. Hozjan, M. Juknat, U.-M. Jumppanen, J. Kirnbauer, J. Kolsek, M. Korzen, H. Lakhani, M. Lion, F. Lo Monte, C. Maluk, F. Meftah, M. J. Miah, A. Millard, J.-C. Mindeguia, B. Moreau, Y. Msaad, M. Ozawa,

F. Pesavento, D. T. Pham, K. Pistol, I. Rickard, J. P. C. Rodrigues, M. Roosefid, M. Schneider, U. K. Sharma, K. Sideris, L. Stelzner, B. Weber, F. Weise, Recommendation of RILEM TC 256-SPF on fire spalling assessment during standardised fire resistance tests: complementary guidance and requirements, Materials and Structures 57 (3) (2023). doi:10.1617/s11527-023-02248-z.

[43] EN 12390-3, Testing hardened concrete – Part 3: Compressive strength of test specimens, CEN, 2019.

[44] Compressive strength for service and accident conditions, Materials and Structures 28 (1995) 410–414. doi:10.1007/BF02473077.