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Gas permeability under varying laboratory conditions

Damjan Grba[1], Thomas Zimmermann[2], Alfred Strauss[1,]
[1]Institute of Structural Engineering, University of Natural Resources and Life Sciences, Peter-Jordan-Straße 82, 1190 Vienna, Austria
[2]Building Inspection Authority, Vienna City Administration, Dresdner Straße 73-75, 1200 Vienna, Austria
email: damjan.grba@students.boku.ac.at, thomas.zimmermann@wien.gv.at, alfred.strauss@boku.ac.at

ABSTRACT: Durability is a critical factor in the long-term performance of concrete structures. Ensuring adequate surface quality – and thus extending the service life of concrete elements – relies significantly on proper curing during the hydration phase. To assess and monitor the effectiveness of the curing process, suitable testing methods are essential. Among these, gas permeability testing provides valuable insights into the porosity of the concrete, which directly affects its durability. This study investigates the influence of various curing methods on gas permeability using both laboratory and field testing. The results demonstrate that insufficient curing leads to higher gas permeability in the near-surface zone of concrete. Concrete specimens and structural components made from identical mix designs but subjected to different curing conditions are analyzed and compared. The findings also take into account the influence of concrete composition and environmental conditions on surface quality. Based on these insights, the study offers recommendations for a reliable evaluation of curing effectiveness through gas permeability as an indicator of surface integrity.

KEY WORDS: concrete curing; non-destructive testing; gas permeability testing; durability; quality control.

1 INTRODUCTION

The results of this study provide a differentiated understanding of how curing quality and external climatic influences interact to affect the permeability and thus the long-term performance of concrete structures. By isolating the effects of curing and environmental conditions, it becomes possible to derive targeted recommendations for construction practice and quality assurance, especially under conditions where optimal curing cannot be ensured. In particular, gas permeability is examined as a practical and sensitive indicator for the assessment of curing effectiveness and surface concrete quality, as highlighted in various previous studies [1–5, 7, 8, 10].

Several works have investigated the applicability of gas permeability as a diagnostic tool in both laboratory and field conditions [3, 4, 10, 11]. Moreover, the significance of environmental parameters during curing and their long-term implications for concrete performance has been documented [5, 6, 7, 9]. This study contributes to this ongoing research by systematically quantifying these influences under controlled yet variable conditions and by using a standardized testing approach (Permeator AC+), thereby ensuring comparability and reproducibility of the findings.

The remainder of this paper is structured as follows: Section 2 outlines the concrete material and details the specimen preparation, climatic conditioning, and measurement procedures. Section 3 presents the results of gas permeability testing under the different environmental scenarios. In Section 4, the results are discussed with regard to the interaction between curing quality and environmental exposure. Finally, Section 5 summarizes the key findings, draws practical implications, and suggests directions for future research.

Objective: This study involved a series of tests aimed at systematically quantifying the influence of time, temperature, and relative humidity on the permeability of concrete. Three different concrete structures were examined under controlled climatic conditions. The resulting data make it possible to analyze the interactions between thermal effects, moisture ingress, and temporal changes in the diffusion behavior of concrete, thereby contributing to a deeper understanding of the long-term durability of concrete under varying environmental conditions.

Relevance: The study evaluated whether curing quality of concrete can still be clearly detected through gas permeability measurements, even under fluctuating environmental conditions. For this purpose, concrete specimens were exposed to different combinations of temperature and humidity, then analyzed for their gas permeability. The aim was to determine how variable environmental parameters influence the effectiveness of the curing process, allowing conclusions to be drawn about the durability of the concrete.

Methodology and Approach: Within the scope of this study, concrete specimens were systematically exposed to different temperature and relative humidity conditions in a climate chamber. The curing performance was assessed by measuring gas permeability, a reliable indicator of concrete tightness and therefore durability. For quantitative determination of gas permeability, the Permeator AC+ device was used, enabling standardized and reproducible measurements. The collected data provide a foundation for analyzing the relationships between specific climatic conditions and the diffusion properties of concrete.

This methodological approach ultimately allows for an assessment of how successful concrete curing is under varying environmental conditions, and which parameters significantly affect gas permeability a key criterion for assessing the durability of concrete.

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As part of a study, nine identical concrete test specimens were initially produced to serve as the base material for examining curing quality. The specimens were divided into three equally sized groups of three units each to apply different curing methods. The curing was carried out as (a) optimal curing (b) neutral/no special conditions and (c) bad curing.

This approach enables a comparison of three different levels of curing quality derived from the same raw material.

Subsequently, all nine specimens were exposed to various environmental conditions in a climate chamber. Variable temperatures and relative humidity levels were simulated to evaluate the impact of these parameters on gas permeability. Gas permeability was measured using a Permeator AC+, ensuring precise and standardized determination of the concrete's diffusion properties.

This systematic investigation makes it possible to analyze in detail the influence of curing quality in conjunction with varying environmental conditions on the durability and impermeability of concrete.

2 CONCRETE MATERIAL

For the present investigation, nine concrete test specimens with dimensions of 15 cm × 15 cm × 15 cm each were produced. All specimens were made from the same batch of concrete to ensure a consistent starting point and to allow for isolated examination of the curing process. After demolding, the specimens were divided into three groups of three and subjected to different curing conditions. These differentiated curing procedures enabled a systematic investigation of how varying curing quality affects gas permeability and, consequently, the durability of the concrete.

2.1 Concrete Composition

All specimens were fabricated from a single concrete batch prepared in accordance with concrete type B3 as specified in ÖNORM B 4710-1. The binder used was a Portland composite cement of type CEM II/A-M (S-L) 42.5 N according to DIN EN 197-1. This cement contains, in addition to Portland clinker, ground granulated blast-furnace slag (S) and limestone (L) as main components, with a combined proportion of 6 to 20 m-%. The strength class 42.5 indicates a standardized strength between at least 42.5 MPa and at most 62.5 MPa after 28 days, while the "N" denotes normal early strength development. Table 1 summarizes the concrete mixture.

Table 1. Main Parameters of the Investigated Concrete Mixture (According to [8]).

Concrete parameter	value	unit
w/b	0.55	-
Slump-value	F52	-
Grain-size	22	mm
Air-content	3-5.5	%
Cement	CEM-II/A-M(S-L)	-

After demolding, the specimens were divided into three groups of three and subsequently subjected to different curing treatments. This systematic variation of curing conditions enabled precise analysis of how different curing qualities affect gas permeability and thus the durability of the concrete. The choice of concrete type in accordance with ÖNORM B 4710-1 and the use of composite cement aimed at a practice-oriented assessment of the interaction between curing, environmental conditions, and permeability characteristics.

2.2 Curing of the Specimens

The specimens were demolded 24 hours after production and then divided into three groups of three. Each group was subjected to the following differentiated curing procedures:

- Good curing: Immediately after demolding, the specimens were completely wrapped in foil to prevent moisture loss. For the first seven days, the specimens were stored at a temperature of 20 ± 2 °C, a relative humidity of ≥80%, and no air flow due to the sealed foil environment. Afterward, they remained wrapped for an additional six days under the same conditions to ensure continued moist curing and optimal hydration.
- No curing: The second group received no further treatment after demolding and was stored under ambient laboratory conditions to simulate natural drying. The specimens were exposed to a temperature of 20 ± 2 °C, a relative humidity of approximately 50 ± 5%, and free air circulation. These conditions served as a reference for unprotected, natural drying in indoor environments.
- Poor curing: The third group was deliberately subjected to suboptimal curing conditions by being placed on a windowsill exposed to natural indoor light and airflow. This setup simulated increased drying conditions, resulting in accelerated surface moisture loss. The environmental conditions during this period were approximately 25 ± 3 °C, relative humidity of 40 ± 10%, and moderate to high air movement due to occasional ventilation and solar exposure. These conditions represent inadequate curing typical of poorly protected elements during early-age concrete exposure.

This methodological differentiation allowed for a systematic investigation of how different curing qualities influence gas permeability and, consequently, the durability of the concrete.

3 TIME-DEPENDENT TESTING

The concrete specimens were examined for gas permeability at 7, 14, 28, and 56 days after demolding. The k_T value was determined on four defined surfaces of each specimen: the troweled top surface, the bottom formwork surface, and two lateral formwork surfaces.

Climate Chamber Testing: The previously defined environmental conditions (temperature, relative humidity, and air flow) were maintained consistently in the climate chamber throughout the entire storage period, in accordance with the respective curing method. The specimens were removed from the chamber at the predefined testing ages, tested, and then returned to their respective environments. The remaining specimens continued to be stored under the assigned climatic conditions until their next scheduled testing.

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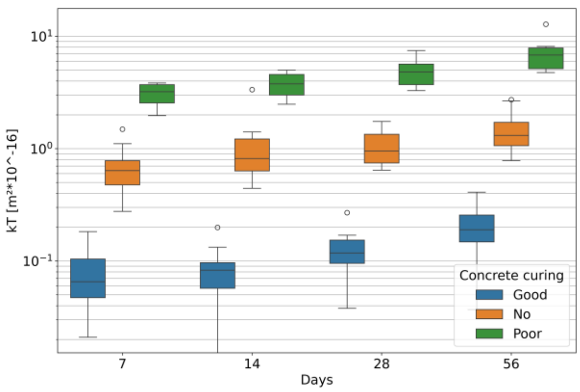

Figure 1. Change in k_T value over time..

Figure 1 illustrates a clear differentiation between the k_T values of the three different curing methods. The optimally cured specimens consistently show the lowest permeability values, while those with poor curing exhibit the highest. Furthermore, a marked increase in the k_T values is observed across all curing types over the observation period from 7 to 56 days. The distinctions between the individual curing classes remain, which can be attributed to continued surface drying of the concrete.

4 CLIMATE CHAMBER TESTING

To further explore the effects of environmental conditions, additional tests were conducted in a climate chamber to assess their influence on the gas permeability of the concrete specimens. Each group was stored for 12 hours under varying combinations of temperature and relative humidity, as shown in Table 1. Subsequently, the k_T values were re-measured on the same surfaces as described in Chapter 3 (troweled top surface, bottom surface, and two sides).

Table 2. Climate chamber testing under different humidity and temperature conditions.

		Temperature in °C			
		25	30	35	40
Relative air moisture in %	60	x	x	x	x
	70	x	x	x	x
	80	x	x	x	x
	90	x	x	x	x

In addition to gas permeability, concrete moisture content was also measured at the same locations using a concrete moisture meter (Type: Tramex). This parallel measurement enables a more detailed analysis of the relationship between moisture content and the diffusion characteristics of concrete, and helps identify possible interactions between environmental conditions and concrete durability.

4.1 Influence of Temperature on Gas Permeability

The results show that the overall impact of temperature on measured gas permeability is relatively minor. However, the effect is most apparent in the optimally cured specimens. In general, a slight but noticeable increase in gas permeability with rising temperature can be observed (see Figure 2).

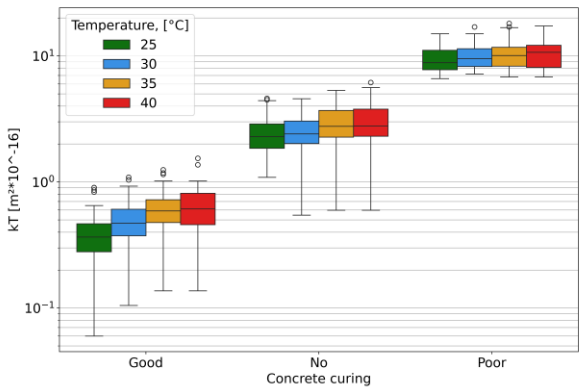

Figure 2. Gas permeability at different temperatures, grouped by curing method, for the corresponding relative humidity see Table 2.

This suggests that higher temperatures may accelerate surface drying, thereby enhancing the diffusion capacity for gases. Although this effect is present across all curing qualities, its magnitude varies significantly depending on the initial curing quality.

4.2 Influence of Relative Humidity on Gas Permeability

As shown in Figure 3, relative humidity has only a minimal influence on the gas permeability of the concrete specimens examined. Across the studied range of relative humidity, the measured permeability values show little to no significant change.

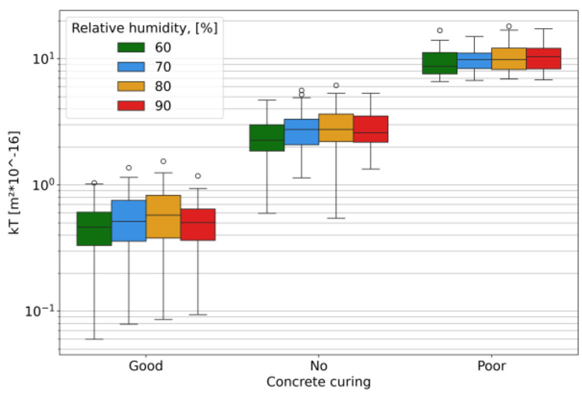

Figure 3. Gas permeability at varying relative humidity, grouped by curing method, for the corresponding temperature see Table 2.

4.3 Influence of Relative Humidity on Concrete Moisture

Changes in relative humidity have a direct impact on measured concrete moisture. The data show a clear correlation: as relative humidity increases, so does the moisture content in the concrete. However, despite this relationship between environmental humidity and concrete moisture, the measured gas permeability remains almost unaffected.

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4.4 Comparison of Gas Permeability and Concrete Moisture

As illustrated in Figure 4, there is a clear inverse correlation between concrete moisture and gas permeability. Higher surface moisture levels correspond to lower kT values, indicating reduced gas permeability—typically a sign of better curing quality. Conversely, lower surface moisture is associated with higher k_T values, suggesting insufficient curing and increased gas permeability.

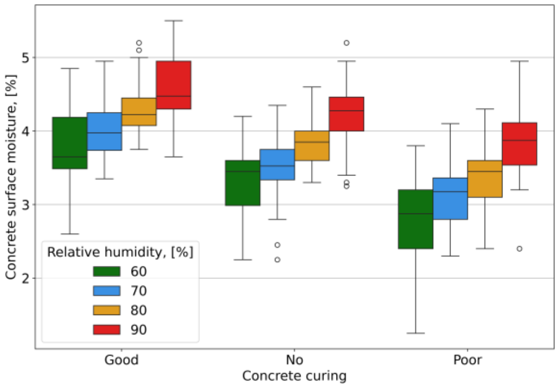

Figure 4. Moisture content of the material (in mass-%) as a function of curing conditions and different ambient humidity levels.

4.5 Corrected k_T Value

Referencing Torrent & Bueno et al. [12]: "Effect of surface moisture on air-permeability k_T and its correction", it is well-established that moisture within concrete pores impedes gas flow and significantly affects gas permeability readings. While laboratory samples are often pre-conditioned through controlled drying, on-site measurements are typically performed under prevailing natural moisture conditions.

According to Swiss Standard SIA 262/1-E:2019, air permeability testing (Torrent method) on construction sites is only permitted if the concrete surface moisture (m), as measured by electrical impedance, does not exceed 5.5%.

In this study, 50 data sets from five independent investigations were analyzed, showing a strong relationship between gas permeability (k_T) and concrete moisture (m). In 84% of the cases (R = 0.95), this relationship could be described using an exponential function of the form:

$$k_T = k_{T_0} \cdot e^{d \cdot m} \quad (1)$$

with d typically ranging between 1.0 and 2.0 (median: 1.45). Based on these results, a practical correction method is proposed to mathematically adjust gas permeability measurements for moisture effects. For moisture levels between 4.5% and 5.5%, the correction is of minor practical relevance. However, incorporating such a correction into future versions of relevant standards is conceivable.

5 CONCLUSIONS

The presented research investigated the impact of various curing methods under otherwise nearly identical conditions. The findings demonstrate that both the type and duration of curing significantly influence the gas permeability of concrete – and, by extension, the long-term durability of the structure. Therefore, gas permeability measurements can serve as an indirect indicator of curing quality.

This approach is notable for its straightforward and non-destructive application, suitable for both laboratory settings and on-site evaluations. The analysis of the collected data is efficient and uncomplicated. Existing recommendations, such as the representation of permeability values per test area according to Swiss Standard SIA 262/1:2019 [13], offer a useful framework for assessing surface quality.

However, since gas permeability is affected not only by curing conditions but also by concrete composition and other factors, it does not allow for a direct measurement of curing quality. One potential solution is to define a permeability threshold during the planning phase as a minimum standard for concrete performance. This threshold could be derived from reference measurements on similar concrete elements with the same composition. Implementing such a method would require extensive research to establish a statistically reliable dataset for defining acceptable limits.

A follow-up research project is currently underway, focusing on gas permeability testing of concrete structures with varying properties and exposed to different climatic conditions. Simultaneously, reference values are being gathered from test specimens with identical formulations and optimal curing to support the evaluation of site-specific results. While this approach shows promise, further research is essential to fully validate its effectiveness and reliability.

Summary of key findings:

- Laboratory investigations have confirmed that gas permeability measurement is a reliable and effective method for assessing the curing quality of concrete.
- A clear distinction in the permeability coefficient was observed between specimens with "good" curing and those with either "poor" or no curing. However, since gas permeability is also influenced by the specific concrete composition, it is not possible to define universal threshold values for curing quality evaluation.
- Inadequate curing leads to increased gas permeability and is also associated with a reduction in compressive strength compared to optimally cured concrete.
- Tests conducted on actual construction sites demonstrated that direct gas permeability measurements on structural elements yield valid insights into the quality of curing.
- Environmental conditions, such as wind, temperature, and humidity, significantly affect on-site measurements. These influences can either improve or impair concrete quality and must therefore be taken into account when choosing measurement locations, scheduling testing, and interpreting curing effectiveness.
- For field assessments, it is recommended – according to Swiss standard SIA 262/1:2019 – that at least six

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individual k_T measurements be performed per testing area to ensure reliable results.

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