submitted: 21.05.2025. *https://doi.org/10.62683/ZRGAF41.2*

Research paper

accepted: 02.06.2025.

CONCRETE PERFORMANCE ASSESSMENT BASED ON GAS PERMEABILITY TESTING

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Abstract

Designing of structures with medium to high performance requirements is a demanding and challenging engineering task. Depending on the location and type of the planned structure, various pre-testing methods should be applied. In recent decades, there has been a focus on the durability of concrete. Concrete is a porous material with a relatively thin protective cover layer, making it vulnerable to the penetration of external agents such as carbon dioxide. Gas permeability testing (kT), a relatively new non-destructive method (NDT), should therefore be considered. This paper presents results of gas permeability testing on a set of larger concrete samples made under controlled conditions with some property variations order to find initial kT parameters important for the quality assurance.

Key words: *Concrete Structure, Gas Permeability, Torrent Tester, Cement Concrete*

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1. INTRODUCTION

Building structures are typically made of concrete, which is generally a porous material - particularly in the concrete cover layer. According to the literature, researchers studying pore size describe pores in a wide range of scales, from nanometers to millimeters [1]. Since the cover layer is the most exposed and sensitive part of the concrete, it is directly affected by various external environmental influences. This relatively thin layer is frequently exposed to moisture, aerosols, and environmental agents, making it closely linked to the durability of concrete structures.

The durability of concrete is often compromised by the ingress of aggressive substances such as carbon dioxide, chlorides, sulfates, and other harmful gases or liquids. The concrete's ability to resist these agents is primarily determined by its porosity [2]. Although the relationship between the pore structure and durability is still under active investigation, and no universally accepted methodology currently exists to fully characterize this link, there is a broad agreement that porosity plays a crucial role in determining durability [3][4].

Currently, water permeability testing is more commonly used than gas permeability testing, despite the fact that concrete typically has much higher internal gas permeability. As noted by Torrent [5], gas, including water vapour, flows more easily through the complex pore structure of concrete than fluid water. This is also reflected in the test duration: gas permeability tests take only minutes to a few hours, while water permeability tests can take several days or even weeks.

However, durability involves more than just porosity. e.g. the size and connectivity of the pores have a large influence on permeability [5]. Reinforcement, a critical component of concrete structures, is particularly vulnerable to corrosion, which is often driven by chemical attack and freeze-thaw cycles [6]. While a structural element's load-bearing capacity depends on its overall behavior, its resistance to environmental degradation is mainly influenced by the effectiveness and thickness of the thin protective concrete cover layer. This concept is illustrated in Figure 1.

Figure 1. The concept of concrete cover layer and reinforcement

Nowadays, several methods for permeability testing are in use. It is worth mentioning that these methods—both water and gas permeability—can be divided into a few categories. The most important distinction is that the methods may be destructive, semi-destructive, or non-destructive [5][7]. However, since the focus of this paper is on non-destructive testing (NDT), the most relevant methods will be discussed.

Several water permeability methods are available on the market, including the Autoclam Permeability System, Initial Surface Absorption Test (ISAT), Surface Water Absorption Test (SWAT), and the Water Intentional Spraying Test (WIST) [7].

On the other hand, the list of gas permeability NDT methods is significantly shorter. One such method was developed by Torrent. The Torrent method is a relatively new testing technique designed to evaluate the gas permeability of the concrete cover layer both in laboratory conditions and in situ. This test belongs to the NDT group of techniques. Measurement involves placing a specialized cell on the concrete surface and creating a vacuum inside it. The rate at which the internal pressure returns to atmospheric levels is then measured [8]. Another option is the Autoclam Permeability System—more commonly referred to in the literature as the "CLAM" test—which can be used for both gas and water permeability testing. The equipment consists of a metal ring, bonded to the concrete surface, with a diameter of 50 mm. Once curing is complete, the apparatus is placed on the base ring. For air permeability testing, the decay of pressure is monitored, while for water testing, water is applied at a constant pressure of 0.01 bar for the sorptivity test and 1.5 bar for the water penetration test [9].

The paper is divided in several sections: the first section shows the introduction to the paper; general description of gas permeability test is shown in the second; the third deals with presenting the methods, results and discussion of real testing of concrete batches by using Torrent tester, while the fourth section is the conclusion based on the obtained results.

2. GAS PERMEABILITY

Gas or air permeability testing results should give us prediction of concrete quality. Gas permeability testing provides insight into the durability and quality of concrete by measuring how easily air passes through its pore structure. High gas permeability suggests greater porosity and a higher risk of structural deterioration, while low permeability indicates better resistance to harmful agents. This method is especially important for concrete exposed to harsh environments like freeze-thaw cycles or chemical attacks. Overall, gas permeability serves as a key indicator of concrete's ability to resist degradation, particularly in aggressive settings such as coastal or industrial areas [3]. Since now, there are several available methods for gas permeability testing but all of them might be classified by test purpose, testing type, type of the used vacuum pressure and operation depth. Accordingly, test type and purpose might be selected as the most important facts to select the appropriate method to be used.

The Torrent tester is a double chamber cell device, developed by researcher Roberto Torrent in 1992 as an improved version of the single chamber method. It uses two concentric chambers under equal vacuum pressure to create a unidirectional airflow into the inner chamber. This nondestructive technique (NDT) allows for the accurate calculation of gas permeability and became the first standardized on-site testing method in 2003. It is now included only in the Swiss

Standard SIA 262/1:2019, which defines testing conditions, calibration procedures, and limit values based on environmental exposure [5]. Components of PermeaTORR AC+ which is better known in scientific circles as Torrent tester is presented in the Figure 2 and 3.

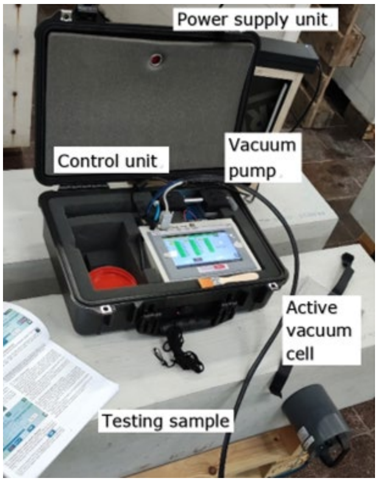

Figure 2. The components of PermeaTORR AC+ tester (Torrent tester). Source: BAM/Bijeljic

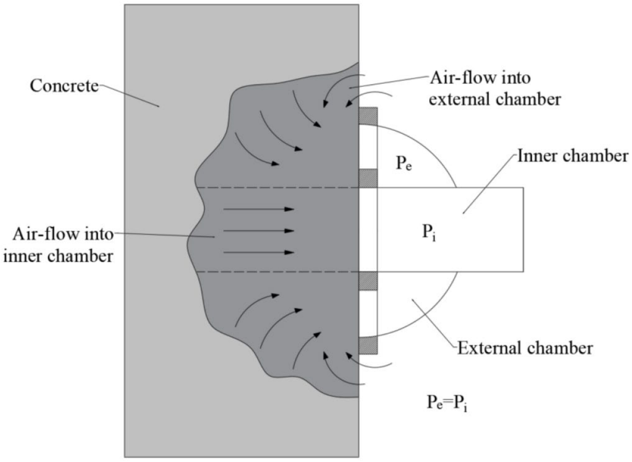

Figure 3. Vacuum cell, pressure regulation and gas flow into its two concentric chambers [10]

A key finding from the previous research is describing the correlation between the concrete's gas permeability and its potential durability by the kT parameter. The parameter (kT) serves as a useful indicator for predicting how well a structure will resist aggressive environmental conditions. Unlike traditional methods based only on sample tests, this approach offers a more accurate reflection of the real-world performance. Standardizing the calculation of kT and setting clear limit values can help engineers better evaluate concrete mixtures and ensure long-term durability of structures [11].

$$kT = \left(\frac{V_C}{A}\right)^2 \cdot \frac{\mu}{2 \cdot \varepsilon \cdot P_a} \left(\frac{ln\left(\frac{P_a+\Delta P}{P_a-\Delta P}\right)}{\sqrt{t_f}-\sqrt{t_0}}\right)^2 \tag{1}$$

where:

kT =gas permeability parameter ($10^{-16}m^2$);
V_C =Volume of the inner test chamber (m^3);
A =area of the inner test chamber (m^2);
μ =dynamic viscosity of gas (Ns/m^2);
ε =open porosity of the concrete (-) which, by defult is taken as 0.15;
P_a =atmospheric pressure (N/m^2);
ΔP =increase in the eff. press. in the inner chamber between time $t_0$and t_f (N/m^2);
t_0 =time at which the increase in the pressure is measured (s);
t_f=time at which the test is finished (s).

For in situ testing, it is recommended [11] that tests be conducted at the age of 28 to 120 days to ensure stable moisture conditions. This is also the recommendation that might be found in the research of Roamer [12]. Additionally, both the air and concrete surface temperatures should be higher than 5 °C during testing and 6 to 12 measurements should be taken per test area to allow for the statistical assessment. The gas permeability coefficient kT [10] has to be expressed in m² which represents the intrinsic permeability of the hardened concrete and should be calculated by using Equation (1) and implemented the measured parameters. After parameter is calculated, classification of the concrete cover quality should be done according to Table 1.

Table 1. Gas permeability classification [10]

Classification of the quality of concrete cover		Sample
PK1	very good	kT<0.01
PK2	good	0.01≤kT<0.1
PK3	normal	0.1≤kT<1.0
PK4	poor	1.0≤kT<10
PK5	very poor	kT≥10

3. METHODS, RESULTS AND DISCUSSION

In this study, three concrete mix designs were prepared, with two samples produced for each mix. All mixtures used CEM I 42.5 N cement, manufactured by the CEMEX cement plant at Rüdersdorf, Germany, as the binder material.

Table 2. Design of tested samples

Mixture	**-**	***G32mm+0.32 %LP***	***G32mm+0.18 %LP***	***G32mm+0%LP***
		Mix design		
Aggregate 0/4 mm	kg/m³	*588*	*623*	*646*
Aggregate 4/8 mm	kg/m³	*221*	*235*	*243*
Aggregate 8/16 mm	kg/m³	*366*	*388*	*402*
Aggregate 16/32 mm	kg/m³	*534*	*566*	*587*
Cement	kg/m³	*340*	*340*	*340*
Water	kg/m³	*155*	*155*	*155*
Additive MasterRheobuild	%	*1.2*	*1.5*	*1.7*
Additive LPS A-94	%	*0.29*	*0.18*	*0*
w/b	-	*0.456*	*0.457*	*0.457*
		Fresh concrete properties		
Consistency EN 12350-5 [13]	mm	F4	F4	F4
Fresh state density EN 12350-6 [14]	kg/m³	2193	2258	2392
Air content EN 12350-7 [15]	%	8	5.5	1.7
		Hardened concrete properties		
Hardened state density EN 12390-7 [16]	kg/m³	2210	2260	2380
Compressive strength at 28 days EN 12390-3 [17]	N/mm²	31.3	43.3	55.9

The concrete mixtures, labeled as G32, incorporated a maximum aggregate size of 32 mm. To enhance workability and investigate the influence of porosity, various additives were introduced. MasterRheobuild 1021 was added to improve workability. To increase the formation of gel pores and examine the impact of a porosity-inducing additive on different concrete NDT parameters, air-entraining agent for concrete Sika LPS A-94 (referred to as LP) was used. Based on the amount of LP added, the mixtures were categorized as follows: G32mm+0.32%LP (maximum LP content), G32mm+0.18%LP (minimum LP content), and G32mm+0%LP (no LP added).

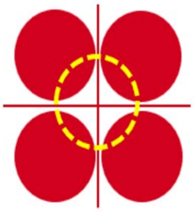
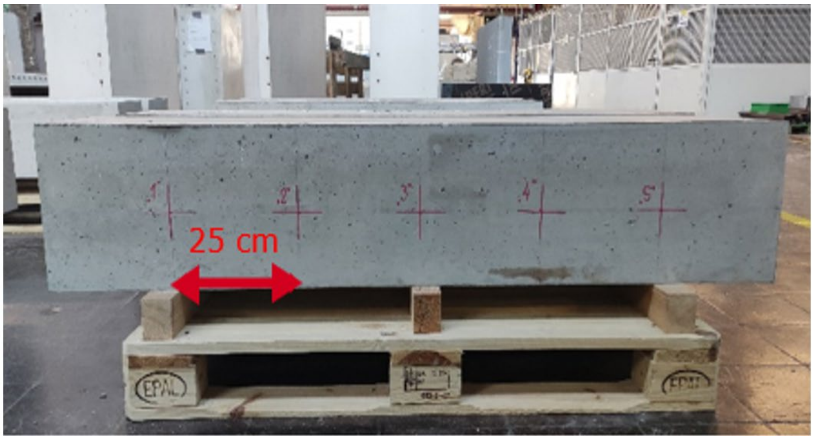

Figure 4. left) testing point, b) measurement locations of gas permeability

The detailed mix designs are presented in Table 2. After mixing, the samples were cured under ambient conditions until testing. All concrete mixtures were designed to meet the requirements of compressive strength class C 40/50, consistency class F4, and a w/b ratio ranging between 0.45 and 0.46. The fresh concrete was cast into molds of dimensions 30×30×150 cm. During testing, measurements were taken at intervals of 25 cm, with each point measured five times for accuracy. The test was performed on the three longer mold-surfaces of the samples (front, back and bottom in Figure 4). The measurement method and measurement locations on one side of each sample are given in the Figure 4 left and 4 right.

Table 3. Minimum (kTmin) and maximum (kTmax) gas permeability values and humidity (m) of mixtures „G32mm+0.32%LP“; „G32mm+0.18%LP“ and „G32mm+0%LP“

Test	**G32mm+0.32%LP**	**G32mm+0.18%LP**	**G32mm+0%LP**
kT_{min} ($10^{-16}m^2$)	1.24	1.12	0.899
kT_{max} ($10^{-16}m^2$)	338	113	69.1
m (%)	1.98	2.05	1.71
Number of kT carried measurments	124	116	112
Classification	PK5	PK5	PK4

In the tested samples with a maximum aggregate size of 32 mm, the gas permeability coefficient (kT) decreased significantly as the LP additive content was reduced. The highest kT value, 112.63×10^{-16} m², was recorded for the mixture "G32mm+0.32%LP." Reducing the LP content to 0.18% in the "G32mm+0.18%LP" mixture resulted in a kT value approximately seven times lower. In the mixture without LP ("G32mm+0%LP"), the kT value is about 73 times lower compared to the mixture with maximum LP content. These gas permeability results align with the air content measured in the fresh concrete. As shown in Table 2, the highest air content—8% of the fresh concrete volume—was observed in mixtures with the highest LP content. Based on these findings, using the maximum LP dosage recommended by the manufacturer is not advisable unless there is a specific reason to do so, as it produces concrete with extremely high gas permeability—falling outside even the "poor" classification, which includes kT values between 1 and 10×10^{-16} m².

Gas permeability was significantly lower when no LP additive was used. This suggests that the gel pores formed by LP may reduce water permeability, but do not have a major effect on gas permeability. In other words, gel pores do not contribute to lowering the gas permeability coefficient. Further research should focus on detailed porosity analysis, which could help explain the high gas permeability values observed. A clear correlation was also found between higher compressive strength (Table 2) and lower gas permeability (Figure 5). This relationship was supported by testing, where the compressive strength of concrete was measured at the age of 28 days, by using standard EN12390-3 [17] and gas permeability was assessed during the later stages of curing by using Torrent method according to Swiss recommendation [11] for the quality control of concrete with air permeability measurements. As can be seen from Table 2 and Figure 5, compressive strength goes from 31.3 MPa, for the mixture with the highest content of LP additive, to 55.9 MPa for the mixture made without LP. The gas permeability results, step-by-step follow the change of the compressive strength of concrete. In general, for the measured mixtures, made of different content of LP additive, might be concluded that there is a connection between the compressive strength and gas permeability. The results showed that, in this case, the increased compressive strength was directly associated with the improved gas tightness, confirming a strong link between these two properties.

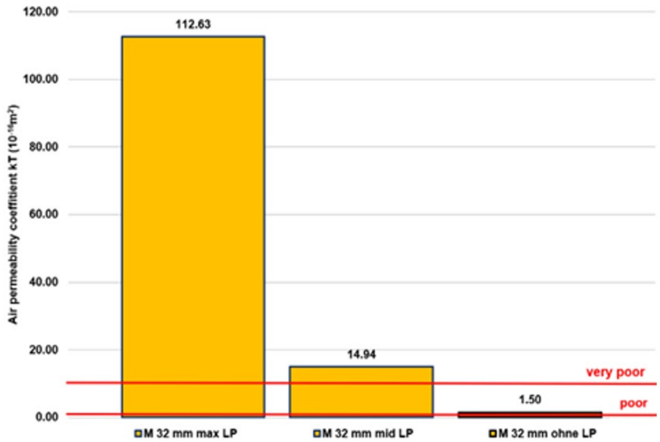

Figure 5. Average values of kT parameter in 10^{-16}

4. CONCLUSION

This paper presents the results of gas permeability testing, aimed at determining the initial gas permeability parameter values (kT) of tested concrete. These values might be used both for structural calculations and for monitoring the evolution of gas permeability after the concrete takes a part of the building structure. The study focused on concrete made with a maximum aggregate size of 32 mm and included variations in the air entraining agent for concrete (LP). Based on the test results, and particularly those related to compressive strength and gas permeability, it might not recommended to use larger amounts of synthetic LP additive unless there is a specific reason. As it significantly increases air permeability, especially maximum doze might not be recommended. The research was conducted to better understand the air permeability but further validate the findings, additional testing using different measurement devices is suggested.

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