- Technical Paper -

AIR LEAKAGE SIMULATION ON CRACKED CONCRETE MATERIAL USING RBSM

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ABSTRACT

To ensure durability and to extend the service life of the nuclear power plants, constructed by concrete material, the Rigid-Body-Spring Model (RBSM) combined with the Truss-network model is proposed for evaluating the leakage of radioactive gases. The simulation results are close to existing experimental results. Furthermore, the proposed model can investigate a concentration of pressure near a cracking area. Due to the abilities, the extension on a structural scale will help to avoid the exceeding amount of air leakage under the safety standard and to detect the maintenance area by a concentration of pressure.

Keywords: durability, concrete material, air leakage, porous spaces, cracks, pressure distribution.

1. INTRODUCTION

As an application of concrete material in Nuclear Power Plants (NPPs), mass transfer like an air leakage has been focused to ensure the performance of concrete vessel containment. It was considered as a final barrier for releasing the radioactive gases from the nuclear reactor systems under the service period or postulated accident conditions [1]. To evaluate the air leakage on concrete vessel containment, several studies have investigated the permeability of concrete which explains the ability of porous material to transfer fluids under a gradient of pressure. Further experimental studies on the permeability of concrete [2-4] have found that cracking behavior strongly affects an increase of gas permeability of concrete.

Among the number of gas permeability measurements, the results show variation due to difficulty and complexity from specimen's preparations, experimental setup, etc. Therefore, a numerical analysis is proposed to facilitate the air leakage measurement of the concrete structure. Various numerical models have been conducted to represent an air leakage of gas through concrete material such as a three-dimensional Finite Element Method (FEM). However, an application of FEM on concrete material has to deal with the discontinuity from cracks. In addition, FEM is not able to represent several macrocracks on a structural level.

To improve the numerical analysis, the 3D-Rigid Body Spring Model (RBSM), which does not require the continuity, combined with the Truss-network model was proposed. The RBSM was used to analyze cracking behavior. Consequently, the Truss-network model was coupled to analyze air leakage through porous spaces and cracks in concrete material. Furthermore, the usages of the RBSM in previous studies reported that it has the potential to analyze macrocracking in a concrete structure. Therefore, an extension on a structural level will help to accurately evaluate an air leakage in a concrete structure.

For the evaluation of the present study, the splitting concrete discs from the experimental work of Vincent Picandet et.al. [4] were simulated to study the air leakage in concrete material due to diffuse fluid percolation and its evolution by localized fluid flow through cracks. The purpose is to study the suitability of the proposed numerical model for evaluating an air leakage in concrete material and its extension on a concrete structure for ensuring the performance of concrete structure from radioactive gas leakage problem.

2. NUMERICAL MODEL

2.1 Three-Dimensional Rigid-Body-Spring Model

The three-dimensional Rigid-Body-Spring Model (RBSM) initially developed by Kawai [5] was implemented in the proposed numerical model. The program employed in this study has been developed based on RBSM for decades. According to a study by Yamamoto et.al. [6], the program has shown the potential to represent not only global behavior but also localized behavior such as crack propagation in concrete material. The RBSM, which represents a continuum material as an assembly of rigid particles interconnected by zero-size springs along its boundary, manipulates a discrete numerical analysis to directly deal with cracks in concrete material.

The continuum material is partitioned into an assemblage of rigid particles based on the Voronoi diagram (Bolander and Saito [7]). The purpose of

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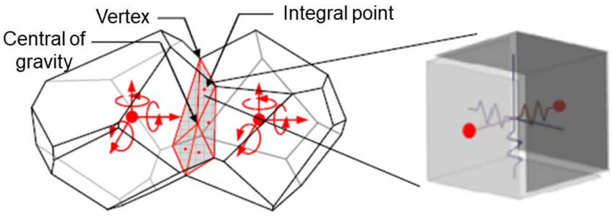


Fig. 1 Rigid-Body-Spring Model
(Yamamoto et.al., 2008)

the Voronoi Diagram is to provide random geometry of the spring network which is able to reduce mesh bias on the potential crack direction. Within each rigid particle, three translations and three rotational degrees of freedom are defined at the nuclei of the particle. The interface between two particles called a boundary surface is divided into several triangle forms by central of gravity point and vertices of the boundary surface with the set of springs (one normal spring and two tangential springs) located at the integral point (Fig. 1).

2.2 Constitutive Model of Concrete

To represent the material characteristic of concrete, the constitutive models for tension, compression, and shear (Fig. 2) are implemented to simulate the behavior of concrete. Fig. 2(a) shows the tensile model for normal spring. The tensile behavior of concrete was modeled as a linear elastic up to tensile strength, followed by a bilinear softening branch according to the 1/4 model. The parameters related to the tension field of concrete are tensile strength (σ_t), tensile fracture energy (G_f) and distance between nuclei (h).

The compression model for normal spring was employed to represent the behavior of concrete in the compression field. The S-shape curve in Fig. 2(b) was derived from the parametric analysis (α_{c1}, ε_{c1}, α_{c2} and ε_{c2}) of the relationship between stress and volume under hydrostatic pressure conditions [6]. There is neither softening behavior nor a failure of the normal springs observed in the compression mode. However, a confinement effect by means of a combination of normal spring and shear spring can simulate the failure under compression behavior.

For modeling of shear spring, the shear spring model in Fig. 2(c) is proposed to represent shear stress (τ_f) and strain (γ_f) corresponding to strength. The elastic regime is applied up to the shear strength with the slope of shear modulus (G) followed by assumed softening behavior. The failure of shear spring was modeled by the Mohr-Coulomb criteria in Fig. 2(d), where c and φ are the cohesion and angle of internal friction, respectively.

2.3 Truss-Network Model

The truss-network model is initially developed by Bolander and Berton [7] along with the RBSM to simulate a mass transfer based on a random lattice defined by the Voronoi diagram. From an extended study of Nakamura et.al. [8], the refined truss-network model was proposed. To represent the mass transport in bulk concrete, the truss elements are generated between the Voronoi nuclei and the intermediate points of particle boundaries called the internal truss element. The truss element is assumed as a linear conduit which has a cross-section area corresponding to the area of the boundary surface. For mass transport through the crack, the boundary truss elements are created where their cross-section depends on the crack width analyzed from the RBSM. In order to represent the mass transfer in concrete material, a simplified one-dimensional Finite Element Method is utilized to simulate the diffusion by the potential flow in the truss-network model (Fig. 3).

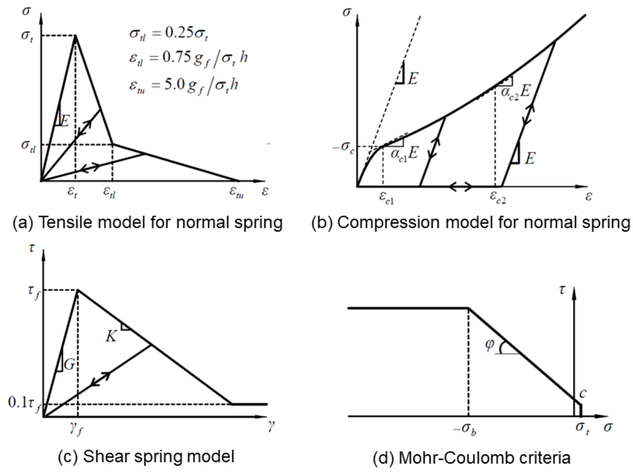


Fig. 2 Constitutive models of concrete
(Yamamoto et.al., 2008)

2.4 Air Leakage Analysis

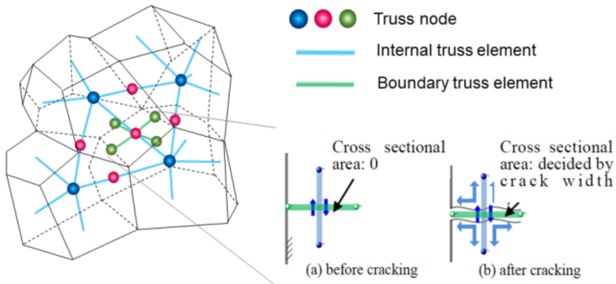


Fig. 3 Truss-network model

In general, fluid flow in porous media is one of the mass transfer problems which can be explained by continuous flow. It is commonly analyzed using a continuum model with the Finite Element approach represented by a partial differential equation. The air leakage flow in the concrete was modeled based on compressible fluid flow, a widely used theory explaining the viscous flow in porous media due to the pressure gradient as a potential function [9-10]. From the characteristic of the fluid flow in concrete, two of the governing equations were proposed to represent an air leakage flow in porous spaces and cracks in concrete.

(1) Air leakage through porous spaces of concrete

In the Truss-network model, the air leakage flow through porous spaces of concrete was represented based on the internal truss element. The governing equation of the potential flow based on Darcy's law was modeled as Eq. 1. By assuming potential flow in the linear conduit, the matrix form can be as described as Eq. 2.

However, the previous study of Klinkenberg [11] reports that a gas percolation through a fine porous (e.g. Concrete) is composed of not only viscous flow but also slip flow. The slippage effect occurs when the flow path is very small compared to the mean free path of the gas. Therefore, the air permeability in porous space was refined based on a widely used calculation of Klinkenberg to consider the effect of slip flow.

$$q_m = \frac{M}{RT}\frac{k}{\eta}\nabla(P^2) \tag{1}$$

$$\frac{M}{RT}\frac{1}{\eta}\frac{Ak}{L}\begin{bmatrix}1 & -1\\ -1 & 1\end{bmatrix}\begin{Bmatrix}P_1^2\\ P_2^2\end{Bmatrix} = \begin{Bmatrix}0\\ 0\end{Bmatrix} \tag{2}$$

where,

q_m : Mass flow rate of the air leakage (Kg/s)
M : Molar mass of air ($Kg \cdot mol^{-1}$)
R : Gas constant ($m^3 \cdot Kg \cdot K^{-1} \cdot mol^{-1}$)
T : Temperature of air (K°)
k : Gas permeability of concrete (m^2)
η : Dynamic viscosity of gas (Pa·s)
P : Pressure in concrete (Pa)
A : Cross-section area of truss element
L : Length of truss element

(2) Air leakage through cracks of concrete

After the occurrence of cracks, the air leakage flow through cracks was represented by the boundary truss element. The governing equation of the potential flow was modeled by a similar form (Eq. 1), but the permeability coefficient was modified by our preliminary analysis on splitting concrete discs (Picandet et.al. [4]). The permeability coefficient was initially modified based on Darcy's law by calibration factor (C_D) for damaged permeability. As a result of calibration (dash lines) in Fig.4, a C_D was calibrated, but it is not able to represent an air leakage through cracks for a large crack range (larger than 12.5 μm).

From further studies, Hagen-Poiseuille's law, a widely used model for the fluid flow through a crack, was implemented. Generally, Hagen-Poiseuille law explains a fluid flow through two infinitely long-smooth parallel plates which corresponds to the cube of the distance between the plate (crack width). To apply on the air leakage through cracks, the calibration factor (C_{HP}) was introduced to adjust an application in the Truss-network model together with obtained calibration factors from the experiment, e.g., a reduction factor (ξ) for tortuosity and roughness of crack, a mean distance between crack (Δ). From calibration results (Fig. 4.), the modification by Hagan-Poiseuille law can represent an air leakage flow through a crack, however, it cannot capture for the small crack range (less than 12.5 μm).

According to the preliminary analysis, the boundary separating each modification was observed at 12.5 μm crack width. This preliminary analysis agrees with the previous study of René de Borst [12] reporting about two flow regimes through the crack. The first regime is fluid flow through a partially open crack which probably contains material inside crack (still similar to porous media). The second regime is fluid flow through a fully open crack (no material inside crack). Thus, those two regimes of fluid flow, Darcy's law, and Hagen-Poiseuille's law are suitable.

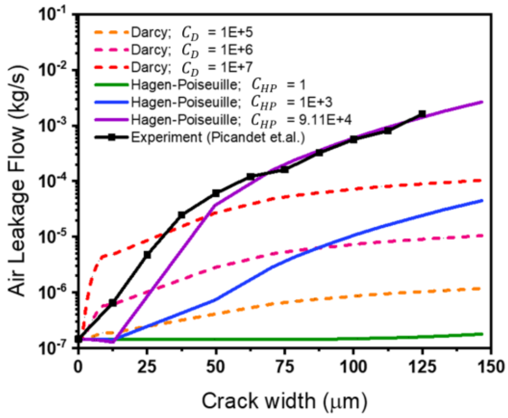


Fig.4 Sensitivity of air leakage through crack

However, the preliminary analysis found that both cannot solely capture the overall crack range. Therefore, the superposition between Darcy's law on damaged permeability and Hagen-Poiseuille's law was proposed to represent the air leakage flow through the crack for the overall crack range as shown in Eq. 3.

$$k(w) = \left(C_D k + C_{HP}\frac{\xi}{\Delta}\frac{w^3}{12}\right) \tag{3}$$

where,

$k(w)$: Modified air permeability due to width cracks (m^2)
k : Intrinsic gas permeability of concrete (m^2)
C_D : Calibration factor for damaged permeability
C_{HP}: Calibration factor for fluid flow due to Hagen-Poiseuille law in our model
ξ : Reduction factor including a reduction due to the tortuosity and roughness of cracks
Δ : Mean distance between crack (m), in the other hand, the reverse $(1/\Delta)$ corresponds to the crack density (m/m^2).
w : Crack width (m)

3. EXPERIMENT DETAIL AND NUMERICAL PARAMETER

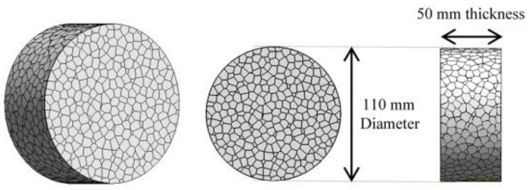
3.1 Target Experiment

In this study, the air leakage analysis of concrete discs was conducted based on the study of Vincent Picandet et.al. [4]. The 110x220-mm Cylindrical specimens were cast by two concrete mixes to investigate an air leakage for two different porosities: (1) ordinary concrete (OC) with w/c ratio of 0.49 and (2) high-performance concrete (HPC) with w/c ratio of 0.29. Their mechanical characteristics at 28 days and material properties were measured from the experiment and the results are given in Table 1.

After sample preparation and dying procedure (to eliminate the effect of moisture content on the air leakage flow in concrete material [13-14]), concrete

Table 1 Material properties

	OC	HPC
Modulus of elasticity (GPa)	42	45
Compressive strength (MPa)	65	110
Tensile Strength (MPa)	4.8	6
Open porosity (%)	12.1	9.6



(a) Mesh size 5 mm ; about 2760 elements (b) Specimen details (Vincent Picandet et.al.)

Fig. 5 Mesh divided using the Voronoi diagram and details of the specimen.

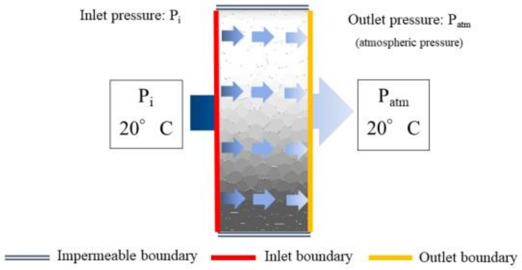


Fig. 6 Boundary condition for the analysis

cylinders were cut to obtain 50 mm-thick discs from each central portion. Their curved surface was sealed with an epoxy resin coat to ensure a one-dimensional gas flow inside the discs during the permeability test. The discs were diametrically loaded with cyclic loading to create splitting crack as a single crack crossing the disc. Then, the gas permeability test was performed after unloading in each cycle. The objective is to investigate gas permeability of the concrete matrix and the effect of single crack to gas permeability. Detailed information on the experiment program is available in the original paper.

3.2 Analytical Outline

The analysis of air leakage in concrete material was conducted to evaluate the performance of the proposed model which is a coupled model between the RBSM and Truss-network model. In the analysis, concrete discs cast by OC and HPC were modeled with a 5-mm element size as shown in Fig. 5.

In order to obtain air leakage flow and its evolution due to cracks inside specimens, the RBSM was used to analyze the mechanical response and cracking behavior from splitting tensile loading. Consequently, the air leakage analysis was conducted by the Truss-network model for investigating the air leakage on sound and splitting specimens. Fig. 6 shows the assigned boundary condition providing the air leakage flow due to the pressure gradient. The gradient of pressure at the inlet and outlet boundary is 0.3 MPa similar to the ranged value reported in the previous study [4]. The air leakage flow was measured by the internal and boundary truss elements at the outlet boundary, which can be calculated by Eq. 1 and its modification by Eq. 3, respectively.

Table 2 Numerical parameter for air leakage analysis

	OC	HPC
Intrinsic gas permeability, k (m^2)	2×10^{-17}	1×10^{-17}
Molar mass of air, M ($Kg \cdot mol^{-1}$)	0.0140067 (N_2)	
Gas Constant, R ($m^3 \cdot Kg \cdot K^{-1} \cdot mol^{-1}$)	8.314472	
Temperature of gas, T (K°)	293	
Dynamic viscosity of gas, η (Pa·s)	1.76×10^{-5}	
Reduction factor, ξ	0.015	0.05
Mean distance between crack, Δ (m)	0.1	

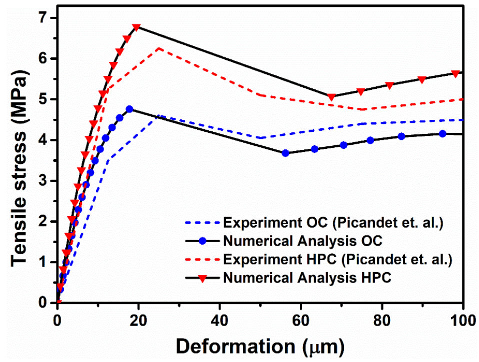


Fig.7 Load-Deformation from splitting tensile test

3.3 Numerical Parameter

the constitutive model in RBSM does not adopt from the macroscopic behavior of the material. The numerical parameters for the springs were modified from an experiment by the study of Yamamoto et.al. [5]. For the Truss-network model, numerical parameters representing the air leakage flow are shown in Table 2, which were obtained from the experiment [4]. In the experiment, Gas permeability (k) was determined from measured gas flow by Darcy's law, and the reduction factor (ξ) is calibrated parameter from the development of gas flow through a crack by Hagen-Poiseuille's law.

4. NUMERICAL RESULTS AND DISCUSSION

4.1 Load-Deformation and Crack Behavior

Fig.7 shows the analytical and experimental results of load and lateral displacement from splitting tensile test (both OC and HPC). The load-deformation from the analysis has the same tendency compared with the experiment result. Furthermore, the cracking patterns from the analysis are quite similar to the crack patterns in the experiment as shown in Table 3 and Table 4. These results ensure that an effect of cracks on air leakage can be directly investigated in a later chapter.

4.2 Air Leakage Analysis on the Sound Specimen

As the porosity of concrete, the air leakage through porous spaces should be captured to evaluate air leakage and to be a reference for analyzing the evolution of air leakage due to an effect of crack. Therefore, simulation for sound OC and HPC concrete discs were as conducted. The resulted air leakage flow of each specimen corresponds with the experiment result as shown in Fig. 8. The result confirms the performance of the proposed model to evaluate air leakage through various porous spaces of concrete material.

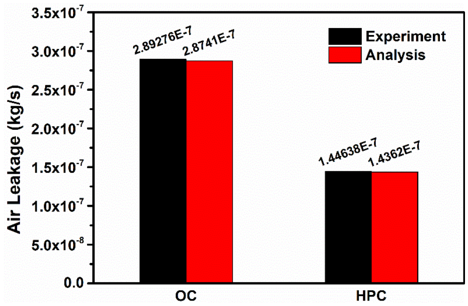


Fig. 8 Air leakage flow through the porous matrix of OC and HPC concrete discs

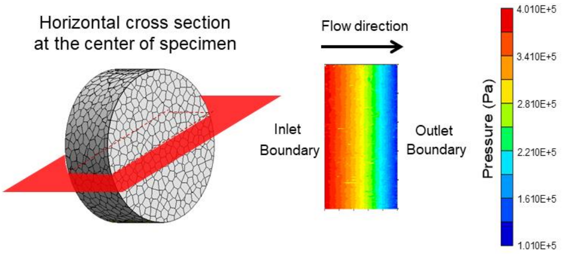
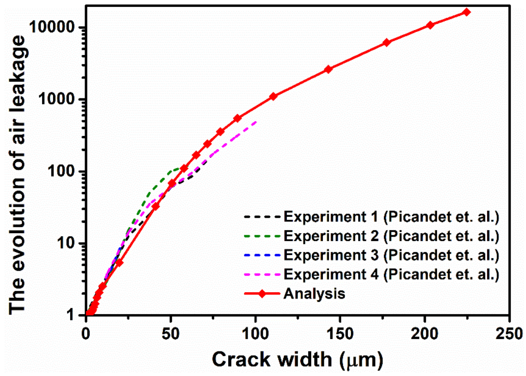


Fig. 9 Pressure distribution in the porous matrix of air leakage flow on OC and HPC concrete disc.

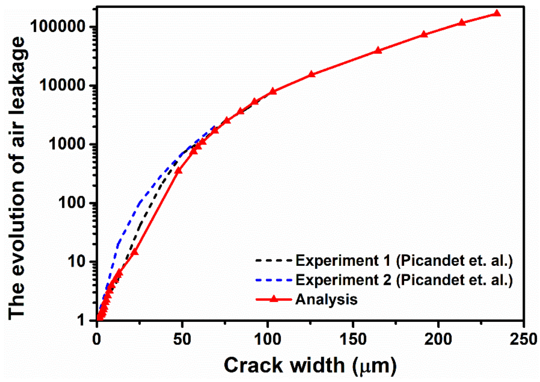
Moreover, the proposed model can investigate the pressure distribution inside the concrete matrix. Fig. 9 shows a pressure field visualized from a horizontal cross-section at the central part of the specimen (perpendicular to splitting crack direction). The pressure field obtained from numerical results, which is gradually decreased from inlet boundary to outlet boundary (from inlet pressure to atmospheric pressure), is consistent with theory; the pressure gradually drops along the direction of viscous flow through porous media by cohesion between fluid and pore surfaces [9,10].

4.3 Air Leakage Analysis on Splitting Specimen

To investigate the effect of cracks, simulations of air leakage for splitting specimen (single crack) was conducted. Fig. 10 shows the evolution of air leakage



(a) OC concrete disc



(b) HPC concrete disc

Fig. 10 the evolution of air leakage due to the growth of splitting crack.

due to the growth of crack propagation as a ratio of air leakage at considered cracking state and sound case (based on exponential scale). The numerical results have the same tendency compared to the experiment results. Moreover, the mechanism of the evolution starts with the initial increase of air leakage for small crack and significant increase when a crack is large which similar to the observed mechanism in the experiment [4]. This confirms that the proposed model can evaluate the air leakage on concrete material.

Table 3 Cracking patterns and their effect on pressure distribution on OC concrete discs.

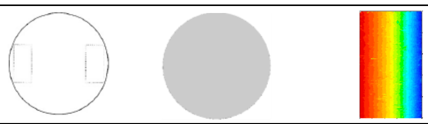
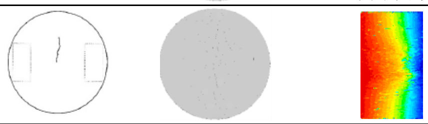
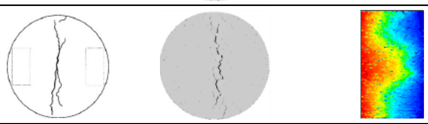
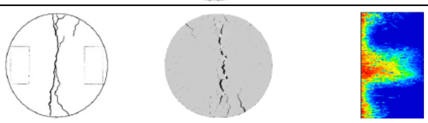
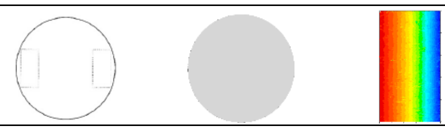
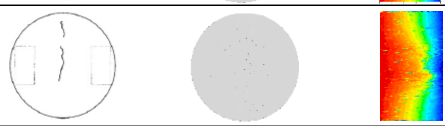
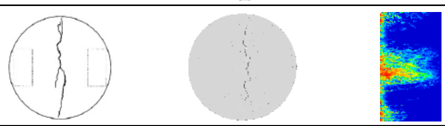
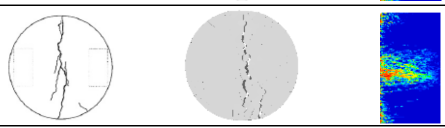
Crack width (μm)	Crack patterns: Experiment	Crack patterns: Analysis	Pressure Distribution
0.0			
25.5			
67.0			
121.5			

Table 4 Cracking patterns and their effect on pressure distribution on HPC concrete discs.

Crack width (μm)	Crack patterns: Experiment	Crack patterns: Analysis	Pressure Distribution
0.0			
25.0			
98.5			
149.5			

Furthermore, we observed that cracking behavior affects the pressure distribution inside the concrete matrix as shown in Table 3 and Table 4. The pressure tends to concentrate near the cracking region corresponding to a growth of crack width, and the air leakage flowing through crack becomes predominant compared to porous spaces of concrete. These observations are reasonable because theoretically, gases flow through the path of lower viscosity (higher permeability) for minimizing the loss of energy in the flow direction.

From the numerical results, the proposed numerical model shows the potential to evaluate the air leakage and effect of the crack. Moreover, it has the ability to investigate pressure distribution inside the concrete that will help to detect damaged areas by a concentration of pressure at the cracking areas. However, there were some issues for improvement such as moisture effect. The moisture content also strongly affects a decrease in an air leakage flow in concrete material [13-14]. Therefore, further study on moisture effect is required to obtain accurate results for an extension on a large-scale structure in the field.

5. CONCLUSION

In this study, to evaluate the safety for air leakage problems in concrete vessel containment, the couple numerical models of RBSM and Truss-network model were proposed to analyze an air leakage flow through concrete material. Based on the experimental study of Vincent Picandet [4], we analyzed the air leakage flow and the effect of crack on the OC and HPC concrete discs subjected to splitting tensile loading. Specimens were oven-dried, to eliminate an effect from moisture. Their curved surface of the specimen was sealed to ensure a one-dimensional gas flow inside the discs. As a result, the following observations were obtained.

(1) Using the proposed numerical model, air leakage through concrete material can be evaluated. Furthermore, the evolution of air leakage flow corresponding to the growth of crack width can be captured.

(2) The proposed numerical model can represent a pressure distribution inside a concrete matrix and be able to capture the change in pressure distribution with the progression of crack width.

From the conclusion of (1) and (2), it was confirmed that the numerical model could appropriately evaluate the air leakage on the concrete material. For an extension on the structural level, the RBSM, which has the potential to analyze localized macrocracks on member structure, will help to accurately evaluate an air leakage compared with a general model (FEM). Additionally, pressure distribution in a concrete matrix will help to detect damaged areas by the concentration of pressure at the cracking area. There are some remaining issues concerning the effects of moisture content because the concrete in fields still has moisture. However, specimens in the present study were oven-dried before. Therefore, further study on moisture effect should be contributed to obtain more accurate results.

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