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Numerical Investigation of Aggregates Size and Volume Fraction on Gas Permeability of 3D Meso-Scale Concrete

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Abstract: In this paper, the influence of aggregate size and volume fraction on the permeability properties of meso-scale concrete is investigated. Three volume fractions of aggregates are investigated, varying from 10, 20 and 30 %. Furthermore, three aggregate sizes are examined, 10, 14, and 16 mm. In this work, numerical results provide some indications: increasing volume fraction leads to increased fracture energy, tensile stress, and crack opening. The results show that increasing crack width and decreasing volume fraction lead to an increase in gas permeability.

Keywords: Tensile splitting test; Meso-scale modelling; Weak discontinuity; Strong discontinuity; Finite Element Method; Gas Permeability

1. Introduction

There are many parameters that play a critical role in controlling the durability of concrete, such as: aggregate size, type, volume fraction, and surface area. Tasdemir et al. [1] investigated the influence of aggregate size and type on mechanical properties. Bisschop and van Mier [2] showed that increasing aggregate size from 2 to 6 mm leads to an increase in total crack length but also in the maximum crack depth. Grassl et al. [3] discovered that permeability increases with aggregate diameter and decreases with volume fraction. Picandet et al. [4] pointed out that the permeability of gas and water increases with the increase in crack opening.

The aim of this study is to investigate the effect of aggregate size and volume fraction on the gas permeability of heterogeneous materials in the context of a tensile splitting test. In this work, we describe a numerical method to model the hydro-mechanical coupling, a 3D computational meso-scale model is used in the framework of the Enhanced Finite Element Method, which was proposed by Benkemoun et al. [5]. This method has two discontinuities: the first one is a weak discontinuity, which refers to a continuous displacement field and a discontinuous strain field (see [6]). The second discontinuity introduced here is the displacement discontinuity (strong) to represent crack opening (discontinuous displacement field) (see [7]).

2. Numerical simulations and results

2.1 Mesostructure and discretization of cylinder specimen

For each cylinder specimen, the resulting particles are round and have a single size. Three groups of specimens with dimensions of 110 x 50 mm in diameter and thickness, respectively, have been simulated. Each group of cylinders has one size of aggregate and three volume fractions of 10, 20, and 30 %. However, three aggregate sizes of 10, 14, and 16 mm are used. The mechanical properties for each (cement paste, aggregate, and interfaces) are summarized in Table 1 for a specimen with aggregate diameters of 10, 14, and 16 mm and volume fractions of 10, 20, and 30 %.

Table 1. Mechanical Properties of Materials

Cement paste	Aggregate	Interfaces
$E_{mor.}$= 35 GPa	$E_{agg.}$= 100 GPa	-
$\boldsymbol{\sigma_u = 3\ MPa}$	-	$\sigma_u = 3\ MPa$
G_u= 80J/m^2	-	G_u= 80J/m^2

2.2 Constitutive maximum crack opening

In this section, authors focus on the effect of aggregate size and volume fraction on the maximum crack opening. The numerical results of the simulations are shown in Fig. 1. There is a significant and effective relationship between the volume fraction and the maximum crack opening. In other words, the increase in volume fraction leads to an increase in the maximum crack opening. This could mean that the bonding regions between the split parts are weaker as a result of the aggregate particles' increased surface area.

Additionally, when a volume percentage of 30% is utilized, the aggregate particle spacing decreases when all of the particles are the same size. The numerical results show a reverse effect of the aggregate size on the maximum crack opening. The increase in aggregate diameter decreases the maximum crack opening. The maximum crack opening is calculated at the peak tensile stress.

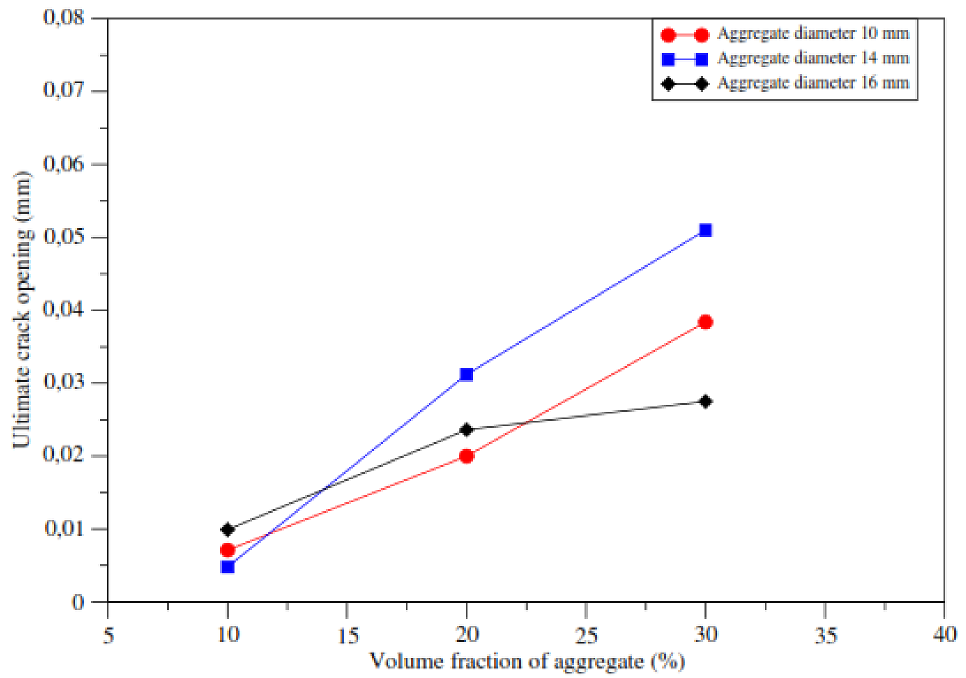

Fig. 1 Effect of aggregates size and volume fraction on maximum crack opening

2.3 Aggregate Volume fraction-ultimate tensile stress relationship

The numerical results are shown in Fig. 2, where the ultimate tensile stress increases as the aggregate volume fraction increases. Also, we note that this increase depends on the aggregate size. This behavior can be explained by the higher modulus elasticity of aggregate particles. This behavior can be explained by the higher modulus of elasticity of aggregate particles. These particles strengthen the cement paste. Increasing the volume from 10 % to 30 % resulted in 38 % increase in splitting tensile stress for aggregates of size 10 mm and 22 % for aggregates of size 16 mm. In addition, the bonding strength between the aggregate particles and cement paste depends on the aggregate size (in other words, increasing the particle size from 10 to 16 mm deescalates the splitting strength by 40%; note that if the results for 14 mm are in hand, the conclusion will be even stronger).

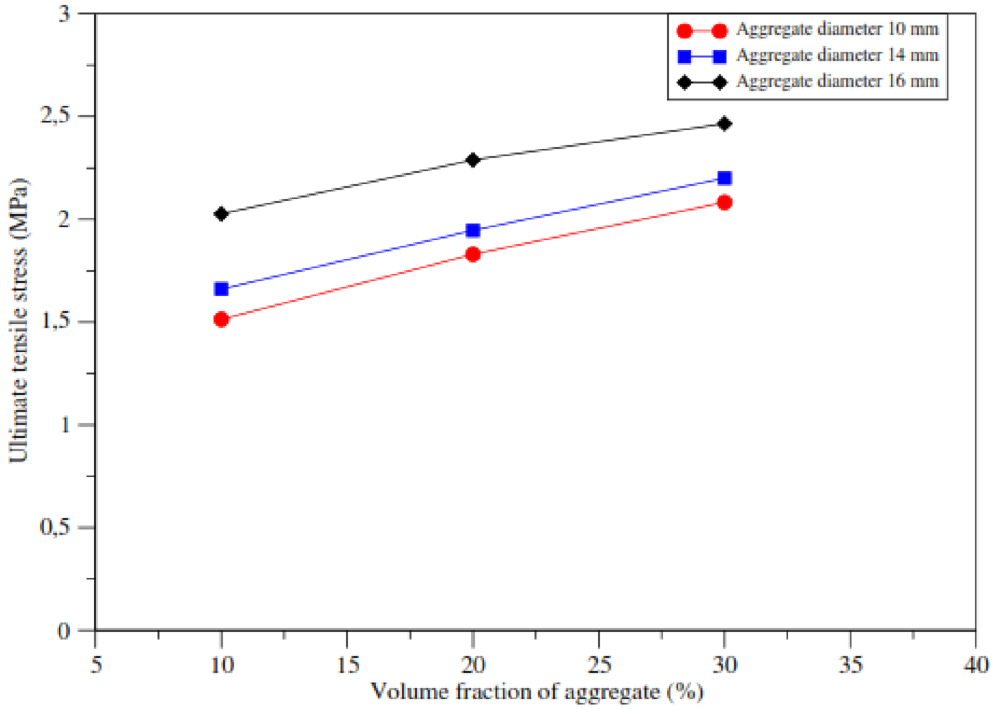

Fig. 2 Effect of aggregates size and volume fraction on ultimate tensile stress

2.4 Influence of volume fraction and aggregate size on fracture energy

Fig. 3 shows the simulation of the results for the impact of volume fraction and aggregate size on the fracture energy. Specimens with a larger aggregate size and a higher volume fraction show higher fracture energy. The increase in aggregate size and volume fraction leads to an increase in fracture energy. Our results are identical or are in good agreement with the results of other authors. Petersson [8] pointed out that increasing the volume fraction leads to increased fracture energy. The influence of aggregate size on fracture energy has already been discussed by Elices et al. [9]. They found out that the bonding force between the aggregate and cement paste influences the fracture energy significantly.

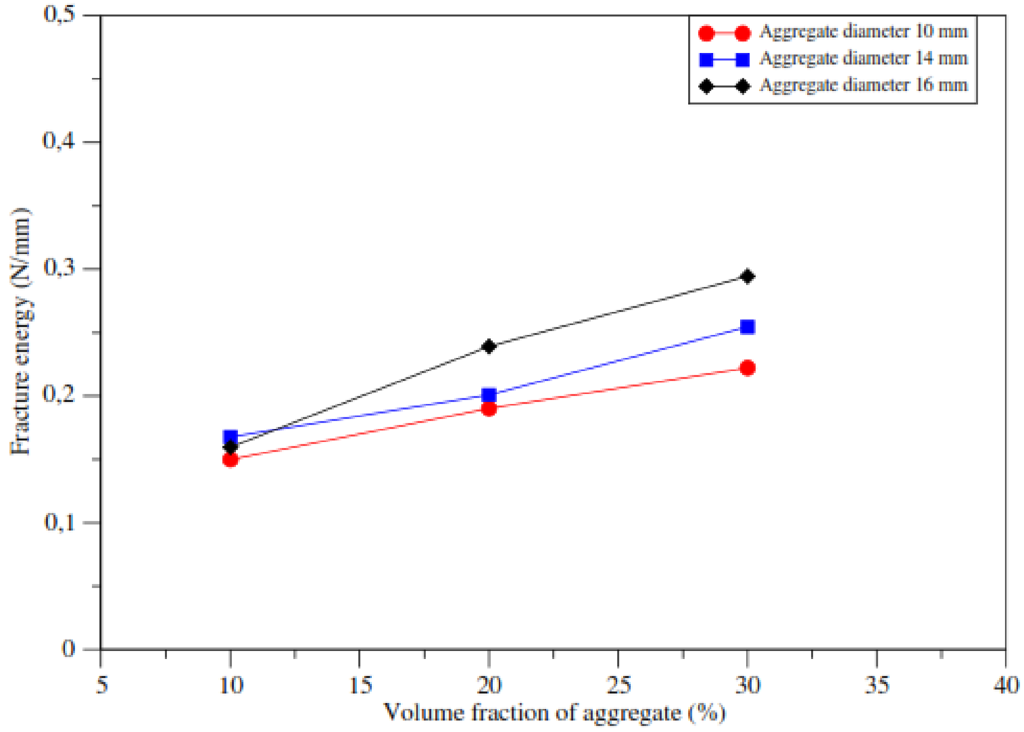

Fig. 3 Effect of aggregates size and volume fraction on fracture energy

2.5 Numerical simulations of crack-induced permeability in concrete

The relationship between crack opening and permeability is examined in this work by modeling crack-induced permeability in concrete. Additionally, authors look into how aggregate size, volume percentage, and crack opening affect gas permeability. The findings demonstrate that whereas permeability increases slightly with crack opening, it considerably reduces as aggregate size and volume fraction increase. To analyze a single controlled crack, six numerical simulations were used. Figs. 4–6 show that the gas permeability increases rapidly when the crack opening is larger than $5\mu m$. These results are in agreement with several studies. Wang et al. [10] investigated whether water permeability increased with crack width. Rastiello et al. [11] offered a relationship between the permeability of fluid and the crack width for saturation concrete specimens based on the Brazilian splitting test. Choinska et al. [12] presented the permeability of concrete as a function of diffuse microcracking, with the level of damage ranging from 0 to 15% before the peak load, and as a function of the macrocracking created after the peak load.

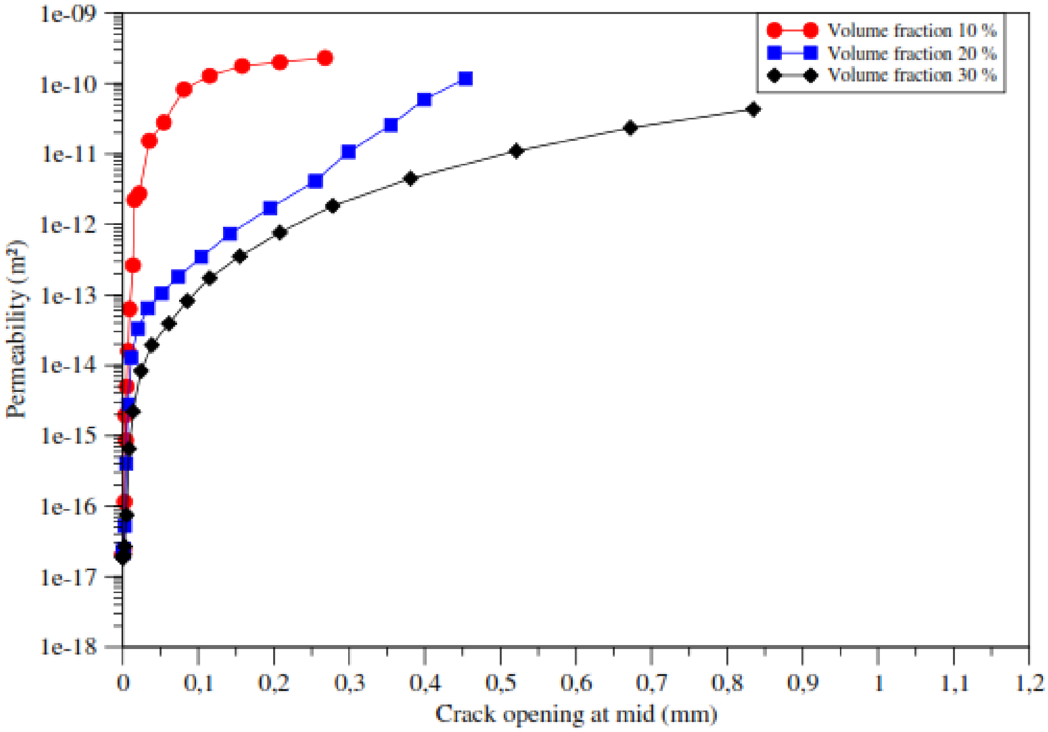

Fig.4 Effect of crack opening and volume fraction on permeability with aggregates size of 10 mm

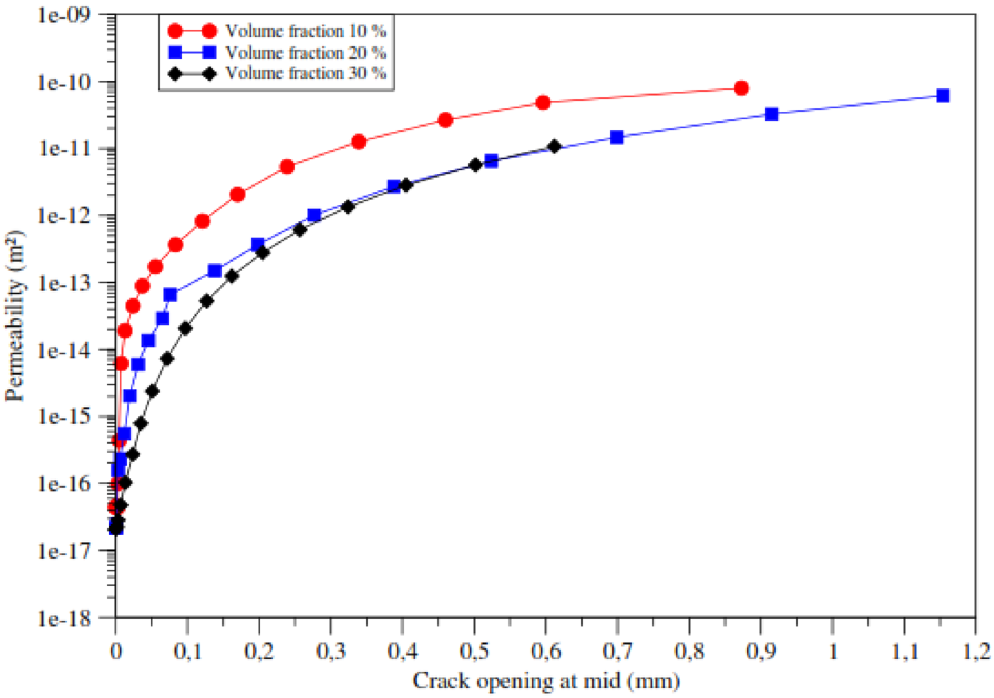

Fig.5 Effect of crack opening and volume fraction on permeability with aggregates size of 14 mm

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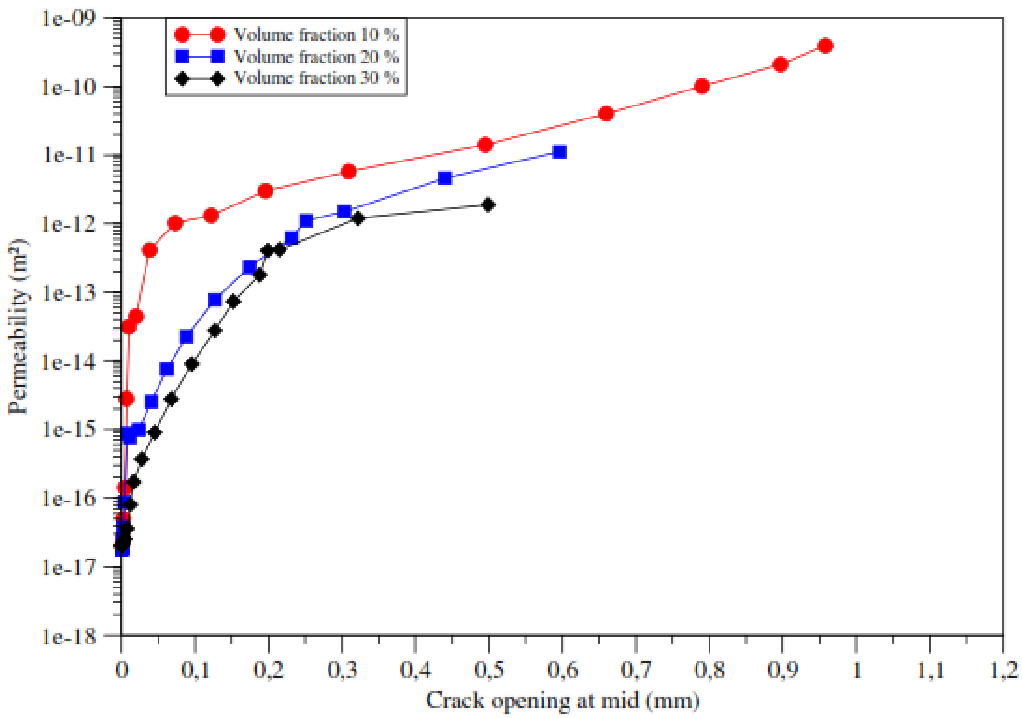

Fig.6 Effect of crack opening and volume fraction on permeability with aggregates size of 16 mm

3. Conclusions

The numerical findings corroborate for the conclusion that:

- The volume fraction and aggregate size have an impact on mechanical behavior. This study discovered that, while crack opening decreased with aggregate size, it increased with volume fraction.
- The results indicate that both ultimate tensile stress and fracture energy increase with aggregate size and volume fraction.
- The permeability of gas increases with crack opening and decreases with aggregate size and volume fraction.

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Conflicts of Interest: The authors declare no conflict of interest.

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