UNIVERSITE BRETAGNE LOIRE

UNIVERSITE DE NANTES

Thèse de Doctorat

Hayder AL-KHAZRAJI

Mémoire présenté en vue de l'obtention du
grade de Docteur de l'Université de Nantes
sous le sceau de l'Université Bretagne Loire

École doctorale : Sciences pour L'ingénieur, Géosciences, Architecture

Discipline : Sciences pour l'ingénieur
Spécialité : Génie Civil
Unité de recherche : Génie Civil et Mécanique UMR CNRS 6183

Soutenue le 30 Novembre 2017

Influence of crack opening, aggregates size and volume fraction on hydro-mechanical properties of concrete in a Brazilian splitting test: 3D meso-macro scale modeling and experimental work

JURY

Président du jury	**Nadia SAIYOURI**	Professeur, Université de Bordeaux
Rapporteurs :	**Farid BENBOUDJEMA**	Professeur, l'ENS Cachan
	Abdelkarim AÏT-MOKHTAR	Professeur, Université de La Rochelle
Invité(s) :	**Frédéric GRONDIN**	Professeur, Ecole Centrale Nantes
Directeur de Thèse :	**Abdelhafid KHELIDJ**	Professeur, Université de Nantes
Co-encadrant de Thèse :	**Nathan BENKEMOUN**	Maitre de Conférences, Université de Nantes
Co-encadrant de Thèse :	**Marta CHOINSKA**	Maitre de Conférences, Université de Nantes

Contents

List of Figures

List of Tables

Acknowledgements

I would like to express my deep gratitude to **Prof. Abdelhafid KHELIDJ**, my supervisor, for his patient guidance, enthusiastic encouragement and useful critiques of this research. I would like to thank **Dr. Nathan BENKEMOUN**, my co-supervisor, for his advice and assistance in keeping my progress on schedule for this work. My grateful thanks are also extended to **Dr. Marta CHOINSKA**, my co-supervisor. I wish to thank my officemates and friends especially **Mohammed Naji** for thier support and encouragement throughout my study.

Last but not least, I would like to thank my mother and father and my wife for their encouragement, unequivocal support and great patience at all times.

Abstract

Permeability is a parameter that may indirectly influence the durability of concrete structures by governing the rate of penetration of aggressive substances responsible for degradation under a pressure gradient.

The aim of this thesis is to study the interaction between the crack opening and the transfer of fluids in concrete of the Brazilian splitting tensile test (BSTT). Herein, the influence of aggregates size and volume fraction on hydro-mechanical properties of concrete is investigated. This study consists of two parts: the numerical and the experimental one. The first one focuses on the meso-scale modeling of a heterogeneous material like a concrete, which may be characterized by two features: multi-phase behavior and 3D crack propagation. The numerical study deals therefore with the coupling between crack opening and gas permeability according to a developed hydro-mechanical model at a meso-scale. The objective of the second, experimental part, is to provide data for numerical models and to validate the latter. This work is carried out on mortar specimens with 3 different aggregate sizes, submitted to gas transfer during a BSTT.

The numerical meso-scale model is based upon a 3D lattice approach to represent the heterogeneity of the material and the failure mechanism of concrete. This model considers concrete as a two-phases material in which aggregates melt within a cement paste. Because a non-adapted meshing process was used to mesh the microstructure, a weak discontinuity was introduced in the first enhancement of the kinematics.

The second enhancement of kinematics introduced here is the displacement discontinuity (strong) to represent crack opening (discontinuous displacement-field). The hydro-mechanical model represents the transport of fluids (gases) through

the concrete, depending on Darcy's law for a uncracked section (porosity) and Poiseuille's law for a cracked section (laminar flow). In this model, the interaction between the crack opening, obtained from the mechanical model (meso-scale), and the gas permeability is investigated.

The experimental work is presented for the validation of the hydro-mechanical model. The numerical results show good agreement with some previous experimental and theoretical studies.

Résumé

La perméabilité influe indirectement sur la durabilité des structures en béton. Elle gouverne le taux de pénétration des agents agressifs, responsables de dégradations, sous un gradient de pression.

Ce travail a pour but l'étude des interactions entre l'ouverture des fissures et le transport des fluides dans le béton, soumis à un essai Brésilien de traction indirect par fendage. Ici, l'influence de la taille des granulats et de la fraction volumique sur les propriétés hydro-mécaniques du béton est étudiée. Cette étude est composée de deux parties : une numérique et une expérimentale. La première concerne la modélisation des matériaux hétérogènes, tels que le béton, et met en évidence ses deux particularités : l'aspect multiphasique du matériau et la propagation 3D de fissures. Ainsi, nous proposons un couplage entre l'ouverture de fissure et la perméabilité au gaz selon un modèle hydro-mécanique à l'échelle mésoscopique. L'objectif de la deuxième partie expérimentale est de fournir des données pour des modèles numériques et de les valider ainsi. Ce travail est réalisé sur des éprouvettes de mortier avec 3 différents tailles de granulat, soumises au transfert de gaz au cours du chargement par l'essai Brésilien.

Le modèle numérique mésoscopique, employé dans cette étude, est basé sur une approche tridimensionnelle pour représenter l'hétérogénéité du matériau et les mécanismes de rupture du béton. Ce modèle considère le béton comme un matériau bi-phasique où les granulats sont fondre dans la pâte du ciment. Afin de pallier aux hétérogénéités du matériau et l'emploi du maillage non-adaptatif, une faible discontinuité a été introduite dans le premier enrichissement de la cinématique.

Le deuxième enrichissement de la cinématique introduite ici est la discontinuité du déplacement (forte) afin de représenter l'ouverture de la fissure (champ du déplacement discontinu). Le modèle hydromécanique représente le transport du fluide (gaz) dans le béton par l'intermédiaire de la loi de Darcy pour la section non fissurée (porosité) et par la loi de Poiseuille pour la section fissurée (flux laminaire). Dans ce modèle, une interaction entre l'ouverture de fissure, obtenue par le modèle mécanique (mésoscopique), et la perméabilité du gaz est considérée.

Le travail expérimental effectué est présenté pour la validation du modèle hydro-mécanique numérique proposé. Les résultats de simulations numériques sont en accord avec des travaux expérimentaux et théoriques précédents.

0.1 Introduction

Le béton est un matériau poreux, hétérogène composé de granulats et de pate de ciment. L'objectif de ce travail de thèse est de fournir une meilleure compréhension du comportement du béton sous un chargement et des interactions entre l'ouverture de fissures et la perméabilité. En effet, deux modèles numériques sont présentés : un modèle mécanique pour expliquer le comportement du matériau hétérogène tel que le béton sous un chargement dans le contexte de l'essai Brésilien. Aussi, un modèle hydromécanique est employé pour l'investigation du couplage entre la perméabilité et l'ouverture de fissure. Plusieurs paramètre influencent le comportement mécanique du béton sous un chargement tels que : le type de ciment, les propriétés des granulats, les conditions environnementales et le type du chargement, etc. Dans cette étude, l'influence de la taille de granulats et du volume granulaire sur le comportement mécanique et hydromécanique du béton sous un chargement est étudié. Deux modèles 3D basés sur la méthode des éléments finis sont présentés. Le premier, mécanique et prend en compte différente tailles de granulats et volume de fraction utilisés. Ces deux paramètres conduisent à des différents comportements du béton sous un chargement basé sur des modèles mécanique à l'échelle mésoscopique. Le deuxième modèle (hydromécanique) explique les interactions entre les propriétés physiques (perméabilité) et la fissuration dues à un chargement mécanique.

Grâce à ce couplage entre les propriétés hydromécaniques, effectué par un modèle numérique (basé sur la méthode des éléments finis) capable de représenter le comportement complexe du béton mentionné ci-dessus. Ce modèle est utilisé pour étudier l'importance de la contrainte du béton sous un chargement et l'évolution de la perméabilité des fluides dans ces conditions. L'objectif derrière est la caractérisation des interactions entre les paramètres influençant la perméabilité du béton dont la perméabilité au gaz est le paramètre primordial qui désigne la capacité du béton à transporter un fluide (liquide ou gaz). La perméabilité du béton peut être affectée, d'une manière significative, par le réseau poreux, la connectivité et la teneur en eau du matériau.

La durabilité du béton est influencée par le flux de fluides, de gaz et de polluants dans la porosité. La présence de fissures dans les structures en béton armé affaiblit la résistance du milieu poreux (béton) vis-à-vis la pénétration de ces fluides et fournit des chemins d'écoulement pour des agents agressifs tels que: l'oxygène (désaération), l'hydrogène sulfuré, les chlorures…etc.

0.2 Motivation et objectif de la recherche effectuée

L'hétérogénéité du béton est l'un des points les plus caractéristiques pour laquelle ce travail a donc été réalisé. Peu de travaux numériques dans la littérature ont considéré que le béton est un matériau multiphasique. En outre, il existe des paramètres qui ont une grande importance sur la durabilité et les performances structurelles des matériaux cimentaires tels que la taille, le contenu et le type des agrégats.

Enfin, la fraction volumique des agrégats occupe environ 75% du volume total de béton. L'étude de ces caractéristiques est le premier objectif de ce travail.

Le second objectif est le phénomène de perméabilité. Cette dernière est définie comme la capacité d'un matériau poreux tel que du béton à transporter des fluides (eau ou gaz) sous un gradient de pression. L'écoulement se produit dans un réseau poreux, y compris des vides ou des fissures de pores initiaux et spécifiques. Ceux-ci sont induits par différentes contraintes, connectant les chemins de percolation, qui réduisent la résistance au flux du milieu poreux et provoquent une augmentation de la perméabilité. La perméabilité peut influencer sur la durabilité des structures en béton en régissant le taux de pénétration des agents agressifs. Cet effet est direct lorsque la structure a une partie scellée tels que les réservoirs et les centres de bâtiment réacteurs nucléaires. Le matériau poreux comprend de nombreuses caractéristiques qui influent sur la durabilité des structures et offrent une protection optimale aux armatures.

De nombreux phénomènes provoquent la corrosion des armatures et, par conséquent, la détérioration du béton armé. Généralement, le dioxyde de carbone (CO_2) contenu dans l'air et les chlorures, venant de sels de mer ou de déverglaçage sont les deux principaux agents qui cause de la corrosion des armatures. La principale complication est ainsi constituée par la nature hétérogène du béton (mortier et granulés), ce qui conduit à la présence de fissures micro / macro inévitables même avec une faible contrainte à un âge précoce. Ces fissures nécessitent une étude approfondie, car elles peuvent former des voies préférentielles pour le transport des fluides (eau ou gaz). Par conséquent, nous nous sommes intéressés à la prédiction du flux dans le béton, ainsi que l'évaluation des performances structurelles associées à la dégradation des propriétés du matériau (corrosion des armatures, carbonatation du béton, etc), ainsi que la prédiction des fissures et de leur impact sur les propriétés de transfert du matériau tels que la perméabilité et le coefficient de diffusion…etc.

Cette recherche a pour objectif le développement d'une méthode numérique permettant d'étudier l'influence de la taille de granulats et la fraction volumique sur le comportement mécanique du béton sous un chargement et d'évaluer la perméabilité dans ce matériau hétérogène. Ainsi, ce travail étudie les interactions entre la fissuration et la perméabilité du fluide dans le test brésilien et étudie l'importance de la taille des granulats et de la fraction volumique sur les propriétés hydromécaniques et la perméabilité des matériaux poreux. Pour obtenir ces conditions, trois catégories doivent être assurées :

1. Les principaux aspects du béton fissuré (hétérogénéité, effet d'échelle…) et les informations locales fournies lors de la fissuration (emplacement, direction et l'ouverture des fissures) doivent être pris en compte dans le modèle.
2. Un modèle de couplage hydromécanique doit être conçu afin de décrire les interactions entre les propriétés de transfert du milieu poreux et l'ouverture de la fissure dans le contexte du test brisé brésilien.
3. Enfin, les lois constitutives pour le travail expérimental doivent être expliquées pour décrire l'influence de la taille de granulats et de la fraction de volume sur les propriétés mécaniques et hydromécaniques du matériau.

Plusieurs modèles dans la littérature décrivent la fissuration dans les milieux poreux. Colliat *et al.* [**Colliat et al., 2007**], Bruggi *et al.* [**Bruggi et al., 2008**], Yang et Frank Xu [**Yang et Xu, 2008**], Ibrahimbegovic *et al.* [**Ibrahimbegovic et al., 2011**], et Syroka-Korol *et al.* [**Syroka-Korol et al., 2013**] décrivent certains des modèles tenant compte de l'hétérogénéité du matériau par l'introduction des champs aléatoire des propriétés mécaniques. Pour cette raison, ces méthodes et leurs hypothèses ont été présentées. Dans cette étude, nous nous basons sur ces modèles. En outre, ces modèles sont en mesure de fournir des informations pertinentes sur les propriétés géométriques des fissures telles que l'ouverture de fissures, l'orientation des fissures…etc. Ceci est primordial lorsque nous considérons le transfert de fluide dans un milieu poreux.

Le contexte de l'approche de modélisation conduit à décrire les propriétés des fissures et la relation entre la perméabilité et l'ouverture des fissures et leurs géométries (tortuosité, rugosité…etc) [**Réthoré et al., 2007**], [**Khoei et al., 2011**], [**Barani et al., 2011**], [**Meschke et al., 2011**]. Il existe dans la littérature une loi permettant de décrire l'impact local de l'ouverture des fissures sur l'augmentation de la conductivité hydraulique à travers les éléments structurels. Le modèle le plus utilisé pour décrire le flux d'un fluide incompressible dans le flux laminaire à travers l'ouverture de fissure est nommé modèle de plaques parallèles (PPC) [**Poiseuille, 1844**], [**Snow, 1969**].

De nombreux travaux théoriques et expérimentaux ont été présentés à cet effet dans le contexte de la mécanique des roches [**Lomize, 1951**], [**Romm, 1966**], [**Louis, 1974**], [**Brush et Thomson, 2003**] et [**Crandall et al., 2010**]. En revanche, très peu d'études ont été réalisées sur des structures en béton. Wang *et al.* [**Wang et al., 1997**], Aldea *et al.* [**Aldea et al., 1999**], Choinska *et al.* [**Choinska et al., 2007**], Picandet *et al.* [**Picandet et al., 2009**], Akhavan *et al.* [**Akhavan et al., 2012**] ont présenté des études expérimentales concernant l'évolution des propriétés de transport dans les structures en béton. Un modèle mécanique numérique 3D pour représenter l'ouverture de fissures dans un matériau hétérogène et un comportement hydromécanique ne permet pas d'obtenir suffisamment d'informations. Par conséquent, un travail expérimental pour la validation et la fourniture de ce contexte seront nécessaires et démontrés dans ce travail.

0.3 Plan de la thèse

L'objectif de cette thèse est de développer un modèle numérique basé sur la méthode des éléments fini enrichis (E-FEM). Cette dernière est réalisée à l'échelle mésoscopique pour représenter l'ouverture de la fissure dans un matériau 3D hétérogène pour simuler l’essai brésilien. Ce modéle est connu sous le nom du modèle mécanique. Le deuxième hydromécanique est utilisé pour le couplage entre l'ouverture de fissures et le transfert de fluide (perméabilité de l'eau ou du gaz). Ce modèle est basé sur l'équation de Poiseuille pour les fluides laminaires dans les tuyaux et la loi de Darcy pour les pores. Un travail expérimental est également présenté pour la validation des modèles numériques.

Afin d'expliquer les méthodes, les caractéristiques choisies et les résultats obtenus, rapport est divisée en six chapitres :

- Le premier chapitre se focalise sur une introduction générale du sujet et explique le comportement mécanique du béton sous un chargement et de la perméabilité du fluide (eau ou gaz) dans les structures en béton sous un gradient de pression. Aussi, nous présentons les modèles hydromécaniques utilisés dans la littérature pour simuler la perméabilité du fluide dans les milieux poreux tenant compte de l'influence de l'ouverture de fissures.
- Le second chapitre expose les travaux expérimentaux présentant le comportement du béton en cours de chargement et les paramètres influençant le comportement mécanique, tels que la taille des agrégats et la fraction de volume. Ensuite, la partie physique explique le transfert de fluide dans les structures en béton (La perméabilité). Dans ce document, certains paramètres influençant la perméabilité est sont présentés. Enfin, nous présentons le couplage entre la fissuration et la perméabilité dans les structures en béton.
- Le troisième chapitre présente le modèle mécanique (à l'échelle mésoscopique) proposé par Benkemoun *et al.* [**Benkemoun et al., 2010**]. Le modèle est basé sur une approche en treillis 3D représentant l'hétérogénéité et le mécanisme de défaillance du béton pour la mise en œuvre de l'ouverture des fissures. Ce modèle considère le béton comme un matériau bi-phasique dans lequel les granulats fondent dans une pâte de ciment. La méthode des éléments finis (E-FEM) et le programme d'analyse des éléments finis (FEAP) sont utilisés dans cette étude pour la simulation 3D de la rupture par le test brésilien. Le modèle mécanique peut représenter un matériau hétérogène 3D et fournit trois types d'éléments de barre (agrégats, mortiers et auréole de transition entre eux). Aussi, nous étudie l'influence de la taille des granulats et de la fraction de volume sur le comportement mécanique d'un matériau hétérogène.

  En plus, se concentre sur le modèle hydromécanique dans cet chapitre, qui repose sur la loi de Darcy pour représenter la perméabilité dans la porosité et la loi de Poiseuille pour la perméabilité de la section fissurée (écoulement laminaire). Nous présentons le modèle hydromécanique (couplage) qui explique lien entre la fissuration et la perméabilité à l'échelle mésoscopique. Ensuite, nous étudions l'effet de l'ouverture de fissures, calculée à partir du modèle exposé dans le chapitre trois, et le lien avec la perméabilité basé sur la loi de Poiseuille. Aussi, la perméabilité dans les milieux poreux est basée sur la loi de Darcy. En fin, l'influence de la taille des granulats et de la fraction volumique sur la perméabilité du béton est présentée.

- Le chapitre quatre se focalise sur le travail expérimental élaboré pour la validation du modèle mécanique et hydromécanique à l'échelle mésoscopique. En effet, quatre types d'échantillons cylindriques ont été réalisés en utilisant des billes de verre comme granulats. Un type est considéré comme référence : ces échantillons sont sans granulats grossiers, mortier seulement. Pour les deux autres types, trois diamètres de granulat sont examinés : 2, 6 et 10 mm, le volume de fraction étant de 20%. Une compagne expérimentale est présentée, à savoir l'essai brésilien de rupture par traction pour le comportement mécanique sous charge diamétrale et l'essai de perméabilité au gaz pour le comportement hydromécanique. Les effets de la taille des granulats, de l'ouverture de la fissure, de la position de la fissure et de son trajet sont étudiés.
  Enfin, les résultats expérimentaux sont comparés à ceux numériques en utilisant un modèle mécanique et hydromécanique à l'échelle mésoscopique.

- Les conclusions et les perspectives sont présentées dans le chapitre cinq.

Chapter 1

INTRODUCTION

1.1 Introduction

Concrete is considered as a heterogeneous material in which composite aggregate particles melt into a cement paste. It is also a porous medium. Therefore, concrete durability is strongly influenced by the flow of fluids, gas and pollutants in the porous matrix.The presence of cracks in concrete structures weakens the strength of the porous medium (concrete) and provides paths of flow for aggressive agents such as: sulphates, chlorides, carbon dioxide, etc. This work aims to provide a better understanding of the mechanical behavior of concrete under loading and to demonstrate the interactions between crack opening and the flow of fluid or permeability. This parameter is the main one that defines the ability of concrete to carry a fluid (liquid or gas). The porous network and its connectivity and the water content of the material significantly affect on the permeability of concrete. In order to develop predictive concrete durability today, two numerical models are investigated in this thesis: a **mechanical one** to represent the behavior of a heterogeneous material such as concrete under diametral loading in the context of the Brazilian splitting tensile test, and a **hydro-mechanical model** to investigate the gas of permeability coupling with the crack opening. There are many parameters that need to be studied which influence the mechanical behavior of concrete under service loading, such as: the type of cement, the aggregate properties, its size and content, the weather conditions, the type of loading, the quality of manufacturing, etc. In this study, the influence of aggregates size and of volume fraction on the mechanical and hydro-mechanical behavior of concrete under loading is investigated. The presented two numerical are based on 3D Embedded Finite Element Method (E-FEM) formulation to describe meso-scale behavior (see [Benkemoun, 2010]). The first model (mechanical one) provides the effects of aggregates size and of volume fraction on concrete tensile behavior. The second model (hydro-mechanical one) is carring out with the interactions between the physical properties (permeability) and crack opening, aggregates size and volume fraction when concrete is under loading.

Through this hydro-mechanical coupling the proposed numerical model is able to represent the complex behavior mentioned above, and especially to investigate the significance of the stress effects under loading and the development of the permeability under these conditions.

To validate and provide the numerical models, mechanical model and hydro-mechanical model, an experimental work is presented. Three aggregate sizes (galss beads) are investigated varying from 2 to 10mm. The numerical results show good agreement with the experimental results and some previous experimental and theoretical studies in literature review.

1.2 Motivations and objectives of the research

The heterogeneity of concrete is one of its most characteristic points, thus this work was carried out. Furthermore, few numerical studies have pointed out that concrete is a multi-phase material in three dimensions. In addition, there are some parameters that greatly affect on the durability and structural performance of concrete material such as aggregates size, content and type. Lastly, the volume fraction of aggregates occupies approximately 75 % of the total volume of concrete. Investigating these features is the first goal of this study.

The second goal is the phenomenon of permeability, which is defined as the ability of a porous material such as concrete to transport fluids (water or gas) under a pressure gradient. The flow occurs in a porous network, including initial and specific pore voids or cracks. These are induced by various stresses, usually interconnecting the percolation paths, which reduce the flow resistance of the porous medium and cause an increase in permeability. Permeability is a parameter that can indirectly influence the durability of concrete structures by governing the rate of penetration of aggressive agents, but this effect is direct when the structure has a sealed part, such as confining structures (reservoir tanks or nuclear power reactors buildings). The porous material includes many characteristics that influence on the durability of structures and provides optimum protection for the steel reinforcement.

There are many problems causing the deterioration of reinforced concrete, which consists of the corrosion of the reinforcement. The pores in the concrete enable the penetration of fluid over time, which leads to the gradual degradation of the material's characteristics. Generally, carbon dioxide (CO_2) contained in the air and the chlorides in marine environmental or de-icing salt are the two main agents that cause corrosion of the reinforcement. The major complication is thus constituted by the heterogeneous nature of concrete (paste and aggregate), which leads to the presence of micro/macro cracks that are inevitable even with weak stress at an early age. These cracks and those that will be introduced are very important to study because they may form preferential pathways for fluid flow (water or gas). Therefore, we are interested in estimating the flow rate in concrete, as well as the evaluation of structural performance associated with the degradation of the material's properties (reinforcement corrosion, carbonation of concrete, etc.) and the prediction of cracks and their effect on the transfer properties of the material such as permeability coefficient, diffusion coefficient, etc.

The aim of this research is the development of a numerical method to study the influence of aggregates size and volume fraction on the mechanical behavior under diametral loading, and to evaluate the permeability in a heterogeneous material such as concrete. Thus, this work investigates the interactions between cracking and the permeability of fluid in the tensile splitting test (Brazilian test) and studies the effect of aggregates size and volume fraction on the hydro-mechanical properties and the permeability of porous materials. To obtain these conditions, three categories must be ensured:

1. For the modeling process, the main aspects of the cracked concrete must be taken into account (such as heterogeneity, scale effects, etc.) and local information provided on cracking (such as location, direction and crack opening).

2. A coupling model (hydro-mechanical) must be devised to describe the interaction between the transfer properties of the porous medium and crack opening in the context of the Brazilian splitting test.

3. Finally, the constitutive laws for the experimental work must be explained to describe the influence of the aggregates size and volume fraction on the mechanical properties and the development of the hydro-mechanical properties of the material.

There are many models in the literature that describe the cracks in a porous medium but few describe the flow in these cracks. Colliat et al. [Colliat et al., 2007], Bruggi et al. [Bruggi et al., 2008], Yang and Frank Xu [Yang and Xu, 2008], Ibrahimbegovic et al. [Ibrahimbegovic et al., 2011], and Syroka-Korol et al. [Syroka-Korol et al., 2013] describe some of the models that take into account the heterogeneity of the material through the introduction of the random distribution of mechanical properties. For this reason, this formulation (the numerical method of finite element) and assumptions were presented. We depended on these models in this study. At the same time, these models are able to provide relevant information about the geometrical properties of cracks such as (crack openings, cracks orientation, etc.). This issue appears to be an essential point when considering the transfer of fluid in a porous medium.

The context of the modeling approach leads to describing the properties of cracks: in fact, the relationship between the permeability and the crack opening and its geometry (tortuosity, roughness, etc.), Réthoré et al. [Réthoré et al., 2007], Khoei et al. [Khoei et al., 2011], Barani et al. [Barani et al., 2011], and Meschke et al. [Meschke et al., 2011]. There is a law which is constitutive of this relationship to estimate the local effect of crack opening on the increase in hydraulic conductivity through the structural elements. The model most commonly used to describe the flow of an incompressible fluid in laminar flow through the crack opening is named the parallel plates model (PPM) (cubic law), Poiseuille [Poiseuille, 1844], Snow in [Snow, 1969].

Many theoretical and experimental works have been presented for this purpose in the context of rock mechanics, Lomize [Lomize, 1951], Romm [Romm, 1966], Louis [Louis, 1974], Brush and Thomson [Brush and Thomson, 2003], Crandall et al. [Crandall et al., 2010], while few studies have been carried out on concrete structures. Wang et al. [Wang et al., 1997], Aldea et al. [Aldea et al., 1999], Choinska et al. [Choinska et al., 2007] Picandet et al. [Picandet et al., 2009], Akhavan et al. [Akhavan et al., 2012] presented experimental studies concerning the evolution of the transport properties in concrete structures. A 3D numerical mechanical model to represent crack opening in a heterogeneous material and hydro-mechanical behavior is not possible to obtain enough information. Therefore, experimental work for validation and providing this context will be needed and demonstrated in this work.

1.3 Plan of the thesis

The objective of this thesis is to develop numerical models using the finite element method (E-FEM); this method is carried out at the meso-scale to represent crack opening in a 3D heterogeneous material for simulating the Brazilian splitting tensile test. This model is known as the mechanical model. The second model is known as the hydro-mechanical model for the coupling between crack opening and the transfer of fluid (permeability of water or gas). This model is based on Poiseuille's equation for laminar fluid in pipes and Darcy's law for the pores.

Experimental work is also presented for the validation of numerical models. To explain the methods and characteristics chosen and the results obtained, this thesis is divided into five chapters:

⇒ Chapter one focuses on a general introduction of the subject including the mechanical behavior of concrete under service load and the permeability of fluid (water or gas) for concrete structures under a fluid pressure gradient. It also consists of some previous studies of researchers who presented a hydro-mechanical model to represent the permeability of fluid in porous media with the influence of crack opening. In addition, this chapter describes the plan of the thesis.

⇒ Chapter two consists of a literature review of the many experimental and theoretical research works to explain the behavior of concrete under loading and provided some parameters that affect on the mechanical behavior, such as aggregates size and volume fraction, and investigated the types of cracks. Then, the physical part is explained about the transfer of fluid (water or gas) in concrete structures thereby defining permeability in porous media. Herein, some of the parameters that affect on the permeability are pointed out. Finally in this chapter, a literature review is presented about coupling cracking and permeability in concrete structures and the influence of cracking on the permeability of porous media such as concrete.

⇒ Chapter three presents the numerical-mechanical model (meso-scale) and hydro-mechanical model which are proposed by Benkemoun et al. [Benkemoun et al., 2010]. The meso-scale model is based on a 3D lattice approach to represent the heterogeneity and failure mechanism of concrete for implementing crack opening. This model considers concrete as a two-phase material in which aggregates melt into a cement paste. The finite element method (E-FEM) and the FEAP (Finite Element Analysis Program) are used in this study for 3D simulation of the Brazilian splitting tensile test. The mechanical model can represent a 3D heterogeneous material and provides three types of bar elements (aggregate, mortar and the interaction zone between them). Herein, the influence of aggregates size and volume fraction on the mechanical behavior of a heterogeneous material is investigated.

The hydro-mechanical (coupling) model is presented, which used to make the link between cracking and permeability at the meso-scale. Herein, is studied the effect of crack openings, which were computed from the meso-scale model and the link with permeability is presented, based on Poiseuille's law, and the permeability in porous media is computed based on Darcy's law. In addition, the influence of aggregates size and volume fraction on the permeability of concrete is presented.

⇒ Chapter four contains the experimental work to validate the meso-scale mechanical and hydro-mechanical models. Four groups of cylinderical specimens have been realised, using glass beads particles as the coarse aggregate. One group is considered as reference: these specimens without coarse aggregates , mortar only. Three aggregate diameters are examined: 2, 6 and 10 mm, with the volume of fraction is 20 %. Two types of tests are presented, firstly is the Brazilian splitting tensile test for mechanical behavior under diametral loading and secondly the gas permeability test for the hydro-mechanical behavior. Effects of aggregates size, crack opening, crack position and its path are investigated. Finally, the experimental results are compared with the mechanical meso-scale and hydro-mechanical models.

⇒ Conclusions and perspectives are presented in chapter five.

Chapter 2

THE MECHANICAL BEHAVIOR OF POROUS STRUCTURES AND THE PERMEABILITY OF CONCRETE

This chapter consists of two parts: the first is the mechanical part, which describes the behavior of porous media under service loading, i.e. the indications of concrete structures under different applied loads. The second part explains the physical part, which is the transfer of fluids, such as water or gas, in porous media. This part also presents the most widely used theories for the coupling between damaged concrete (cracked section) and uncracked section / permeability. Finally, this chapter provides a literature review of experimental and theoretical studies.

2.1 Introduction

Concrete durability is related to its permeability. There are many authors pointed out that a well designed and manufactured of concrete structure according to transport fluids (gas and water), this behavior due to the porosity of material and microcracks.Concrete structures are deteriorating and cracking caused by the service loads or weathering should be taken into account during durability design. Cracks in concrete consider pathway of fluids, therefore the permeability increases in cracked concrete.

There are many parameters play a critical role in controlling a durability of concrete such as: aggregates size, type, volume fraction and surface area. Tasdemir et al. [Tasdemir et al., 1996]investigated the influence of aggregates size and its type on the mechanical properties. Tasdemir et al. [Tasdemir et al., 1996] investigated the effecting of maximum aggregate size and its length on the number of cracks and its width. While there is a little informations in the previous studies about the effect of volume fraction of aggregate on the fracture properties of concrete, therefore this study is presented. Petersson [Petersson, 1980] and Zhang et al. [Zhang et al., 2005] explained the influence of maximum aggregate size on the mechanical properties of concrete and fracture energy. Hillerborg [Hillerborg, 1985] reported that the fracture energy values for the concretes larger than corresponding mortars. Bisschop and van Mier [Bisschop and Van Mier, 2002] showed increasing aggregates size from 2 to 6 mm leads to an increase in total crack length but also in the maximum crack depth. Chen and Lui [Chen and Liu, 2004] found that the increasing volume of aggregate from 40 % to 80 % both fracture energy and critical stress intensity increase, this indication for low-strength concrete, while for high-strength concrete this percent was achieved 60 %. Saouma et al. [Saouma et al., 1991] showed the fracture energy increases when the volume fraction is increasing, while the tensile strength shows a reserve tendency with the volume fraction for high-strength concrete. Burcu Akcay et al. [Akcay et al., 2012] carried out the increasing of splitting tensile strength, compressive strength, modulus of elasticity and bending strength of concrete with the increasing volume fraction of aggregate.

Some of the authors found a reverse result that corresponds the volume fraction. On the other word, Grassl et al. [Grassl et al., 2010] carried out the increasing of volume fraction in concrete caused to decrease of tensile strength, fracture energy, crack width and modulus of elasticity. The experimental study was presented by Amparano et al. [Amparano et al., 2000], it explained the decreasing of fracture energy caused by the increasing of volume fraction of aggregate before its minimum value at 65 % volume of aggregate, and when the minimum percent is more than 65 % leads to increase the fracture energy. Also, the coarsenes of random grain structure of concrete effects on the fracture transition zone and , based on a morphological model: mosaic pattern.

Grassl et al. [Grassl et al., 2010] found out that permeability increases with the increasing of aggregates diameter and decreasing of the volume fraction. Picandet et al. [Picandet et al., 2009] pointed out the permeability of gas and water increase with the increasing of crack opening . Care et al. [Care and Derkx, 2011] presented the correlation between the aggregate size and volume fraction with the permeability of gas, i.e. gas permeability depends upon aggregate size and its content.

2.2 Mechanical part

This part presents the type of fractures (cracks) in concrete and shows the characteristics that affect on the properties of transferring fluids in concrete structures, such as: type of load, cracks, crack width, orientation of cracks, aggregates size, volume fraction, etc.

2.2.1 Type of fractures (cracks)

There are three types of fracture in concrete structures. However, to understand the fracture mechanics, which depend on many characteristics such as the properties of materials, the geometry of the body, loads, etc., the type of crack must be known. The aggregate particles melt into a cement paste in three dimensions and to evaluate the numerical results, a good model for the engineering work will be necessary when applying a load (tensile stress) until the ultimate tensile stress is reached (tensile strength) in the context of splitting tensile strength. As shown in Figure (2.1), the three modes of cracking in bodies are:

1. **Mode I**: the crack opens when the loading is normal (tensile load).

2. **Mode II**: the in-plane shear when the loading is perpendicular to the surface of the body.

3. **Mode III**: the out of plane shear when the rupture or crack is parallel to the loading.

2.2.2 Effects of mechanical stress on the initial porous structure

This section presents the types of cracks corresponding to the kinds of loading for different works. When applying load on the concrete structure causing damage of the material (cracks), this damage will decrease the module of elasticity and bond strength between the cement and the aggregate, i.e. the presence of cracks in concrete structures weakens the strength of the concrete under loading. Figure

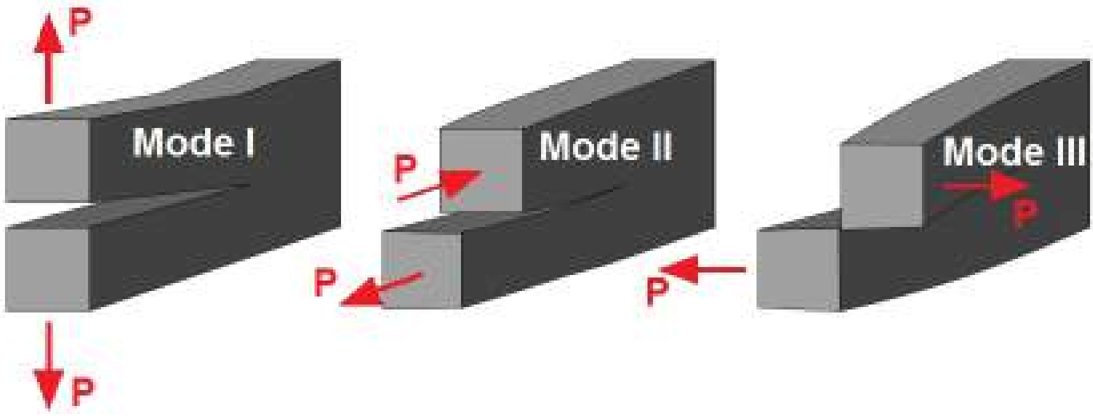

Figure 2.1: Three types of fractures by Bao-Chan Do in [Bao-Chan, 2014].

(2.2) shows the stress-strain relations for the cement paste, aggregate and concrete. There are many methods in experimental work for locating and showing the position of cracks (optical microscopy, X-ray, ultrasonic wave propagation, acoustic emission and strain gauge). Mehta in [Mehta, 1986] investigated the type of cracks when applying a compression load on a concrete structure. The cracks are divided into two types that correspond to their position: the first one is the interaction zone between the aggregates and cement paste, i.e. the crack surrounds the aggregate particles; the second one is through the mortar or cement paste, see Figure (2.3).

The properties of concrete under a compression load are used more in concrete structures, therefore there are many studies regarding the behavior of concrete with cracks under a compression force [Mehta, 1986], [Neville, 1997]. Although the tensile strength of concrete is 10 % of the compression strength, it is an important factor that affects on the durability of concrete through the penetration of aggressive agents. Thus, some experimental studies will be reported that explain the tensile stress with cracks, this relation depending on the applied loads and the crack opening. Through this relationship, the behavior of concrete under tensile loading can be understood.

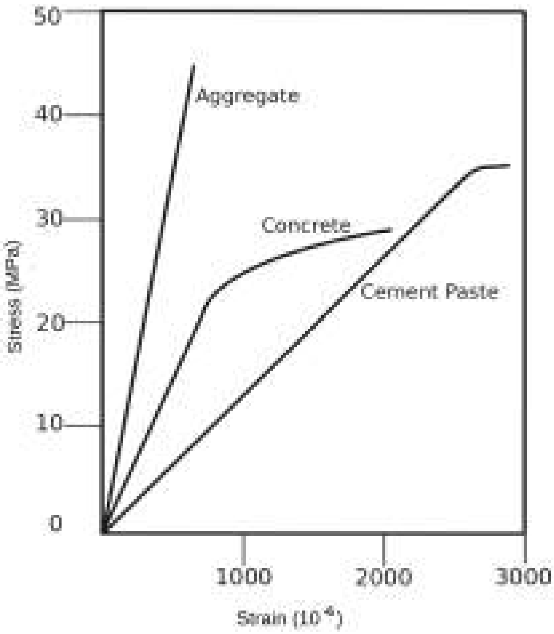

Figure 2.2: Typical stress-strain relations for cement paste, aggregate and concrete by Neville [Neville, 1997].

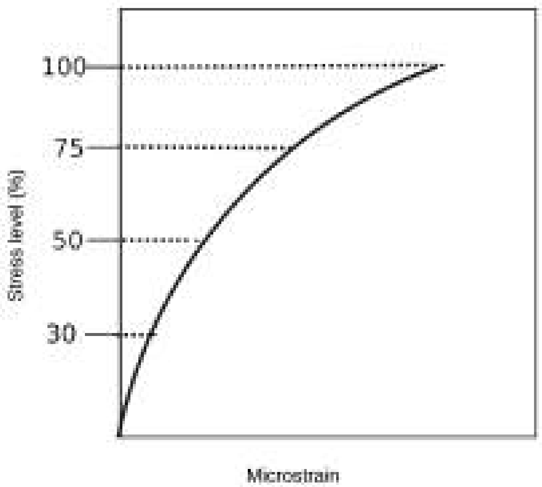

Figure 2.3: Schematic illustration of the cracking of concrete under a compression load (a) stress level with microstrain; (b) form of cracks under compression load by Mehta [Mehta, 1986].

[Amparano et al., 2000] Amparano, F. E., Xi, Y., and Roh, Y.-S. (2000). Experimental study on the effect of aggregate content on fracture behavior of concrete. *Engineering Fracture Mechanics*, 67(1):65–84.

[ASTM C496, 1996] ASTM C496, C. (1996). *Test Method for Splitting Tensile Strength of Cylindrical Concrete Specimens.* Taylor and Francis, New York (USA).

[Bao-Chan, 2014] Bao-Chan, D. (2014). *Extending the Novel A-FEM to Model Arbitrary Cracking in Thermo-elastic Solids.* . PhD thesis, University of Miami Scholarly Repository.

[Barani et al., 2011] Barani, O., Khoei, A., and Mofid, M. (2011). Modeling of cohesive crack growth in partially saturated porous media; a study on the permeability of cohesive fracture. *International Journal of Fracture*, 167(1):15–31.

[Baroghel-Bouny, 1994] Baroghel-Bouny, V. (1994). Caractérisation des pâtes de ciment et des bétons-méthodes, analyse, interprétations.

[Basheer et al., 2005] Basheer, L., Basheer, P., and Long, A. (2005). Influence of coarse aggregate on the permeation, durability and the microstructure characteristics of ordinary portland cement concrete. *Construction and Building Materials*, 19(9):682–690.

[Bayramov et al., 2004] Bayramov, F., Akçay, B., Ağar, A., Atahan, H., Şengül, C., and Taşdemir, M. (2004). Determination of the true specific fracture energy of concrete. In *6th International Congress on Advances in Civil Engineering, Boğaziçi University, Istanbul, Turkey*, pages 6–8.

[Bažant, 2004] Bažant, Z. P. (2004). Probability distribution of energetic-statistical size effect in quasibrittle fracture. *Probabilistic Engineering Mechanics*, 19:307–319.

[Bazant and Jirásek, 2002] Bazant, Z. P. and Jirásek, M. (2002). Nonlocal integral formulations of plasticity and damage: survey of progress. *Journal of Engineering Mechanics*, 128(11):1119–1149.

[Bažant and Raftshol, 1982] Bažant, Z. P. and Raftshol, W. J. (1982). Effect of cracking in drying and shrinkage specimens. *Cement and Concrete Research*, 12(2):209–226.

[Bažnt and Raftshol, 1982] Bažnt, Z. P. and Raftshol, W. J. (1982). Effect of cracking in drying and shrinkage specimens. *Cement and Concrete Research*, 12(2):209–226.

[Benkemoun, 2010] Benkemoun, N. (2010). *Sequential multi-scale approch : application to heterogeneous quasi-brittle material.* Theses, École normale supérieure de Cachan - ENS Cachan.

[Benkemoun et al., 2010] Benkemoun, N., Hautefeuille, M., Colliat, J.-B., and Ibrahimbegovic, A. (2010). Modeling heterogeneous materials failure: 3D meso-scale models with embedded discontinuities. *International Journal of Numerical Methods in Engineering*, 82:1671–1688.

[Benkemoun et al., 2013] Benkemoun, N., Jourdain, X., Choinska, M., and Khelidj, A. (2013). Numerical modelling of the tensile splitting test and its coupling with gas permeability. VIII International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS-8, Toledo, Spain.

[Biot, 1955] Biot, M. A. (1955). Theory of elasticity and consolidation for a porous anisotropic solid. *Journal of Applied Physics*, 26(2):182–185.

[Biot, 1962] Biot, M. A. (1962). Mechanics of deformation and acoustic propagation in porous media. *Journal of applied physics*, 33(4):1482–1498.

[Bisschop and Van Mier, 2002] Bisschop, J. and Van Mier, J. (2002). Effect of aggregates on drying shrinkage microcracking in cement-based composites. *Materials and Structures*, 35(8):453–461.

[Bolander and Saito, 1998] Bolander, J. E. and Saito, S. (1998). Fracture analyses using spring networks with random geometry. *Engineering Fracture Mechanics*, 61(5):569–591.

[Borja and Andrade, 2006] Borja, R. I. and Andrade, J. E. (2006). Critical state plasticity, part VI: Meso-scale finite element simulation of strain localization in discrete granular materials. *Computer Methods in Applied Mechanics and Engineering*, 195:5115–5140.

[Boulay et al., 2009] Boulay, C., Dal Pont, S., and Belin, P. (2009). Real-time evolution of electrical resistance in cracking concrete. *Cement and Concrete Research*, 39(9):825–831.

[Breysse and Gérard, 1997] Breysse, D. and Gérard, B. (1997). Transport of fluids in cracked media. *Rilem report*, pages 123–154.

[Bruggi et al., 2008] Bruggi, M., Casciati, S., and Faravelli, L. (2008). Cohesive crack propagation in a random elastic medium. *Probabilistic Engineering Mechanics*, 23(1):23–35.

[Brush and Thomson, 2003] Brush, D. J. and Thomson, N. R. (2003). Fluid flow in synthetic rough-walled fractures: Navier-stokes, stokes, and local cubic law simulations. *Water Resources Research*, 39(4).

[Cairns, 1961] Cairns, S. (1961). *Introductory Topology*. Ronald Press, New York.

[Camacho and Ortiz, 1996] Camacho, G. T. and Ortiz, M. (1996). Computational modelling of impact damage in brittle materials. *International Journal of solids and structures*, 33(20):2899–2938.

[Care and Derkx, 2011] Care, S. and Derkx, F. (2011). Determination of relevant parameters influencing gas permeability of mortars. *Construction and Building Materials*, 25(3):1248–1256.

[Carman, 1956] Carman, P. C. (1956). *Flow of gases through porous media.* Academic press.

[Chatzigeorgiou, 2004] Chatzigeorgiou, G. (2004). Coupling between damage, temperature and permeability of concrete: Experimental and numerical study. *Rapport technique, Ecole Centrale Nantes.*

[Chen and Liu, 2004] Chen, B. and Liu, J. (2004). Effect of aggregate on the fracture behavior of high strength concrete. *Construction and Building Materials*, 18(8):585–590.

[Choinska, 2006] Choinska, M. (2006). *Effets de la température, du chargement mécanique et de leurs interactions sur la perméabilité du béton de structure.* Theses, Ecole Centrale de Nantes (ECN) (ECN) (ECN) (ECN) ; Université de Nantes.

[Choinska et al., 2008a] Choinska, M., Dufour, F., Pijaudier-Cabot, G., Huerta, A., and Khelidj, A. (2008a). How can a crack opening be extracted from a continuous damage finite element computation? application for the estimation of permeability. In *Thermo-Hydromechanical and Chemical Coupling in Geomaterials and Applications: Proceedings of the 3 International Symposium GeoProc'2008*, pages 605–612. Wiley Online Library.

[Choinska et al., 2008b] Choinska, M., Dufour, F., Pijaudier-Cabot, G., Huerta, A., and Khelidj, A. (2008b). How to extract a crack opening from a continuous damage finite element computation ? application for the estimation of permeability. GeoProc2008: Proceedings of the 3rd International Symposium GeoProc'2008 (ISTE).

[Choinska et al., 2007] Choinska, M., Khelidj, A., Chatzigeorgiou, G., and Pijaudier-Cabot, G. (2007). Effects and interactions of temperature and stress-level related damage on permeability of concrete. *Cement and Concrete Research*, 37(1):79–88.

[Code,] Code, C.-F. M. 90. 1993. model code for concrete structures. comité euro-international du béton (ceb)–fédération internationale de la précontrainte (fip).

[Colliat et al., 2007] Colliat, J.-B., Hautefeuille, M., Ibrahimbegovic, A., and Matthies, H. G. (2007). Stochastic approach to size effect in quasi-brittle materials. *Comptes Rendus Mécanique*, 335(8):430–435.

[Committee et al., 2014] Committee, A., Institute, A. C., and for Standardization, I. O. (2014). Building code requirements for structural concrete (aci 318-08) and commentary. American Concrete Institute.

[Crandall et al., 2010] Crandall, D., Bromhal, G., and Karpyn, Z. T. (2010). Numerical simulations examining the relationship between wall-roughness and fluid flow in rock fractures. *International Journal of Rock Mechanics and Mining Sciences*, 47(5):784–796.

[Cunha et al., 2011] Cunha, V. M., Barros, J. A., and Sena-Cruz, J. (2011). An integrated approach for modelling the tensile behaviour of steel fibre reinforced self-compacting concrete. *Cement and Concrete Research*, 41(1):64–76.

[Dal Pont et al., 2005] Dal Pont, S., Schrefler, B., and Ehrlacher, A. (2005). Experimental and finite element analysis of a hollow cylinder submitted to high temperatures. *Materials and structures*, 38(7):681–690.

[Damgaard Jensen and Chatterji, 1996] Damgaard Jensen, A. and Chatterji, S. (1996). State of the art report on micro-cracking and lifetime of concretepart 1. *Materials and Structures*, 29(1):3–8.

[Darcy, 1856] Darcy, H. (1856). *Les fontaines publiques de la ville de Dijon: exposition et application...* Victor Dalmont.

[Djerbi et al., 2008] Djerbi, A., Bonnet, S., and Khelidj, A. (2008). Influence of traversing crack on chloride diffusion into concrete. *Cement and Concrete Research*, 38 (6):877–883.

[Dormieux and Kondo, 2004] Dormieux, L. and Kondo, D. (2004). Approche micromécanique du couplage perméabilité–endommagement. *Comptes Rendus Mécanique*, 332(2):135–140.

[Dullien, 2012] Dullien, F. A. (2012). *Porous media: fluid transport and pore structure*. Academic press.

[Dvorkin et al., 1990] Dvorkin, E. N., Cuitiño, A. M., and Gioia, G. (1990). Finite elements with displacement interpolated embedded localization lines insensitive to mesh size and distortions. *International journal for numerical methods in engineering*, 30(3):541–564.

[El Dandachy et al., 2016] El Dandachy, E., Briffaut, M., Dufour, F., and Dal Pont, S. (2016). An original semi-discrete approach to assess gas conductivity of concrete structures. *International Journal for Numerical and Analytical Methods in Geomechanics*.

[Elices and Rocco, 2008] Elices, M. and Rocco, C. (2008). Effect of aggregate size on the fracture and mechanical properties of a simple concrete. *Engineering Fracture Mechanics*, 75(13):3839–3851.

[Elsharief et al., 2003] Elsharief, A., Cohen, M. D., and Olek, J. (2003). Influence of aggregate size, water cement ratio and age on the microstructure of the interfacial transition zone. *Cement and Concrete Research*, 33(11):1837–1849.

[Escadeillas and Maso, 1990] Escadeillas, G. and Maso, J. (1990). Approach of the initial state in cement paste, mortar, and concrete. *Ceram. Trans.*, 16:169–184.

[Fabien, 2012] Fabien, A. J. (2012). *Etude du couplage comportement hydromécanique–durabilité dans le béton de la structure: application à la maquette MAREVA*. PhD thesis, Nantes.

[Fairbairn and Ulm, 2002] Fairbairn, E. M. and Ulm, F. J. (2002). A tribute to fernando llb carneiro (1913–2001) engineer and scientist who invented the brazilian test. *Materials and Structures*, 35(3):195–196.

[FaL, 1992] FaL, D. (1992). Porous media: fluid transport and pore structure. *AcademicPress, SanDiego,*, 1:992.

[Feyel and Chaboche, 2001] Feyel, F. and Chaboche, J.-L. (2001). Multi-scale non-linear $FE^{\mathbf{2}}$ analysis of composite structures: damage and fiber size effects. *Revue européenne des Éléments Finis: NUMDAM'00 issue*, 10:449–472.

[Fischmeister, 1974] Fischmeister, H. (1974). *Pore Structure and Properties of Materials*. Academia, Prague.

[Gerard, 1996] Gerard, B. (1996). *Contribution of the mechanical, chemical, and transport couplings in the long-term behavior of radioactive waste repository structures*. PhD thesis, Univ. Laval and Ecole Normale Supérieure de Cachan.

[Gérard et al., 1996] Gérard, B., Breysse, D., Ammouche, A., Houdusse, O., and Didry, O. (1996). Cracking and permeability of concrete under tension. *Materials and Structures*, 29(3):141–151.

[Gerard et al., 1997] Gerard, B., Reinhardt, H., and Breysse, D. (1997). Measured transport in cracked concrete. *Rilem report*, pages 265–324.

[Gettu et al., 1996] Gettu, R., Mobasher, B., Carmona, S., and Jansen, D. C. (1996). Testing of concrete under closed-loop control. *Advanced Cement Based Materials*, 3(2):54–71.

[Grabiec et al., 2015] Grabiec, A. M., Zawal, D., and Szulc, J. (2015). Influence of type and maximum aggregate size on some properties of high-strength concrete made of pozzolana cement in respect of binder and carbon dioxide intensity indexes. *Construction and Building Materials*, 98:17–24.

[Grassl et al., 2012] Grassl, P., Grégoire, D., Rojas-Solano, L., and Pijaudier-Cabot, G. (2012). Meso-scale modelling of the size effect on the fracture process zone of concrete. *International Journal of Solids and Structures*, 49(13):1818–1827.

[Grassl et al., 2010] Grassl, P., Wong, H. S., and Buenfeld, N. R. (2010). Influence of aggregate size and volume fraction on shrinkage induced micro-cracking of concrete and mortar. *Cement and concrete research*, 40(1):85–93.

[Guinea et al., 2002] Guinea, G., El-Sayed, K., Rocco, C., Elices, M., and Planas, J. (2002). The effect of the bond between the matrix and the aggregates on the cracking mechanism and fracture parameters of concrete. *Cement and concrete research*, 32(12):1961–1970.

[Hearn, 1999] Hearn, N. (1999). Effect of shrinkage and load-induced cracking on water permeability of concrete. *Materials Journal*, 96(2):234–241.

[Hearn and Lok, 1998] Hearn, N. and Lok, G. (1998). Measurement of permeability under uniaxial compression–a test method. *ACI Materials Journal*, 95(6).

[Herrmann et al., 1989] Herrmann, H. J., Hansen, A., and Roux, S. (1989). Fracture of disordered, elastic lattices in two dimensions. *Physical Review B*, 39(1):637.

[Hillerborg, 1983] Hillerborg, A. (1983). Concrete fracture energy tests performed by 9 laboratories according to a draft rilem recommendation: Report to rilem tc50-fmc. *Report TVBM*.

[Hillerborg, 1984] Hillerborg, A. (1984). Additional concrete fracture energy tests performed by 6 laboratories according to a draft rilem recommendation. *Report TVBM*.

[Hillerborg, 1985] Hillerborg, A. (1985). Results of three comparative test series for determining the fracture energyg f of concrete. *Materials and Structures*, 18(5):407–413.

[Hobbs, 1974] Hobbs, D. (1974). Influence of aggregate restraint on the shrinkage of concrete. In *Journal Proceedings*, volume 71, pages 445–450.

[Hoseini et al., 2009] Hoseini, M., Bindiganavile, V., and Banthia, N. (2009). The effect of mechanical stress on permeability of concrete: a review. *Cement and Concrete Composites*, 31(4):213–220.

[Hudson et al., 1972] Hudson, J. A., Crouch, S. L., and Fairhurst, C. (1972). Soft, stiff and servo-controlled testing machines: a review with reference to rock failure. *Engineering Geology*, 6(3):155–189.

[Hwang and Young, 1984] Hwang, C.-L. and Young, J. (1984). Drying shrinkage of portland cement pastes i. microcracking during drying. *Cement and Concrete Research*, 14(4):585–594.

[Ibrahimbegovic, 2006] Ibrahimbegovic, A. (2006). Mécanique non linéaire des solides déformables: formulation théorique et résolution par éléments finis. *Lavoisier*.

[Ibrahimbegovic et al., 2011] Ibrahimbegovic, A., Colliat, J.-B., Hautefeuille, M., Brancherie, D., and Melnyk, S. (2011). Probability based size effect representation for failure in civil engineering structures built of heterogeneous materials. In *Computational Methods in Stochastic Dynamics*, pages 291–313. Springer.

[Ibrahimbegovic and Wilson, 1991] Ibrahimbegovic, A. and Wilson, E. (1991). A modified method of incompatible modes. *Communications in Applied Numerical Methods*, 7(3):187–194.

[Jacobs, 1998] Jacobs, F. (1998). Permeability to gas of partially saturated concrete. *Magazine of concrete research*, 50(2).

[Jirásek, 2000] Jirásek, M. (2000). Comparative study of finite elements with embedded discontinuities. *Computer Methods in Applied Mechanics and Engineering*, 188:307–330.

[Johnston, 1970] Johnston, C. (1970). Strength and deformation of concrete in uniaxial tension and compression. *Magazine of concrete research*, 22(70):5–16.

[Jourdain, 2014] Jourdain, X. (2014). *Étude numérique méso-macro des propriétés de transfert des bétons fissurés*. PhD thesis, École normale supérieure de Cachan-ENS Cachan.

[Jourdain et al., 2013] Jourdain, X., Colliat, J., De Sa, C., Benboudjema, F., and Gatuingt, F. (2013). Upscaling permeability for fractured concrete: mesomacro numerical approach coupled to strong discontinuities. *International Journal for Numerical and Analytical Methods in Geomechanics*, 38(5):536–550.

[Khoei et al., 2011] Khoei, A., Barani, O., and Mofid, M. (2011). Modeling of dynamic cohesive fracture propagation in porous saturated media. *International Journal for Numerical and Analytical Methods in Geomechanics*, 35(10):1160–1184.

[Kleinschrodt and Winkler, 1986] Kleinschrodt, H. and Winkler, H. (1986). The influence of the maximum aggregate size and the size of the specimen on fracture mechanics parameters. *Fracture toughness and fracture energy of concrete*, 18(8):391–402.

[Klinkenberg et al., 1941] Klinkenberg, L. et al. (1941). The permeability of porous media to liquids and gases. In *Drilling and production practice*. American Petroleum Institute.

[Kollek, 1989] Kollek, J. (1989). The determination of the permeability of concrete to oxygen by the cembureau methoda recommendation. *Materials and structures*, 22(3):225–230.

[Lachihab and Sab, 2005] Lachihab, A. and Sab, K. (2005). Aggregate composites: a contact based modeling. *Computational Material Science*, 33:467–490.

[Lawler et al., 2002] Lawler, J. S., Zampini, D., and Shah, S. P. (2002). Permeability of cracked hybrid fiber-reinforced mortar under load. *Materials Journal*, 99(4):379–385.

[Li et al., 2011] Li, K., Ma, M., and Wang, X. (2011). Experimental study of water flow behaviour in narrow fractures of cementitious materials. *Cement and Concrete Composites*, 33(10):1009–1013.

[Li et al., 2004a] Li, Q., Deng, Z., and Fu, H. (2004a). Effect of aggregate type on mechanical behavior of dam concrete. *ACI materials journal 101*, 6:483–492.

[Li et al., 2004b] Li, Q., Deng, Z., and Fu, H. (2004b). Effect of aggregate type on mechanical behavior of dam concrete. *ACI materials journal*, 101(6):483–492.

[Lomize, 1951] Lomize, G. (1951). Flow in fractured rocks. *Gosenergoizdat, Moscow*, 127:197.

[Louis, 1974] Louis, C. (1974). Introduction à l'hydraulique des roches. *BULL BRGM, III*, (4).

[Maleki and Pouya, 2010] Maleki, K. and Pouya, A. (2010). Numerical simulation of damage – Permeability relationship in brittle geomaterials. *Computers and Geotechnics*, 37(5):619 – 628.

[Maso, 1982] Maso, J. (1982). La liaison entre les granulats et la pâte de ciment hydratée, 7ième congrès international de la chimie des ciments.

[Matallah and La Borderie, 2016] Matallah, M. and La Borderie, C. (2016). 3D numerical modeling of the crack-permeability interaction in fractured concrete. 9th International Conference on Fracture Mechanics of Concrete and Concrete Structures, FraMCoS-9, Berkeley, USA.

[Matallah et al., 2010] Matallah, M., La Borderie, C., and Maurel, O. (2010). A practical method to estimate crack openings in concrete structures. *International Journal for Numerical and Analytical Methods in Geomechanics*, 34(15):1615–1633.

[Mazars, 1984] Mazars, J. (1984). *Application de la mécanique de l'endommagement au comportement non linéaire et à la rupture du béton de structure*. PhD thesis.

[Mechtcherine and Müller, 1998] Mechtcherine, V. and Müller, H. (1998). Effect of the test set-up on fracture mechanical parameters of concrete. *Fracture mechanics of concrete structures, Proceedings FraMCoS-3, Gifu (Japan), Aedificatio*, pages 377–386.

[Mehta and Monteiro, 2006] Mehta, P. and Monteiro, P. J. M. (2006). *Concrete: Microstructure, Properties and Materials*. McGraw-Hill Companies, New York, USA.

[Mehta, 1986] Mehta, P. K. (1986). Concrete. structure, properties and materials.

[Meschke et al., 2011] Meschke, G., Grasberger, S., Becker, C., and Jox, S. (2011). Smeared crack and x-fem models in the context of poromechanics. In *Numerical Modeling of Concrete Cracking*, pages 265–327. Springer.

[Meziani and Skoczylas, 1999] Meziani, H. and Skoczylas, F. (1999). An experimental study of the mechanical behaviour of a mortar and of its permeability under deviatoric loading. *Materials and structures*, 32(6):403–409.

[Mihashi et al., 1989a] Mihashi, H., Nomura, N., and Izumi, M. (1989a). Fracture of concrete and rock. In Shah, S., Swartz, S., and Barr, B., editors, *Influence of matrix strength and gravel size on fracture properties of concrete*, pages 503–512. Elsevier.

[Mihashi et al., 1989b] Mihashi, H., Nomura, N., and Izumi, M. (1989b). Influence of matrix strength and gravel grain size on fracture properties of concrete. fracture of concrete and rock: Recent developments. papers presented at the international conference, university of wales, college of cardiff, school of engineering, september 20-22, 1989. *Publication of: Society of Automotive Engineers.*

[Mihashi et al., 1991] Mihashi, H., Nomura, N., and Niiseki, S. (1991). Influence of aggregate size on fracture process zone of concrete detected with three dimensional acoustic emission technique. *Cement and Concrete Research*, 21(5):737–744.

[Moës and Belytschko, 2002] Moës, N. and Belytschko, T. (2002). Extended finite element method for cohesive crack growth. *Engineering fracture mechanics*, 69(7):813–833.

[Moës et al., 2003] Moës, N., Cloirec, M., Cartraud, P., and Remacle, J.-F. (2003). A computational approach to handle complex microstructure geometries. *Computer Methods in Applied Mechanics and Engineering*, 192:3163–3177.

[Muskat and Meres, 1936] Muskat, M. and Meres, M. W. (1936). The flow of heterogeneous fluids through porous media. *Journal of Applied Physics*, 7(9):346–363.

[Neithalath et al., 2006] Neithalath, N., Weiss, J., and Olek, J. (2006). Characterizing enhanced porosity concrete using electrical impedance to predict acoustic and hydraulic performance. *Cement and Concrete Research*, 36(11):2074–2085.

[Neville, 1997] Neville, A. M. (1997). Aggregate bond and modulus of elasticity of concrete. *ACI Materials Journal*, 94(1):71–74.

[Neville, 2011] Neville, A. M. (2011). *Properties of concrete.*

[Nilenius et al., 2015] Nilenius, F., Larsson, F., Lundgren, K., and Runesson, K. (2015). Mesoscale modelling of crack-induced diffusivity in concrete. *Computational Mechanics*, 55(2):359–370.

[Ortiz et al., 1987] Ortiz, M., Leroy, Y., and Needleman, A. (1987). A finite element method for localized failure analysis. *Computer Methods in Applied Mechanics and Enginnering*, 61:189–214.

[Park et al., 2001] Park, S., Song, H., and Byun, K. (2001). Model for chloride diffusivity and water permeability in cracked concrete. *J. KSCE*, 21(6-A):915–924.

[Park et al., 2012] Park, S.-S., Kwon, S.-J., Jung, S. H., and Lee, S.-W. (2012). Modeling of water permeability in early aged concrete with cracks based on micro pore structure. *Construction and building materials*, 27(1):597–604.

[Peng, 2009] Peng, C. (2009). *Apports de lanalyse microtomographique dans la modélisation des effets du séchage des matériaux à matrice cimentaire.* PhD thesis, Lille 1.

[Pereira et al., 2009] Pereira, C. G., Castro-Gomes, J., and de Oliveira, L. P. (2009). Influence of natural coarse aggregate size, mineralogy and water content on the permeability of structural concrete. *Construction and Building Materials*, 23(2):602–608.

[Petersson, 1980] Petersson, P. (1980). Fracture energy of concrete: practical performance and experimental results. *Cement and Concrete research*, 10(1):91–101.

[Picandet, 2001] Picandet, V. (2001). *Influence dun endommagement mécanique sur la perméabilité et sur la diffusivité hydrique des bétons.* PhD thesis, Ecole Centrale de Nantes.

[Picandet et al., 2001] Picandet, V., Khelidj, A., and Bastian, G. (2001). Effect of axial compressive damage on gas permeability of ordinary and high-performance concrete. *Cement and Concrete Research*, 31(11):1525–1532.

[Picandet et al., 2009] Picandet, V., Khelidj, A., and Bellegou, H. (2009). Crack effects on gas and water permeability of concretes. *Cement and Concrete Research*, 39(6):537–547.

[Pijaudier-Cabot et al., 2009] Pijaudier-Cabot, G., Dufour, F., and Choinska, M. (2009). Permeability due to the increase of damage in concrete : From diffuse to localized damage distributions. *Journal of Engineering Mechanics*, 135:1022–1028.

[Poiseuille, 1844] Poiseuille, J. L. (1844). *Recherches expérimentales sur le mouvement des liquides dans les tubes de très-petits diamètres*. Imprimerie Royale.

[Pouya and Courtois, 2002a] Pouya, A. and Courtois, A. (2002a). Définition de la perméabilité équivalente des massifs fracturés par des méthodes d'homogénéisation. *Surface Geosciences (Hydrology-Hydrogeology)*, 334:975–979.

[Pouya and Courtois, 2002b] Pouya, A. and Courtois, A. (2002b). Définition de la perméabilité équivalente des massifs fracturés par des méthodes d'homogénéisation. *Comptes Rendus Geoscience*, 334(13):975 – 979.

[Quenard and Sallee, 1991] Quenard, D. and Sallee, H. (1991). *Le transfert isotherme de la vapeur d'eau condensable dans les matériaux microporeux du bâtiment*. CSTB.

[Ramtani, 1990] Ramtani, S. (1990). *Contribution à la modélisation du comportement multiaxial du béton endommagé avec description du caractère unilatéral*. PhD thesis, Paris 6.

[Ramtani et al., 1992] Ramtani, S., Berthaud, Y., and Mazars, J. (1992). Orthotropic behavior of concrete with directional aspects: modelling and experiments. *Nuclear Engineering and Design*, 133(1):97–111.

[Rao and Prasad, 2002] Rao, G. A. and Prasad, B. R. (2002). Fracture energy and softening behavior of high-strength concrete. *Cement and Concrete Research*, 32(2):247–252.

[Rapoport et al., 2002] Rapoport, J., Aldea, C.-M., Shah, S. P., Ankenman, B., and Karr, A. (2002). Permeability of cracked steel fiber-reinforced concrete. *Journal of materials in civil engineering*, 14(4):355–358.

[Rastiello et al., 2014] Rastiello, G., Boulay, C., Dal Pont, S., Tailhan, J.-L., and Rossi, P. (2014). Real-time water permeability evolution of a localized crack in concrete under loading. *Cement and Concrete Research*, 56:20–28.

[Rastiello et al., 2015] Rastiello, G., Tailhan, J.-L., Rossi, P., and Dal Pont, S. (2015). Macroscopic probabilistic cracking approach for the numerical modelling of fluid leakage in concrete. *Annals of Solid and Structural Mechanics*, 7(1-2):1–16.

[Réthoré et al., 2007] Réthoré, J., Borst, R. d., and Abellan, M.-A. (2007). A two-scale approach for fluid flow in fractured porous media. *International Journal for Numerical Methods in Engineering*, 71(7):780–800.

[Reynouard et al., 2009] Reynouard, J.-M., Pijaudier-Cabot, G., and Torrenti, J.-M. (2009). *Mechanical behavior of concrete*. Wiley, New-York.

[Rocco et al., 1999] Rocco, C., Guinea, G. V., Planas, J., and Elices, M. (1999). Mechanism of rupture in splitting test. *Materials Journal*, 96(1):52–60.

[Romm, 1966] Romm, E. (1966). Flow characteristics of fractured rocks. *Nedra, Moscow*, 283.

[Rossi and Boulay, 1990] Rossi, P. and Boulay, C. (1990). Influence of free water in concrete on the cracking process. *Magazine of concrete research*, 42(152):143–146.

[Rossi et al., 1992] Rossi, P., Van Mier, J., Boulay, C., and Le Maou, F. (1992). The dynamic behaviour of concrete: influence of free water. *Materials and Structures*, 25(9):509–514.

[Roubin, 2013] Roubin, E. (2013). *Meso-scale FE and morphological modeling of heterogeneous media : applications to cementitious materials*. PhD thesis, École Normal Supérieure de Cachan.

[Roubin et al., 2015] Roubin, E., Vallade, A., Benkemoun, N., and Colliat, J.-B. (2015). Multi-scale failure of heterogeneous materials: A double kinematics enhancement for embedded finite element method. *International Journal of Solids and Structures*, 52:180–196.

[Samaha and Hover, 1992] Samaha, H. R. and Hover, K. C. (1992). Influence of microcracking on the mass transport properties of concrete. *Materials Journal*, 89(4):416–424.

[Saouma et al., 1991] Saouma, V. E., Broz, J. J., Brühwiler, E., and Boggs, H. L. (1991). Effect of aggregate and specimen size on fracture properties of dam concrete. *Journal of Materials in Civil Engineering*, 3(3):204–218.

[Schlangen and Garboczi, 1997] Schlangen, E. and Garboczi, E. J. (1997). Fracture simulations of concrete using lattice models: computational aspects. *Engineering Fracture Mechanics*, 57:319–332.

[Schlangen and van Mier, 1992] Schlangen, E. and van Mier, J. G. M. (1992). Simple lattice model for numerical simulation of fracture of concrete materials and structures. *Materials and Structures*, 25:534–542.

[Scrivener, 2001] Scrivener, K. (2001). *Cours on-line.* EPFL.

[Scrivener et al., 2004] Scrivener, K. L., Crumbie, A. K., and Laugesen, P. (2004). The interfacial transition zone (itz) between cement paste and aggregate in concrete. *Interface Science*, 12(4):411–421.

[Setzer, 1975] Setzer, M. (1975). Zum mikrogefüge des zementsteins und dessen einfluss auf das mechanische verhalten des betons. *ZEMENT U BETON*, (85/86).

[Shah and Sankar, 1987] Shah, S. and Sankar, R. (1987). Internal cracking and strain softening response of concrete under uniaxial compression. *Materials Journal*, 84(3):200–212.

[Simo and Hughes, 1997] Simo, J. and Hughes, T. (1997). *Computational Inelasticity.* Interdisciplinary Applied Mathematics. Springer Verlag, New York, Berlin, Heidelberg.

[Simo et al., 1993] Simo, J., Oliver, J., and Armero, F. (1993). An analysis of strong discontinuities induced by strain-softening in rate independent inelastic solids. *Computational Mechanics*, 12:277–296.

[Simo and Oliver, 1994] Simo, J. C. and Oliver, J. (1994). A new approach to the analysis an simulation of strain softening in solids. In *Fracture and Damage in Quasibrittle Structures*, E & FN Spon, pages 25–39. London, z. p. bazant, z. bittar, m. jirásek and j. mazars edition.

[Slattery, 1967] Slattery, J. C. (1967). Flow of viscoelastic fluids through porous media. *AIChE Journal*, 13(6):1066–1071.

[Snow, 1969] Snow, D. (1969). *A Parallel Plate Model of Permeable Fractured Media.* . PhD thesis, University of California at Berkley.

[Stock et al., 1979] Stock, A., Hannantt, D., and Williams, R. (1979). The effect of aggregate concentration upon the strength and modulus of elasticity of concrete. *Magazine of concrete research*, 31(109):225–234.

[Struble, 1987] Struble, L. (1987). Microstructure and fracture at the cement paste-aggregate interface. In *MRS Proceedings*, volume 114, page 11. Cambridge Univ Press.

[Syroka-Korol et al., 2013] Syroka-Korol, E., Tejchman, J., and Mróz, Z. (2013). Fe calculations of a deterministic and statistical size effect in concrete under bending within stochastic elasto-plasticity and non-local softening. *Engineering Structures*, 48:205–219.

[Tasdemir et al., 1996] Tasdemir, C., Tasdemir, M. A., Lydon, F. D., and Barr, B. I. (1996). Effects of silica fume and aggregate size on the brittleness of concrete. *Cement and Concrete Research*, 26(1):63–68.

[TCS, 1985] TCS, R. (1985). Determination of the fracture energy of mortar and concrete by means of three-point bend tests on notched beams. *EnMaterials and Structures*, 18(6):287–290.

[Terrien, 1980] Terrien, M. (1980). Emission acoustique et" comportement mecanique post-critique" d'un beton sollicite en traction. *BULL LIAISON LAB PONTS CHAUSS*, (105).

[Van Mier and Van Vliet, 2002] Van Mier, J. and Van Vliet, M. (2002). Uniaxial tension test for the determination of fracture parameters of concrete: state of the art. *Engineering Fracture Mechanics*, 69(2):235–247.

[Villain et al., 2001] Villain, G., Baroghel-Bouny, V., Kounkou, C., and Hua, C. (2001). Measuring the gas permeability as a function of saturation rate of concrete. *Fr J Civ Eng*, 5:251–268.

[Wang, 1994] Wang, J. (1994). Development and application of a micromechanics-based numerical approach for the study of crack propagation in concrete.

[Wang et al., 1997] Wang, K., Jansen, D. C., Shah, S. P., and Karr, A. F. (1997). Permeability study of cracked concrete. *Cement and Concrete Research*, 27(3):381–393.

[Ward, 1969] Ward, M. (March 1969). *The testing of concrete materials by precisely controlled uniaxial tension*. PhD thesis, University of London for the degree of PhD.

[Washizu, 1982] Washizu, K. (1982). *Variational methods in elasticity and plasticity*. Technical Report 25-18, MIT, Pergamon Press, New York, 3 edition edition.

[Whitaker, 1986a] Whitaker, S. (1986a). Flow in porous media i: A theoretical derivation of darcy's law. *Transport in porous media*, 1(1):3–25.

[Whitaker, 1986b] Whitaker, S. (1986b). Flow in porous media ii: The governing equations for immiscible, two-phase flow. *Transport in porous media*, 1(2):105–125.

[Wilson et al., 1973] Wilson, E., Taylor, R., Doherty, W., and Ghaboussi, J. (1973). Incompatible displacement models. *Numerical and computer methods in structural mechanics*, 43.

[Witherspoon et al., 1980] Witherspoon, P. A., Wang, J. S., Iwai, K., and Gale, J. E. (1980). Validity of cubic law for fluid flow in a deformable rock fracture. *Water resources research*, 16(6):1016–1024.

[Wong et al., 2009] Wong, H., Zobel, M., Buenfeld, N., and Zimmerman, R. (2009). Influence of the interfacial transition zone and microcracking on the diffusivity, permeability and sorptivity of cement-based materials after drying. *Mag. Concr. Res*, 61(8):571–589.

[Wriggers and Moftah, 2006] Wriggers, P. and Moftah, S. O. (2006). Mesoscale models for concrete: Homogenisation and damage behaviour. *Finite Elements in Analysis and Design*, 42:623–636.

[Wu et al., 2015] Wu, Z., Wong, H., and Buenfeld, N. (2015). Influence of drying-induced microcracking and related size effects on mass transport properties of concrete. *Cement and Concrete Research*, 68:35–48.

[Yaman et al., 2002] Yaman, I. Ö., Hearn, N., and Aktan, H. M. (2002). Active and non-active porosity in concrete. part I: experimental evidence. *Materials and Structures*, 35:102–109.

[Yang and Xu, 2008] Yang, Z. and Xu, X. F. (2008). A heterogeneous cohesive model for quasi-brittle materials considering spatially varying random fracture properties. *Computer methods in applied mechanics and engineering*, 197(45):4027–4039.

[Yi et al., 2011] Yi, S.-T., Hyun, T.-Y., and Kim, J.-K. (2011). The effects of hydraulic pressure and crack width on water permeability of penetration crack-induced concrete. *Construction and Building Materials*, 25(5):2576–2583.

[Yip et al., 2005] Yip, M., Mohle, J., and Bolander, J. E. (2005). Automated modeling of three-dimensional structural components using irregular lattices. *Computer-Aided Civil anf Infrastructure Engineering*, 120:393–407.

[Yssorche-Cubaynes and Ollivier, 1999] Yssorche-Cubaynes, M.-P. and Ollivier, J. (1999). La microfissuration d'autodessiccation et la durabilité des bhp et bthp. *Materials and Structures*, 32(1):14–21.

[Zhang et al., 2005] Zhang, J., Liu, Q.-q., and Wang, L.-s. (2005). Effect of coarse aggregate size on relationship between stress and crack opening in normal and high strength concretes. *JOURNAL OF MATERIALS SCIENCE AND TECHNOLOGY-SHENYANG-*, 21(5):691.

[Zhou et al., 2006] Zhou, J., Shao, J.-F., and Xu, W. (2006). Coupled modeling of damage growth and permeability variation in brittle rocks. *Mechanics Research Communications*, 33(4):450–459.

UNIVERSITE BRETAGNE LOIRE

UNIVERSITE DE NANTES

Thèse de Doctorat

Hayder AL-KHAZRAJI

Influence of crack opening, aggregates size and volume fraction on hydro-mechanical properties of concrete in a Brazilian splitting test: 3D meso-macro scale modeling and experimental work

Résumé

La perméabilité influe indirectement sur la durabilité des structures en béton. Elle gouverne le taux de pénétration des agents agressifs, responsables de dégradations, sous un gradient de pression. Ce travail a pour but l'étude des interactions entre l'ouverture des fissures et le transport des fluides dans le béton, soumis à un essai Brésilien de traction indirect par fendage. Cette étude est composée de deux parties : une numérique et une expérimentale. La première concerne la modélisation des matériaux hétérogènes, tels que le béton, et met en évidence ses deux particularités : l'aspect multiphasique du matériau et la propagation 3D de fissures. Ainsi, nous proposons un couplage entre l'ouverture de fissure et la perméabilité au gaz selon un modèle hydro-mécanique à l'échelle mésoscopique. L'objectif de la deuxième partie expérimentale est de fournir des données pour des modèles numériques et de les valider ainsi. Ce travail est réalisé sur des éprouvettes de mortier avec 3 différents tailles de granulat, soumises au transfert de gaz au cours du chargement par l'essai Brésilien. Le modèle numérique mésoscopique, employé dans cette étude, est basé sur une approche tridimensionnelle pour représenter l'hétérogénéité du matériau et les mécanismes de rupture du béton. Ce modèle considère le béton comme un matériau bi-phasique où les granulats sont fondus dans la pâte du ciment. Afin de pallier aux hétérogénéités du matériau et l'emploi du maillage non-adaptatif, une faible discontinuité a été introduite dans le premier enrichissement de la cinématique. Le deuxième enrichissement de la cinématique introduite ici est la discontinuité du déplacement (forte) afin de représenter l'ouverture de la fissure (champ du déplacement discontinu). Le modèle hydromécanique représente le transport du fluide (gaz) dans le béton par l'intermédiaire de la loi de Darcy pour la section non fissurée (porosité) et par la loi de Poiseuille pour la section fissurée (flux laminaire). Dans ce modèle, une interaction entre l'ouverture de fissure, obtenue par le modèle mécanique (mésoscopique), et la perméabilité du gaz est considérée. Le travail expérimental effectué est présenté pour la validation du modèle hydro-mécanique numérique proposé. Les résultats de simulations numériques sont en accord avec des travaux expérimentaux et théoriques précédents.

Mots clés

Essai Brésilien de traction indirecte par fendage, Modélisation méso-échelle, Faible discontinuité, Forte discontinuité, Méthode des éléments finis, Perméabilité aux gaz

Abstract

Permeability is a parameter that may indirectly influence the durability of concrete structures by governing the rate of penetration of aggressive substances responsible for degradation under a pressure gradient. The aim of this thesis is to study the interaction between the crack opening and the transfer of fluids in concrete of the Brazilian splitting tensile test (BSTT). Herein, the influence of aggregates size and volume fraction on hydro-mechanical properties of concrete is investigated. This study consists of two parts: the numerical and the experimental one. The first one focuses on the meso-scale modeling of a heterogeneous material like a concrete, which may be characterized by two features: multi-phase behavior and 3D crack propagation. The numerical study deals therefore with the coupling between crack opening and gas permeability according to a developed hydro-mechanical model at a meso-scale. The objective of the second, experimental part, is to provide data for numerical models and to validate the latter. This work is carried out on mortar specimens with 3 different aggregate sizes, submitted to gas transfer during a BSTT. The numerical meso-scale model is based upon a 3D lattice approach to represent the heterogeneity of the material and the failure mechanism of concrete. This model considers concrete as a two-phases material in which aggregates melt within a cement paste. Because a non-adapted meshing process was used to mesh the microstructure, a weak discontinuity was introduced in the first enhancement of the kinematics. The second enhancement of kinematics introduced here is the displacement discontinuity (strong) to represent crack opening (discontinuous displacement-field). The hydro-mechanical model represents the transport of fluids (gases) through the concrete, depending on Darcy's law for a uncracked section (porosity) and Poiseuille's law for a cracked section (laminar flow). In this model, the interaction between the crack opening, obtained from the mechanical model (meso-scale), and the gas permeability is investigated. The experimental work is presented for the validation of the hydro-mechanical model. The numerical results show good agreement with some previous experimental and theoretical studies.

Key Words

Brazilian splitting tensile test, Meso-scale modeling, Weak discontinuity, Strong discontinuity, Finite Element Method, Gas permeability

L'Université Bretagne Loire