# NUMERICAL SIMULATION OF CAPILLARY FLOW AND CURING BEHAVIOUR OF HEALING AGENT IN ENCAPSULATED-BASED SELF-HEALING CONCRETE

YIP BAO FANG

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy

Faculty of Civil Engineering
Universiti Teknologi Malaysia

OCTOBER 2022

## DEDICATION

This thesis is dedicated to my father, who taught me that the best kind of knowledge to have is that which is learned for its own sake. It is also dedicated to my mother, who taught me that even the largest task can be accomplished if it is done one step at a time.

## ACKNOWLEDGEMENT

In preparing this thesis, I was in contact with many people, researchers, and academicians. They have contributed towards my understanding and thoughts. In particular, I wish to express my sincere appreciation to my main thesis supervisor, Dr. Erwan Hafizi Kasiman, for encouragement, guidance, critics and friendship. I am also very thankful to my co-supervisor Dr. Ahmad Razin Zainal Abidin for his guidance, advice and motivation. Without their continued support and interest, this thesis would not have been the same as presented here.

I am also indebted to Ministry of Higher Education Malaysia and Universiti Teknologi Malaysia (UTM) for funding my Ph.D study under Skim Latihan Akademik IPTA (SLAI) scholarship.

My fellow postgraduate student should also be recognised for their support. My sincere appreciation also extends to all my colleagues and others who have provided assistance at various occasions. Their views and tips are useful indeed. Unfortunately, it is not possible to list all of them in this limited space. I am grateful to all my family member.

# ABSTRACT

A self-healing concrete has emerged as a potential solution for tackling cracking issues in concrete. Self-healing works through the infiltration of healing agents into the cracks, followed by the curing process that prevents further crack penetration in the concrete matrix. As far as the literature is concerned, the effect of the curing reaction on its rheological properties has not been addressed adequately. In addition, a fluid flow model considering the capillary effect and curing reaction has not been established for flow behaviours within discrete cracks in the encapsulation-based self-healing concrete. Therefore, in this study, a coupled fluid flow and curing reaction model was proposed to simulate the concrete encapsulation system's mechanics better. The healing agent flow was modelled using the Volume-of-Fluid (VOF) method. This study proposed using the viscosity function to describe the curing effect using the Castro-Macosko model. The dynamic mechanical analysis experiment cured and changed the cyanoacrylate's rheological properties. The fluid flow and curing reaction models were coupled in ANSYS Fluent in the form of self-developed user-defined functions. Parametric studies were carried out to determine the influence of healing agent rheological properties (surface tension, contact angle and viscosity) and crack geometries (planar, inclined and tapered) on the healing efficiency. The coupled model was validated against available experiment results and the model's capability to predict the healing agent's flow accurately and the curing process was shown. For flows in small cracks driven by capillary action, the simulated VOF outcomes with constant contact angles were in poor agreement with the experiment. The simulation results showed a better prediction of the capillary flow with the use of dynamic contact angles (DCA). For example, when validated against the modified Lucas-Washburn equation (LWE), the VOF predictions considering the velocity-dependent DCA have mean absolute percentage errors of between 3.1 – 5.3%, much lower than that of classical LWE with errors between 17.0 – 42.9%. The results indicated that a DCA influences the initial speed of the capillary flow and plays a vital role in the healing efficiency of fast-curing healing agents. Due to the curing reaction, the increasing viscosity arrests the capillary flow of the healing agent in a small discrete crack. DCA and viscosity control the infiltration speed of capillary flow via frictional dissipation and flow resistance, respectively. However, they do not affect the final equilibrium height in capillary rise. A higher frictional coefficient in the DCA model decreases the infiltration speed at the initial state of the capillary rise. In said capillary flow, the infiltration length of the healing agent depends on the capillary pressure, which is strongly influenced by the surface tension, equilibrium contact angle and crack widths. Based on the Young-Laplace equation, the capillary pressure is directly proportional to the surface tension force and inversely proportional to the crack width. A lower contact angle indicates good wettability and provides faster liquid spreading on a surface. Overall, this study has provided a new coupled self-healing model for predicting the transport and curing processes in encapsulation-based self-healing systems in concrete. The model can provide a better understanding of flow mechanisms and serves as a sound basis for future researchers to design a more efficient concrete self-healing system.

# ABSTRAK

Konkrit penyembuhan diri muncul sebagai penyelesaian yang berpotensi untuk menangani masalah retakan dalam konkrit. Penyembuhan diri bertindak melalui penyusupan agen penyembuhan ke dalam retakan, diikuti dengan proses pengawetan yang menghalang penembusan retakan selanjutnya dalam matriks konkrit. Kajian literatur menunjukkan kesan tindak balas pengawetan agen penyembuhan terhadap sifat rheologi masih belum difahami dengan baik. Di samping itu, model aliran bendalir yang mengambil kira kesan daya kapilari dan tindak balas pengawetan belum ditetapkan untuk aliran dalam retakan diskret dalam konkrit penyembuhan diri berasaskan pengkapsulan. Oleh itu, mekanisme yang terlibat dalam sistem pengkapsulan konkrit dapat disimulasikan dengan baik menggunakan model gandingan antara aliran bendalir dan tindak balas pengawetan. Aliran agen penyembuhan dimodelkan dengan menggunakan kaedah Volume-of-Fluid (VOF). Kajian ini mencadangkan penggunaan fungsi kelikatan untuk menerangkan kesan pengawetan dengan menggunakan model Castro-Macosko. Eksperimen menggunakan analisis mekanikal dinamik menunjukkan bukti korelasi antara pengawetan dan perubahan dalam sifat rheologi agen penyembuhan. Model aliran bendalir dan model tindak balas pengawetan telah digandingkan dalam ANSYS Fluent dengan menggunakan fungsi takrifan pengguna. Kajian parametrik telah dijalankan untuk mengenalpasti kesan pengaruh sifat rheologi agen penyembuhan (tegangan permukaan, sudut sentuhan dan kelikatan) dan geometri retakan (planar, cenderung dan tirus) terhadap kecekapan penyembuhan. Keputusan eksperimen yang sedia mengesahkan keupayaan model gandingan tersebut dalam meramalkan aliran agen penyembuhan dan proses pengawetannya. Untuk aliran kapilari dalam retakan kecil, keputusan simulasi VOF dengan sudut sentuhan malar tidak selari dengan keputusan eksperimen. Keputusan simulasi menunjukkan ramalan aliran kapilari yang lebih baik dengan penggunaan sudut sentuhan dinamik. Keputusan tersebut menunjukkan bahawa sudut sentuhan dinamik mempengaruhi kelajuan aliran kapilari di peringkat permulaan dan memainkan peranan penting dalam kecekapan dan tindak balas penyembuhan. Ini disebabkan oleh tindak balas pengawetan dan peningkatan kelikatan yang merencatkan aliran kapilari agen penyembuhan dalam retakan diskret yang kecil. Sudut sentuhan dinamik dan kelikatan mengawal kelajuan infiltrasi aliran kapilari melalui pelesapan geseran dan rintangan aliran. Namun, kedua-dua parameter tersebut tidak memberi kesan terhadap ketinggian keseimbangan dalam peningkatan kapilari. Panjang infiltrasi agen penyembuh bergantung kepada tekanan kapilari yang merangkumi tegangan permukaan dan sudut sentuhan keseimbangan. Dalam aliran kapilari, panjang infiltrasi agen penyembuh sangat dipengaruhi oleh ketegangan permukaan, sudut sentuhan keseimbangan dan lebar retakan. Kesimpulannya, kajian ini telah menyediakan model penyembuhan diri gandingan yang baru untuk meramalkan aliran dan proses pengawetan dalam konteks sistem penyembuhan diri berasaskan pengkapsulan. Model tersebut boleh digunakan untuk memberikan pemahaman yang lebih baik tentang mekanisme aliran dan menyediakan asas kukuh kepada penyelidik di masa hadapan dalam usaha untuk mereka bentuk sistem penyembuhan diri konkrit yang lebih cekap.

## TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## LIST OF ABBREVIATIONS

| | | |
|---|---|---|
| 2D | - | Two-Dimensional |
| 3D | - | Three-Dimensional |
| ADE | - | Advection-Diffusion Equation |
| CFD | - | Computational Fluid Dynamic |
| CIDB | - | Construction Industry Development Board |
| CSF | - | Continuum Surface Force |
| CSH | - | Calcium Silicate Hydrates |
| DCA | - | Dynamic Contact Angle |
| DSC | - | Differential Scanning Calorimetry |
| ECCs | - | Engineered Cementitious Composites |
| EDTA | - | Ethylene Diamine Tetra-acetic Acid |
| EMC | - | Epoxy Moulding Compound |
| EPSRC | - | Engineering and Physical Science Research Council |
| ESM | - | Electron Scanning Microscopy |
| GGBS | - | Ground-Granulated Blast-Furnace Slag |
| GNF | - | Generalised Newtonian fluid |
| LVE | - | Linear Viscoelastic |
| LWE | - | Lucas-Washburn equation |
| MMA | - | Methyl Methacrylate |
| NDT | - | Non-Destructive Tests |
| RH | - | Relative Humidity |
| RM4L | - | Resilient Materials 4 Life |
| S-CSP | - | Stacked-Chip Scale Package |
| SEM | - | Scanning Electron Microscopy |
| SIMPLE | - | Semi-Implicit Pressure Linked Equations |
| SMP | - | Shape Memory Polymer |
| TGA | - | Thermogravimetric Analysis |
| UDF | - | User-Defined Function |
| VOF | - | Volume of Fluid |

# LIST OF SYMBOLS

| | | |
|---|---|---|
| $F_{st}$ | - | Surface tension force term in momentum equation |
| $K_p$ | - | Permeability of cured adhesive layer |
| $P_v$ | - | Vapour pressure |
| $T_b$ | - | Activation-energy dependent parameter |
| $c_p$ | - | Specific heat capacity |
| $\hat{n}$ | - | Unit normal vector |
| $z_c$ | - | Wall factor |
| $z_{c0}$ | - | Critical curing depth |
| $\alpha_g$ | - | Degree of cure at gel point |
| $\dot{\gamma}$ | - | Shear rate |
| $\eta_0$ | - | Viscosity when the shear rate approaches zero |
| $\theta_D$ | - | Dynamic contact angle |
| $\theta_E$ | - | Equilibrium contact angle |
| $\tau^*$ | - | Shear stress at the transition between Newtonian and non-Newtonian flow |
| $\Delta t$ | - | Time step |
| $\Delta x$ | - | Mesh size |
| $h$ | - | Capillary rise height |
| $A$ | - | Area |
| $B$ | - | Exponential-fitted constant |
| $C$ | - | Fitting constant |
| $Ca$ | - | Dimensionless Capillary number |
| $Co$ | - | Dimensionless Courant number |
| $D$ | - | Diffusion coefficient |
| $F$ | - | Scalar for volume fraction in a cell |
| $I$ | - | Identity matrix |
| $L$ | - | Length |
| $R$ | - | Radius |
| $T$ | - | Temperature |

| | | |
|---|---|---|
| $V$ | - | Equilibrium adhesive volume that involved in reaction |
| $W$ | - | Lambert W function |
| $b$ | - | Crack width |
| $g$ | - | Gravitational acceleration |
| $k$ | - | Heat conductivity |
| $n$ | - | Reaction order |
| $p$ | - | Pressure |
| $t$ | - | Time |
| $u$ | - | Velocity at x-direction |
| $v$ | - | Velocity at y-direction |
| $z$ | - | Curing front depth |
| $\alpha$ | - | Degree of cure |
| $\beta$ | - | Frictional coefficient in dynamic contact angle model |
| $\eta$ | - | Dynamic viscosity |
| $\theta$ | - | Contact angle |
| $\kappa$ | - | Mean curvature |
| $\mu$ | - | Constant viscosity |
| $\pi$ | - | Mathematical constant, Pi |
| $\rho$ | - | Density |
| $\sigma$ | - | Surface tension |
| $\tau$ | - | Curing rate parameter |
| $\phi$ | - | Crack inclination angle |

## LIST OF APPENDICES

# CHAPTER 1

# INTRODUCTION

## 1.1 Background of the study

Self-healing concrete is emerging as an innovative construction material to tackle the environmental issues caused by carbon dioxide emissions from concrete manufacturing industries. By mimicking the natural healing ability in the human body, self-healing concrete is designed to heal itself without external human intervention. Self-healing concrete can also play an essential role in addressing concrete structures' durability and serviceability issues, as the inevitable formation of cracks in the concrete matrix allows the penetration of harmful substances and thus reduces the durability of the concrete over time.

Over the past decade, self-healing concrete has been garnering interest from many researchers. With the support from the government and policymakers, the development of self-healing concrete is getting traction in recent years. For instance, in 2017, an ongoing five-year research project, Resilient Materials 4 Life (RM4L), was funded and firmly supported by Engineering and Physical Science Research Council (EPSRC) (Al-Tabbaa *et al.*, 2018; Davies *et al.*, 2018; Paine *et al.*, 2019). To show the extent of support from various parties, the project is in fact joined by Cardiff, Cambridge, Bath and Bradford universities and a whopping amount of 22 industrial companies as well. The project aims to develop a sustainable construction material with self-healing, self-sensing and self-diagnosing abilities, as well as being immune against physical and chemical damages.

Figure 1.1 shows the taxonomy in self-healing concrete. The self-healing process in concrete is classified into two major groups: autogenous and autonomous healing (De Belie *et al.*, 2018; Sidiq *et al.*, 2019; Van Tittelboom & De Belie, 2013; Xue *et al.*, 2019). Autogenous healing occurs via the hydration process of un-hydrated cement particles in the concrete matrix without any external intervention, while autonomous healing involves the addition of external engineered materials such as polymers, microorganisms, chemical compounds and admixtures for healing purposes. Autogenous healing occurs naturally in concrete, but is limited to the healing of crack widths of less than 300 µm (De Belie *et al.*, 2018). Autonomous healing provides better healing for crack widths of more than 300 µm and can heal cracks up to 1 mm.

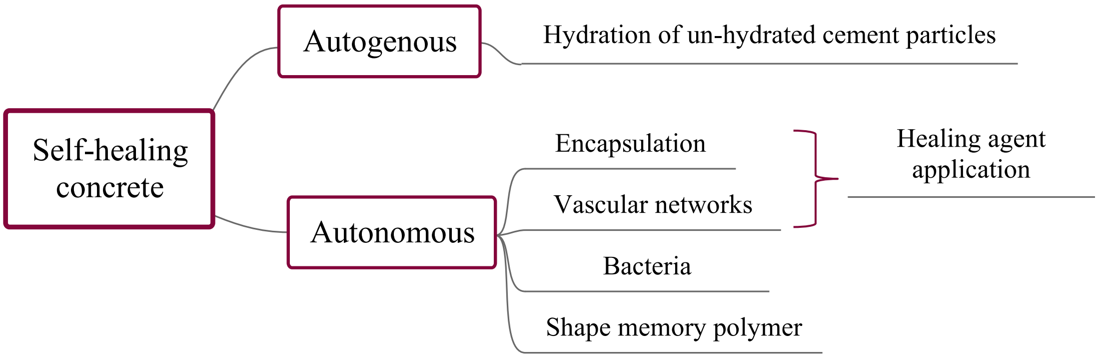


Figure 1.1 Taxonomy in self-healing concrete.

A significant number of studies on self-healing concrete have used encapsulation techniques, in which the healing agent are released and delivered to the damaged areas when cracking occurs (Gupta & Kua, 2016; Xue *et al.*, 2019). Different techniques have been introduced to encapsulate and deliver the healing agent in the self-healing concrete, such as encapsulation and vascular networks methods. Different healing agents have been studied as well, such as polymers, adhesives, mineral admixtures and chemical compounds. Various experimental characterisation techniques have been introduced to evaluate the performance of self-healing systems in concrete too (Ferrara *et al.*, 2018; Muhammad *et al.*, 2016; Sidiq *et al.*, 2019). At the same time, significant research works have been done in the numerical modelling of self-healing systems in concrete as well (T. Jefferson *et al.*, 2018; Mauludin & Oucif, 2019).

As presented in Figure 1.1, self-healing techniques such as encapsulation and vascular networks methods are rely on healing agents to achieve mechanical and durability recovery after healing action. While abundant progress has been done on many aspects in encapsulation-based self-healing concrete, the transportation of healing agent in the concrete itself has rarely been researched (Z. Dong *et al.*, 2015). In addition, the researchers have acknowledged the complexity of self-healing processes in concrete. They have highlighted that the self-healing process in concrete is a set of multi-physics problems as it involves three interacting physical processes: fracture mechanism, fluid flow, and chemical reactions as presented in Figure 1.2. For the encapsulation techniques in self-healing concrete, the capsules containing a liquid healing agent are mixed in the concrete. If the crack forms, it will rupture the capsules, the glue-like healing agent that will glue together the cracks after the healing agent cures.

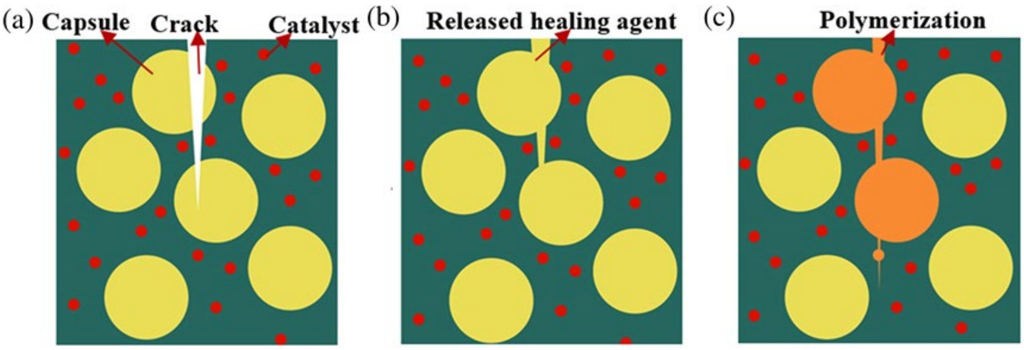


Figure 1.2 The schematic concept of encapsulation-based autonomic healing for cementitious materials (Xue *et al.*, 2019).

Fast-curing healing agent, such as, cyanoacrylate cures rapidly when contacts with the moisture on the concrete surface. During the rapid curing process, the viscosity of the healing agent increases and might retards the healing agent flow in the discrete crack. In order to achieve satisfying healing efficiency, it is required to ensure that a sufficient amount of healing agent is delivered to the discrete crack before the healing agent is fully cured. Therefore, the in-depth investigation on the combination effects of the fluid flow and the curing processes is getting interested and requires further discussion within the field of encapsulation-based self-healing system in concrete.

## 1.2 Problem Statement

In the autonomic self-healing system, the transportation of the healing agent plays a primary role in determining the concrete healing efficiency. Self-healing techniques like encapsulation and vascular networks store, deliver and release the embedded healing agent to the damaged site when cracking occurs. In order to understand the self-healing mechanisms, it is required to study the transport processes of healing agents in concrete. Several numerical works that address transport processes in self-healing concrete have focused on the transportation of moisture and ions associated with carbonation and autogenous healing (Aliko-Benítez *et al.*, 2015; Freeman, 2017; Huang *et al.*, 2010; Huang & Ye, 2016; Ranaivomanana & Benkemoun, 2017). Although they are related to this study, the present work places more focus on the transportation of healing agents in autonomous self-healing concrete instead.

In the actual healing agent flow in discrete cracks within the concrete matrix, the visualisation of the healing agent flow phenomenon is inherently challenging and is constrained by the limitation of visualisation equipment, small crack size and concrete opaqueness. In terms of flow modelling, the classical Lucas-Washburn equation (LWE) has a limitation in predicting the capillary flow in non-uniform channels and complex porous media since the LWE is developed with the assumption on the fluid flow as one-dimensional laminar flow in a uniform channel with a constant contact angle. The LWE equation is required to be modified to describe the capillary flow in different porous systems. Therefore, a numerical simulation might be an alternative to better characterise the capillary flow process and provide a better depiction of the multiscale physical process of capillary flow. Numerical simulation can also aid with the visualisation and examination of the capillary flow from a microscopic perspective. However, to date, a limited number of numerical models have taken into account the coupled effects of flow and curing processes in self-healing systems.

Apart from the works by previous researchers (Freeman & Jefferson, 2020; Gardner *et al.*, 2012, 2014, 2017; Gilabert *et al.*, 2017; Selvarajoo *et al.*, 2020), there is no other work on the investigation of healing agent flow in autonomic self-healing concrete. It has been proven that the viscosity of the healing agent increases during the curing reaction process and undergoes a liquid/solid transition (Freeman & Jefferson, 2020; Gardner *et al.*, 2017). To date, the influence of the curing process on its rheological properties has not been adequately addressed during the healing agent infiltration. In addition, a numerical simulation model considering the combination effects between capillary action and curing processes in encapsulation-based self-healing concrete has not been established yet. To consider the curing effect, the inclusion of Castro-Macosko viscosity model in the capillary flow model needs further investigation and validity checking. Thus, in the present study, experimental and numerical investigations are performed to study the influence of the curing reaction on the rheological properties of healing agents during the capillary flow event in the encapsulation-based self-healing system in concrete.

## 1.3 Objectives

The present study looks into the transportation of healing agents during the curing process in encapsulation-based self-healing concrete. Understanding the transport process of the healing agent is essential to designing a better self-healing system in concrete. Some of the specific objectives in this study include:

- To determine the correlation between curing effect and changes in rheological properties of the healing agent by using dynamic mechanical analysis.
- To simulate the capillary flow of the healing agent in discrete cracks using the Volume-of-Fluid method together with the implementation of the dynamic contact angle model.
- To describe the viscosity change of the healing agent using the Castro-Macosko viscosity model and couple the model with the aforementioned fluid flow model to better simulate the curing effect of healing agents under varying capillary flows.

- To examine the various parametric effects on the capillary flow and corresponding self-healing efficiency by using the coupled model.

## 1.4 Scope of the Study

In the present study, both experimental and numerical studies are carried out to provide a better insight into the physics of the problems and to allow for the enhancement of the self-healing performance by comprehensively simulating and designing a better self-healing system. This work is not trying to replicate the embedded capsules in any particular vascular or encapsulated self-healing system in concrete. The key target for this study is to investigate the effects of curing reaction on the capillary flow during the infiltration of the healing agent in discrete cracks in concrete. This work focuses on encapsulation-based self-healing systems that use cyanoacrylate as a healing agent but could readily be extended to a wide range of other healing agents as well.

In terms of experimental measurement and analysis, the measurement of rheological properties of the cyanoacrylate-based healing agent are performed by using dynamic mechanical analysis in a rotational rheometer. The rheological measurement results are utilized specifically to show the correlation between the viscosity properties and the curing reaction of the cyanoacrylate adhesive. In terms of numerical modelling, a viscosity function is used to describe the curing effect on the rheological properties. The Castro-Macosko model is selected and specified as the viscosity function for this study. Material constitutive models, such as dynamic contact angle model, Castro-Macosko viscosity model, and degree of cure functions, is written in the form of user-defined functions and coupled via ANSYS Fluent with ANSYS 2021 R1 Student Version. ANSYS Fluent, a Finite Volume-based computational fluid dynamic (CFD) simulation software is selected as the software of choice for this study as it can be used to solve the fluid flow modelling by simulating the transport processes of the healing agent in a discrete crack. A Volume-of-Fluid (VOF) technique is applied to track the moving meniscus in the crack.

In the simulation, healing agent flow is assumed to be laminar and incompressible. When cracking occurs, the embedded capsule ruptures and releases the healing agent into discrete concrete cracks. Therefore, the healing agent flow is assumed to be driven by capillary action (Z. Dong *et al.*, 2015). Surface tension and wall adhesion models are used to determine the capillary pressure in the capillary flow. As the scope of this study encompasses both the healing agent flow and the viscosity change (corresponding to the curing degree of the healing agent in the crack) during the curing reaction (polymerisation), the capillary flow model is coupled with the Castro-Macosko model to comprehensively predict the healing agent flow and its reaction in discrete concrete cracks. The coupled model is validated with available capillary rise data, and hopefully the simulation results will provide a better visualisation for the transport process of the healing agent in discrete cracks. To supplement the numerical modelling and experimental validation, parametric studies are conducted to investigate the influence of the healing agent's rheological properties and crack geometry on the capillary flow and corresponding self-healing efficiency in discrete concrete cracks.

## 1.5 Significance of the Study

This study contributes to the knowledge development in self-healing concrete with practical and theoretical significances as follows:

a) Theoretical significance

  a. This study introduces a VOF multiphase model combined with surface tension and dynamic contact angle models to simulate the capillary rise of liquids in discrete cracks. The velocity-dependent dynamic contact angle model can be determined from capillary rise measurement data.

  b. This study develops a novel, coupled model consisting of the VOF, surface tension, dynamic contact angle, and viscosity models. The coupled model can comprehensively simulate a reacting healing agent flow in the discrete cracks within self-healing concrete and allows for a better understanding of the intricate mechanism of reaction-based healing in encapsulation-based self-healing concrete. This, in turn, can serve as a sound basis for future researches in the similar vein.

c. This study proposes a new experimental measurement method in order to determine the material and rheological properties of cyanoacrylate-based healing agent used in encapsulation-based self-healing concrete. With the novel implementation of said measurement method in this field, it allows for a more comprehensive measurement and analysis of the material and rheological properties of self-healing concrete samples, thus improving related research analysis efforts as a whole.

b) Practical significance

a. The numerical simulation technique provides a clear visualisation and a reliable prediction of the transport processes of the healing agent in discrete cracks. The result provides a better understanding of the healing agent's flow behaviours and shows how the curing reaction affects the capillary flow with increasing viscosity. Thus, the result can be used for selecting a suitable healing agent with an optimised healing rate and volume. The numerical model is ready to be extended to simulate the healing agent flow in a more complex crack geometry. In addition, the model can be used for a wide range of healing agents, thus expanding the model's inherent practicality.

b. The parametric studies provide a better understanding of healing agent flow mechanisms and help related industries to design a better self-healing system. The results give a deeper insight into the impacts of the parameters (surface tension, contact angle, viscosity, crack configurations) on the capillary flow of the healing agent in discrete cracks and can help other researchers in their investigations by modifying the healing agent's material properties to improve the healing efficiency of the self-healing system, thus benefiting the concrete manufacturing industry and tackling the ensuing sustainability issues in the long run.

## 1.6 Outlines

The thesis presents the development of a numerical simulation model for the healing agent's capillary flow in the concrete's discrete crack. This thesis includes six chapters which are organised as follows:

Chapter 2 presents a literature review on self-healing concrete and specifies the knowledge gaps that have to be bridged by this research. The review starts with the background and the types of healing mechanisms in self-healing concrete, such as autogenous and autonomic healings. The review also discusses different techniques used in the autonomic healing system and the evaluation methods for assessing self-healing efficiency. Next, the review discusses the experimental and numerical investigation of healing agent flow in capillary cracks and its curing process.

Chapter 3 presents the detailed methodology of the study. The numerical model and its governing equations for simulating the healing agent's capillary flow in the discrete crack are discussed. The testing methods in order to determine the rheological properties of a cyanoacrylate-based healing agent is presented.

Chapter 4 presents the validation of the VOF capillary flow model and the simulation of the capillary flow with the help of Computational Fluid Dynamic (CFD) packages in ANSYS Fluent simulation software. The inclusion of the dynamic contact angle model in improving the capillary flow prediction is discussed. Later, the validation of the VOF capillary flow model coupling the Castro-Macosko viscosity model is presented and discussed.

Chapter 5 presents the simulation of the healing agent flow in discrete cracks, considering the curing effect after validating the coupled model (coupling of fluid flow model and Castro-Macosko viscosity model) as presented in Chapter 4. The capillary flow of the healing agent in the discrete crack and its flow characteristics are investigated with various flow parameters, which in turn affect the infiltration rate and the final location of the healing agent in the discrete crack.

Chapter 6 summarises and concludes this research with some recommendations for future works.

## REFERENCES


Abdullah, M. K., Abdullah, M. Z., Kamarudin, S., & Ariff, Z. M. (2007). Study of flow visualization in stacked-Chip Scale Packages (S-CSP). *International Communications in Heat and Mass Transfer*, 34(7), 820–828. https://doi.org/10.1016/j.icheatmasstransfer.2007.04.003

Abdullah, M. K., Abdullah, M. Z., Mujeebu, M. A., Kamaruddin, S., & Ariff, Z. M. (2009). A Study on the Effect of Epoxy Molding Compound (EMC) Rheology During Encapsulation of Stacked-CHIP Scale Packages (S-CSP). *Journal of Reinforced Plastics and Composites*, 28(20), 2527–2538. https://doi.org/10.1177/0731684408092409

ACI Committee 201. (2000). Guide to Durable Concrete. In *ACI 201.2R*. https://doi.org/10.1002/jlcr.3535

Aldea, C.-M., Song, W. J., Popovics, J. S., & Shah, S. P. (2000). Extent of healing of cracked normal strength concrete. *Journal of Materials in Civil Engineering*, 12(1), 92–96. https://doi.org/10.1061/(ASCE)0899-1561(2000)12:1(92)

Alghamri, R., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Impregnation and encapsulation of lightweight aggregates for self-healing concrete. *Construction and Building Materials*, 124, 910–921. https://doi.org/10.1016/j.conbuildmat.2016.07.143

Aliko-Benítez, A., Doblaré, M., & Sanz-Herrera, J. A. (2015). Chemical-diffusive modeling of the self-healing behavior in concrete. *International Journal of Solids and Structures*, 69–70, 392–402. https://doi.org/10.1016/j.ijsolstr.2015.05.011

Al-Tabbaa, A., Lark, B., Paine, K., Jefferson, T., Litina, C., Gardner, D., & Embley, T. (2018). Biomimetic cementitious construction materials for next-generation infrastructure. *Proceedings of the Institution of Civil Engineers - Smart Infrastructure and Construction*, 171(2), 67–76. https://doi.org/10.1680/jsmic.18.00005

Al-Tabbaa, A., Litina, C., Giannaros, P., Kanellopoulos, A., & Souza, L. (2019). First UK field application and performance of microcapsule-based self-healing concrete. *Construction and Building Materials*, 208, 669–685. https://doi.org/10.1016/j.conbuildmat.2019.02.178

Araújo, M., Chatrabhuti, S., Gurdebeke, S., Alderete, N., Van Tittelboom, K., Raquez, J.-M., Cnudde, V., Van Vlierberghe, S., De Belie, N., & Gruyaert, E. (2018). Poly (methyl methacrylate) capsules as an alternative to the 'proof-of-concept' glass capsules used in self-healing concrete. *Cement and Concrete Composites*, 89, 260–271. https://doi.org/10.1016/j.cemconcomp.2018.02.015

Araújo, M., Van Tittelboom, K., Feiteira, J., Gruyaert, E., Chatrabhuti, S., Raquez, J. M., Šavija, B., Alderete, N., Schlangen, E., & De Belie, N. (2017). Design and testing of tubular polymeric capsules for self-healing of concrete. *IOP Conference Series: Materials Science and Engineering*, 251(1). https://doi.org/10.1088/1757-899X/251/1/012003

Baek, S., Jeong, S., Seo, J., Lee, S., Park, S., Choi, J., Jeong, H., & Sung, Y. (2021). Effects of Tube Radius and Surface Tension on Capillary Rise Dynamics of Water/Butanol Mixtures. *Applied Sciences*, 11(8), 3533. https://doi.org/10.3390/app11083533

Blake, T. D. (2006). The physics of moving wetting lines. *Journal of Colloid and Interface Science*, 299(1), 1–13. https://doi.org/10.1016/j.jcis.2006.03.051

Blake, T. D., & Haynes, J. M. (1969). Kinetics of liquidliquid displacement. *Journal of Colloid and Interface Science*, 30(3), 421–423. https://doi.org/10.1016/0021-9797(69)90411-1

Blake, T. D., & Ruschak, K. J. (1997). Wetting: Static and Dynamic Contact Lines. In S. F. Kistler & P. M. Schweizer (Eds.), *Liquid Film Coating: Scientific principles and their technological implications* (pp. 63–97). Springer Netherlands. https://doi.org/10.1007/978-94-011-5342-3_3

Blake, T. D., & Shikhmurzaev, Y. D. (2002). Dynamic Wetting by Liquids of Different Viscosity. *Journal of Colloid and Interface Science*, 253(1), 196–202. https://doi.org/10.1006/jcis.2002.8513

Blunt, M., King, M. J., & Scher, H. (1992). Simulation and theory of two-phase flow in porous media. *Physical Review A*, 46(12), 7680–7699. https://doi.org/10.1103/PhysRevA.46.7680

Brackbill, J. U., Kothe, D. B., & Zemach, C. (1992). A continuum method for modeling surface tension. *Journal of Computational Physics*, 100(2), 335–354. https://doi.org/10.1016/0021-9991(92)90240-Y

Bracke, M., De Voeght, F., & Joos, P. (1989). The kinetics of wetting: The dynamic contact angle. In P. Bothorel & E. J. Dufourc (Eds.), *Trends in Colloid and Interface Science III* (pp. 142–149). Steinkopff. https://doi.org/10.1007/BFb0116200

Cai, J., Jin, T., Kou, J., Zou, S., Xiao, J., & Meng, Q. (2021). Lucas–Washburn Equation-Based Modeling of Capillary-Driven Flow in Porous Systems. *Langmuir*, 37(5), 1623–1636. https://doi.org/10.1021/acs.langmuir.0c03134

Cai, J., Luo, L., Ye, R., Zeng, X., & Hu, X. (2015). Recent advances on fractal modeling of permeability for fibrous porous media. *Fractals*, 23(01), 1540006. https://doi.org/10.1142/S0218348X1540006X

Cai, J., & Yu, B. (2011). A Discussion of the Effect of Tortuosity on the Capillary Imbibition in Porous Media. *Transport in Porous Media*, 89(2), 251–263. https://doi.org/10.1007/s11242-011-9767-0

Cai, J., Yu, B., Zou, M., & Luo, L. (2010). Fractal Characterization of Spontaneous Co-current Imbibition in Porous Media. *Energy & Fuels*, 24(3), 1860–1867. https://doi.org/10.1021/ef901413p

Cambridge Polymer Group. (2004). *Determination of the kinetics of curing of cyanoacrylate-based adhesives with Fourier Transform Infrared Spectroscopy*. Cambridge Polymer Group, Inc.

Cao, H., Amador, C., Jia, X., & Ding, Y. (2015). Capillary Dynamics of Water/Ethanol Mixtures. *Industrial & Engineering Chemistry Research*, 54(48), 12196–12203. https://doi.org/10.1021/acs.iecr.5b03366

Carciofi, B. A. M., Prat, M., & Laurindo, J. B. (2011). Homogeneous Volume-of-Fluid (VOF) Model for Simulating the Imbibition in Porous Media Saturated by Gas. *Energy & Fuels*, 25(5), 2267–2273. https://doi.org/10.1021/ef200233j

Castro, J. M., & Macosko, C. (1980). *Kinetics and rheology of typical polyurethane reaction injection molding systems*. 434–438. https://experts.umn.edu/en/publications/kinetics-and-rheology-of-typical-polyurethane-reaction-injection-

Castro-Alonso, M. J., Montañez-Hernandez, L. E., Sanchez-Muñoz, M. A., Macias Franco, M. R., Narayanasamy, R., & Balagurusamy, N. (2019). Microbially Induced Calcium Carbonate Precipitation (MICP) and Its Potential in Bioconcrete: Microbiological and Molecular Concepts. *Frontiers in Materials*, 6, 126. https://doi.org/10.3389/fmats.2019.00126

CIDB. (2017). *Construction Quarterly Statistical Bulletin – Second Quarter 2017*.

Clear, C. A. (1985). Effects of autogenous healing upon the leakage of water through cracks in concrete. In *Technical Report—Cement and Concrete Association*.

COMSOL Inc. (2018). COMSOL Multiphysics Reference Manual (version 5.3a). *Comsol*.

Comyn, J. (1998). Moisture cure of adhesives and sealants. *International Journal of Adhesion and Adhesives*, 18(4), 247–253. https://doi.org/10.1002/0470014229.ch12

Cox, R. G. (1986). The dynamics of the spreading of liquids on a solid surface. Part 1. Viscous flow. *Journal of Fluid Mechanics*, 168, 169–194. https://doi.org/10.1017/S0022112086000332

Danish, A., Mosaberpanah, M. A., & Usama Salim, M. (2020). Past and present techniques of self-healing in cementitious materials: A critical review on efficiency of implemented treatments. *Journal of Materials Research and Technology*, 9(3), 6883–6899. https://doi.org/10.1016/j.jmrt.2020.04.053

Davies, R., Jefferson, A., Lark, R., & Gardner, D. (2015). A novel 2D vascular network in cementitious materials. *Concrete - Innovation and Design: Fib Symposium Proceedings*, 249–250.

Davies, R., Jefferson, T., & Gardner, D. (2021). Development and Testing of Vascular Networks for Self-Healing Cementitious Materials. *Journal of Materials in Civil Engineering*, 33(7), 04021164. https://doi.org/10.1061/(ASCE)MT.1943-5533.0003802

Davies, R., Teall, O., Pilegis, M., Kanellopoulos, A., Sharma, T., Jefferson, A., Gardner, D., Al-Tabbaa, A., Paine, K., & Lark, R. (2018). Large scale application of self-healing concrete: Design, construction, and testing. *Frontiers in Materials*, 5, 51. https://doi.org/10.3389/fmats.2018.00051

De Belie, N. (2016). Application of bacteria in concrete: A critical review. *RILEM Technical Letters*, 1, 56–61. https://doi.org/10.21809/rilemtechlett.2016.14

De Belie, N., Gruyaert, E., Al-Tabbaa, A., Antonaci, P., Baera, C., Bajare, D., Darquennes, A., Davies, R., Ferrara, L., Jefferson, T., Litina, C., Miljevic, B., Otlewska, A., Ranogajec, J., Roig-Flores, M., Paine, K., Lukowski, P., Serna, P., Tulliani, J. M., … Jonkers, H. M. (2018). A review of self-healing concrete for damage management of structures. *Advanced Materials Interfaces*, 5(17), 1–28. https://doi.org/10.1002/admi.201800074

De Belie, N., & Wang, J. (2016). Bacteria-based repair and self-healing of concrete. *Journal of Sustainable Cement-Based Materials*, 5(1–2), 35–56. https://doi.org/10.1080/21650373.2015.1077754

De Muynck, W., De Belie, N., & Verstraete, W. (2010). Microbial carbonate precipitation in construction materials: A review. *Ecological Engineering*, 36(2), 118–136. https://doi.org/10.1016/j.ecoleng.2009.02.006

De Nardi, C., Gardner, D., & Jefferson, A. D. (2020). Development of 3D Printed Networks in Self-Healing Concrete. *Materials*, 13(6), 1328. https://doi.org/10.3390/ma13061328

de Souza, L. R. (2017). *Design and synthesis of microcapsules using microfluidics for autonomic self-healing in cementitious materials* (Issue July). https://doi.org/10.17863/CAM.16673

de Souza, L. R., Al-Tabbaa, A., & Rossi, D. (2019). Taking a microfluidic approach to the production of self-healing construction materials. *Metal Powder Report*, 74(3), 121–125. https://doi.org/10.1016/j.mprp.2019.01.001

Dimitrov, D. I., Milchev, A., & Binder, K. (2007). Capillary Rise in Nanopores: Molecular Dynamics Evidence for the Lucas-Washburn Equation. *Physical Review Letters*, 99(5), 054501. https://doi.org/10.1103/PhysRevLett.99.054501

Dimitrov, D. I., Milchev, A., & Binder, K. (2008). Molecular Dynamics Simulations of Capillary Rise Experiments in Nanotubes Coated with Polymer Brushes. *Langmuir*, 24(4), 1232–1239. https://doi.org/10.1021/la7019445

Diotallevi, F., Biferale, L., Chibbaro, S., Lamura, A., Pontrelli, G., Sbragaglia, M., Succi, S., & Toschi, F. (2009). Capillary filling using lattice Boltzmann equations: The case of multi-phase flows. *The European Physical Journal Special Topics*, 166(1), 111–116. https://doi.org/10.1140/epjst/e2009-00889-7

Dong, B., Wang, Y., Fang, G., Han, N., Xing, F., & Lu, Y. (2015). Smart releasing behavior of a chemical self-healing microcapsule in the stimulated concrete pore solution. *Cement and Concrete Composites*, 56, 46–50. https://doi.org/10.1016/j.cemconcomp.2014.10.006

Dong, Z., Zhu, H., Yan, Z., & Zhou, S. (2015). Investigation of an agent's transportation in microcapsule self-healing concrete. *Innovative Materials and Design for Sustainable Transportation Infrastructure*, 119–127. https://doi.org/10.1061/9780784479278.012

Dry, C. (1994). Matrix craking repair and filling using active and passive modes for smart timed release of chemicals from fibers into cement matrices. *Smart Materials and Structures*, 3, 118–123.

Dry, C. (1996a). Procedures developed for self-repair of polymer matrix composite materials. *Composite Structures*, 35(3), 263–269. https://doi.org/10.1016/0263-8223(96)00033-5

Dry, C. (1996b). Release of smart chemicals for the in-service repair of bridges and roadways. *Proceedings of SPIE - The International Society for Optical Engineering*, 3321, 140–144. https://doi.org/10.1117/12.305543

Dry, C. (1996c). Smart bridge and building materials in which cyclic motion is controlled by internally released adhesives. *Proceedings of SPIE - The International Society for Optical Engineering*, 2719, 247–254.

Dry, C. (1996d). Smart earthquake-resistant materials: Using time-released adhesives for damping, stiffening, and deflection control. *3rd International Conference on Intelligent Materials and 3rd European Conference on Smart Structures and Materials*, 2779, 958–967.

Dry, C. (1999). Repair and prevention of damage due to transverse shrinkage cracks in bridge decks. *Proceedings of SPIE - The International Society for Optical Engineering*, 3671, 253–256. Scopus.

Dry, C. (2000). Three designs for the internal release of sealants, adhesives, and waterproofing chemicals into concrete to reduce permeability. *Cement and Concrete Research*, 30(12), 1969–1977. https://doi.org/10.1016/S0008-8846(00)00415-4

Dry, C. (2001). IN-SERVICE REPAIR OF HIGHWAY BRIDGES AND PAVEMENTS BY INTERNAL TIME-RELEASE REPAIR CHEMICALS. *NCHRP-IDEA Program Project Final Report*, Article NCHRP-IDEA Project 37. https://trid.trb.org/view.aspx?id=692570

Dry, C., & Corsaw, M. (2003). A comparison of bending strength between adhesive and steel reinforced concrete with steel only reinforced concrete. *Cement and Concrete Research*, 33(11), 1723–1727. https://doi.org/10.1016/S0008-8846(03)00102-9

Dry, C., Corsaw, M., & Bayer, E. (2003). A comparison of internal self-repair with resin injection in repair of concrete. *Journal of Adhesion Science and Technology*, 17(1), 79–89. https://doi.org/10.1163/15685610360472457

Dry, C., & Unzicker, J. (1998). Preserving performance of concrete members under seismic loading conditions. *Proceedings of SPIE - The International Society for Optical Engineering*, 3325, 74–80. https://doi.org/10.1117/12.310622

Dunn, S. (2017). Self Healing Concrete—A Sustainable Future. *Procedia Engineering*, 171, 238–249.

Duvivier, D., Blake, T. D., & De Coninck, J. (2013). Toward a predictive theory of wetting dynamics. *Langmuir: The ACS Journal of Surfaces and Colloids*, 29(32), 10132–10140. https://doi.org/10.1021/la4017917

Ebnesajjad, S. (2014). Chapter 2—Surface Tension and Its Measurement. In S. Ebnesajjad (Ed.), *Surface Treatment of Materials for Adhesive Bonding (Second Edition)* (pp. 7–24). William Andrew Publishing. https://doi.org/10.1016/B978-0-323-26435-8.00002-2

Edvardsen, C. (1999). Water Permeability and Autogenous Healing of Cracks in Concrete. *ACI Materials Journal*, 96(4), 448–454. https://doi.org/10.14359/645

Edwards, H. G. M., & Day, J. S. (2004). Fourier transform Raman spectroscopic studies of the curing of cyanoacrylate glue. *Journal of Raman Spectroscopy*, 35(7), 555–560. https://doi.org/10.1002/jrs.1184

Feiteira, J., Gruyaert, E., & De Belie, N. (2016). Self-healing of moving cracks in concrete by means of encapsulated polymer precursors. *Construction and Building Materials*, 102, 671–678. https://doi.org/10.1016/j.conbuildmat.2015.10.192

Feiteira, J., Tsangouri, E., Gruyaert, E., Lors, C., Louis, G., & De Belie, N. (2017). Monitoring crack movement in polymer-based self-healing concrete through digital image correlation, acoustic emission analysis and SEM in-situ loading. *Materials and Design*, 115, 238–246. https://doi.org/10.1016/j.matdes.2016.11.050

Ferrara, L. (2017). An overview on the research on self-healing concrete at Politecnico di Milano. *ASCMCES 2017*, 1–10. https://doi.org/10.1051/matecconf/201712002001

Ferrara, L. (2018). Self-healing cement-based materials: An asset for sustainable construction industry. *IOP Conference Series: Materials Science and Engineering*, 442(1), 012007. https://doi.org/10.1088/1757-899X/442/1/012007

Ferrara, L., Krelani, V., & Carsana, M. (2014). A 'fracture testing' based approach to assess crack healing of concrete with and without crystalline admixtures. *Construction and Building Materials*, 68, 535–551. https://doi.org/10.1016/j.conbuildmat.2014.07.008

Ferrara, L., Krelani, V., & Moretti, F. (2016). On the use of crystalline admixtures in cement based construction materials: From porosity reducers to promoters of self healing. *Smart Materials and Structures*, 25(8), 084002. https://doi.org/10.1088/0964-1726/25/8/084002

Ferrara, L., Van Mullem, T., Alonso, M. C., Antonaci, P., Borg, R. P., Cuenca, E., Jefferson, A., Ng, P. L., Peled, A., Roig-Flores, M., Sanchez, M., Schroefl, C., Serna, P., Snoeck, D., Tulliani, J. M., & De Belie, N. (2018). Experimental characterization of the self-healing capacity of cement based materials and its effects on the material performance: A state of the art report by COST Action SARCOS WG2. *Construction and Building Materials*, 167, 115–142. https://doi.org/10.1016/j.conbuildmat.2018.01.143

Fisher, L. R., & Lark, P. D. (1979). An experimental study of the washburn equation for liquid flow in very fine capillaries. *Journal of Colloid and Interface Science*, 69(3), 486–492. https://doi.org/10.1016/0021-9797(79)90138-3

Freeman, B. L. (2017). *A Numerical and Experimental Investigation into Multi-Ionic Reactive Transport Behaviour in Cementitious Materials*.

Freeman, B. L., & Jefferson, T. (2020). The simulation of transport processes in cementitious materials with embedded healing systems. *International Journal for Numerical and Analytical Methods in Geomechanics*, 44(2), 293–326. https://doi.org/10.1002/nag.3017

Fries, N., & Dreyer, M. (2008). An analytic solution of capillary rise restrained by gravity. *Journal of Colloid and Interface Science*, 320(1), 259–263. https://doi.org/10.1016/j.jcis.2008.01.009

Gardner, D., Herbert, D., Jayaprakash, M., Jefferson, A., & Paul, A. (2017). Capillary flow characteristics of an autogenic and autonomic healing agent for self-healing concrete. *Journal of Materials in Civil Engineering*, 29(11), 04017228. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002092

Gardner, D., Jefferson, A., & Hoffman, A. (2012). Investigation of capillary flow in discrete cracks in cementitious materials. *Cement and Concrete Research*, 42(7), 972–981. https://doi.org/10.1016/j.cemconres.2012.03.017

Gardner, D., Jefferson, A., Hoffman, A., & Lark, R. (2014). Simulation of the capillary flow of an autonomic healing agent in discrete cracks in cementitious materials. *Cement and Concrete Research*, 58, 35–44. https://doi.org/10.1016/j.cemconres.2014.01.005

Gardner, D., Lark, R., Jefferson, T., & Davies, R. (2018). A survey on problems encountered in current concrete construction and the potential benefits of self-healing cementitious materials. *Case Studies in Construction Materials*, 8, 238–247. https://doi.org/10.1016/j.cscm.2018.02.002

Garside, M. (2020). *Major countries in worldwide cement production 2015-2019*. Statista. https://www.statista.com/statistics/267364/world-cement-production-by-country/

Ghosh, S. K. (2009). Self-Healing Materials: Fundamentals, Design Strategies, and Applications. In *Self-Healing Materials: Fundamentals, Design Strategies, and Applications*. Wiley-VCH Verlag GmbH & Co. https://doi.org/10.1002/9783527625376.ch5

Giannaros, P., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Sealing of cracks in cement using microencapsulated sodium silicate. *Smart Materials and Structures*, 25(8), 084005. https://doi.org/10.1088/0964-1726/25/8/084005

Gilabert, F. A., Van Tittelboom, K., Van Stappen, J., Cnudde, V., De Belie, N., & Van Paepegem, W. (2017). Integral procedure to assess crack filling and mechanical contribution of polymer-based healing agent in encapsulation-based self-healing concrete. *Cement and Concrete Composites*, 77, 68–80. https://doi.org/10.1016/j.cemconcomp.2016.12.001

Gründing, D., Smuda, M., Antritter, T., Fricke, M., Rettenmaier, D., Kummer, F., Stephan, P., Marschall, H., & Bothe, D. (2020). A comparative study of transient capillary rise using direct numerical simulations. *Applied Mathematical Modelling*, 86, 142–165. https://doi.org/10.1016/j.apm.2020.04.020

Grzybowski, H., & Mosdorf, R. (2014). Modelling of two-phase flow in a minichannel using level-set method. *Journal of Physics: Conference Series*, 530(1). https://doi.org/10.1088/1742-6596/530/1/012049

Gupta, S., & Kua, H. W. (2016). Encapsulation technology and techniques in self-healing concrete. *Journal of Materials in Civil Engineering*, 28(12), 04016165. https://doi.org/10.1061/(ASCE)MT.1943-5533

Gupta, S., Pang, S. D., & Kua, H. W. (2017). Autonomous healing in concrete by bio-based healing agents – A review. *Construction and Building Materials*, 146, 419–428. https://doi.org/10.1016/j.conbuildmat.2017.04.111

Hager, M. D., Greil, P., Leyens, C., Van Der Zwaag, S., & Schubert, U. S. (2010). Self-healing materials. *Advanced Materials*, 22(47), 5424–5430. https://doi.org/10.1002/adma.201003036

Hall, J., Qamar, I. P. S., Rendall, T. C. S., & Trask, R. S. (2015). A computational model for the flow of resin in self-healing composites. *Smart Materials and Structures*, 24(3), 037002. https://doi.org/10.1088/0964-1726/24/3/037002

Hamraoui, A., & Nylander, T. (2002). Analytical Approach for the Lucas–Washburn Equation. *Journal of Colloid and Interface Science*, 250(2), 415–421. https://doi.org/10.1006/jcis.2002.8288

Hamraoui, A., Thuresson, K., Nylander, T., & Yaminsky, V. (2000). Can a Dynamic Contact Angle Be Understood in Terms of a Friction Coefficient? *Journal of Colloid and Interface Science*, 226(2), 199–204. https://doi.org/10.1006/jcis.2000.6830

Hassan, A. A. A., Suhaimi, A. B., Abdul Rahman, M. S., & Ahmad Razin, Z. A. (2018). Crack-healing in cementitious material to improve the durability of structures: Review. *MATEC Web of Conferences*, 250, 03005. https://doi.org/10.1051/matecconf/201825003005

Hazelwood, T., Jefferson, A. D., Lark, R. J., & Gardner, D. R. (2014). Long-term stress relaxation behavior of predrawn poly(ethylene terephthalate). *Journal of Applied Polymer Science*, 131(23). https://doi.org/10.1002/app.41208

Hearn, N. (1998). Self-sealing, autogenous healing and continued hydration: What is the difference? *Materials and Structures*, 31(8), 563–567. https://doi.org/10.1007/BF02481539

Heshmati, M., & Piri, M. (2014). Experimental Investigation of Dynamic Contact Angle and Capillary Rise in Tubes with Circular and Noncircular Cross Sections. *Langmuir*, 30(47), 14151–14162. https://doi.org/10.1021/la501724y

Hilloulin, B., Van Tittelboom, K., Gruyaert, E., De Belie, N., & Loukili, A. (2015). Design of polymeric capsules for self-healing concrete. *Cement and Concrete Composites*, 55, 298–307. https://doi.org/10.1016/j.cemconcomp.2014.09.022

Hirt, C. W., & Nichols, B. D. (1981). Volume of fluid (VOF) method for the dynamics of free boundaries. *Journal of Computational Physics*, 39(1), 201–225. https://doi.org/10.1016/0021-9991(81)90145-5

Hou, D., Li, T., & Wang, P. (2018). Molecular Dynamics Study on the Structure and Dynamics of NaCl Solution Transport in the Nanometer Channel of CASH Gel. *ACS Sustainable Chemistry & Engineering*, 6(7), 9498–9509. https://doi.org/10.1021/acssuschemeng.8b02126

Hu, Z.-X., Hu, X.-M., Cheng, W.-M., Zhao, Y.-Y., & Wu, M.-Y. (2018). Performance optimization of one-component polyurethane healing agent for self-healing concrete. *Construction and Building Materials*, 179, 151–159. https://doi.org/10.1016/j.conbuildmat.2018.05.199

Huang, H., & Ye, G. (2011). *Application of sodium silicate solution as self-healing agent in cementitious materials*.

Huang, H., & Ye, G. (2016). Numerical Studies of the Effects of Water Capsules on Self-Healing Efficiency and Mechanical Properties in Cementitious Materials. *Advances in Materials Science and Engineering*. https://doi.org/10.1155/2016/8271214

Huang, H., Ye, G., & Damidot, D. (2014). Effect of blast furnace slag on self-healing of microcracks in cementitious materials. *Cement and Concrete Research*, 60, 68–82. https://doi.org/10.1016/j.cemconres.2014.03.010

Huang, H., Ye, G., Qian, C., & Schlangen, E. (2016). Self-healing in cementitious materials: Materials, methods and service conditions. *Materials and Design*, 92, 499–511. https://doi.org/10.1016/j.matdes.2015.12.091

Huang, H., Ye, G., & Shui, Z. (2014). Feasibility of self-healing in cementitious materials—By using capsules or a vascular system? *Construction and Building Materials*, 63, 108–118. https://doi.org/10.1016/j.conbuildmat.2014.04.028

Huang, H., Ye, G., & Van Breugel, K. (2010). Numerical simulation on moisture transport in cracked cement-based materials in view of self-healing of crack. *Journal of Wuhan University of Technology, Materials Science Edition*, 25(6), 1077–1081. https://doi.org/10.1007/s11595-010-0153-5

Hyde, G. W., & Smith, J. W. (1889). Results of experiments made to determine the permeability of cements and cement mortars. *Journal of the Franklin Institute*, 128(3), 199–207. https://doi.org/10.1016/0016-0032(89)90217-2

Ichikawa, N., Hosokawa, K., & Maeda, R. (2004). Interface motion of capillary-driven flow in rectangular microchannel. *Journal of Colloid and Interface Science*, 280(1), 155–164. https://doi.org/10.1016/j.jcis.2004.07.017

Ichikawa, N., & Maeda, R. (2005). Interface motion driven by capillary action in circular and rectangular microchannel. *Microscale Thermophysical Engineering*, 9(3), 237–254. https://doi.org/10.1080/10893950500196006

Isaacs, B., Lark, R., Jefferson, T., Davies, R., & Dunn, S. (2013). Crack healing of cementitious materials using shrinkable polymer tendons. *Structural Concrete*, 14(2), 138–147. https://doi.org/10.1002/suco.201200013

Jacobsen, S., & Sellevold, E. J. . (1996). Self-healing of high strength concrete after deterioration by freeze/thaw. *Cement and Concrete Research*, 26(1), 55–62. https://doi.org/10.1016/0008-8846(95)00179-4

Jefferson, A., Joseph, C., Lark, R., Isaacs, B., Dunn, S., & Weager, B. (2010). A new system for crack closure of cementitious materials using shrinkable polymers. *Cement and Concrete Research*, 40(5), 795–801. https://doi.org/10.1016/j.cemconres.2010.01.004

Jefferson, A., Selvarajoo, T., Freeman, B., & Davies, R. (2019). An experimental and numerical study on vascular self-healing cementitious materials. *MATEC Web of Conferences*, 289, 01004. https://doi.org/10.1051/matecconf/201928901004

Jefferson, T., Javierre, E., Freeman, B., Zaoui, A., Koenders, E., & Ferrara, L. (2018). Research progress on numerical models for self-healing cementitious materials. *Advanced Materials Interfaces*, 5(17), 1–19. https://doi.org/10.1002/admi.201701378

Jia, P., Dong, M., & Dai, L. (2007). Threshold pressure in arbitrary triangular tubes using RSG concept for all wetting conditions. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 302(1), 88–95. https://doi.org/10.1016/j.colsurfa.2007.01.053

Jian-Chao, C., Bo-Ming, Y., Mao-Fei, M., & Liang, L. (2010). Capillary Rise in a Single Tortuous Capillary. *Chinese Physics Letters*, 27(5), 054701. https://doi.org/10.1088/0256-307X/27/5/054701

Joekar-Niasar, V., & Hassanizadeh, S. M. (2012). Effect of Initial Hydraulic Conditions on Capillary Rise in a Porous Medium: Pore-Network Modeling. *Vadose Zone Journal*, 11(3), vzj2011.0128. https://doi.org/10.2136/vzj2011.0128

Joekar-Niasar, V., Hassanizadeh, S. M., & Leijnse, A. (2008). Insights into the Relationships Among Capillary Pressure, Saturation, Interfacial Area and Relative Permeability Using Pore-Network Modeling. *Transport in Porous Media*, 74(2), 201–219. https://doi.org/10.1007/s11242-007-9191-7

Jong, W. R., Kuo, T. H., Ho, S. W., Chiu, H. H., & Peng, S. H. (2007). Flows in rectangular microchannels driven by capillary force and gravity. *International Communications in Heat and Mass Transfer*, 34(2), 186–196. https://doi.org/10.1016/j.icheatmasstransfer.2006.09.011

Joos, P., Van Remoortere, P., & Bracke, M. (1990). The kinetics of wetting in a capillary. *Journal of Colloid and Interface Science*, 136(1), 189–197. https://doi.org/10.1016/0021-9797(90)90089-7

Joseph, C., Gardner, D., Jefferson, T., Isaacs, B., & Lark, B. (2011). Self-healing cementitious materials: A review of recent work. *Proceedings of Institution of Civil Engineers: Construction Materials*, 164(1), 29–41. https://doi.org/10.1680/coma.900051

Joseph, C., Jefferson, A. D., & Cantoni, M. B. (2007). Issues relating to the autonomic healing of cementitious materials. *First International Conference on Self Healing Materials*, *April*, 1–8.

Joseph, C., Jefferson, A. d., Isaacs, B., Lark, R., & Gardner, D. (2010). Experimental investigation of adhesive-based self-healing of cementitious materials. *Magazine of Concrete Research*, 62(11), 831–843. https://doi.org/10.1680/macr.2010.62.11.831

Joshi, S., Goyal, S., Mukherjee, A., & Reddy, M. S. (2017a). Microbial healing of cracks in concrete: A review. *Journal of Industrial Microbiology and Biotechnology*, 44(11), 1511–1525. https://doi.org/10.1007/s10295-017-1978-0

Joshi, S., Goyal, S., Mukherjee, A., & Reddy, M. S. (2017b). Microbial healing of cracks in concrete: A review. *Journal of Industrial Microbiology & Biotechnology*, 44(11), 1511–1525. https://doi.org/10.1007/s10295-017-1978-0

Kanellopoulos, A., Giannaros, P., Palmer, D., Kerr, A., & Al-Tabbaa, A. (2017). Polymeric microcapsules with switchable mechanical properties for self-healing concrete: Synthesis, characterisation and proof of concept. *Smart Materials and Structures*, 26(4). https://doi.org/10.1088/1361-665X/aa516c

Karaiskos, G., Tsangouri, E., Aggelis, D. G., Van Tittelboom, K., De Belie, N., & Van Hemelrijck, D. (2016). Performance monitoring of large-scale autonomously healed concrete beams under four-point bending through multiple non-destructive testing methods. *Smart Materials and Structures*, 25(5), 0. https://doi.org/10.1088/0964-1726/25/5/055003

Karen Cilento. (2010). *Smart Concrete / Michelle Pelletier*. https://www.archdaily.com/62357/smart-concrete-michelle-pelletier

Katti, D., & Krishnamurti, N. (1999). Anionic polymerization of alkyl cyanoacrylates: In vitro model studies for in vivo applications. *Journal of Applied Polymer Science*, 74(2), 336–344. https://doi.org/10.1002/(SICI)1097-4628(19991010)74:2<336::AID-APP15>3.0.CO;2-S

Kessler, M. R., Sottos, N. R., & White, S. R. (2003). Self-healing structural composite materials. *Composites Part A: Applied Science and Manufacturing*, 34(8), 743–753. https://doi.org/10.1016/S1359-835X(03)00138-6

Khor, C. Y., Abdullah, M. Z., Abdullah, M. K., Mujeebu, M. A., Ramdan, D., Majid, M. F. M. A., Ariff, Z. M., & Abdul Rahman, M. R. (2011). Numerical analysis on the effects of different inlet gates and gap heights in TQFP encapsulation process. *International Journal of Heat and Mass Transfer*, 54(9), 1861–1870. https://doi.org/10.1016/j.ijheatmasstransfer.2010.10.038

Khor, C. Y., Abdullah, M. Z., & Ani, F. C. (2012). Underfill process for two parallel plates and flip chip packaging. *International Communications in Heat and Mass Transfer*, 39(8), 1205–1212. https://doi.org/10.1016/j.icheatmasstransfer.2012.07.006

Khor, C. Y., Abdullah, M. Z., Lau, C.-S., & Azid, I. A. (2014). Recent fluid–structure interaction modeling challenges in IC encapsulation – A review. *Microelectronics Reliability*, 54(8), 1511–1526. https://doi.org/10.1016/j.microrel.2014.03.012

Kim, E., & Whitesides, G. M. (1997). Imbibition and Flow of Wetting Liquids in Noncircular Capillaries. *The Journal of Physical Chemistry B*, 101(6), 855–863. https://doi.org/10.1021/jp961594o

Kim, H., Lim, J.-H., Lee, K., & Choi, S. Q. (2020). Direct Measurement of Contact Angle Change in Capillary Rise. *Langmuir*, 36(48), 14597–14606. https://doi.org/10.1021/acs.langmuir.0c02372

Kishi, T., Ahn, T., Hosoda, A., Suzuki, S., & Takaoka, H. (2007). Self-healing behaviour by cementitious recrystallization of cracked concrete incorporating expansive agent. *Proceedings of the First International Conference on Self Healing Materials*, 1–10. https://www.semanticscholar.org/paper/SELF-HEALING-BEHAVIOUR-BY-CEMENTITIOUS-OF-CRACKED-Kishi-Ahn/ba7a72b25d4076c8bf0cd1185231e2f1653230b9

Kuang, Y., & Ou, J. (2008). Self-repairing performance of concrete beams strengthened using superelastic SMA wires in combination with adhesives released from hollow fibers. *Smart Materials and Structures*, 17(2), 025020. https://doi.org/10.1088/0964-1726/17/2/025020

Laiveniece, L., & Morozovs, A. (2016). Impact of water on rheological behavior of polyurethane glues. *Rural Sustainability Research*, 35(330), 7–18. https://doi.org/10.1515/plua-2016-0002

Lee, M. W., Jung, W. K., Sohn, E.-S., Lee, J.-Y., Hwang, C., & Lee, C. (2008). A study on the rheological characterization and flow modeling of molded underfill (MUF) for optimized void elimination design. *2008 58th Electronic Components and Technology Conference*. https://doi.org/10.1109/ECTC.2008.4550000

LeGrand, E. J., & Rense, W. A. (1945). Data on Rate of Capillary Rise. *Journal of Applied Physics*, 16(12), 843–846. https://doi.org/10.1063/1.1707550

Li, C., Shen, Y., Ge, H., Yang, Z., Su, S., Ren, K., & Huang, H. (2016). Analysis of capillary rise in asymmetric branch-like capillary. *Fractals*, 24(02), 1650024. https://doi.org/10.1142/S0218348X16500249

Li, H., Wang, R., & Liu, W. (2012). Preparation and self-healing performance of epoxy composites with microcapsules and tungsten (VI) chloride catalyst. *Journal of Reinforced Plastics and Composites*, 31(13), 924–932. https://doi.org/10.1177/0731684412442990

Li, Q., Siddaramaiah, Kim, N. H., Hui, D., & Lee, J. H. (2013). Effects of dual component microcapsules of resin and curing agent on the self-healing efficiency of epoxy. *Composites Part B: Engineering*, 55, 79–85. https://doi.org/10.1016/j.compositesb.2013.06.006

Li, V. C., & Herbert, E. (2012). Robust self-Healing concrete for sustainable infrastructure. *Journal of Advanced Concrete Technology*, 10(6), 207–218. https://doi.org/10.3151/jact.10.207

Li, V. C., Lim, Y. M., & Chan, Y.-W. (1998). Feasibility study of a passive smart self-healing cementitious composite. *Composites Part B: Engineering*, 29(6), 819–827. https://doi.org/10.1016/S1359-8368(98)00034-1

Li, Y. J., Barthès-Biesel, D., & Salsac, A.-V. (2017). Polymerization kinetics of n-butyl cyanoacrylate glues used for vascular embolization. *Journal of the Mechanical Behavior of Biomedical Materials*, 69, 307–317. https://doi.org/10.1016/j.jmbbm.2017.01.003

Lide, D. R. (2004). *CRC Handbook of Chemistry and Physics, 85th Edition*. CRC Press.

Litina, C., & Al-Tabbaa, A. (2020). First generation microcapsule-based self-healing cementitious construction repair materials. *Construction and Building Materials*, 255, 119389. https://doi.org/10.1016/j.conbuildmat.2020.119389

Liu, T., Zhou, T., Yao, Y., Zhang, F., Liu, L., Liu, Y., & Leng, J. (2017). Stimulus methods of multi-functional shape memory polymer nanocomposites: A review. *Composites Part A: Applied Science and Manufacturing*, 100, 20–30. https://doi.org/10.1016/j.compositesa.2017.04.022

Lu, G., Wang, X.-D., & Duan, Y.-Y. (2013). Study on initial stage of capillary rise dynamics. *Colloids and Surfaces A: Physicochemical and Engineering Aspects*, 433, 95–103. https://doi.org/10.1016/j.colsurfa.2013.05.004

Lucas, R. (1918). Ueber das Zeitgesetz des kapillaren Aufstiegs von Flüssigkeiten. *Kolloid-Zeitschrift*, 23(1), 15–22. https://doi.org/10.1007/BF01461107

Lucio, B., & De La Fuente, J. L. (2014). Rheological cure characterization of an advanced functional polyurethane. *Thermochimica Acta*, 596, 6–13. https://doi.org/10.1016/j.tca.2014.09.012

Lv, L., Yang, Z., Chen, G., Zhu, G., Han, N., Schlangen, E., & Xing, F. (2016). Synthesis and characterization of a new polymeric microcapsule and feasibility investigation in self-healing cementitious materials. *Construction and Building Materials*, 105, 487–495. https://doi.org/10.1016/j.conbuildmat.2015.12.185

Lv, Z., & Chen, D. (2014). Overview of recent work on self-healing in cementitious materials. *Materiales De Construcción*, 64(316), 1–12. https://doi.org/10.4028/www.scientific.net/MSF.546-549.775

Maes, M., Van Tittelboom, K., & De Belie, N. (2014). The efficiency of self-healing cementitious materials by means of encapsulated polyurethane in chloride containing environments. *Construction and Building Materials*, 71, 528–537. https://doi.org/10.1016/j.conbuildmat.2014.08.053

Mason, G., & Morrow, N. R. (1991). Capillary behavior of a perfectly wetting liquid in irregular triangular tubes. *Journal of Colloid and Interface Science*, 141(1), 262–274. https://doi.org/10.1016/0021-9797(91)90321-X

Mauludin, L. M., & Oucif, C. (2019). Modeling of Self-Healing Concrete: A Review. *Journal of Applied and Computational Mechanics*, 5, 526–539. https://doi.org/10.22055/jacm.2017.23665.1167

Mehrabian, H., Gao, P., & Feng, J. J. (2011). Wicking flow through microchannels. *Physics of Fluids*, 23(12), 122108. https://doi.org/10.1063/1.3671739

Mihashi, H., Kaneko, Y., Nishiwaki, T., & Otsuka, K. (2000). Fundamental study on development of intelligent concrete characterized by self-healing capability for strength. *Transactions of the Japan Concrete Institute*, 22, 441–450.

Millet, G. H. (1986). Cyanoacrylate Adhesives. In *Structural Adhesives* (pp. 249–307). Springer US. https://doi.org/10.1007/978-1-4684-7781-8_7

Minnebo, P., Thierens, G., De Valck, G., Van Tittelboom, K., Belie, N. De, Van Hemelrijck, D., & Tsangouri, E. (2017). A novel design of autonomously healed concrete: Towards a vascular healing network. *Materials*, 10(1), 1–23. https://doi.org/10.3390/ma10010049

Mistry, M., & Shah, S. (2021). Concrete with Encapsulated Self-healing Agent: A Critical Review. In D. K. Ashish, J. de Brito, & S. K. Sharma (Eds.), *3rd International Conference on Innovative Technologies for Clean and Sustainable Development* (pp. 207–230). Springer International Publishing. https://doi.org/10.1007/978-3-030-51485-3_14

Mondal, S., & (Dey) Ghosh, A. (2019). Review on microbial induced calcite precipitation mechanisms leading to bacterial selection for microbial concrete. *Construction and Building Materials*, 225, 67–75. https://doi.org/10.1016/j.conbuildmat.2019.07.122

Mostavi, E., Asadi, S., Hassan, M. M., & Alansari, M. (2015). Evaluation of self-healing mechanisms in concrete with double-walled sodium silicate microcapsules. *Journal of Materials in Civil Engineering*, 27(12), 04015035. https://doi.org/10.1061/(ASCE)MT.1943-5533.0001314

Muhammad, N. Z., Shafaghat, A., Keyvanfar, A., Majid, M. Z. A., Ghoshal, S. K., Mohammadyan Yasouj, S. E., Ganiyu, A. A., Samadi Kouchaksaraei, M., Kamyab, H., Taheri, M. M., Rezazadeh Shirdar, M., & McCaffer, R. (2016). Tests and methods of evaluating the self-healing efficiency of concrete: A review. *Construction and Building Materials*, 112, 1123–1132. https://doi.org/10.1016/j.conbuildmat.2016.03.017

Naghashnejad, M., & Shabgard, H. (2020). A Computational Model for the Capillary Flow between Parallel Plates. *ArXiv:2003.05036 [Physics]*. http://arxiv.org/abs/2003.05036

Nguyen, L., Quentin, C., Lee, W., Bayyuk, S., Bidstrup-Allen, S. A., & Wang, S.-T. (2000). Computational modeling and validation of the encapsulation of plastic packages by transfer molding. *Journal of Electronic Packaging, Transactions of the ASME*, 122(2), 138–146. Scopus. https://doi.org/10.1115/1.483146

Nguyen, L. T. (1993). Reactive flow simulation in transfer molding of IC packages. *Proceedings of IEEE 43rd Electronic Components and Technology Conference (ECTC '93)*, 375–390. https://doi.org/10.1109/ECTC.1993.346818

Nishiwaki, T., Mihashi, H., Jang, B. K., & Miura, K. (2006). Development of self-healing system for concrete with selective heating around crack. *Journal of Advanced Concrete Technology*, 4(2), 267–275. https://doi.org/10.3151/jact.4.267

Office for National Statistics. (2018). *Construction statistics*. https://www.ons.gov.uk/businessindustryandtrade/constructionindustry/articles/constructionstatistics/number192018edition

Osher, S., & Sethian, J. A. (1988). Fronts propagating with curvature-dependent speed: Algorithms based on Hamilton-Jacobi formulations. *Journal of Computational Physics*, 79(1), 12–49. https://doi.org/10.1016/0021-9991(88)90002-2

Paine, K., Al-Tabbaa, A., Gardner, D., & Jefferson, T. (2019). Resilient materials for life: Biomimetic self-healing and self-diagnosing concretes. *UKIERI Concrete Congress: Concrete: The Global Builder*.

Palakurthi, N. K., Konangi, S., Ghia, U., & Comer, K. (2015). Micro-scale simulation of unidirectional capillary transport of wetting liquid through 3D fibrous porous media: Estimation of effective pore radii. *International Journal of Multiphase Flow*, 77, 48–57. https://doi.org/10.1016/j.ijmultiphaseflow.2015.07.010

Patankar, S. V., & Spalding, D. B. (1972). A calculation procedure for heat, mass and momentum transfer in three-dimensional parabolic flows. *International Journal of Heat and Mass Transfer*, 15(10), 1787–1806. https://doi.org/10.1016/0017-9310(72)90054-3

Pavuluri, S., Maes, J., & Doster, F. (2018). Spontaneous imbibition in a microchannel: Analytical solution and assessment of volume of fluid formulations. *Microfluidics and Nanofluidics*, 22(8), 90. https://doi.org/10.1007/s10404-018-2106-9

Pelletier, M. M., Brown, R., Shukla, A., & Bose, A. (2011). *Self-healing concrete with a microencapsulated healing agent*.

Perez, G., Erkizia, E., Gaitero, J. J., Kaltzakorta, I., Jiménez, I., & Guerrero, A. (2015). Synthesis and characterization of epoxy encapsulating silica microcapsules and amine functionalized silica nanoparticles for development of an innovative self-healing concrete. *Materials Chemistry and Physics*, 165, 39–48. https://doi.org/10.1016/j.matchemphys.2015.08.047

Pooley, C. M., Kusumaatmaja, H., & Yeomans, J. M. (2009). Modelling capillary filling dynamics using lattice Boltzmann simulations. *The European Physical Journal Special Topics*, 171(1), 63–71. https://doi.org/10.1140/epjst/e2009-01012-0

Popescu, M. N., Ralston, J., & Sedev, R. (2008). Capillary Rise with Velocity-Dependent Dynamic Contact Angle. *Langmuir*, 24(21), 12710–12716. https://doi.org/10.1021/la801753t

Prodanović, M., & Bryant, S. L. (2006). A level set method for determining critical curvatures for drainage and imbibition. *Journal of Colloid and Interface Science*, 304(2), 442–458. https://doi.org/10.1016/j.jcis.2006.08.048

Qureshi, T., & Al-Tabbaa, A. (2020). Self-Healing Concrete and Cementitious Materials. In *Advanced Functional Materials*. IntechOpen. https://doi.org/10.5772/intechopen.92349

Raeini, A. Q., Blunt, M. J., & Bijeljic, B. (2014). Direct simulations of two-phase flow on micro-CT images of porous media and upscaling of pore-scale forces. *Advances in Water Resources*, 74, 116–126. https://doi.org/10.1016/j.advwatres.2014.08.012

Rajczakowska, M., Habermehl-Cwirzen, K., Hedlund, H., & Cwirzen, A. (2019). Autogenous self-healing: A better solution for concrete. *Journal of Materials* *in Civil Engineering*, 31(9), 1–19. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002764

Ramdan, D., Abdullah, M. Z., & Yee, K. C. (2011). Plastic Ball Grid Array Encapsulation Process Simulation on Rheology Effect. *TELKOMNIKA (Telecommunication Computing Electronics and Control)*, 9(1), 27–36. https://doi.org/10.12928/telkomnika.v9i1.642

Ranaivomanana, H., & Benkemoun, N. (2017). Numerical modelling of the healing process induced by carbonation of a single crack in concrete structures: Theoretical formulation and Embedded Finite Element Method implementation. *Finite Elements in Analysis and Design*, 132, 42–51. https://doi.org/10.1016/j.finel.2017.05.003

Reinhardt, H.-W., & Jooss, M. (2003). Permeability and self-healing of cracked concrete as a function of temperature and crack width. *Cement and Concrete Research*, 33(7), 981–985. https://doi.org/10.1016/S0008-8846(02)01099-2

Remmers, J. J. C., & de Borst, R. (2007). Numerical Modelling of Self Healing Mechanisms. In S. van der Zwaag (Ed.), *Self Healing Materials: An Alternative Approach to 20 Centuries of Materials Science* (Vol. 100, pp. 365–380). Springer Series in Materials Science. https://doi.org/10.1177/00220345850640051201

Reynolds, S., Oxley, D. P., & Pritchard, R. G. (1982). An adhesive study by electron tunnelling: Ethyl α-cyanoacrylate adsorbed on an oxidized aluminium surface. *Spectrochimica Acta Part A: Molecular Spectroscopy*, 38(1), 103–111. https://doi.org/10.1016/0584-8539(82)80183-9

Riccardo Maddalena. (2019, November 1). *The adventure of RM4L and self-healing concrete*. https://www.youtube.com/watch?v=uFs4KI_XvDw

Ridgway, C. J., Gane, P. A. C., Abd, A. E.-G. E., & Czachor, A. (2006). Water Absorption into Construction Materials: Comparison of Neutron Radiography Data with Network Absorption Models. *Transport in Porous Media*, 63(3), 503–525. https://doi.org/10.1007/s11242-005-1125-7

Roig-Flores, M., Moscato, S., Serna, P., & Ferrara, L. (2015). Self-healing capability of concrete with crystalline admixtures in different environments. *Construction and Building Materials*, 86, 1–11. https://doi.org/10.1016/j.conbuildmat.2015.03.091

Roig-Flores, M., Pirritano, F., Serna, P., & Ferrara, L. (2016). Effect of crystalline admixtures on the self-healing capability of early-age concrete studied by means of permeability and crack closing tests. *Construction and Building Materials*, 114, 447–457. https://doi.org/10.1016/j.conbuildmat.2016.03.196

Rokhforouz, M. R., & Akhlaghi Amiri, H. A. (2017). Phase-field simulation of counter-current spontaneous imbibition in a fractured heterogeneous porous medium. *Physics of Fluids*, 29(6), 062104. https://doi.org/10.1063/1.4985290

Rooij, M. de, Tittelboom, K. V., Belie, N. D., & Schlangen, E. (Eds.). (2013). *Self-Healing Phenomena in Cement-Based Materials: State-of-the-Art Report of RILEM Technical Committee 221-SHC: Self-Healing Phenomena in Cement-Based Materials*. Springer Netherlands. https://doi.org/10.1007/978-94-007-6624-2

Rooij, M. De, Van Tittelboom, K., De Belie, N., & Schlangen, E. (2013). *Self-healing phenomena in cement-based materials: State-of-the-art report of RILEM technical committee 221-SHC: self-healing phenomena in cement-based materials (Vol 11)*. Springer Science & Business Media.

Sadjadi, Z., Jung, M., Seemann, R., & Rieger, H. (2015). Meniscus Arrest during Capillary Rise in Asymmetric Microfluidic Pore Junctions. *Langmuir*, 31(8), 2600–2608. https://doi.org/10.1021/la504149r

Şahmaran, M., Keskin, S. B., Ozerkan, G., & Yaman, I. O. (2008). Self-healing of mechanically-loaded self consolidating concretes with high volumes of fly ash. *Cement and Concrete Composites*, 30(10), 872–879. https://doi.org/10.1016/j.cemconcomp.2008.07.001

Şahmaran, M., & Li, V. C. (2008). Durability of mechanically loaded engineered cementitious composites under highly alkaline environments. *Cement and Concrete Composites*, 30(2), 72–81. https://doi.org/10.1016/j.cemconcomp.2007.09.004

Sangadji, S. (2017). Can self-healing mechanism helps concrete structures sustainable? *Procedia Engineering*, 171, 238–249. https://doi.org/10.1016/j.proeng.2017.01.331

Šavija, B., & Schlangen, E. (2016). Autogenous healing and chloride ingress in cracked concrete. *Heron*, 61(1), 15–32.

Scheidegger, A. E. (1954). Statistical Hydrodynamics in Porous Media. *Journal of Applied Physics*, 25(8), 994–1001. https://doi.org/10.1063/1.1721815

Schlangen, E., Jonkers, H., Qian, S., & Garcia, A. (2010). Recent advances on self healing of concrete. *Proceedings FRAMCOS7*, 1–8.

Schlangen, E., & Joseph, C. (2009). Self-Healing Processes in Concrete. In *Self-Healing Materials: Fundamentals, Design Strategies, and Applications* (pp. 141–182). Wiley-VCH Verlag GmbH & Co. https://doi.org/10.1002/9783527625376.ch5

Schlangen, E., & Joseph, C. (2013). Modelling of self-healing cementitious materials. In *Self-Healing Phenomena in Cement-Based Materials* (pp. 217–240). https://doi.org/10.1007/978-94-007-6624-2

Schlangen, E., & Sangadji, S. (2013). Addressing infrastructure durability and sustainability by self healing mechanisms—Recent advances in self healing concrete and asphalt. *Procedia Engineering*, 54, 39–57. https://doi.org/10.1016/j.proeng.2013.03.005

Seifan, M., Samani, A. K., & Berenjian, A. (2016). Bioconcrete: Next generation of self-healing concrete. *Applied Microbiology and Biotechnology*, 100(6), 2591–2602. https://doi.org/10.1007/s00253-016-7316-z

Selvarajoo, T. (2020). *Characterisation of a vascular self-healing cementitious material system* [Phd, Cardiff University]. https://orca.cardiff.ac.uk/130332/

Selvarajoo, T., Davies, R. E., Gardner, D. R., Freeman, B. L., & Jefferson, A. D. (2020). Characterisation of a vascular self-healing cementitious material system: Flow and curing properties. *Construction and Building Materials*, 245, 118332. https://doi.org/10.1016/j.conbuildmat.2020.118332

Shavit, A., & Riggleman, R. A. (2015). The dynamics of unentangled polymers during capillary rise infiltration into a nanoparticle packing. *Soft Matter,* 11(42), 8285–8295. https://doi.org/10.1039/C5SM01866H

Shou, D., Ye, L., & Fan, J. (2014). Treelike networks accelerating capillary flow. *Physical Review E*, 89(5), 053007. https://doi.org/10.1103/PhysRevE.89.053007

Sidiq, A., Gravina, R., & Giustozzi, F. (2019). Is concrete healing really efficient? A review. *Construction and Building Materials*, 205, 257–273. https://doi.org/10.1016/j.conbuildmat.2019.02.002

Snoeck, D., Van Tittelboom, K., Steuperaert, S., Dubruel, P., & De Belie, N. (2014). Self-healing cementitious materials by the combination of microfibres and superabsorbent polymers. *Journal of Intelligent Material Systems and Structures*, 25(1), 13–24. https://doi.org/10.1177/1045389X12438623

Stapf, G., Zisi, N., & Aicher, S. (2013). Curing behaviour of structural wood adhesives—Parallel plate rheometer results. *Pro Ligno*, 9(4), 109–117.

Sun, L., Zong, Z., Xue, W., & Zeng, Z. (2020). Mechanism and kinetics of moisture-curing process of reactive hot melt polyurethane adhesive. *Chemical Engineering Journal Advances*, 4, 100051. https://doi.org/10.1016/j.ceja.2020.100051

Sun, Y., Kharaghani, A., & Tsotsas, E. (2016). Micro-model experiments and pore network simulations of liquid imbibition in porous media. *Chemical Engineering Science*, 150, 41–53. https://doi.org/10.1016/j.ces.2016.04.055

Tang, W., Kardani, O., & Cui, H. (2015). Robust evaluation of self-healing efficiency in cementitious materials—A review. *Construction and Building Materials*, 81, 233–247. https://doi.org/10.1016/j.conbuildmat.2015.02.054

Tang, Y., Min, J., Zhang, X., & Liu, G. (2018). Meniscus behaviors and capillary pressures in capillary channels having various cross-sectional geometries. *Chinese Journal of Chemical Engineering*, 26(10), 2014–2022. https://doi.org/10.1016/j.cjche.2018.04.031

Teall, O., Davies, R., Pilegis, M., Kanellopoulos, A., Sharma, T., Paine, K., Jefferson, A., Lark, R., Gardner, D., & Al-Tabbaa, A. (2016, August). *Self-healing concrete full scale site trials*.

ter Heide, N., & Schlangen, E. (2007). Self-healing of early age cracks in concrete. *Proceedings of the 1st International Conference on Self Healing Materials*, 1–12.

ter Heide, N., Schlangen, E., & Van Breugel, K. (2005). Experimental study of crack healing of early age cracks. *Proceedings of Knud Hojgaard Conference on Advanced Cement-Based Materials, Lyngby, Denmark.*

Thao, T. D. P., Johnson, T. J. S., Tong, Q. S., & Dai, P. S. (2009). Implementation of self-healing in concrete–Proof of concept. *IES Journal Part A: Civil and Structural Engineering*, 2(2), 116–125. https://doi.org/10.1080/19373260902843506

Tomlinson, S. K., Ghita, O. R., Hooper, R. M., & Evans, K. E. (2006). The use of near-infrared spectroscopy for the cure monitoring of an ethyl cyanoacrylate adhesive. *Vibrational Spectroscopy*, 40(1), 133–141. https://doi.org/10.1016/j.vibspec.2005.07.009

Tsangouri, E., Aggelis, D. G., Belie, N. De, Shiotani, T., & Hemelrijck, D. Van. (2018). Experimental techniques synergy towards the design of a sensing tool for autonomously healed concrete. *Multidisciplinary Digital Publishing Institute Proceedings*, 2(8), 449. https://doi.org/10.3390/icem18-05310

Tsangouri, E., Lelon, J., Minnebo, P., Asaue, H., Shiotani, T., Van Tittelboom, K., De Belie, N., Aggelis, D. G., & Van Hemelrijck, D. (2019). Feasibility study on real-scale, self-healing concrete slab by developing a smart capsules network and assessed by a plethora of advanced monitoring techniques. *Construction and Building Materials*, 228, 116780. https://doi.org/10.1016/j.conbuildmat.2019.116780

Tziviloglou, E., Van Tittelboom, K., Palin, D., Wang, J., Sierra-Beltrán, M. G., Erşan, Y. Ç., Mors, R., Wiktor, V., Jonkers, H. M., Schlangen, E., & De Belie, N. (2016). Bio-based self-healing concrete: From research to field aplication. In M. Hager, S. Van Der Zwaag, & U. S. Schubert (Eds.), *Self-healing materials. Advances in polymer science* (pp. 345–385). Springer. https://doi.org/10.1007/12

Van Belleghem, B., Kessler, S., Van Den Heede, P., Van Tittelboom, K., & De Belie, N. (2018). Chloride induced reinforcement corrosion behavior in self-healing concrete with encapsulated polyurethane. *Cement and Concrete Research*, 113, 130–139. https://doi.org/10.1016/j.cemconres.2018.07.009

Van Belleghem, B., Montoya, R., Dewanckele, J., Van Den Steen, N., De Graeve, I., Deconinck, J., Cnudde, V., Van Tittelboom, K., & De Belie, N. (2016). Capillary water absorption in cracked and uncracked mortar—A comparison between experimental study and finite element analysis. *Construction and Building Materials*, 110, 154–162. https://doi.org/10.1016/j.conbuildmat.2016.02.027

Van Belleghem, B., Van Tittelboom, K., & De Belie, N. (2018). Efficiency of self-healing cementitious materials with encapsulated polyurethane to reduce water ingress through cracks. *Materiales de Construccion*, 68(330). https://doi.org/10.3989/mc.2018.05917 van Breugel, K. (2007). Is there a market for self-healing cement-based materials? *Proceedings of the 1st International Conference on Self Healing Materials*, *April*, 1–9.

Van den Heede, P., Van Belleghem, B., Alderete, N., Van Tittelboom, K., & De Belie, N. (2016). Neutron radiography based visualization and profiling of water uptake in (un)cracked and autonomously healed cementitious materials. *Materials*, 9(5). https://doi.org/10.3390/ma9050311

Van den Heede, P., Van Belleghem, B., Alderete, N., Van Tittelboom, K., & De Belie, N. (2017). Influence of the curing period of encapsulated polyurethane precursor on the capillary water absorption of cracked mortar with self-healing properties. *Proceedings of the 14th International Conference on Durability of Building Materials and Components*.

Van Mullem, T., Gruyaert, E., Caspeele, R., & De Belie, N. (2020). First Large Scale Application with Self-Healing Concrete in Belgium: Analysis of the Laboratory Control Tests. *Materials*, 13(4), 997. https://doi.org/10.3390/ma13040997

Van Tittelboom, K., Adesanya, K., Dubruel, P., Van Puyvelde, P., & De Belie, N. (2011). Methyl methacrylate as a healing agent for self-healing cementitious materials. *Smart Materials and Structures*, 20(12), 125016. https://doi.org/10.1088/0964-1726/20/12/125016

Van Tittelboom, K., & De Belie, N. (2013). Self-healing in cementitious materials—A review. *Materials*, 6, 2182–2217. https://doi.org/10.3390/ma6062182

Van Tittelboom, K., De Belie, N., Lehmann, F., & Grosse, C. U. (2012). Acoustic emission analysis for the quantification of autonomous crack healing in concrete. *Construction and Building Materials*, 28(1), 333–341. https://doi.org/10.1016/j.conbuildmat.2011.08.079

Van Tittelboom, K., De Belie, N., Van Loo, D., & Jacobs, P. (2011). Self-healing efficiency of cementitious materials containing tubular capsules filled with healing agent. *Cement and Concrete Composites*, 33(4), 497–505. https://doi.org/10.1016/j.cemconcomp.2011.01.004

Van Tittelboom, K., Gruyaert, E., Rahier, H., & De Belie, N. (2012). Influence of mix composition on the extent of autogenous crack healing by continued hydration or calcium carbonate formation. *Construction and Building Materials*, 37, 349–359. https://doi.org/10.1016/j.conbuildmat.2012.07.026

Van Tittelboom, K., Snoeck, D., Vontobel, P., Wittmann, F. H., & De Belie, N. (2013). Use of neutron radiography and tomography to visualize the autonomous crack sealing efficiency in cementitious materials. *Materials and Structures/Materiaux et Constructions*, 46(1–2), 105–121. https://doi.org/10.1617/s11527-012-9887-1

Van Tittelboom, K., Snoeck, D., Wang, J., & De Belie, N. (2013). Most recent advances in the filed of self-healing cementitious materials. *ICSHM 2013 : 4th International Conference on Self-Healing Materials*, 406–413.

Van Tittelboom, K., Tsangouri, E., Van Hemelrijck, D., & De Belie, N. (2015). The efficiency of self-healing concrete using alternative manufacturing procedures and more realistic crack patterns. *Cement and Concrete Composites*, 57, 142–152. https://doi.org/10.1016/j.cemconcomp.2014.12.002

Van Tittelboom, K., Wang, J., Araújo, M., Snoeck, D., Gruyaert, E., Debbaut, B., Derluyn, H., Cnudde, V., Tsangouri, E., Van Hemelrijck, D., & De Belie, N. (2016). Comparison of different approaches for self-healing concrete in a large-scale lab test. *Construction and Building Materials*, 107, 125–137. https://doi.org/10.1016/j.conbuildmat.2015.12.186

Vijay, K., Murmu, M., & Deo, S. V. (2017). Bacteria based self healing concrete – A review. In *Construction and Building Materials* (Vol. 152, pp. 1008–1014). Elsevier Ltd. https://doi.org/10.1016/j.conbuildmat.2017.07.040

Viljugrein, T. (2017). *Rheological methods to simulate adhesive properties for the wood working industry*. 69–76.

Voinov, O. V. (1976). Hydrodynamics of wetting. *Fluid Dynamics*, 11(5), 714–721. https://doi.org/10.1007/BF01012963

Wang, D., Liu, P., Wang, J., Bao, X., & Chu, H. (2019). Direct Numerical Simulation of Capillary Rise in Microtubes with Different Cross-Sections. *Acta Physica Polonica A*, 135, 532–538. https://doi.org/10.12693/APhysPolA.135.532

Wang, J., Ersan, Y. C., Boon, N., & De Belie, N. (2016). Application of microorganisms in concrete: A promising sustainable strategy to improve concrete durability. *Applied Microbiology and Biotechnology*, 100(7), 2993–3007. https://doi.org/10.1007/s00253-016-7370-6

Wang, W., Zhong, T., Wang, X., & He, Z. (2019). Research Status of Self-healing Concrete. *IOP Conference Series: Earth and Environmental Science*, 218(1), 012037. https://doi.org/10.1088/1755-1315/218/1/012037

Washburn, E. W. (1921). The Dynamics of Capillary Flow. *Physical Review*, 17(3), 273–283. https://doi.org/10.1103/PhysRev.17.273

White, S. R., Sottos, N., R., Geubelle, P., H., Moore, Jeffrey, S., Kessler, M., R., Sriram, S., R., Brown, E., N., & Viswanathan, S. (2001). Autonomic healing of polymer composites. *Nature*, 409(6822), 794. https://doi.org/10.1038/35057232

Wolf, F. G., dos Santos, L. O. E., & Philippi, P. C. (2010). Capillary rise between parallel plates under dynamic conditions. *Journal of Colloid and Interface Science*, 344(1), 171–179. https://doi.org/10.1016/j.jcis.2009.12.023

Wu, M., Hu, X. M., Hu, Z. X., Zhao, Y., Cheng, W. M., & Lu, W. (2019). Two-component polyurethane healing system: Effect of different accelerators and capsules on the healing efficiency of dynamic concrete cracks. *Construction and Building Materials*, 227, 116700. https://doi.org/10.1016/j.conbuildmat.2019.116700

Wu, M., Johannesson, B., & Geiker, M. (2012). A review: Self-healing in cementitious materials and engineered cementitious composite as a self-healing material. *Construction and Building Materials*, 28(1), 571–583. https://doi.org/10.1016/j.conbuildmat.2011.08.086

Wu, P., Nikolov, A. D., & Wasan, D. T. (2017a). Capillary Rise: Validity of the Dynamic Contact Angle Models. *Langmuir*, 33(32), 7862–7872. https://doi.org/10.1021/acs.langmuir.7b01762

Wu, P., Nikolov, A., & Wasan, D. (2017b). Capillary dynamics driven by molecular self-layering. *Advances in Colloid and Interface Science*, 243, 114–120. https://doi.org/10.1016/j.cis.2017.02.004

Xiao, J., Cai, J., & Xu, J. (2018). Saturated imbibition under the influence of gravity and geometry. *Journal of Colloid and Interface Science*, 521, 226–231. https://doi.org/10.1016/j.jcis.2018.03.050

Xiao, J., Luo, Y., Niu, M., Wang, Q., Wu, J., Liu, X., & Xu, J. (2019). Study of imbibition in various geometries using phase field method. *Capillarity*, 2(4), 57–65.

Xing, F., Ni, Z., Han, N., Biqin, Du, X., Huang, Z., & Zhang, M. (2008). Self-healing mechanism of a novel cementitious composite using microcapsules. *International Conference on Durability of Concrete Structures*, 195–204.

Xue, C., Li, W., Li, J., Tam, V. W. Y., & Ye, G. (2019). A review study on encapsulation-based self-healing for cementitious materials. *Structural Concrete*, 20(1), 198–212. https://doi.org/10.1002/suco.201800177

Yaghmaei, A., Torbati, M. K., & Zebarjad, S. M. (2010). Role of nano-dize SiO2 additive on the thermal behavior of cyanoacrylate nanocomposite. *Journal of Vinyl and Additive Technology*, 16(3), 204–208. https://doi.org/10.1002/vnl

Yang, H.-Q., Bayyuk, S., Mazumder, S., Lowry, S., Krishnan, A., Przekwas, A., & Nguyen, L. (2001). Time-accurate, 3-D computation of wire sweep during plastic encapsulation of electronic components. *Journal of Pressure Vessel Technology, Transactions of the ASME*, 123(4), 501–509. Scopus. https://doi.org/10.1115/1.1401024

Yu, T., Zhou, J., & Doi, M. (2018). Capillary imbibition in a square tube. *Soft Matter*, 14(45), 9263–9270. https://doi.org/10.1039/C8SM01494A

Zhang, J., Liu, G., Chen, B., Song, D., Qi, J., & Liu, X. (2014). Analysis of CO2 emission for the cement manufacturing with alternative raw materials: A LCA-based framework. *Energy Procedia*, 61, 2541–2545. https://doi.org/10.1016/j.egypro.2014.12.041

Zhmud, B. V., Tiberg, F., & Hallstensson, K. (2000). Dynamics of Capillary Rise. *Journal of Colloid and Interface Science*, 228(2), 263–269. https://doi.org/10.1006/jcis.2000.6951

Zhong, W., & Yao, W. (2008). Influence of damage degree on self-healing of concrete. *Construction and Building Materials*, 22(6), 1137–1142. https://doi.org/10.1016/j.conbuildmat.2007.02.006

Zhou, J., Ye, G., & van Breugel, K. (2016). Cement hydration and microstructure in concrete repairs with cementitious repair materials. *Construction and Building Materials*, 112, 765–772. https://doi.org/10.1016/j.conbuildmat.2016.02.203

Zhou, S., Zhu, H., & Yan, Z. (2014). The materials, theories and experiments of microcapsule self-healing method—A review. *Tunneling and Underground Construction*, 195–204.

# LIST OF PUBLICATIONS

## Indexed Journal

- **Yip, B. F.**, Mohd Haniffah, M. R., Kasiman, E. H., & Zainal Abidin, A. R. (2022). Research Progress on Microbial Self-Healing Concrete. *Jurnal Teknologi*, 84(3), 25-45. https://doi.org/10.11113/jurnalteknologi.v84.17895. **(Indexed by SCOPUS)**

## Indexed Conference Proceedings

- **Yip, B.F.**, Alias, N.A.F., Kasiman, E.H. (2021). Numerical Modelling of Pollutant Transport in a Straight Narrow Channel using Upwind Finite Difference Method. *IOP Conf. Ser.: Mater. Sci. Eng*. 1153, 012003. https://doi.org/10.1088/1757-899X/1153/1/012003. **(Indexed by Clarivate, Web of Science under Conference Proceedings Citation Index—Science (CPCI-S))**