UNIVERSITI TEKNOLOGI MARA

ENHANCEMENT OF AUTONOMOUS HEALING MORTAR THROUGH ENCAPSULATED BACTERIA BIOMINERALISATION

RADEN MAIZATUL AIMI BINTI MOHD AZAM

Thesis submitted in fulfilment
of the requirements for the degree of
Doctor of Philosophy

Faculty of Civil Engineering

July 2017

ABSTRACT

The autonomous healing by Microbially Induced Calcite Precipitation (MICP) mechanism has become significant interest in a sustainable approach to concrete repair and maintenance. Previous research works reported that *Bacillus pasteurii* and *Bacillus sphaericus* are the most common bacterial species used in concrete associated with bacteria. However, there is limited information on other types of bacteria species as MICP agent in concrete. The vegetative cells of *Geobacillus stearothermophilus* introduced in this study. First, an experimental work was conducted directly incorporating bacteria to assess the improvement that can be made by bacteria without encapsulating it. The results confirmed that direct incorporation increased compressive strength and flexural strength up to 24 % while decreased water absorption rate as compared to control specimens. For further improvement, secondly, vegetative cells of *Geobacillus stearothermophilus* were encapsulated into alginate-hydrogel prior incorporation into the mortar. The urease activity, viability, swelling and water retention properties of the bacterial *Geobacillus stearothermophilus* cell encapsulated in alginate hydrogel were examined. Also, the performance of alginate-encapsulated *Geobacillus stearothermophilus* (AE-GS) in mortar mix as a self-healing agent measured regarding compressive strength, flexural strength, water absorption and crack healing efficiency. The precipitation of calcium carbonate ($CaCO_3$) of AE-GS mortar was confirmed using Thermogravimetric Analysis (TGA). Maximum crack healed at the percentage of 100 % (corresponding to the initial crack width) in average achieved by incorporating 15 % AE-GS (replacement of total weight of mortar) at 60 days of age. However, the lower result of compressive strength and flexural strength, along with higher absorption rate portrayed by the mortar specimens that contained 15 % of AE-GS replacement as compared to control mortar (AE-R) and with those of AE-GS replacement level at 3 % and 9 %. Healing efficiency observed by the whitish precipitation as a crack filling material confirmed by TGA analysis and Scanning Electron Microscopy (SEM) microstructure examination. The optimisation process was conducted using Response Surface Methodology (RSM) to obtain a relationship between factors of bacterial concentration (BC, cfu/ml) and alginate encapsulation (AE, %). Using the RSM evaluation and analysis, the prediction based on the desirability function to achieve higher results of compressive strength, flexural strength and healing efficiency along with lower water absorption rate for BC and AE were 10×10^{10} cfu/ml and 5.37 %, respectively. The establishment of alginate-encapsulated *Geobacillus stearothermophilus* (AE-GS) mortar would give insight on varying the utilisation of bacteria as a repair material. It also would benefit by adopting natural and sustainable approach towards concrete structure crack remediation method.

ACKNOWLEDGEMENT

First and above all, I praise Allah, the Almighty for providing me with this opportunity and granting me the capability to complete writing the thesis. I would like to express my sincere gratitude to my main supervisor Professor Dr Hamidah Binti Mohd Saman for the continuous support during my tenure as a PhD student, for her patience, motivation, enthusiasm, and immense knowledge. I am also very appreciative to my co-supervisors, Associate Professor Ir Dr Kartini Binti Kamaruddin, Associate Professor Dr Noor Hana Binti Hussain and Professor Ir Dr Erik Schlangen for their diligent advice and encouragements. I wish to express my sincere appreciation to Dr Khalilah Binti Abd Khalil for the constant help in encapsulating the bacteria, the optimisation process using response surface methodology (RSM) software and in using the facilities in the Microbiology Laboratory. Without their continued support and interest, this thesis would not have been the same as presented here.

I am greatly indebted to Ministry of Higher Education (MOHE) for providing scholarship MyPhD under a MyBrain15 scheme, Ministry of Science, Technology and Innovation (MOSTI) for the grant. Also, Universiti Teknologi MARA (UiTM) for given me this golden opportunity to pursue PhD; mainly Institute of Graduate Studies (IPSIS), Faculty of Civil Engineering (FCE), Faculty of Applied Sciences (FSG), Institute of Research Management and Innovation (IRMI), Tun Abdul Razak Library (PTAR). Special appreciation to all technicians and laboratory assistants that involved throughout the completion of this thesis.

I wish to acknowledge the support received from my MSc and PhD colleague from FCE and FSG Nur Hanani Abdul Rahim, Nursyazreen Ahmad Mirza, Noor Hana Abdul Rahman, Nurul Ainain Mohd Salim, Normi Idayu, Nurul Fithriah Mohd Amin, Saiyidah Hazirah Zurin Adnan, Dr Suhaidi Ariffin, Dr Anis Low Muhammad Low and Nur Syahirah Sallehudin who knowingly and unknowingly led me to an understanding of some of the subtle challenge in this journey and to our ability to thrive till the end.

I would like to thank my parents late Mohd Azam Bin Asnawi and my mother in law, for their material and spiritual support in all aspects of my life. I also would like to thank my brother, sisters, and brother and sister-in-law, for their support in numerous ways.

Finally, My lovely husband, Ahmad Syamsul Anuar Bin Zainal Abidin. I would like to thank you, without your supports, encouragements and understanding, I may be unable to go through the PhD journey.

TABLE OF CONTENTS

CHAPTER ONE
INTRODUCTION

1.1 BACKGROUND OF STUDY

Concrete broadly used as an engineering material in construction because of its excellent mechanical, durability properties and relatively low cost as compared to other building materials (Araújo et al., 2016; Mignon et al., 2016). However, concrete is susceptible to progression and coalescence in the micro-crack formation due to its inherent heterogeneity, low tensile strength and non-ideal service environment (Khaliq & Ehsan, 2016; Krishnapriya, Venkatesh Babu, & Prince Arulraj, 2015; J. Wang et al., 2015). This major drawback of concrete does not only lead to low strength concrete with reduction of quality and durability but has become an open pathway for the ingress of water and harmful substances that vulnerable to the concrete. The variety of treatment techniques is available all over the globe to repair the concrete cracks with a substantial cost needed. The majority of conventional treatment techniques such as epoxy system, acrylic resins and silicone based materials used as surface treatment are health and environmentally hazardous (Khaliq & Ehsan, 2016; Krishnapriya et al., 2015; Pacheco-Torgal & Labrincha, 2013). It also requires manual and constant observation to reduce crack propagation as limited availability of access for observation in indiscernible location. For that reason, a self-healing approach has become researchers interest as a natural way to remediate cracks.

An alternative technique was introduced which using biomineralisation derived by Microbially Induced Calcite Precipitation (MICP). MICP utilises the ability of urease positive bacteria activity in producing urease enzyme to influence the precipitation calcium carbonate ($CaCO_3$) or calcite. It is an innovative method that has a multi-application in engineering (Abo-El-Enein, Ali, Talkhan, & Abdel-Gawwad, 2012; Anbu, Kang, Shin, & So, 2016; Cardoso et al., 2016; Cheng & Cord-Ruwisch, 2012; Cheng, Cord-Ruwisch, & Shahin, 2013; Chou, Seagren, Aydilek, & Lai, 2011; Colwell et al., 2005; DeJong, Fritzges, & Nüsslein, 2006; Fujita et al., 2004; Hamdan, Kavazanjian Jr, & Rittmann, 2011; Otlewska & Gutarowska, 2016; Varenyam & Zhang, 2012). Bacteria from genus *Bacillus* were widely studied as their capabilities to produce endospore and producing calcium carbonate ($CaCO_3$) by outsourcing nutrient under permitted condition. An endospore is a unit that has been adapted for bacterial survivability because they are resistant to many environmental stresses and are metabolically dormant (Driks, 2002; Perkins & Pero, 2001). To date, among of the bacteria used as MICP in con-