# IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE USING POLYVINYL ALCOHOL FOR PAVEMENT APPLICATIONS

**Teerasak Yaowarat**

มหาวิทยาลัยเทคโนโลยีสุรนารี

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# การปรับปรุงมวลรวมจากคอนกรีตที่ถูกนำกลับมาใช้ใหม่โดยใช้โพลีไวนิลแอลกอฮอล์เพื่อการประยุกต์ใช้ในงานถนน

**นายธีรศักดิ์ เยาวราช**

มหาวิทยาลัยเทคโนโลยีสุรนารี

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิศวกรรมศาสตรดุษฎีบัณฑิต
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มหาวิทยาลัยเทคโนโลยีสุรนารี
ปีการศึกษา 2561

# IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE USING POLYVINYL ALCOHOL FOR PAVEMENT APPLICATIONS

Suranaree University of Technology has approved this thesis submitted in partial fulfillment of the requirements for the Degree of Doctor of Philosophy.

Thesis Examining Committee

(Prof. Dr. Panich Voottipruex)
Chairperson

(Prof. Dr. Suksun Horpibulsuk)
Member (Thesis Advisor)

Arulrajah
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ธีรศักดิ์ เยาวราช : การปรับปรุงมวลรวมจากคอนกรีตที่ถูกนำกลับมาใช้ใหม่โดยใช้โพลีไวนิลแอลกอฮอล์เพื่อการประยุกต์ใช้ในงานถนน (IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE USING POLYVINYL ALCOHOL FOR PAVEMENT APPLICATIONS) อาจารย์ที่ปรึกษา : ศาสตราจารย์ ดร.สุขสันติ์ หอพิบูลสุข, 178 หน้า.

วิทยานิพนธ์ฉบับนี้มีจุดประสงค์เพื่อศึกษาความเป็นไปได้ของการประยุกต์ใช้เศษคอนกรีตโดยการปรับปรุงคุณสมบัติทางวิศวกรรมด้วยโพลิไวนิลแอลกอฮอล์ (PVA) เพื่อเป็นมวลรวมในผิวทางคอนกรีตและชั้นพื้นทางและรองพื้นทาง ซึ่งมีประโยชน์อย่างยิ่งในการลดปริมาณเศษคอนกรีตจากการรื้อถอนโครงสร้างอาคาร และเพิ่มคุณค่าให้กับวัสดุเหลือทิ้ง รวมทั้งช่วยอนุรักษ์แหล่งหินตามธรรมชาติ แต่ความคงทนต่อแรงกระแทกและการขัดสีที่ต่ำของเศษคอนกรีตทำให้คอนกรีตและวัสดุชั้นพื้นทางมีคุณสมบัติด้านกำลังที่ด้อย โดยเฉพาะอย่างยิ่ง กำลังดัด

บทที่หนึ่งและบทที่สองจะกล่าวถึงความเป็นมาของปัญหาและจุดประสงค์หลักของงานวิจัย สรุปข้อดีและข้อเสียของการประยุกต์ใช้เศษคอนกรีตเป็นมวลรวมในงานวิศวกรรมการทาง รวมทั้งผลงานวิจัยในอดีตที่เกี่ยวข้องกับการปรับปรุงคุณสมบัติทางวิศวกรรมของคอนกรีตและวัสดุพื้นทางที่ใช้เศษคอนกรีตเป็นมวลรวม

บทที่สามศึกษากำลังอัดและกำลังดัดของคอนกรีตที่ใช้เศษคอนกรีต (RCA) เป็นมวลรวมหยาบ การออกแบบส่วนผสมใช้วิธีสองขั้นตอน (Two stage mixing approach) ผลการทดสอบแสดงให้เห็นว่ากำลังอัดเพิ่มขึ้นเมื่ออัตราส่วนซีเมนต์ต่อน้ำ (w/c) ลดลง และปริมาณโพลิไวนิลแอลกอฮอล์ (PVA) ลดลง ปริมาณ PVA ที่ให้กำลังดัดสูงสุดมีค่าเท่ากับร้อยละ 1 สำหรับทุกอัตราส่วนซีเมนต์ต่อน้ำ (w/c) และทุกอายุบ่ม ภาพถ่ายจากกล้องจุลทรรศน์อิเล็กตรอนแบบส่องกราด (SEM) ชี้ชัดว่าแผ่นฟิล์มที่เกิดจากโพลิไวนิลแอลกอฮอล์ (PVA) เข้าแทรกตัวอยู่ในโครงสร้างของผลิตภัณฑ์ไฮเดรชั่น ช่วยเสริมแรงและยึดประสานมวลรวมเข้าด้วยกัน และช่วยเพิ่มกำลังดัด แต่ผลการวิเคราะห์การเลี้ยวเบนของรังสีเอ็กซ์ (XRD) บ่งชี้ว่าปริมาณ PVA ที่เพิ่มขึ้น ทำให้ผลิตภัณฑ์ไฮเดรชั่นลดลง และส่งผลให้กำลังอัดของคอนกรีตลดลง

บทที่สี่แสดงถึงความเป็นไปได้ของการใช้เถ้าลอย(FA) ในการปรับปรุงสมบัติด้านกำลังอัดและกำลังดัดของคอนกรีต PVA-RCA อัตราส่วนเถ้าลอยต่อปูนซีเมนต์ในการศึกษานี้เท่ากับ 0:100, 10:90, 20:80 และ 30:70 และอัตราส่วน PVA ต่อวัสดุประสาน (FA และปูนซีเมนต์) เท่ากับร้อยละ 0, 0.5, 1, 1.5 และ 2 ผลการทดสอบแสดงให้เห็นว่าที่อายุบ่มมากกว่า 28 วัน กำลังอัดเพิ่มขึ้นสูงสุดเมื่ออัตราส่วนเถ้าลอยต่อปูนซีเมนต์ (FA/c) เท่ากับ 20:80 การเติมโพลิไวนิลแอลกอฮอล์ร้อยละ 1 ให้กำลังดัดสูงสุด สำหรับทุกอัตราส่วนซีเมนต์ต่อน้ำ (w/c) และทุกอายุบ่มคอนกรีต ภาพถ่าย SEM

แสดงให้เห็นว่า ในช่วงอายุบ่ม 28 วัน เถ้าลอย (FA) ทำปฏิกิริยากับปูนซีเมนต์ส่งผลให้โครงสร้างคอนกรีตแน่นขึ้น และทำให้กำลังรับแรงอัดเพิ่มขึ้น แผ่นฟิล์มที่ปริมาณโพลิไวนิลแอลกอฮอล์ (PVA) ร้อยละ 1 ช่วยเสริมแรงให้โครงสร้างคอนกรีต มีความสามารถต้านทานแรงดัดได้สูงที่สุด

บทที่ห้าแสดงให้เห็นถึงการประยุกต์ใช้เศษคอนกรีต ร่วมกับปูนซีเมนต์และ PVA ในงานพื้นทางและรองพื้นทาง โดยเปรียบเทียบกับเศษคอนกรีตที่ปรับปรุงด้วยปูนซีเมนต์เพียงอย่างเดียว ปริมาณปูนซีเมนต์ในการศึกษานี้เท่ากับร้อยละ 3% ต่อน้ำหนักของเศษคอนกรีต ปริมาณ PVA ที่ใช้ในการศึกษาแปรผันที่ร้อยละ 0.5, 1, 1.5 และ 2 ต่อน้ำหนักของปริมาณน้ำเหมาะสม ผลการทดสอบแสดงให้เห็นว่า การผสม PVA ร้อยละ 2 ช่วยเพิ่มความแกร่ง (Toughness) และกำลังอัดเกือบสามเท่า ซึ่งยืนยันได้จากผล SEM ที่แสดงให้เห็นว่าโครงสร้างของวัสดุมีความแน่น และยึดติดกันด้วยแผ่นฟิล์ม PVA ทำให้โครงสร้างมีช่องว่างลดลง ส่งผลให้กำลังอัดและความแกร่งเพิ่มขึ้น

บทที่หกแสดงถึงบทสรุปโดยรวมของวิทยานิพนธ์ฉบับนี้รวมทั้งข้อเสนอแนะสำหรับงานวิจัยในอนาคต การประยุกต์ใช้เศษคอนกรีตร่วมกับ PVA และเถ้าลอย ในงานวิศวกรรมถนน มีประโยชน์อย่างยิ่งในทางวิศวกรรมและเศรษฐศาสตร์ รวมทั้งเป็นการอนุรักษ์ทรัพยากรมวลรวมตามธรรมชาติ

มหาวิทยาลัยเทคโนโลยีสุรนารี

สาขาวิชา วิศวกรรมโยธา
ปีการศึกษา 2561

ลายมือชื่อนักศึกษา______
ลายมือชื่ออาจารย์ที่ปรึกษา______
ลายมือชื่ออาจารย์ที่ปรึกษาร่วม______

TEERASAK YAOWARAT : IMPROVEMENT OF RECYCLED CONCRETE AGGREGATE USING POLYVINYL ALCOHOL FOR PAVEMENT APPLICATIONS. THESIS ADVISOR : PROF. SUKSUN HORPIBULSUK, Ph.D., 178 PP.

RECYCLED CONCRETE AGGREGATE/POLYVINYL ALCOHOL/PAVEMENT

The objective of this thesis is to study the possibility of Recycled Concrete Aggregate (RCA) modified by Polyvinyl Alcohol (PVA) for using in pavement applications. Utilities of RCA reduce both waste concrete from demolition and the devastating of natural aggregate sources effectively. But, certain limitations such as low crushing strength and low abrasion resistance makes the unfavorable strength properties of RCA concrete and RCA base/subbase especially on the flexural strength.

The first and second chapters present the statement of the problems and the objectives of this study, summary of the advantages and disadvantages of using RCA in pavement applications and the results from previous research on the improvement of engineering properties of RCA.

The third chapter presents the compressive and flexural strengths of concrete using RCA as aggregate. The RCA concrete was made using two-stage mixing approach (TSMA). The results reveal that the compressive strength increases with decreasing water to cement (w/c) ratio. The polyvinyl alcohol to cement (p/c) ratio of 1% is found to be appropriate for achieving the maximum flexural strength for water contents and curing times tested. The SEM results indicate that the PVA films reinforce the hydration products, which increase the flexural strength. However, the XRD results shown that increasing PVA content causes the reduction in hydration products and therefore the lower compressive strength

shown that increasing PVA content causes the reduction in hydration products and therefore the lower compressive strength

The fourth chapter presents the possibility of using Fly Ash (FA) for improving strength properties of PVA-RCA concrete. The Fly Ash to cement (FA/c) ratios in this study were 0:100, 10:90, 20:80 and 30:70. At 28 days, the replacement of 20% FA to c (FA/c = 20:80) is the best proportion to reach the highest compressive strength. The p/b ratio of 1% provides the maximum flexural and split tensile strengths for all FA/c and curing times tested. The SEM result of 28 day-samples shows that the reaction between FA and cement causes denser matrix and higher strength. The PVA films at 1% PVA reinforce the cementitious matrices and hence cause the highest flexural strength.

The fifth chapter presents the possibility of using PVA and cement to stabilize RCA to be used as a pavement base/subbase materials. PVA contents were varied at 0.5%, 1%, 1.5% and 2.0% by weight of optimum water content. 2% PVA increases UCS and toughness of cement stabilized RCA almost 3 times when comparing to those of the samples without PVA. The SEM results reveal that at 2% PVA, the matrix was dense and less voids because PVA films cover RCA and entwine it together, resulting in high toughness and compressive strength.

The sixth chapter presents the conclusions of this study. The recommendations for future work were also presented in this chapter. The use of RCA together with PVA and FA in road engineering applications is useful in term of engineering and economic and environmental perspectives.

มหาวิทยาลัยเทคโนโลยีสุรนารี

School of Civil Engineering

Academic Year 2018

Student's Signature ธีรศักดิ์ เยาวราช

Advisor's Signature

Co-Advisor's Signature

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Teerasak Yaowarat

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# ABBREVIATIONS AND SYMBOLS

RCA = Recycled Concrete Aggregate

RA = Recycled Aggregate

OPC = Ordinary Portland Cement

PMC = Polymer modified concretes

PVA = Polyvinyl alcohol

FA = Fly ash

NA = Natural aggregate

SEM = Scanning Electron Microscope

XRD = X-ray Diffraction

w/c = Water to cement ratio

p/c = Polyvinyl alcohol to cement ratio

wt% = Percentage by weight

TSMA = Two-stage mixing approach

NMA = Normal Mixing approach

C&D = Construction and demolition waste

$C_3S$ = Tricalcium Silicate

$C_2S$ = Dicalcium Silicate

$C_3A$ = Tricalcium Aluminate

$C_4AF$ = Tetracalcium Aluminoferrite

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# ABBREVIATIONS AND SYMBOLS (Continued)

C-S-H = Calcium-Silicate-Hydrate

CH = Calcium Hydroxide

ITZ = The interfacial transition zone

RAC = Recycled Aggregate Concrete

NC = Natural Concrete

EDS = Energy-dispersive X-ray spectroscopy

GFA = Ground fly ash

GBA = Ground bagasse ash

CON = Conventional concrete

POFA = Ground palm oil fuel ash

cNA = Crushed aggregates

rNA = River aggregates

P = Maximum applied load

L = Span length

b = Average width of the specimens

h = Average depth of the specimens

d = average diameter of the specimens

w/b = Water to binder ratio

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# ABBREVIATIONS AND SYMBOLS (Continued)

FA/c = Fly Ash to cement ratio

p/b = Polyvinyl alcohol to binder ratio

UCS = Unconfined Compressive Strength

CBR = California bearing ratio

RLT = Repeated load triaxial

LA = Los Angeles abrasion

GP = General Portland

USCS = Unified Soil Classification System\

MDD = Maximum dry density

OMC = Optimum moisture content

$\gamma$ = Dry unit weight (kN/m$^3$)

$\omega$ = Moisture Content (%)

$M_R$ = Resilient modulus

$\sigma_d$ = Deviator stress

$\varepsilon_r$ = Resilient strain

$\sigma_3$ = Confining Pressure

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# CHAPTER I

# INTRODUCTION

## 1.1 Statement of the problem

Nowadays, the infrastructure development such as highways, bridges and buildings is being constructing. Granular materials are then increasingly being used for concrete production and pavement applications. Subsequently, large amount of natural resources are consumed every day while large amount of waste materials have occurred from demolition of the concrete structure which are mainly destined for landfill.

Construction sectors generate large amount of Recycled Concrete Aggregate (RCA) from demolition concrete structures. FHWA (2004) mentioned that RCA is generally generated from old concrete pavements, bridge structures or decks, sidewalks, curbs and gutters. RCA is increasing globally due to rapid increase in construction and demolition activities in construction sectors.

Several countries, states, and agencies have raised concerns of availability of natural aggregate and the growth of amount of waste dispose back to environment. Therefore, the reuse of the construction and demolition waste materials as an alternative aggregate in infrastructure applications is significant.

To reduce the usage of natural resources and the waste disposed to the environment, RCA has been increasingly used by the infrastructure sectors. It can be used as coarse aggregate in concrete pavement and in stabilized base. Several studies

(Behera et al. 2014; Dilbas et al. 2014; Omary et al. 2016; Otsuki et al. 2003) reported that RCA concrete often exhibited low compressive strength, wide variability in quality, high drying shrinkage, large creep and low elastic modulus. Nogchi (2001) and Olorunsogo (2002) indicated that the compressive strength and durability against chloride resistance of RCA concrete gradually decreased as the amount of RCA increased. Silva at el. (2014) suggested that RCA concrete should only be used in non-structural applications such as rigid pavement and canal. However, Disfani et al. (2012); and Tam and Tam (2007) found that the usage of Recycled Concrete Aggregate would significantly reduce carbon footprints and environmental friendly.

Even though research works on the RCA concrete and cement stabilized RCA are available, they are mainly paid attention on compressive strength, while the research on flexural strength of concrete pavement and cyclic response of cement stabilized RCA has been very limited. The failure of concrete pavement is mostly due to low flexural resistance and the failure of cement stabilized base is mainly caused by the excessive cyclic loads.

Allahverdi et al. 2010 have found that the water-soluble polymer, Polyvinyl alcohol (PVA), is able to improve the flexural strength of concrete. The flexural strength of the concrete specimens increased with increasing PVA-to-cement (by weight), p/c ratio due to a significant reduction of both total permeable pore volume and water absorption of the specimens. PVA effectively packs the specimen and results in a dense matrix which is similar to improvement of concrete by adding Fly Ash (FA).

The application of PVA to cement stabilized soil for pavement base and subbase has been limited due to the lack of laboratory and field testing. Previously, the effect of PVA-stabilized soil was investigated by Brown et al. (2004) and the results indicated that PVA acts as a polymeric binder by entwining within the soil particles and thus stabilizing the loose soil into a relatively firm mass with higher strength. PVA has also been reported to enhance the ductility as well as the toughness of clay similar to the fiber reinforcement (Mirzababaei et al. 2018a; Mirzababaei et al. 2017a).

Therefore, this thesis attempts to study the strength development and flexural strength in RCA concrete with polyvinyl alcohol (PVA) and also to investigate the factors controlling strength development of the RCA-PVA concrete when added fly-ash (FA). Moreover, this research investigates the usage of polyvinyl alcohol (PVA) and cement for the improvement of mechanical strengths of RCA to be used as an alternative material in pavement base/subbase applications.

## 1.2 Objectives of the study

1.2.1 To investigate a possibility of using Recycled Concrete Aggregate (RCA) as coarse aggregate to manufacture polyvinyl alcohol (PVA) modified concretes for pavement application.

1.2.2 To investigate the combined effect of PVA and Fly Ash (FA) on the mechanical properties improvement of RCA concrete.

1.2.3 To study the performance of PVA with cement stabilized RCA as a material for pavement base/subbase applications.

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## 1.3 Organization of the dissertation

This thesis consists of six chapters and outlines of each chapter are presented as follows:

**Chapter I** presents the introduction part, describing the statement of the problems, the objectives of the study and the organization of the dissertation.

**Chapter II** presents the literature review of Ordinary Portland Cement (OPC), Recycled Concrete Aggregate (RCA), Polyvinyl alcohol (PVA) modified concretes, precursor for producing concrete, factors affecting compressive and flexural strength, analytical techniques, cement binder and concrete applications.

**Chapter III** presents the possibility of using RCA to fully replace natural coarse aggregate in concrete production and modified concrete by added Polyvinyl alcohol (PVA) for pavement applications. The initial and final setting times were investigated for all samples to explain the influences of PVA content on the hydration process. Compressive and Flexural Strength is used as an indicator for this investigation. The microstructural and chemical development of RCA- PVA concrete is observed through Scanning Electron Microscope (SEM) and X-ray Diffraction (XRD) analysis for understanding the role of influential factors controlling the strength development. The influential factors studied in this study include w/c, p/c (wt%) ratio and curing time in a water. The PVA solution was prepared in five different percentages with respect to the cement weight, viz. 0, 0.5, 1, 1.5, 2.0, respectively, and four different w/c ratios including 0.3, 0.4, 0.5 and 0.6 were studied. The mixtures with different ingredients are mixed under two-stage mixing approach (TSMA). Compressive and Flexural Strength analysis on the concrete samples are undertaken after 7, 14 and 28 days of curing time.

**Chapter IV** This chapter evaluates the usage of using PVA and FA for the improvement of mechanical strengths of RCA concrete. The specimens were prepared at a fixed w/b = 0.5 with various PVA and FA replacement ratios. The PVA solution was prepared in five different percentages with respect to the binder (p/b) weight: 0, 0.5, 1, 1.5, 2.0 and the FA replacement (FA to cement, FA/c) ratios were 10/90, 20/80 and 30/70. The influences of PVA to binder (p/b) and FA/cement (FA/c) ratios on the mechanical strengths of RCA-PVA-FA concrete were assessed by the compressive, split tensile and flexural strength tests. The mechanisms controlling the improvement of mechanical strengths are discussed based on the results of microstructural analysis using scanning electron microscopy (SEM) and energy-dispersive X-ray (EDX) methods

**Chapter V** This chapter studies the usage of polyvinyl alcohol (PVA) and cement for improving the mechanical strengths of RCA to be used as an alternative material in pavement base/subbase applications. OPC cement was used to stabilize RCA in 3% by weight of the dry RCA and the four PVA percentages by dry weight of RCA which were evaluated were with 0.5%, 1%. 1.5% and 2% dosages. The laboratory evaluation was comprised of pH, particle size distribution analysis and was investigated the influence of the PVA on unconfined compressive strength (UCS), California bearing ratio (CBR) and repeated load triaxial (RLT) of cement-stabilized RCA, which this research study seeks to address. A systematic experimental program was conducted by varying the percentage of PVA combined with cement and comparing to the unbound-RCA sample and explains the results using scanning electron microscope (SEM).

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**Chapter VI** concludes the present work and suggests the topics for further study.

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# CHAPTER II

# LITERATURE REVIEW

## 2.1 Introduction

Since 2001s, several researchers have studied the usage of recycled materials as substitute materials for concrete production. In term of engineering, economic and environmental reasons, C&D materials have been used in infrastructure sector (Dosho, 2007; FHWA, 2004). Due to the limitation of natural resources and high cost of waste disposal, recycled materials have been studied and have been used in Europe. Even though Asia is rich in natural resources, the use of by-product materials has been also used. It can reduce the demand of natural aggregate, reduce carbon footprint and sustain the usage of virginal aggregate. Furthermore, quarry blasting process, crushing, transport, and stocking consumes a lot of energy and seriously ruin the environment. Then we need to break the way curb using virginal material and reuse by product materials.

The viability of recycled material in construction industry would benefit in two ways. First, the extraction of natural aggregate and waste disposal would reduce. Second, the cost of construction might be cheaper.

To increase and enhance the utilization of recycled materials, the extensive study has widely investigated the possibility of usage of Recycled Concrete Aggregate (RCA) which obtained from demolition of structure for producing concrete to be an alternative pavement material.

## 2.2 Ordinary Portland Cement (OPC)

Portland cement is a hydraulic cement composed primarily of hydraulic calcium silicates. Hydraulic cements harden by reacting chemically with water. During this reaction, cement combines with water to form a stonelike mass, called paste. When the paste (cement and water) is added to aggregates (sand and gravel, crushed stone, or other granular materials) it binds the aggregates together to form concrete, the most widely used construction material. Although the words "cement" and "concrete" are used interchangeably in everyday usage, cement is one of the constituents of concrete. Cement is a very fine powder and concrete is a stonelike material. Cement constitutes 7% to 15% of concrete's total mass by weight.

Portland cement is a fine, gray powder that consists of a mixture of the hydraulic cement minerals, Tricalcium silicate, Dicalcium silicate, Tricalcium aluminate, and Tetracalcium aluminoferrite which can present the Chemical compound and initials as shown **Table 2.1.**

**Table 2.1** the main composition of Portland cement.

| **Composition name** | **Chemical composition** | **initials** |
|---|---|---|
| Tricalcium Silicate | $3CaO \cdot SiO_2$ | $C_3S$ |
| Dicalcium Silicate | $2CaO \cdot SiO_2$ | $C_2S$ |
| Tricalcium Aluminate | $3CaO \cdot Al_2O_3$ | $C_3A$ |
| Tetracalcium Aluminoferrite | $4CaO \cdot Al_2O_3 \cdot Fe_2O_3$ | $C_4AF$ |

For producing Portland cement, raw materials are selected, crushed, ground, and proportioned so that the resulting mixture has the desired fineness and chemical composition for delivery to the pyroprocessing system. The major chemical constituents of Portland cement are calcium, silicon, aluminum, iron, and oxygen. Minor constituents, generally in a total amount of less than 5% by weight of the mixture, include magnesium, sulfur, sodium, and potassium, which can see the SEM micrographs of OPC in **Figure 2.1**, while the physical and chemical properties of OPC are enlisted in **Tables 2.2**.

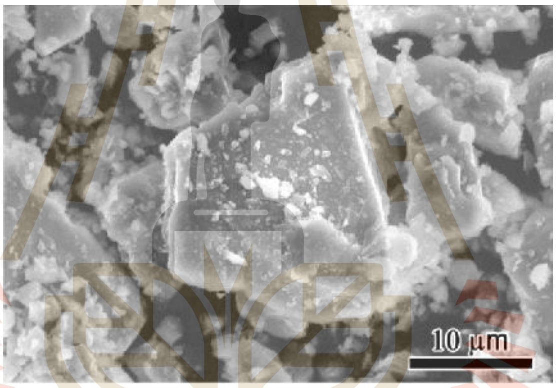

**Figure 2.1** the SEM micrographs of OPC (Hongfang, 2015).

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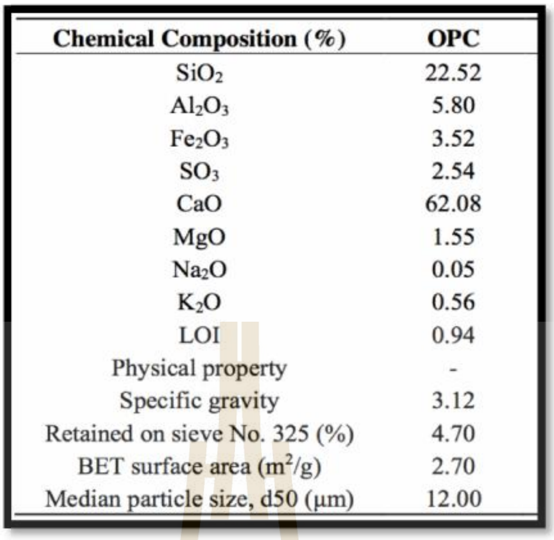

| Chemical Composition (%) | OPC |
|---|---|
| $SiO_2$ | 22.52 |
| $Al_2O_3$ | 5.80 |
| $Fe_2O_3$ | 3.52 |
| $SO_3$ | 2.54 |
| CaO | 62.08 |
| MgO | 1.55 |
| $Na_2O$ | 0.05 |
| $K_2O$ | 0.56 |
| LOI | 0.94 |
| Physical property | - |
| Specific gravity | 3.12 |
| Retained on sieve No. 325 (%) | 4.70 |
| BET surface area ($m^2/g$) | 2.70 |
| Median particle size, d50 (μm) | 12.00 |

**Tables 2.2** the physical and chemical properties of OPC (Hongfang, 2015).

There are wet-process and dry-process portland cement plants. In the wet process, the ground raw materials are suspended in sufficient water to form a pumpable slurry. In the dry process, they are dried to a flowable powder. New portland cement plants in the United States have exclusively used the dry process because of its lower thermal energy requirement. Thermal energy consumption ranges from about 2.7 to 7.3 million Btu per ton.

The wet process uses rotary kilns exclusively. The dry process also can employ simple rotary kilns. Thermal efficiency can be improved, however, through the use of one or more cyclone-type preheater vessels that are arranged vertically, in series, ahead of the rotary kiln in the material flow path. It can be further improved by diverting up to 60% of the thermal energy (i.e. fuel) required by the pyroprocessing system to a special calciner vessel located between the preheater vessels and the rotary kiln.

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The rotary kiln is the heart of the Portland cement process since the several and complex chemical reactions necessary to produce portland cement take place there. The Portland cement kiln is a slightly inclined, slowly rotating steel tube that is lined with appropriate refractory materials. Fuel is supplied at the lower or discharge end of the kiln. The hot, gaseous combustion products move countercurrent to the material flow, thereby transferring heat to the solids in the kiln load.

The product of the rotary kiln is known as clinker. Heat from just produced clinker is recuperated in a clinker cooling device and returned to the pyroprocess by heating combustion air for the kiln and/or calciner.

The cooled clinker is mixed with a form of calcium sulfate, usually gypsum, and ground in ball or tube mills in the finish mill department to produce portland cement. Portland cements are shipped from the packhouse or shipping department in bulk or in paper bags by truck, rail, barge, or ship.

## 2.3 The Hydration Reactions

Each of the four main cement minerals reacts at a different rate and tends to form different solid phases when it hydrates. The behavior of each of these minerals has been studied by synthesizing it in its pure form and hydrating it under controlled conditions, and these reactions are discussed in this section. It should be noted that during the actual cement hydration process all the minerals dissolve into the same pore solution, and thus the solid hydration products are associated with the pore solution as a whole rather than a particular cement mineral. However, the individual reactions provide a good approximation of the overall hydration behavior of cement.

### 2.3.1 Hydration of the calcium silicate minerals ($C_3S$ and $C_2S$)

Tricalcium silicate ($C_3S$) is the most abundant and important cement mineral in Portland cements, contributing most of the early strength development. The hydration of $C_3S$ can be written as:

$$2(3CaO \cdot SiO_2) + 6H_2O \longrightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2$$

$$\text{Or : } 2C_3S+6H_2O \longrightarrow C_3S_2H_3+3Ca(OH)_2 \qquad (2.1)$$

The dicalcium silicate phase ($C_2S$) reacts according to:

$$2(2CaO \cdot SiO_2) + 4H_2O \longrightarrow 3CaO \cdot 2SiO_2 \cdot 3H_2O + 3Ca(OH)_2$$

$$\text{Or : } 2C_2S+4H_2O \longrightarrow C_3S_2H_3+Ca(OH)_2 \qquad (2.2)$$

The hydration products of $C_2S$ are the same as those of $C_3S$, but the relative amount of $Ca(OH)_2$ formed is less. $C_2S$ is much less soluble than $C_3S$, so the rate of hydration is much slower. $C_2S$ hydration contributes little to the early strength of cement, but makes substantial contributions to the strength of mature cement paste and concrete.

### 2.3.2 Hydration of the calcium aluminate/ferrite minerals ($C_3A$ and $C_4AF$)

The hydration of the aluminate and ferrite minerals is somewhat more complex than that of the calcium silicate minerals, and the reactions that take place depend on whether sulfate ions are present in the pore solution. $C_3A$ is highly soluble, even more so than $C_3S$. If $C_3A$ is hydrated in pure water, calcium aluminate hydrates form. The reaction sequence is:

$$3CaO \bullet Al_2O_3 + 6H_2O \longrightarrow 3CaO \bullet Al_2O_3 \bullet 6H_2O$$

$$\text{Or : } C_3A + 6H_2O \longrightarrow 3C_3AH_6 \qquad (2.3)$$

The final reaction product, $C_3AH_6$, is called hydrogarnet. The initial reaction is so rapid that if it is allowed to occur in a portland cement paste it would release large amounts of heat and could cause the paste to set within a few minutes after mixing, an undesirable condition known as flash set. The purpose of adding gypsum ($CaSO_4 \bullet 2H_2O$) to Portland cement is to prevent this from happening. The gypsum is also highly soluble, rapidly releasing calcium and sulfate ions into the pore solution. The presence of the sulfate ions causes the $C_3A$ to undergo a different hydration reaction. The reaction of $C_3A$ and gypsum together is:

$$3CaO \bullet Al_2O_3 + CaSO_4 \bullet 2H_2O \longrightarrow 3CaO \bullet Al_2O_3 \bullet 3CaSO_4 + 31H_2O$$

$$\text{Or : } C_3A + \text{Gypsum} \longrightarrow \text{Ettringite} \qquad (2.4)$$

Where $3CaO \bullet Al_2O_3 \bullet 3CaSO_4 + 31H_2O$ is the mineral Ettringite.

The ferrite phase ($C_4AF$) reacts in a similar fashion to the $C_3A$, but more slowly. One important difference is that some of the aluminum in the reaction products is substituted for iron. The amount of substitution depends on many factors including the composition of the $C_4AF$ and the local conditions in the paste. The reaction of $C_4AF$ had occur at first stage, by $C_4AF$ will react with Gypsum and $Ca(OH)_2$ to form like a needle structures of Sulphoaluminate and Sulphoferrite, A convenient way to represent these reactions is:

$$4CaO\cdot Al_2O_3+Fe_2O_3+CaSO_4\cdot 2H_2O+Ca(OH)_2 \rightarrow 3CaO(Al_2O_3,Fe_2O_3)\cdot 3CaSO_4$$

$$\text{Or : } C_4AF + \text{Gypsum} + Ca(OH)_2 \rightarrow \text{Sulphoaluminate and Sulphoferrite} \quad (2.5)$$

### 2.3.3 Influence of the Compound Composition on Properties of Cement

$C_3S$ and $C_2S$ are the most important compounds, it is responsible for strength by the $C_3S$ will contributes most the strength development during the first four weeks and $C_2S$ influences the gain in strength development from 4 weeks onwards. At the age of about one year, two compounds, contribute approximately equally to ultimate strength of Portland cement. $C_3A$ contribute to the strength of the cement paste at one to three days, and possibly longer, but causes retrogression at an advanced age, particularly in cements with a high $C_3A$ or ($C_3A$+$C_4AF$) content. The role of $C_4AF$ in the development of strength of cement is not clear till now, but there certainly is no appreciable positive contribution. The compressive strength of main compounds compared with time can see in **Figure 2.2.**

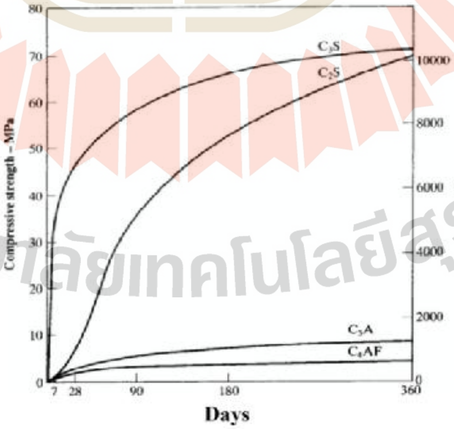

**Figure 2.2** Contribution of Compressive strength of $C_3S$, $C_2S$, $C_3A$ and $C_4AF$ with time (Lerch, 2008)

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### 2.3.4 Calcium-Silicate-Hydrate (C-S-H) gel

The C-S-H gel is not only the most abundant reaction product, occupying about 50% of the paste volume, but it is also responsible for most of the engineering properties of cement paste. This is not because it is an intrinsically strong or stable phase but because it forms a continuous layer that binds together the original cement particles into a cohesive whole (see **Figure 2.3**). All the other hydration products form as discrete crystals that are intrinsically strong but do not form strong connections to the solid phases they are in contact with and so cannot contribute much to the overall strength. The ability of the C-S-H gel to act as a binding phase arises from its nanometer-level structure. Because of its importance and complexity, an entire is devoted to the structure and properties of C-S-H. Here we will discuss two of its most important general features: the internal pore system and the two morphologies.

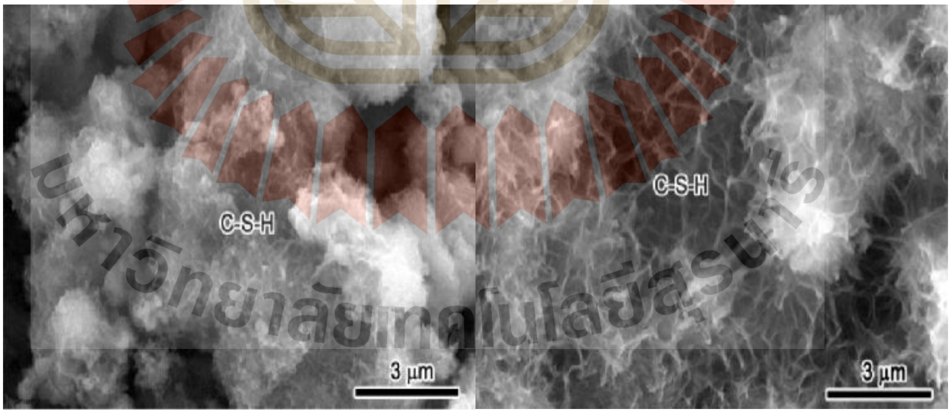

**Figure 2.3** The SEM images of C-S-H structure (Li, 2015).

As C-S-H gel grows outward from the cement particles, it does not take the form of a monolithic solid phase but instead develops an internal system of tiny pores, called gel pores, which are hundreds or thousands of times smaller than the original capillary pores. Although the liquid water in the gel pores is not part of the solid C-S-H phase in a chemical sense, it is physically isolated and thus cannot undergo further chemical reaction with the cement minerals. This is the main reason for the range of water contents of C-S-H gel. The C-S-H gel, including its internal gel pores, occupies significantly more volume than the original $C_3S$ and $C_2S$ mineral that it replaces.

This causes the layers of C-S-H gel to expand outward and interconnect into a continuous phase, causing the cement paste to first set and then harden into a strong solid. Because the overall volume of the cement paste does not change significantly after mixing, the increase in the volume of solid phases causes the capillary pore system to decrease in volume and, if the w/c is reasonably low, to become discontinuous. This greatly decreases the permeability of the cement paste, meaning that it is more difficult for liquid water and dissolved ions to move through the pore system.

### 2.3.5 Calcium Hydroxide (CH)

Calcium hydroxide, also known by its mineral name portlandite, forms from $C_3S$ and $C_2S$. It occupies about 15% of the volume of a normal portland cement paste. Calcium hydroxide forms as crystals with a wide range of shapes and sizes, depending primarily on the amount of room available for growth. Crystals that nucleate (form initially) in the capillary pores tend to form irregular hexagonal plate-shaped crystals several microns across, large enough to be seen in an optical microscope (see **Figure 2.4**).

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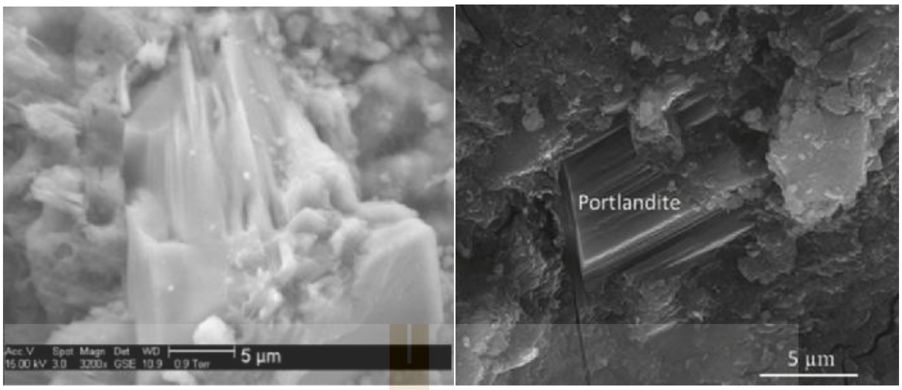

**Figure 2.4** The SEM images of CH structure (Wang, 2008; Frias, 2015).

These crystals can completely engulf a small cement particle next to it. A significant proportion of the calcium hydroxide forms as an intimate mixture with the C-S-H gel, particularly the low-density C-S-H. These crystals tend to be much smaller, with many under 1 £gm in diameter, because their growth is impeded by the surrounding solid. There is some evidence of nanometer-scale CH in cement pastes as well. This is logical considering the fact that C-S-H, which has a nanometer-level morphology, forms in conjunction with CH. At such a small length scale, which is on the order of hundreds of atoms, it is difficult to clearly distinguish between CH and C-S-H, since the latter contains a significant proportion of Ca-OH bonds.

### 2.3.6 Calcium trisulfoaluminate hydrate (Ettringite)

The reaction occurs very rapidly once cement comes into contact with mix water. Usually, the gypsum is consumed first and the remaining tricalcium aluminate ($C_3A$) will continue to react with the previously formed ettringite (see **Figure 2.5a**) to create a compound called calcium monosulfoaluminate ($3CaO•Al_2O_3•CaSO_4•12H_2O$) as shown in **Figure 2.5b**. Monosulfoaluminate takes up less space than ettringite. It is a stable compound unless additional sulfates become

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available whereby it can combine with these sulfates to reform ettringite in an expansive reaction. This is the basic mechanism for sulfate attack in hardened concrete subjected to external sulfate solutions.

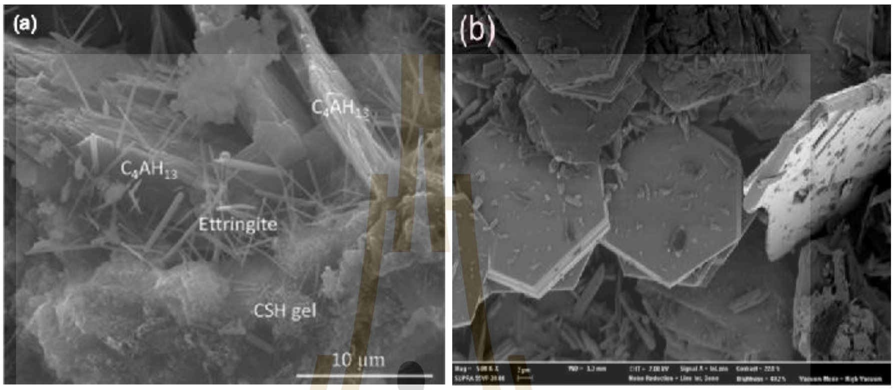

**Figure 2.5** The SEM images of (a) Ettringite (Frias, 2015) (b) Monosulfate (Choi, 2012)

Locher et al. (1974) explained about the formation of the hydration product and the creation of cement paste structure after mixing, the hydration process of cement and development of cement paste structure can be presented in three stages, depicted in **Figure 2.6**.

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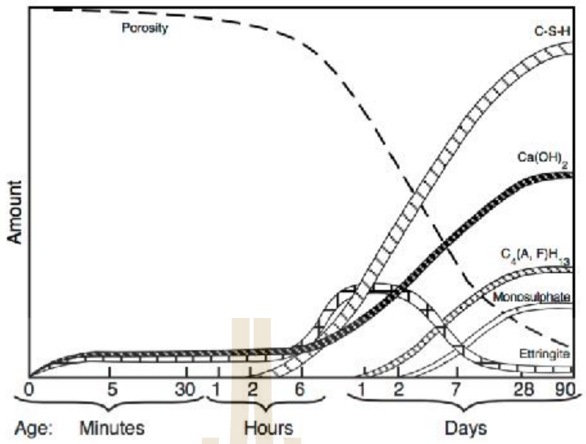

**Figure 2.6** Formation of the of hydration products and the creation of cement paste structure (Locher, 1974)

And later, Franus et al. (2015) investigate the microstructure of hydration products of Portland cement by using SEM images. In the first stage of cement hydration the calcium hydroxide (portlandite) is separated. Its formation is a result of the hydrolysis of tricalcium ($C_3S$) and dicalcium ($C_2S$) silicates, what has a place after a few hours of mixing Portland cement with water. The resulting calcium hydroxide at solid phase of paste is present primarily in the form of portlandite. It creates massive, hexagonal crystals about size of 40 microns (**Figure 2.7a**), which aggregates taking the form of column (**Figure 2.7b**). The morphology of the resulting portlandite crystals is dependent on available free space for crystallization (w/c), the type of admixtures and additives. Portlandite in hydratated paste of Portland cement is up to 25% by volume of solid phase.

In the second period of hydration of cement paste the first forms of hydrated calcium silicates are created. Their quantitative contents in completely hydrated paste

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of Portland cement is between 50-60% of the volume of all solid phases. Proposed by Diamond (1986) model of the morphological distribution of C-S-H gel in cement

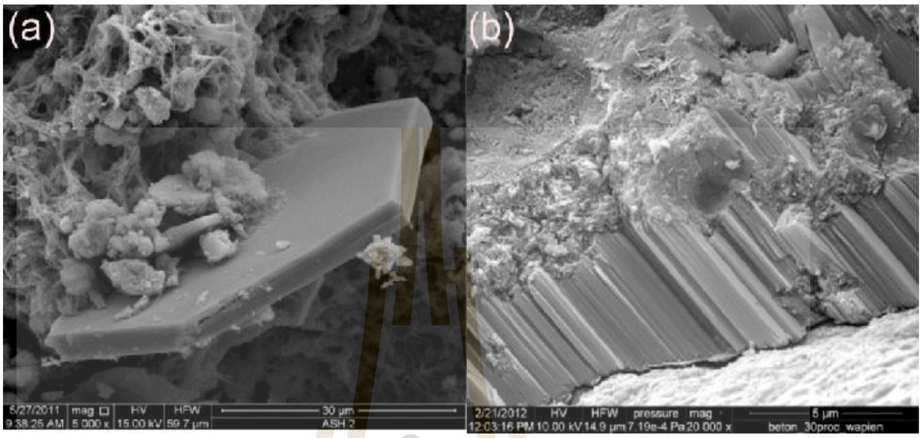

**Figure 2.7** (a) Hexagonal plate of portlandite (b) Column aggregate of portlandite (Franus, 2015)

paste distinguish form of fiber from size of 2 microns - characteristic for the early stages of hydration (**Figure 2.8a**), which goes in the form of a mesh, so-called "honeycomb" (**Figure 2.8b**). Subsequent stages of maturing the paste constituted forms becoming more and more massive consisting of a packed and interspersed with each other thin crystals (so called foils), up to the formless and massive gel characteristic for old pastes.

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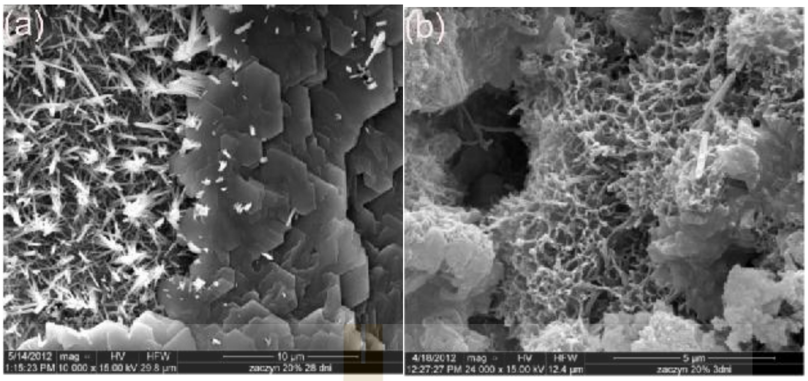


**Figure 2.8** (a) Needle form of C-S-H and plates of portlandite (b) Transformations of portlandite into solid forms, and needle forms of C-S-H into “honeycomb” structure (Franus, 2015)

In the third period of paste hydration occurs pore filling of hardening cement paste by short fibers or lamellar phases of hydrated calcium silicates. The duration of this stages is a period of several days to several months, and covers almost complete hydration of the cement. A characteristic feature of this phase is transformation of calcium aluminate trisulfate $3CaO{\cdot}Al_2O_3{\cdot}3CaSO_4{\cdot}32H_2O$ to calcium aluminate monosulfate $3CaO{\cdot}Al_2O_3{\cdot}CaSO_4{\cdot}12H_2O$. Ettringite crystals phases typically form an elongated crystals about circular habit similar to the needle (**Figure 2.9a**), while tobermorite create lamellar aggregates (**Figure 2.9b**). The spectra of the chemical composition of the main phase formed during the maturation of the cement paste is shown in **Figure 2.10**.

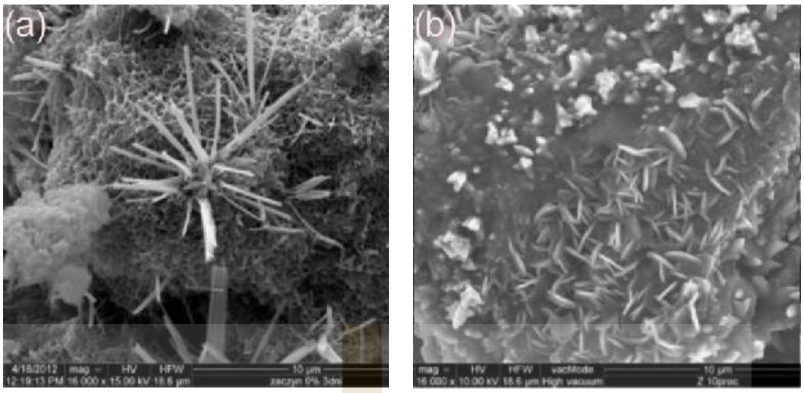
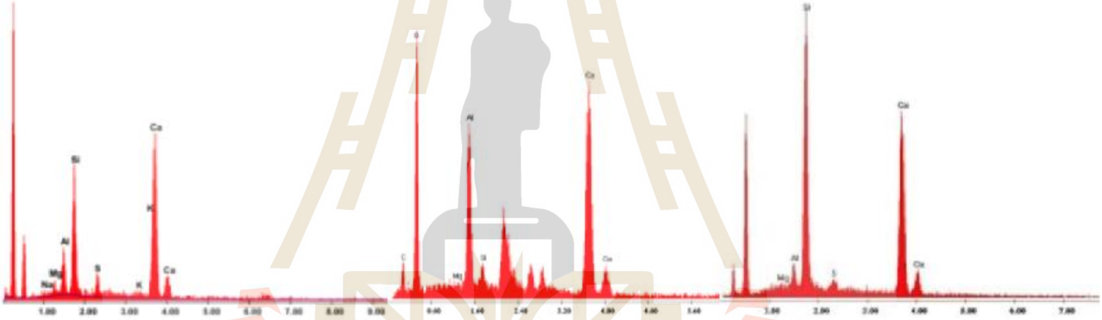


**Figure 2.9** (a) Needle crystal of ettrigite (b) plate crystals of tobemorite (Franus, 2015)



EDS of C-S-H phase EDS of portlandite EDS of C-S-H honeycomb

**Figure 2.10** Mineral phases occurring in maturing cement paste (Franus, 2015)

## 2.4 General features

The hydration products in cement paste do not exist in isolation, but are entangled with one another at the scale of microns and even nanometers. The possible exception to this is the high-density C-S-H phase that forms within the boundaries of the original cement grains. Thus in describing the microstructure of cement paste the structure of the individual solid phases is not as relevant as the overall distribution of

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solid phases and porosity. With this in mind, a basic but useful description of cement paste microstructure is comprised of just three "phases" (see **Figure 2.11**).

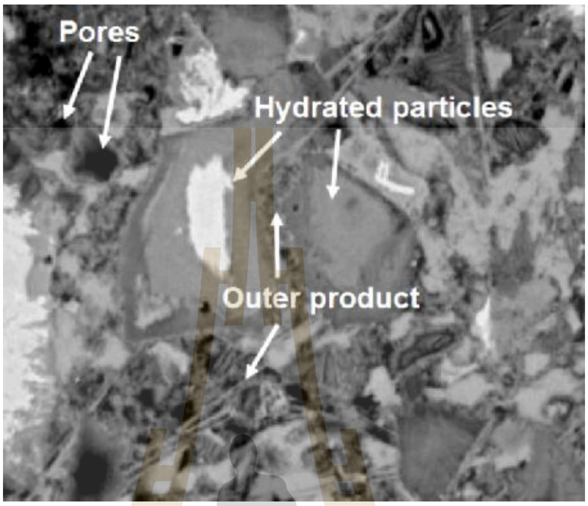

**Figure 2.11** Backscattered SEM image of a mature cement paste showing the main microstructural features. (Image courtesy of Paul Stutzmann, Concrete Microscopy Library).

**2.4.1 Hydrated cement particles:** These consist of high-density C-S-H, and in some cases an interior core of unhydrated cement. These behave as individual solid particles within a continuous matrix analogous to the aggregate particles in concrete. These features are sometimes called "phenograins", which simply refers to the fact that they are distinctly visible in a microscope.

**2.4.2 Outer hydration product:** This is the continuous phase that grows within the capillary pore space and binds the cement together. Following the analogy used above, it plays a role similar to cement paste in concrete. It consists of solid C-S-H gel, gel pores, calcium hydroxide, and calcium sulfoaluminate phases. This "phase" appears as various shades of speckled grey in an optical or electron microscope, and is sometimes referred to as "groundmass." By far the most important individual phase is, of course, the low density C-S-H gel (and its gel pores), because its high surface area gives this phase its strength.

**2.4.3 Large pores:** These consist of true capillary pores, entrapped air voids, and the entrained air system. These features appear as discrete black voids in a microscope. The large pore system can be continuous or discontinuous, depending on the degree of hydration and starting w/c, but this cannot be determined from microscopy.

**2.4.4 The interfacial transition zone (ITZ):** The cement particles in fresh concrete, which are suspended in the mix water, cannot pack together as efficiently when they are in the close vicinity of a much larger solid object, such an aggregate particle. This is actually a general phenomenon associated with particle packing, known as the "wall effect." In the case of concrete, this is effect is magnified by the shearing stresses exerted on the cement paste by the aggregate particles during mixing, which tend to cause the water to separate from the cement particles. The result is a narrow region around the aggregate particles with fewer cement particles, and thus more water. This is called the interfacial transition zone, abbreviated ITZ which can see in **Figure 2.12**.

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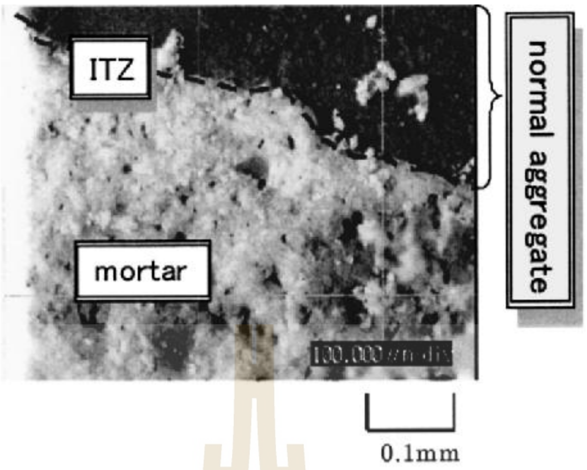

**Figure 2.12** The ITZ between mortar and aggregate in concrete (Otsuki, 2003).

### 2.4.5 Effect of w/c Ratio

Kim et al. (2014) concluded that, the additional mixing water can help easy mixing and workability but causes increased porosity, which yields degradation of durability and structural performances by the larger water content in cement mortar leads coarse pore distribution. **Figure 2.13** shows changes in strength and porosity with w/c ratios, with increasing w/c ratio (additional water amount) from 0.45 to 0.60, porosity goes up to 150% and compressive strength is reduced to 75.6%, This also similarly result to Albano et al. (2009), Ait-Aider et al. (2007), Ma et al. (2014), Alawode et al. (2011), Moghadam et al. (2012) and Singh et al. (2015). Although they have the same cement amount, 33% additional water causes considerable changes in the performances. This can confirm that, increasing w/c ratio leads coarse larger pore and also increase porosity of cement paste sample which affecting to the compressive strength, elastic modulus, durability and stiffness of cement paste directly as seen in **Figure 2.14.**

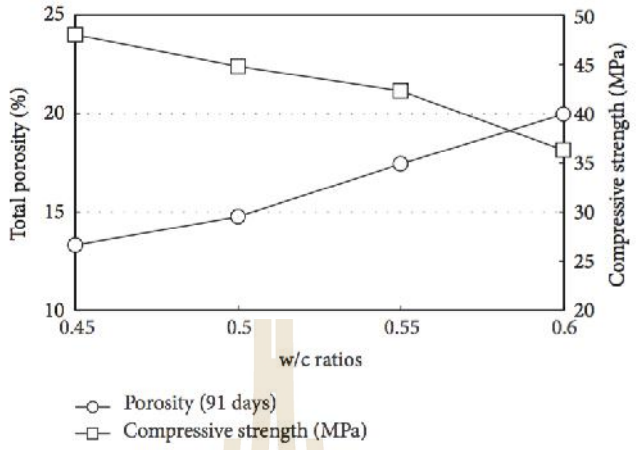

**Figure 2.13** Strength and porosity with different w/c ratios (Kim, 2014)

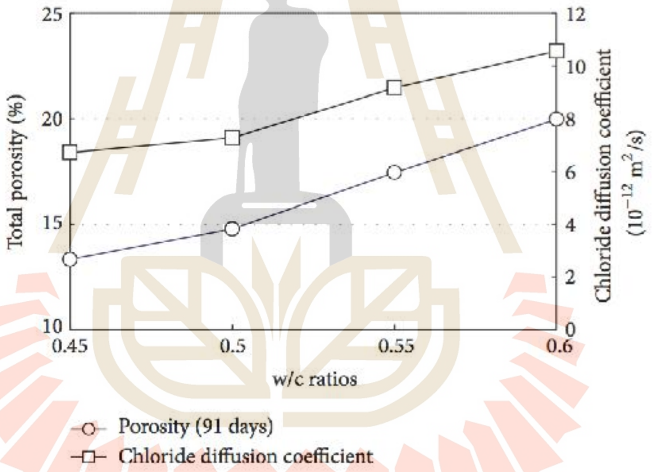

**Figure 2.14** Chloride diffusion coefficient and porosity with different w/c ratios (Kim, 2014)

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## 2.5 Recycled Concrete Aggregate (RCA)

Olorunsogo et al. (2002) reported of an investigation into the performance of concrete manufactured with recycled aggregate (RA) using durability indexes as indicators. Durability indexes, such as chloride conductivity, oxygen permeability and water sorptivity, of three different concrete mixes containing 0%, 50% and 100% RA were monitored at ages 3, 7, 28 and 56 days. The results show that durability quality reduced with increase in the quantities of RA included in a mix; however, as expected, the quality improved with the age of curing as shown in **Figure 2.15**. At the age of 56 days, increases in index value of a concrete mix made with 100% RA over that made with 100% natural aggregate were 86.5% and 28.8%, respectively, for chloride conductivity and water sorptivity.

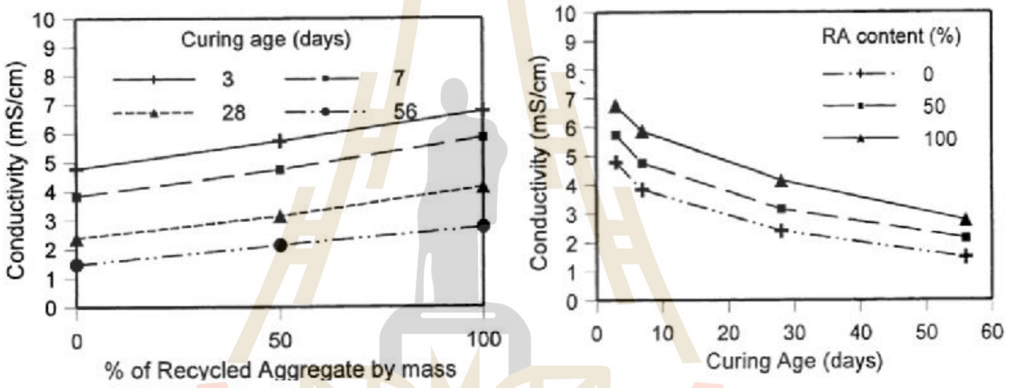

**Figure 2.15** Chloride conductivity (Olorunsogo, 2002)

The reductions in chloride conductivity and water sorptivity indexes at the curing age of 56 days compared to 3 days were 62.7% and 42.7%, respectively. The poor performance of the RA concrete is associated with the cracks and fissures, which were formed in RA during processing, thereby rendering the aggregate susceptible to permeation, diffusion and absorption of fluids.

Behera et al. (2014) reported that, RA is generally poorly graded due to its poor particle size distribution. It may be too coarse or too fine as a result of the processing and crushing through various types of crushers. The quantity of finer fractions in RA is more. It has an old interfacial transition zone (ITZ) due to the presence of the old adhered mortar or cement paste surrounding it. This is weak in nature because of the presence of minute pores in the clinging mortar, continuous cracks and fissures developed inside the aggregate in consequence to the crushing process. These basic features of RA are presented schematically in a pictorial format in **Figure 2.16**. It has rough surface texture and irregular shape, mostly rounded in nature due to the wrapped mortar. RA is having inferior mechanical properties such as low crushing strength, low impact resistance and low abrasion resistance than natural aggregate.

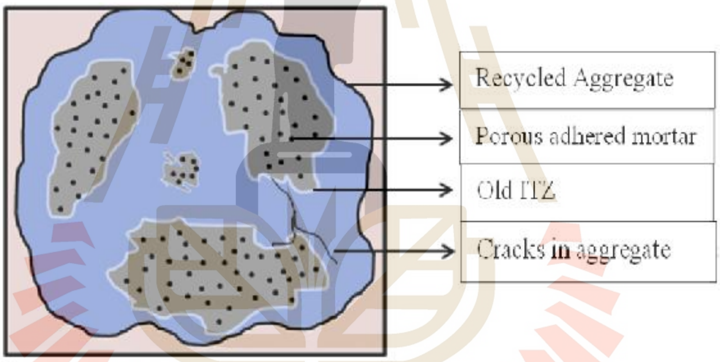

**Figure 2.16** Pictorial representation of physical characteristics of recycled aggregate (Bahera, 2014)

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With this reasons, RAC mainly consists of three phases such as the aggregate phase, mortar phase and the interfacial transition zones between the coarse aggregate and the matrix and the adhered mortar as another matrix. **Figure 2.17a and b** shows the schematic diagrams of natural aggregate concrete and RAC respectively, showing the basic difference of matrix in between two concrete. These three phases are responsible for limiting the properties of RAC. So it needs more attention regarding the performance of concrete when RA is to be used in concrete.

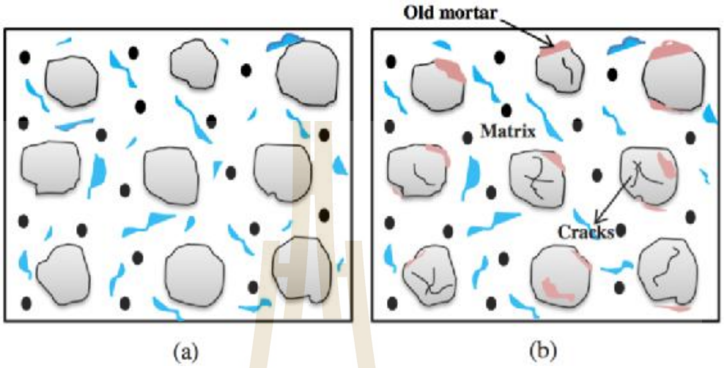

**Figure 2.17** Difference between matrixes of (a) natural aggregate concrete and (b) recycle aggregate concrete (Bahera, 2014)

Next, Thomas et al. (2013) observed the microstructure of RAC, some samples have been analysed by SEM. **Figure 2.18** shows for these concretes how the new cement paste wraps the recycled aggregates, which are composed of old paste and natural aggregate. It can be observed that the new cement paste is more compact and closed than the one observed in the recycled aggregate.

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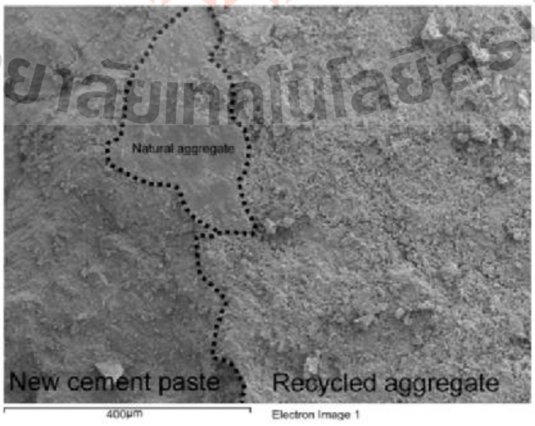

**Figure 2.18** Micrograph of RAC structure (Thomas, 2013)

And Lee et al. (2013) has described that, In recycled aggregate concrete in particular, there are more interfacial transition zone (ITZ) than normal aggregate concrete as can be seen in **Figure 2.19**, which is a sectional view of recycled aggregate concrete (RAC).

Hansen et al. (1993) was found that the compressive strength of recycled concrete is largely controlled by the water-to-cement ratio of the original concrete when other factors are essentially identical. If the water-cement ratio of the original concrete is the same as or lower than that of the recycled concrete, the new strengths will be as good as or better than the original strengths.

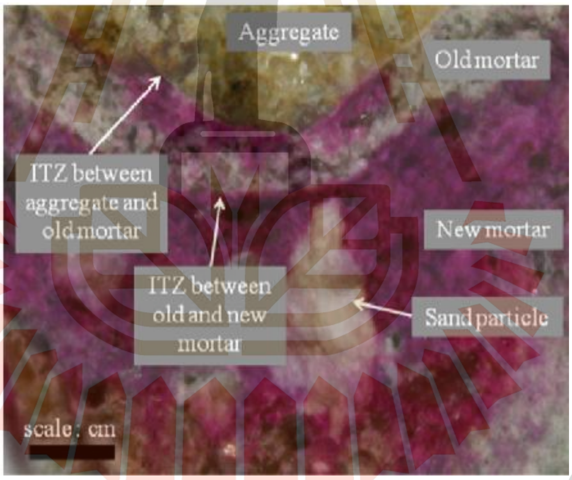

**Figure 2.19** Classification of aggregate, old mortar and new mortar by discoloration of phenolphthalein solution (Lee, 2013)

Ravindrajah et al. (1985) was found that, the Recycled Concrete Aggregates have lower specific gravity and higher absorption capacity than the original crushed granite aggregate. The resistance to mechanical actions such as impact, crushing and abrasion for the Recycled Concrete Aggregates is also lower. The effects of using

Recycled Concrete Aggregates instead of natural aggregates in concrete are, reduction in compressive strength up to 25%, reduction in modulus of elasticity up to 30%, improvement in damping capacity up to 30%, and higher amounts of drying shrinkage and creep. Available methods of predicting the modulus of elasticity on the basis of compressive strength for conventional concrete overestimate the modulus of elasticity for recycled-aggregate concretes.

Buck AD. (1997) indicate that crushed old concrete will have higher absorption and yield concrete of lower strength at equal water-cement ratio and slump than concrete made with similar aggregate not previously used. Where the original concrete was of low resistance to frost action, concrete made using it as aggregate had improved frost resistance. It is concluded that recycling concrete for use as aggregate in new concrete is feasible and may become routine.

Limbachiya et al. (2000) study the use of recycled concrete aggregate (RCA) in high-strength, 50 N/mm$^2$ or greater, concrete. The effects of coarse RCA content on the ceiling strength, bulk engineering and durability properties of such concretes have been established. The results showed that up to 30% coarse RCA had no effect on concrete strength, but thereafter there was a gradual reduction as the RCA content increased. A method of accommodating the effects of high RCA content, involving simple adjustment to water/cement ratio of the mix is given. It is shown that high-strength RCA concrete will have equivalent engineering and durability performance to concrete made with natural aggregates, for corresponding 28-day design strengths.

Poon et al. (2004) studies the influence of these aggregates (recycled and natural) on the microstructure and compressive strength of the new concrete. SEM observations revealed that the NC aggregate–cement interfacial zone consisted mainly

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of loose and porous hydrates whereas the HPC aggregate–cement interfacial zone consisted mainly of dense hydrates. The compressive strength results that the concrete prepared with natural aggregates was higher than that of the recycled aggregate concrete. Also, the strength development of the HPC recycled aggregate concrete was faster than that of the NC recycled aggregate concrete. At 90 days, the HPC recycled aggregates concrete achieved similar strength values to the natural aggregate concrete. The results are explained by the differences in porosity and pore structure of the two types of aggregates, and possible interactions between the aggregates and the cement paste.

Hansen and Boegh. (1985) was found that, recycled-aggregate concretes were found to have 15 to 30 percent lower modulus of elasticity and 40 to 60 percent higher shrinkage than corresponding conventional concretes.

Kou et al. (2007) showed that the compressive strengths, tensile strengths, and static modulus of elasticity values of the concrete at all ages decreased as the recycled aggregate and the Fly Ash contents increased. Further, an increase in the recycled aggregate content decreased the resistance to chloride ion penetration and increased the drying shrinkage and creep of concrete. Nevertheless, the use of Fly Ash as a substitute for cement improved the resistance to chloride-ion penetration and decreased the drying shrinkage and creep of the recycled aggregate concrete. The results showed that one of the practical ways to utilize a high percentage of recycled aggregate in structural concrete is by incorporating 25–35% of Fly Ash as some of the drawbacks induced by the use of recycled aggregates in concrete could be minimized.

Topcu and Sengel (2008) carried out experimental studies on concrete specimens with varying substitution percentages of RCA up to 100% by weight. Test

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results showed that the density decreased as the waste concrete materials were increased, but the difference in density was not as large as those in water absorption.

Thus, the influence of replacement of RA on 28 days compressive strength of RAC as reported by several authors has been presented in **Figure 2.20.** Which can claim that, the compressive strength decreased as replacement of RA increase.

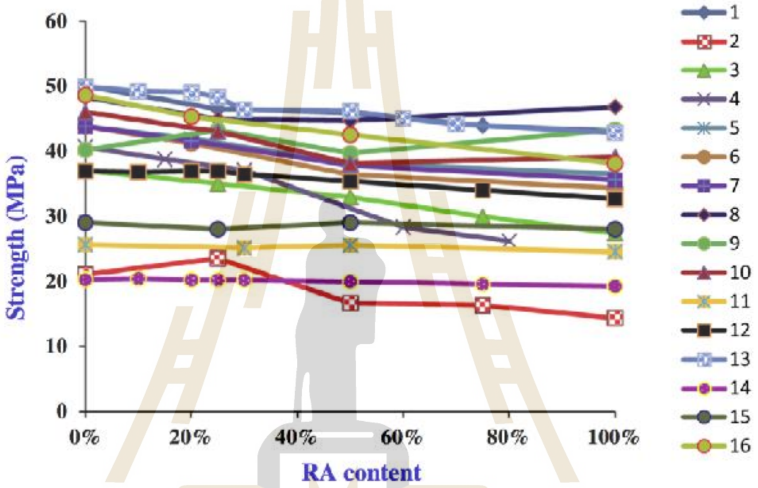

**Figure 2.20** Variation in 28 days strength compressive strength w.r.t. RA replacement percentage by various researchers (1) Rao et al. (2011), (2) (3) Elhakam et al. (2012), (4) Kwan et al. (2012), (5) (6) (7) Kou et al. (2008), (8) (9) (10) Poon et al. (2004), (11) Limbachiya et al. (2012), (12) (13) (14) Limbachiya et al. (2004), (15) Etxeberria et al. (2007), (16) Kou et al. (2012).

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It was stated that the reduction in compressive strength of recycled concrete was largely controlled by water/cement ratio, water absorption of RCA and replacement ratio (Ajdukiewicz et al. 2004). Rao et al. (2007) found that the strength of concrete with RCA and NA was comparable even at full replacement, but the water/cement ratio needed to be maintained at a ratio higher than 0.55. If the water/cement ratio was reduced to 0.4, the strength of RCA was only 75% of control mix.

Many researchers have explained that the decrease in mechanical strength of RCA concrete was primarily due to the existence of cement paste residue in aggregate particles. Sanchez and Alaejos (2004) further pointed out that the main properties unfavorably affected by mortar content were absorption, density and Los Angeles abrasion. There is also a great deal of research conducted with the aim of improving the compressive strength of recycled concrete. Kou et al. (2004) has recommended that the practical way to optimize the strength characteristics of paving blocks was by incorporating 25–35% of Fly Ash and by doing so, test results indicated that compressive strength had reached 49 MPa at 28 days.

Apart from strength, other properties that require attentions are drying shrinkage and creep. Ravindrajah et al. (1988) in their tests found that the creep of recycled concrete made with coarse recycled aggregate were 30–60% higher than that in conventional concrete.

Tam et al. (2004) proposes a new approach in mixing concrete, namely, two-stage mixing approach (TSMA), intended to improve the compressive strength for recycled aggregate concrete and hence lower its strength variability. Based upon experimental works, improvements in strength to recycled aggregate concrete were achieved. The effect can be attributable to the porous nature of the recycled aggregate, and hence, the premix process can fill up some pores and cracks, resulting in a denser concrete, an improved interfacial zone around recycled aggregate and thus a higher strength when compared with the traditional mixing approach. **Figure 2.21** illustrates the TSMA mixing procedure comparing with normal mixing approach.

Under the examination of scanning electron microscopy (SEM), the cracks within RA are filled after adopting TSMA (see **Figure 2.22a**), while similar cracks in RA still remain unfilled for NMA (see **Figure 2.22b**).

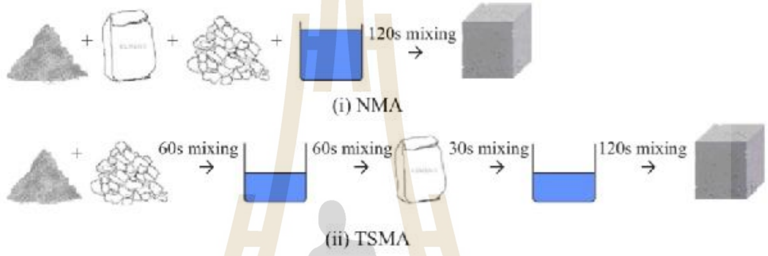

**Figure 2.21** Mixing procedures of the (i) normal mixing approach and (ii) two-stage mixing approach (Tam, 2004)

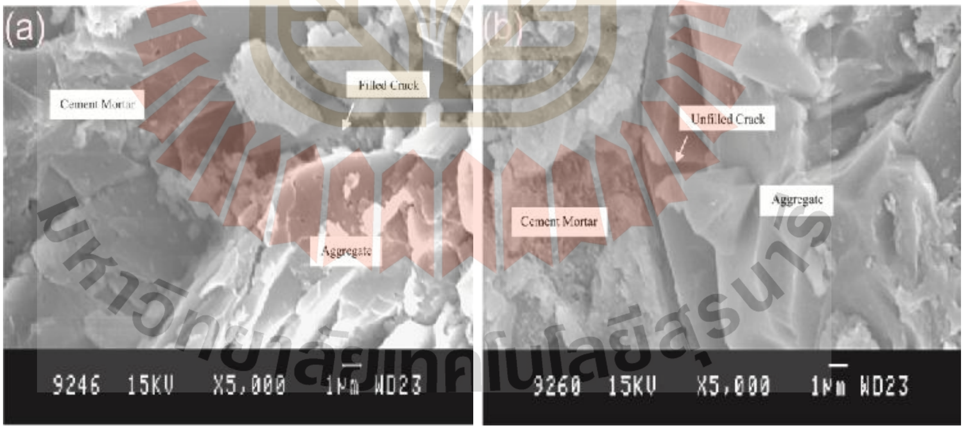

**Figure 2.22** (a) Filled crack in RA using TSMA. (b) Unfilled crack in RA using NMA.

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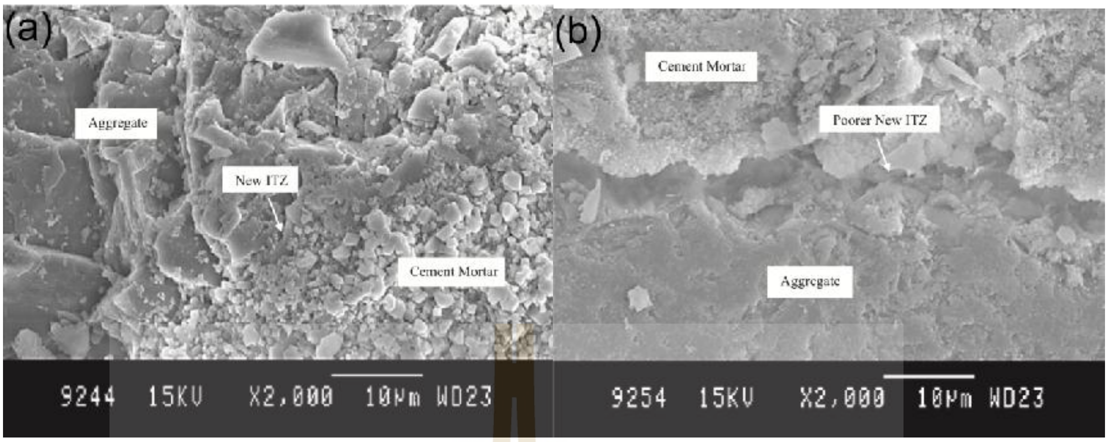

**Figure 2.23** (a) New interfacial zone for TSMA. (b) Poorer new interfacial zone for NMA.

While both the new interfacial zone and old interfacial zone of RAC are identified. **Figure 2.23a** shows a stronger and denser new interfacial zone in RAC after adopting TSMA compared to the poorer ITZ for NMA, as shown in **Figure 2.23b.**

Somna et al. (2012) study the effect of ground Fly Ash (GFA) and ground bagasse ash (GBA) on the durability of recycled aggregate concrete. Recycled aggregate concrete was produced with recycled aggregate to fully replace crushed limestone in the mix proportion of conventional concrete (CON) and GFA and GBA were used to partially replace Portland cement type I at the rate of 20%, 35%, and 50% by weight of binder. The results reveal that, the use of GFA and GBA to partially replace cement in recycled aggregate concrete was highly effective in improving the durability of recycled aggregate concrete. The suitable replacement of GFA or GBA in recycled aggregate concrete to obtain the suitable compressive strength, low water permeability, high chloride penetration resistance, and high sulfate resistance is 20%

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by weight of binder. **Figure 2.24** showed the Compressive strength of concrete use of GFA (F20, 35, 50) and GBA (B20, 35, 50) to partially replace cement. While chloride penetration depth of concrete are shown in **Figure 2.25.**

Tangchirapat et al. (2012) proposed the use of ground palm oil fuel ash (POFA) with high fineness to improve the mechanical properties and durability of concrete containing high amount of Recycled Concrete Aggregates. The results showed that ground POFA could improve the compressive strength and reduce the water permeability of recycled aggregate concretes. With 20% replacement of OPC

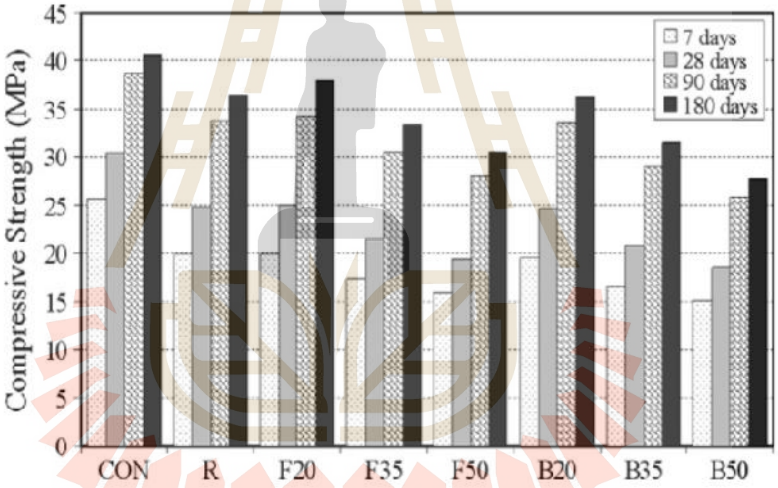

**Figure 2.24** Compressive strength of concrete replacement by GFA and GBA

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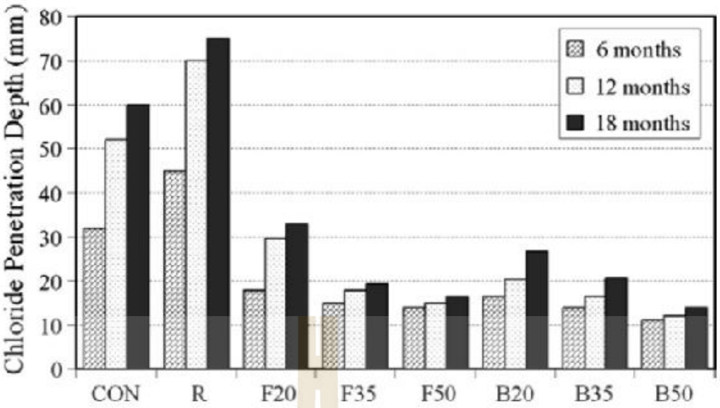

**Figure 2.25** Chloride penetration depth of concrete immersed in 3% sodium chloride solution at 6, 12, and 18 months.

by ground POFA, the compressive strength of recycled aggregate concretes was only 7% lower than that of the conventional concrete. The modulus of elasticity of recycled aggregate concrete with and without ground POFA was lower than that of the conventional concrete by approximately 25% as illustrate in **Figure 2.26**.

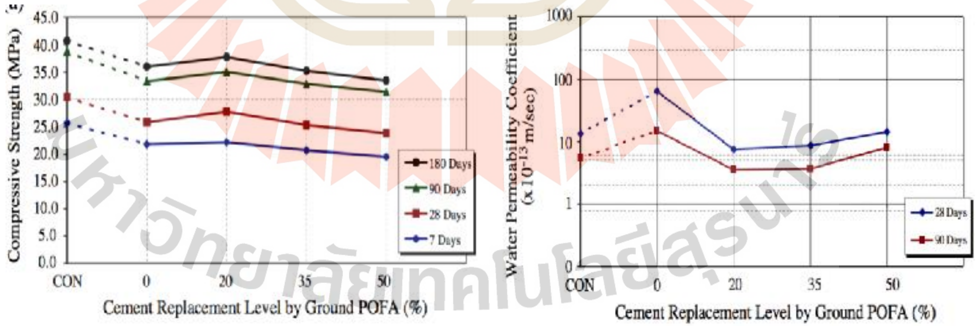

**Figure 2.26** Compressive strength and Water permeability of replacement POFA in concrete.

In the durability study test, they discovered that RCA can be used in the range of high strength concrete only if the engineering properties were satisfied. Other

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researchers pointed out that the replacement of 100% for both the coarse and fine RCA had led to a decrease in concrete strength by 16% at 28 days in comparison with the control specimen (Park and Sim. 2006; Goncalves et al. 2004).

Buyle-Bodin and Hadjieva-Zaharieva (2002) found that porosity and RCA substitution percentage affected the quality of concrete cover and hence permeability as well. They also suggested that the main problems of durability were caused by the use of fine recycled aggregate and higher water/cement ratio.

Ceia et al. (2016) was concluded that RAC exhibits adequate mechanical properties for structural use, although declining with the increase of the replacement rate. Regarding roughness, results corroborated previous studies, since an increase of strength for rougher substrates was observed by using Slant shear test. Finally, it is found that the values obtained by the codes are very conservative for all types of tested concrete, including for RAC100 despite their low concrete strengths.

Laserna and Montero. (2016) reports a study on recycled aggregates concrete to analyze the influence of using two different types of natural aggregates, river aggregates and crushed aggregates, on the strength properties of recycled aggregates concrete. A total of twenty different mixes were analyzed with an effective water/cement ratio of 0.5 and cement contents of 260–300–340 kg/m3 for recycled rates of coarse aggregates of 0–20– 50–100%. The results show that the strength property depends of the type of natural aggregate used and of the recycled replacement ratio. An increment of 15% on compressive strength was obtained for river natural aggregates and 100% recycled replacement ratio (see **Figure 2.27**), while a decrease of approximately 10–25% was observed for mixtures with crushed natural aggregates performed under similar manufacturing conditions.

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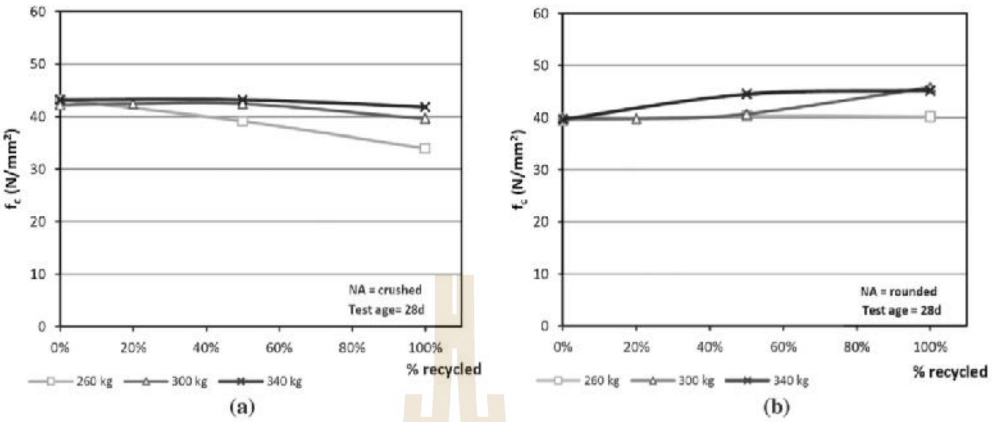

**Figure 2.27** Compressive strength at 28 days in the cNA (a) & rNA (b) mixtures.

Ismail and Ramli (2013) studying the effect of using different molarities of acid solvent and age of treatment (soaking) on properties of RCA, as well as the influence of using this treated aggregate on the properties of concrete. The results show that the use of different acid molarities to remove or minimise loose mortar particles attached on the surfaces of RCA can significantly improves its physical and mechanical properties. In addition, the reduction of loose mortar that covers RCA particles can significantly improves surface contact between the new cement paste and the aggregate (**see Figure 2.28**) which subsequently resulted in a significant improvement in the strength of concrete mechanical.

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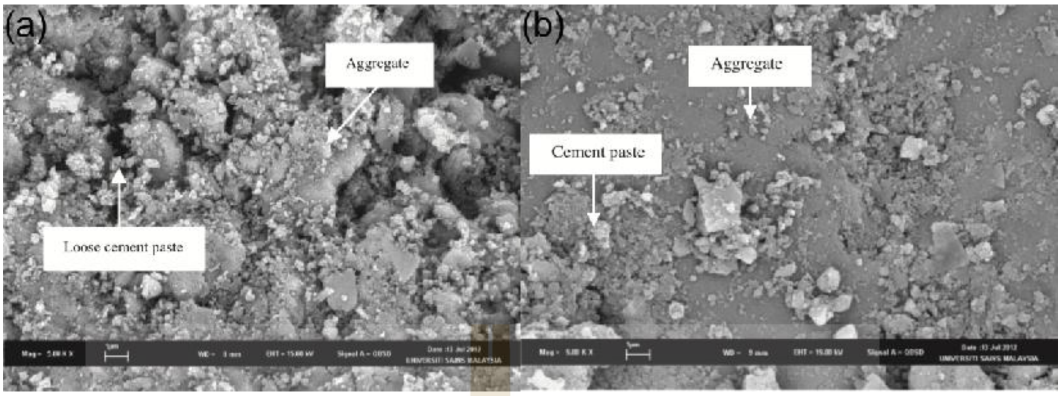

**Figure 2.28** (a) Normal (untreated) RCA (b) Treated RCA with 0.5 M HCl

Shi et al. (2015) reviews the published enhancement methods for recycled concrete aggregate, and points out their advantages and disadvantages so as to facilitate the selection and further development of suitable enhancement methods for recycled concrete aggregate. It suggests that carbonation treatment is an efficient and feasible method for improving the mechanical properties and durability of recycled concrete aggregate. Carbonation treatment of recycled concrete aggregate is not only an efficient way for enhancing the properties of recycled concrete aggregate, but also an environmental friendly approach.

Tam et al. (2008) highlights that improvements have been recorded resulted from the use of various RA percentages from both TSMAs and TSMAsc. The additions of silica fume and proportional cement content in the pre-mix on TSMAs and TSMAsc can fill up the weak areas in the RA and thus develop a stronger interfacial layer around aggregate, and hence a higher strength of the concrete. It, thus, concludes that $\text{TSMA}_{\text{s}}$ and $\text{TSMA}_{\text{sc}}$ can provide alternative methodologies for further improvement in quality of this recyclable material as illustrated in **Figure 2.29**.

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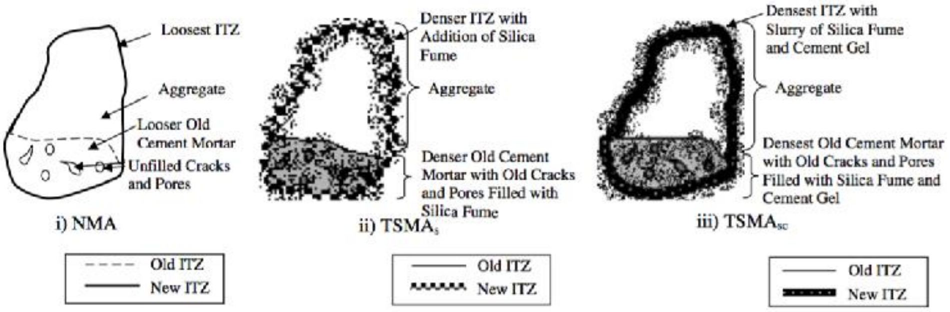

**Figure 2.29** RA structure after adopting (i) NMA, (ii) TSMA$_s$ and (iii) TSMA$_{sc}$.

## 2.6 Polyvinyl Alcohol modified concrete

Polyvinyl Alcohol (PVA), It is a synthetic polymer that is achromatic, odorless and soluble water (temperatures of 90～95℃ are generally required for complete solution). PVA had a specific gravity, hydrolyzed, and molecular weight of 1.27-1.31, 87.83%, and 22,000, respectively. PVA has a film forming property, high corrosion resistance to the solvents and lubricating oil and is excellent in adhesion. The flammable properties such as flashpoint and auto-ignition temperatures are above 70℃ and 440℃, respectively, while the combustibility of PVA is very low (Hassan and Peppas, 2000a; 2000b).

Ohama (1995) is believed that a co-matrix phase which consists of cement gel and polymer films is generally formed as a binder according to a three-step simplified model shown in **Figure 2.30**. Grosskurth (1991) proposed a similar model indicating the formation of the polymer-cement co-matrix. Sugita et al. (1995) have recently investigated the microstructures and composite mechanism of latex-modified pastes and mortars, and found the interfacial layer of cement hydrates with a large amount of polymer particles on the aggregates and cement particles. As a result, both the particle

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dispersion of the polymer and the formation of polymer films are necessary for explaining the composite mechanism of the latex-modified systems.

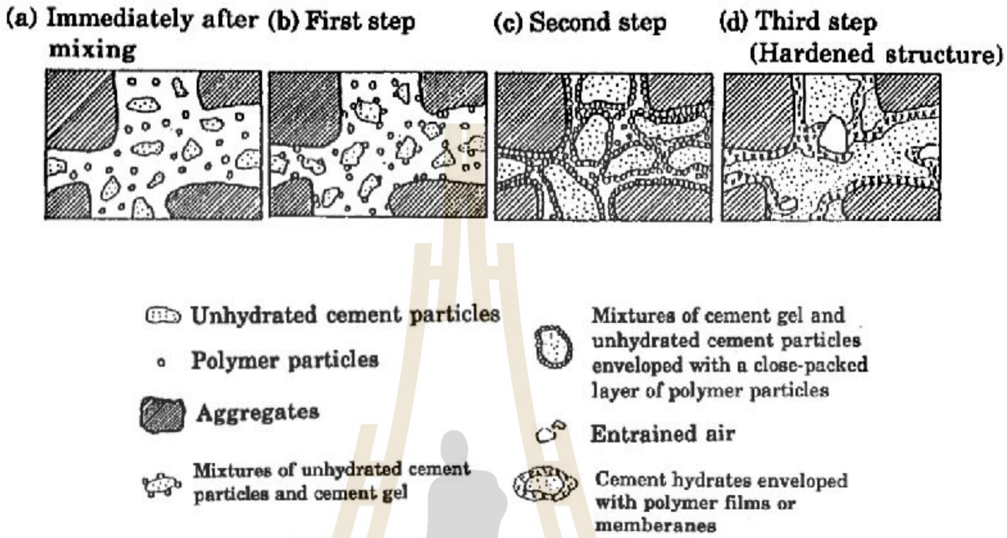

**Figure 2.30** Simplified model of formation of Polymer-concrete-matrix.

Sclofani and Contrafatto (2013) reports the results of experimental tests on Polyvinyl-Alcohol modified concrete. The mechanical properties, such as uniaxial compression strength and elastic modulus, and the influence of a cross-linking agent are investigated. Uniaxial tests under displacement control both monotonic and cyclic are performed to study the ductility properties of the new composite material and the degradation evolution of the secant stiffness. In some cases a really significant reduction of the compressive strength is observed due to a pronounced air entrapment in the mixture (**Figure 2.31**). Nevertheless, the presence of the polymer introduces a considerable improvement in the ductility of the material, drastically reduces the surface cracking, which is prerequisite for increasing the durability and for reducing stiffness damage which is similarly result to Contrafatto (2013).

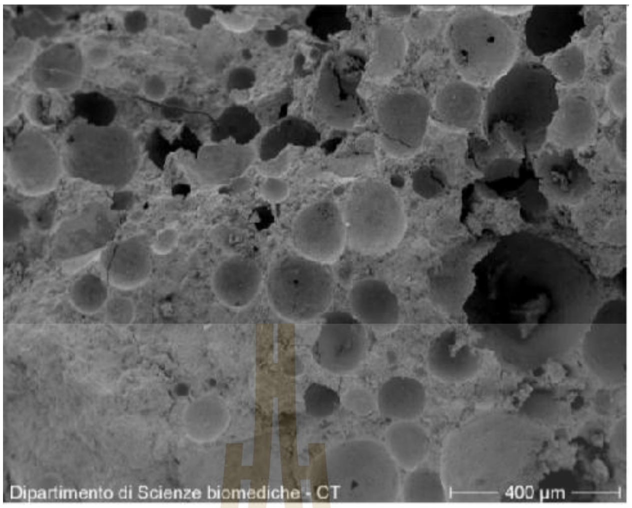

**Figure 2.31** SEM image of air entrapment in the mixture

Viswanath and Thachil (2008) reported that, the compressive strength of the polyvinyl alcohol–phenol formaldehyde cement paste was found to be inferior to the other, but the retention of compressive strength after immersing in each of acid, base and kerosene was much better. In general, polyvinyl alcohol when added to cement pastes improves the chemical resistance properties in terms of retention of compressive strength after exposure to chemicals as illustrate in **Figure 2.32**.

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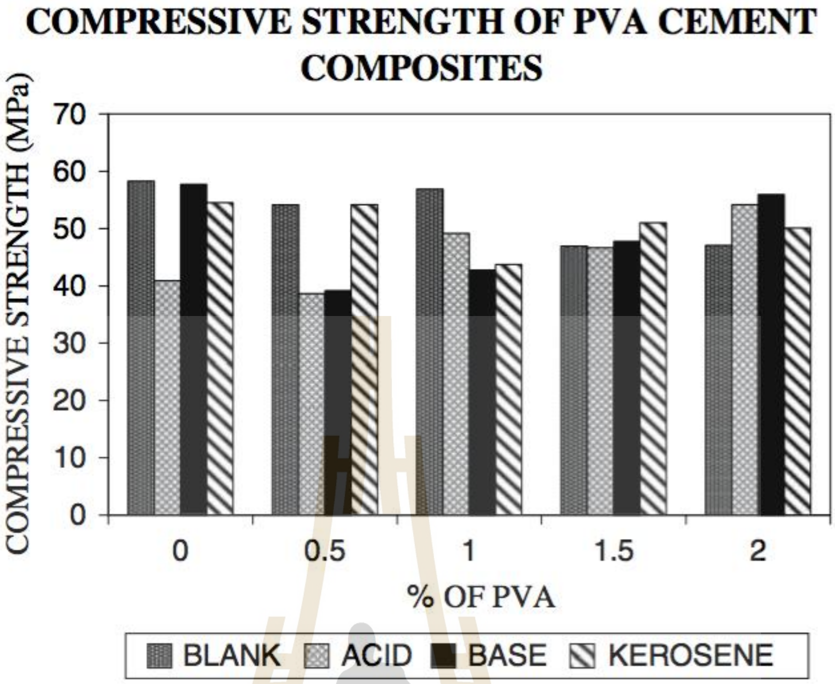

**Figure 2.32** Variation of compressive strength of PVAL cement pastes on exposure to different chemical environments

Knapen and Van Gemert (2009, 2015) shown evidence is given of the presence of polymer films or bridges in mortars modified with 1% of polyvinyl alcohol-acetate or methylcellulose. A contribution to the flexural strength of these mortars is found (**Figure 2.33**). By means of SEM investigation, polymer bridges are detected between the layered $Ca(OH)_2$ crystals (**Figure 2.34**). Additional bonds are created which strengthen the preferential cleavage sites. Furthermore, polymer films or bridges are intergrown within the cement matrix on a submicron scale.

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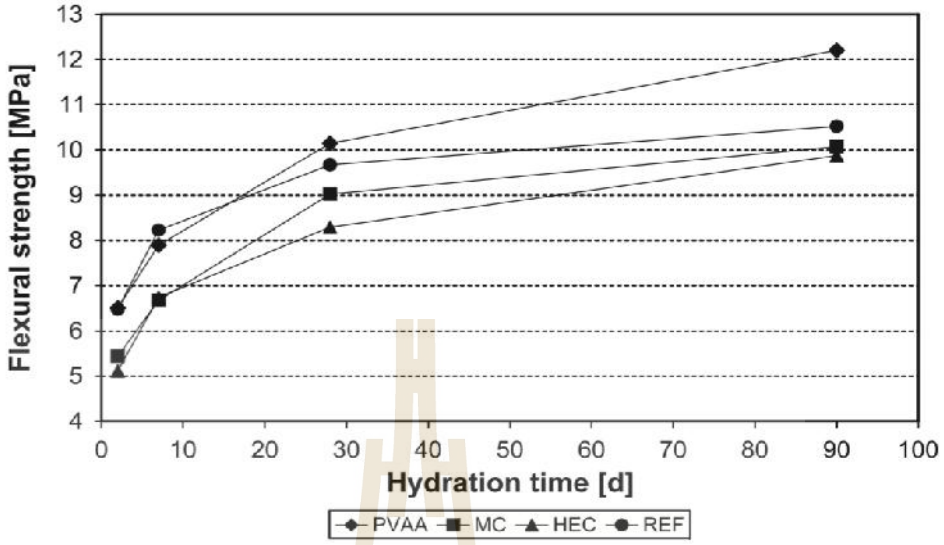

**Figure 2.33** Flexural strength for unmodified mortars and mortars modified with 1% PVAA, MC and HEC (w/c = 0.45).

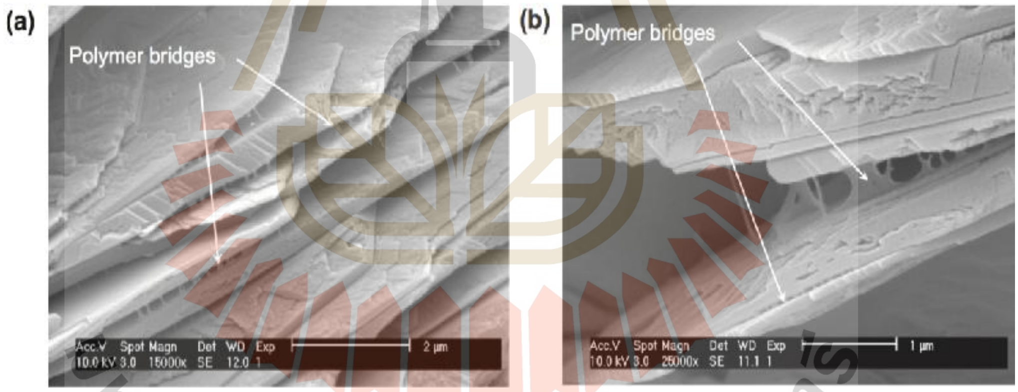

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**Figure 2.34** Polymer films between layered Ca(OH)2 crystals in 1% MC modified mortars (w/c = 0.45).

Topic et al. (2015) reported the influence of modifying the volume with water soluble polymers, such as polyvinyl alcohol (PVA), on the properties of a cement paste, and to find an optimal additive. It turned out that the addition of a PVA solution into fresh cement paste increases the porosity and therefore reduces the stiffness and the compressive strength (**Figure 2.35**). However, the bending strength of PVA-rich specimens was significantly higher (**Figure 2.36**) and their water absorption decreased as illustrate in **Figure 2.37**.

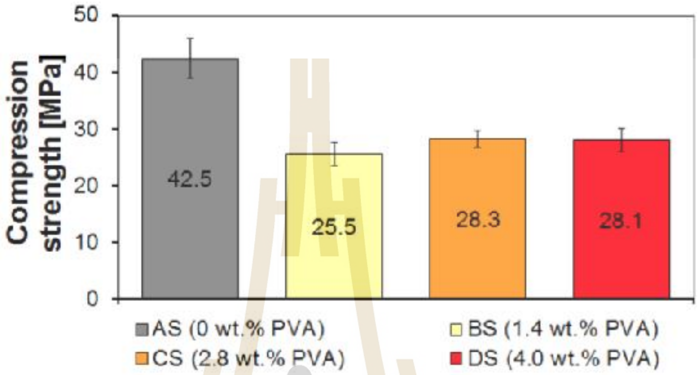

**Figure 2.35** Dependence of compressive strength on the amount of PVA in cement pastes with w/c = 0.35 after 28 days of curing

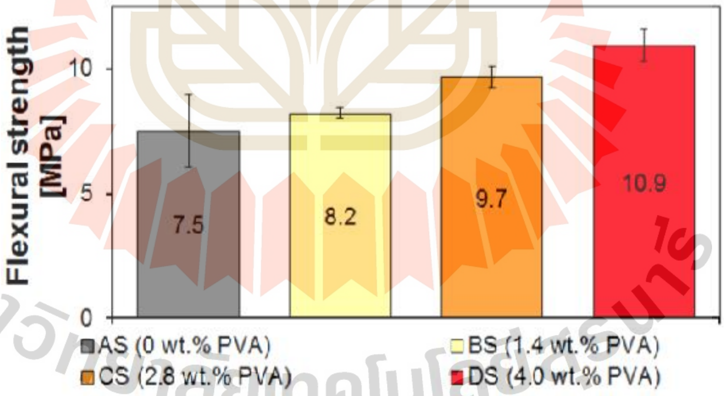

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**Figure 2.36** Dependence of flexural strength on the amount of PVA in cement pastes with w/c = 0.35 after 28 days of curing**.**

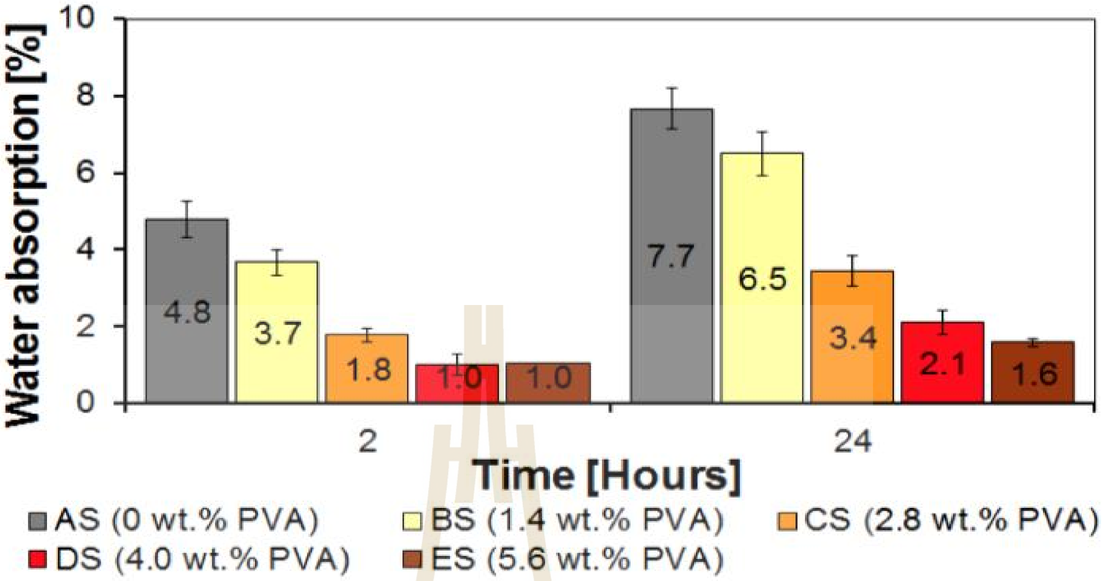

**Figure 2.37** Water absorption (after 2 hours and 24 hours) of the PVA-modified cement pastes with w/c = 0.35.

Kim et al. (1999) studied the structure and properties of mortars and concretes containing up to 2 wt% (based on cement) of poly(vinyl alcohol) (PVA) were examined and compared with those without PVA. Among changes occurring with the addition of PVA were increases in air void content and apparent fluidity and a reduction in the bleeding of fresh mortar and concrete. The increased fluidity caused increased slump for fresh concrete (**Figure 2.38**). The porous interfacial transition zones around sand grains and coarse aggregate were significantly reduced, and the cement particles were uniformly distributed without significant depletion near aggregate surfaces. For mortars, using a prewetting mixing technique, the compressive strength was decreased moderately, but the flexural strength was unchanged. For concretes, with the same mixing technique, the compressive strengths after 28 days of hydration were relatively unchanged, but the post peak area of the compression stress-strain curve was reduced (**Figure 2.39**), accompanying a change in fracture behavior from debonding to cohesive failure of the coarse aggregate. When concrete having the same air void content with PVA as without was made, the compressive strength was moderately increased.

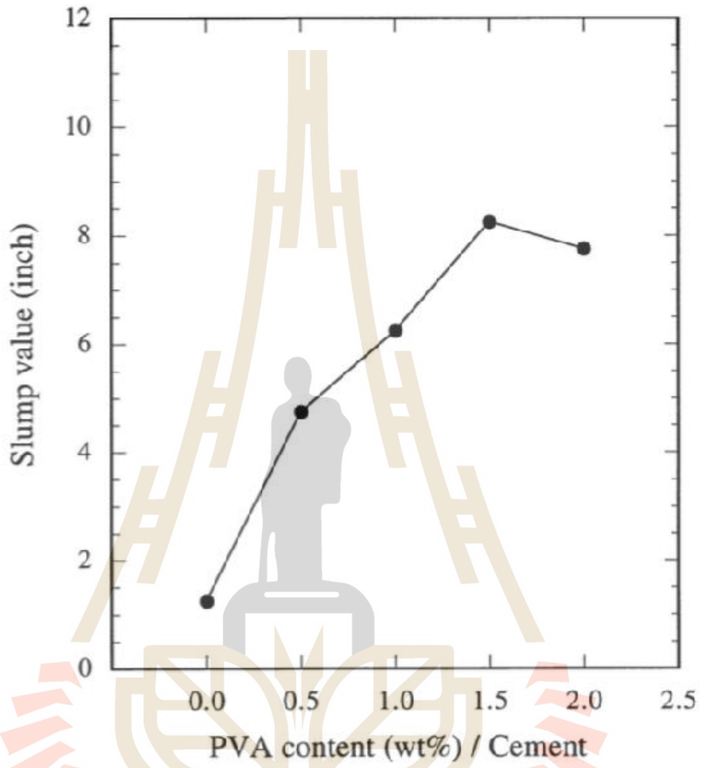

**Figure 2.38** Effect of PVA on the slump values of concrete for the w/c ratio of 0.50.

Kim and Robertson (1998) reported that, the addition of 1.4 wt% PVA based on the mass of cement increased the strength for both limestone-paste and granite-paste bonds. The strength increase was about five-fold for limestone and nearly two-fold for granite (**Figure 2.40**). The failure mode also changed, from pure adhesive failure without PVA to cohesive failure of the aggregate with limestone and to a mixed cohesive failure of the paste and adhesive failure with granite. The gain in bond strength with the addition of PVA seems to arise from suppression of the porous

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interfacial transition zone and an inhibition of calcium hydroxide nucleation on the aggregate surface as represented in **Figure 2.41**.

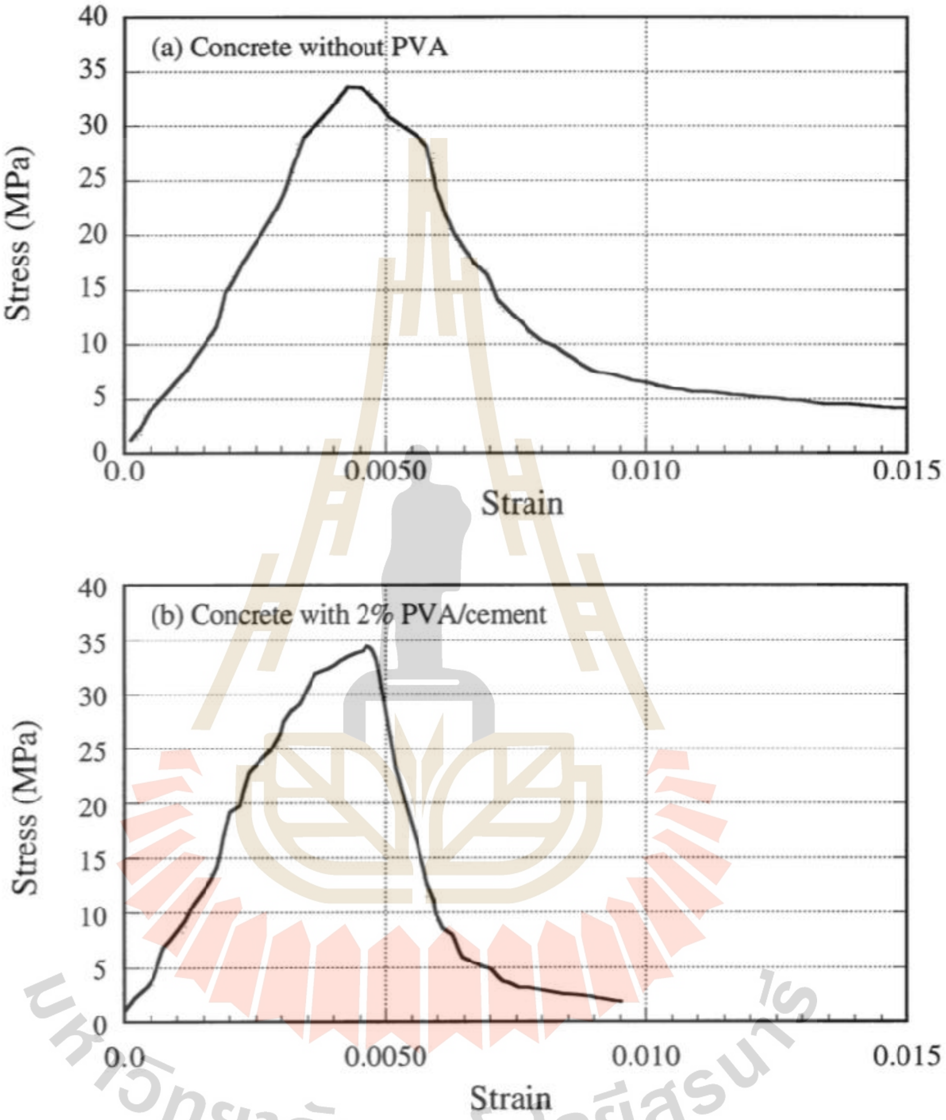

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**Figure 2.39** Typical stress-strain curves of concretes from compression test. (a) Concrete without PVA, (b) concrete with 2 wt% PVA (based on cement). Hydration time, 28 days; w/c ratio, 0.5.

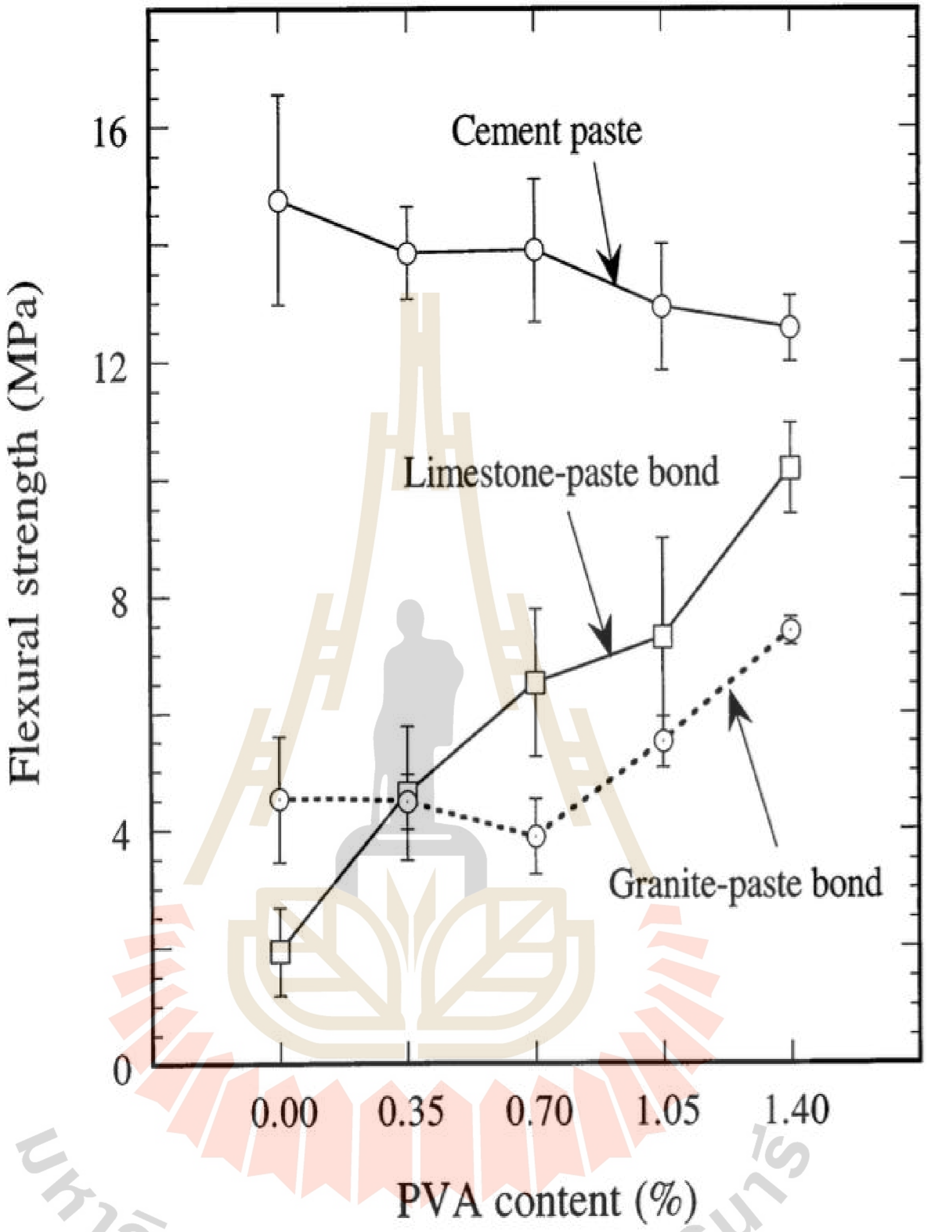

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**Figure 2.40** Flexural strengths of cement paste, limestone- paste bond, and granite-paste bond measured in three-point bending vs. PVA content. Tests were done with the specimens in a wet state after 28 days curing in lime-saturated water.

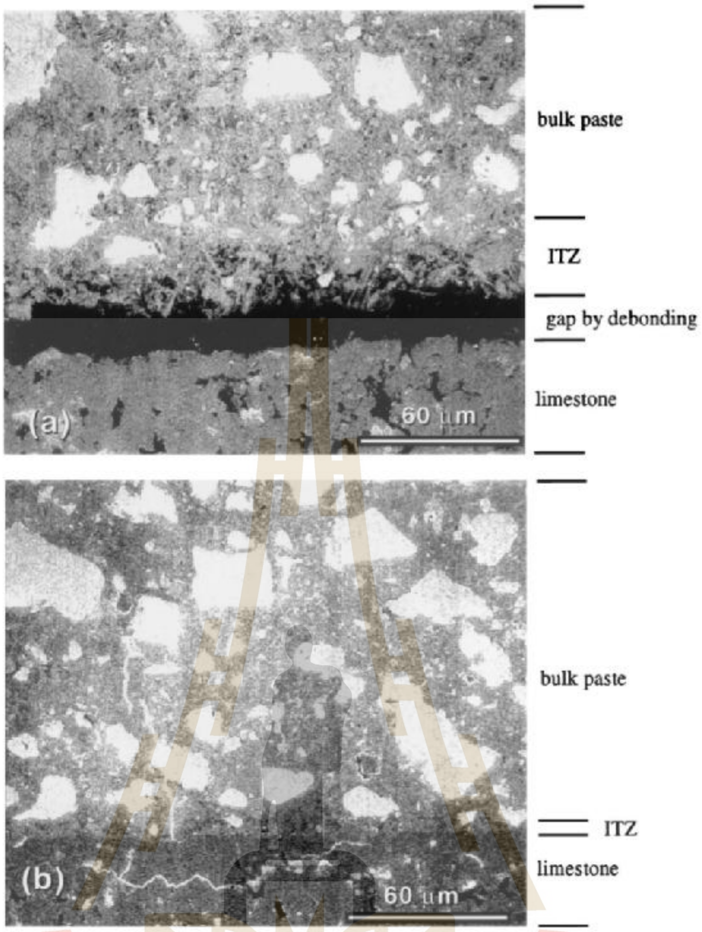

**Figure 2.41** SEM obtained in backscatter mode of cut and polished specimens showing the interfacial transition zone (ITZ) between the aggregate (limestone) and the cement paste. (a) Cement paste without PVA. (b) Cement paste with 1.4% PVA.

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Afridi et al.(2003) results that mortar constituents of unmodified mortar are loosely joined with each other due to the absence of polymer films, thus having a structure with comparatively lower mechanical and durability characteristics. By contrast, mortar constituents in powdered polymer-modified mortars (PPMMs) and aqueous polymer-modified mortars (APMMs) are compactly joined with each other due to the presence of interweaving polymer films, thereby forming a monolithic structure with improved mechanical and durability characteristics. However, the results make obvious the poor coalescence of polymer particles or development of inferior quality polymers films in PPMMs as compared to that observed in APMMs. Moreover, PPMMs show less uniform distribution of polymer films as compared to that in APMMs. Different powdered cement modifiers have different film-forming capabilities.

Ohama (1998) show some chemical reactions may take place between the particle surfaces of reactive polymers such as polyacrylic esters (PAE) and calcium ions ($Ca^{2+}$), $Ca(OH)_2$ solid surfaces, or silicate surfaces over the aggregates, as illustrated in **Figure 2.42**. Such reactions are expected to improve the bond between the cement hydrates and aggregates, and to improve the properties of hardened latex-modified mortar and concrete.

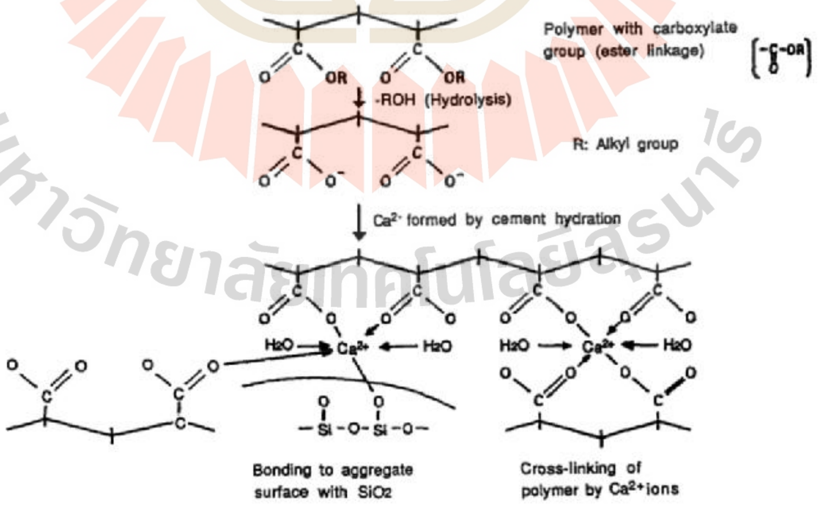

**Figure 2.42** Schematic illustration of reaction between polymer with carboxylate group (ester linkage), ordinary Portland cement and aggregate

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Allahverdi et al. (2009) was designed to investigate the simultaneous effect of both water-to-cement (w/c) and polymer-to-cement (p/c) ratios on flexural strength of type V Portland cement pastes containing polyvinyl alcohol. The obtained results confirmed the strong effect of w/c-ratio on the effectiveness of the added polymer so that there exist optimum values for both w/c and p/c-ratios. Pastes prepared at optimum w/c and p/c-ratios of respectively 0.30 and 0.016 exhibited the highest flexural strength which was more than two times the strength of unmodified pastes (**Figure 2.43**). Further measurements on hardened paste specimens prepared at w/c=0.30 show that increasing the p/c-ratio increases dry bulk specific gravity of the specimens and result in significant reductions in both total permeable pore volume and water absorption (**Figure 2.44**) of the specimens confirming the effective packing caused by polyvinyl alcohol acetate.

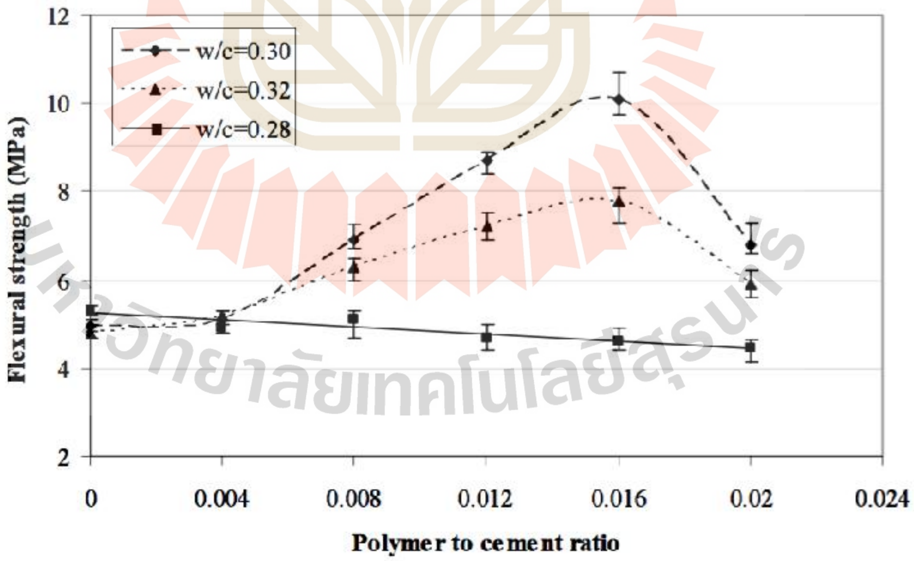

**Figure 2.43** Flexural strength of cement pastes modified by polyvinyl alcohol at different W/C- and P/C-ratios.

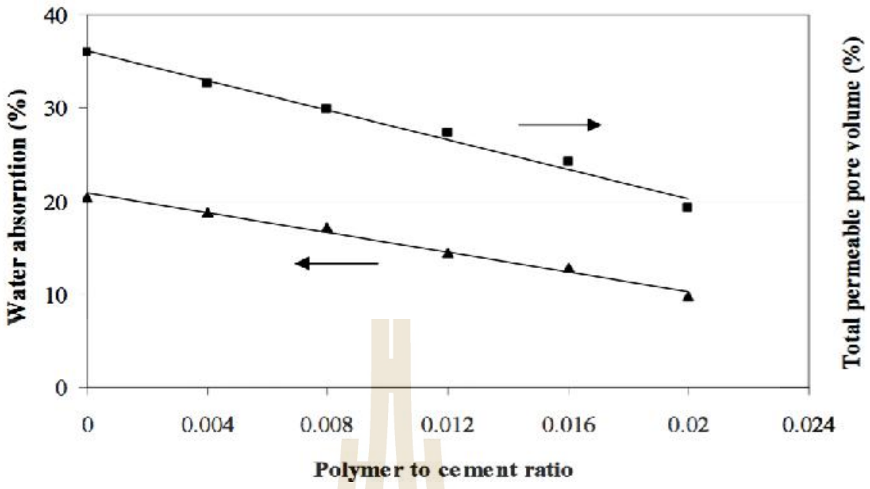

**Figure 2.44** Effect of polymer addition on total permeable pore volume and water absorption

Singh and Rai (2000) was studied the effect of 3.0-wt.% polyvinyl alcohol (PVA) on the hydration of ordinary Portland cement in the presence and absence of 10% rice husk ash (RHA) by employing different techniques. The results have shown that PVA increases the strength and decreases the porosity. The increase in strength is due to the interaction of PVA with cement, forming some new compounds that fill the pores or improve the bond between the cement. The two cements behave in a similar way, and hence, replacement of cement by 10-wt.% RHA is beneficial.

Kou and Poon (2010) reports an experimental study to improve the properties of Recycled Concrete Aggregates (RCA) by their impregnation with polyvinyl alcohol (PVA). The effects of PVA on the development of strength and durability properties of the recycled aggregate concrete were evaluated. The experimental investigation was conducted in two parts. Firstly, the optimal concentration of PVA solution required to improve the recycled aggregates was determined. The RCA was

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soaked in 6%, 8%, 10%, 12% PVA solutions, and impregnation was conducted under a controlled laboratory environment. Density, crushing value (10% fines value), and water absorption of the PVA impregnated RCA (PI-RCA) were determined. Secondly, the slump, slump loss, compressive and tensile splitting strength, dimensional change (shrinkage) and chloride penetrability of the concretes prepared with the RCA that had been impregnated with the optimal (10%) PVA concentration were determined. It was found that the 10% fines value of the PI-RCA was higher, and the water absorption of the PI-RCA were lower when compared to the untreated RCA. The results show that there was not only an improvement in the mechanical properties of the concrete made with PI-RCA, but also the shrinkage of PI-RCA decreased while the resistance to chloride-ion penetration of the concrete produced increased as see in **Figure 2.45**.

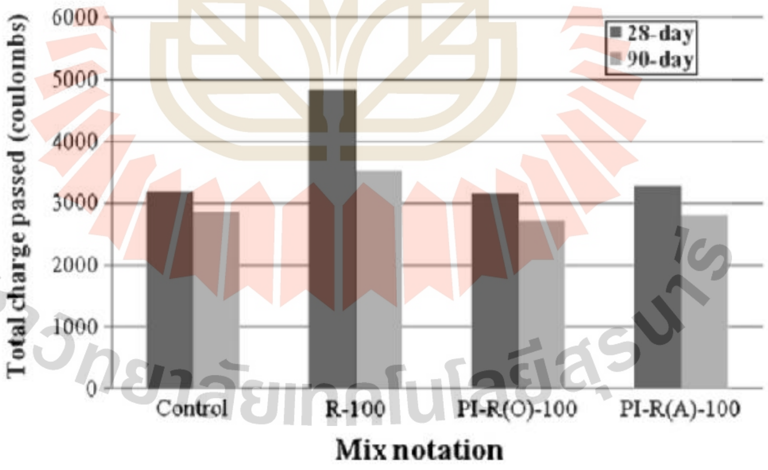

**Figure 2.45** Total charge passed of the concrete mixtures**.**

Nguyen et al. (2015) shows that the addition of PVA increases the yield stress and viscosity of the cement paste. These effects were amplified with increasing content and Mw of PVA. The results suggest that the resistance to sagging and slumping of the cement pastes will be increased by using higher contents of PVA as well as by using PVAs of higher Mw. However, the amount of PVA added should not exceed an optimal level since that can lower the tensile strength of the pastes.

Sivakumar (2011) describes the results of an experimental study performed to gain insight into the performance of polymer modified concrete and its mechanism. In addition to this the optimum dosage of polymer that influences the mechanical and structural properties Such as Compressive strength (**Figure 2.46**), Flexural strength (**Figure 2.47**), and Split tensile strength (**Figure 2.48**) are reported. At last the styrene acrylic polymer has shown its superiority over latex polymer because of its fine particle size and relatively less viscous.

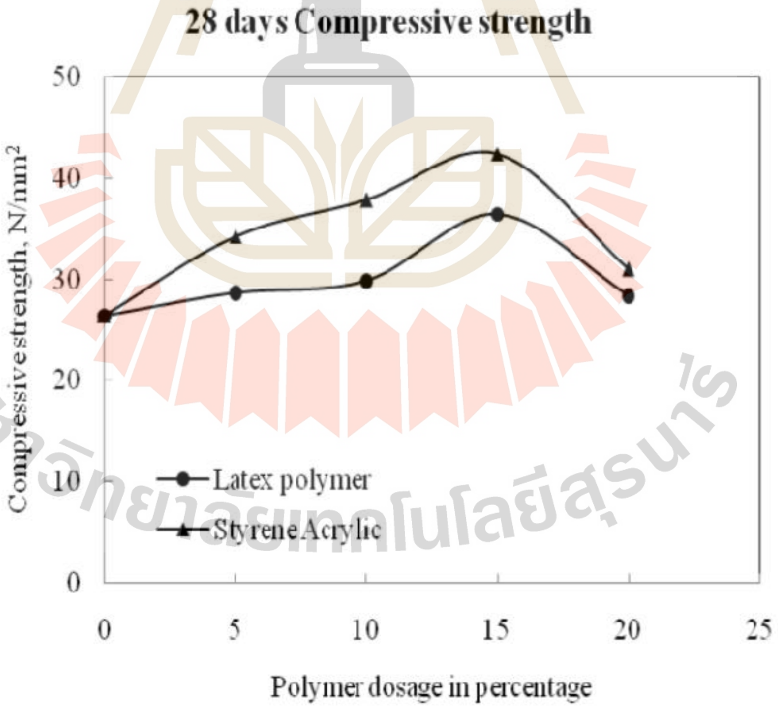

**Figure 2.46** Details of 28days compressive strength

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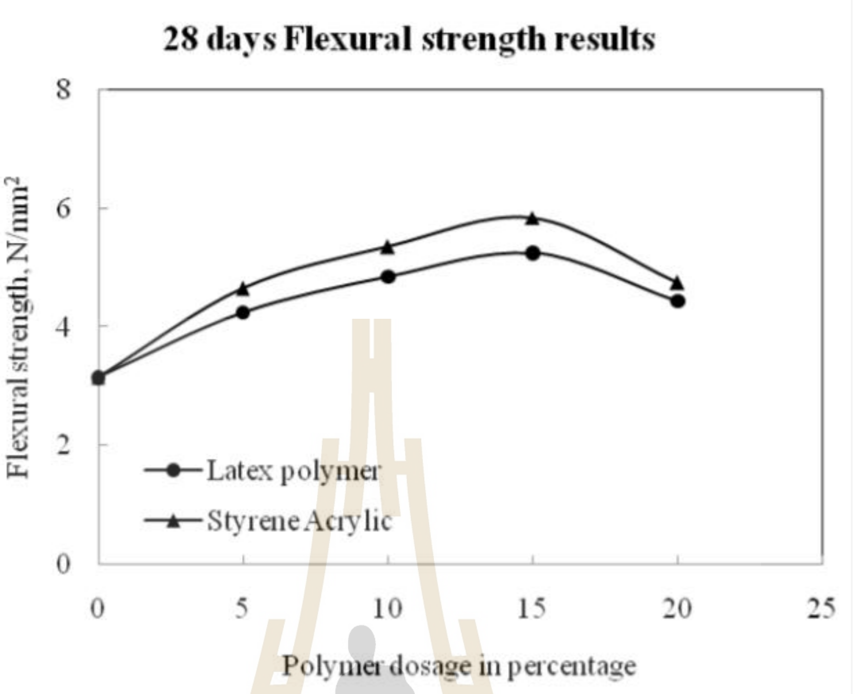

**Figure 2.47** Details of 28days flexural strength

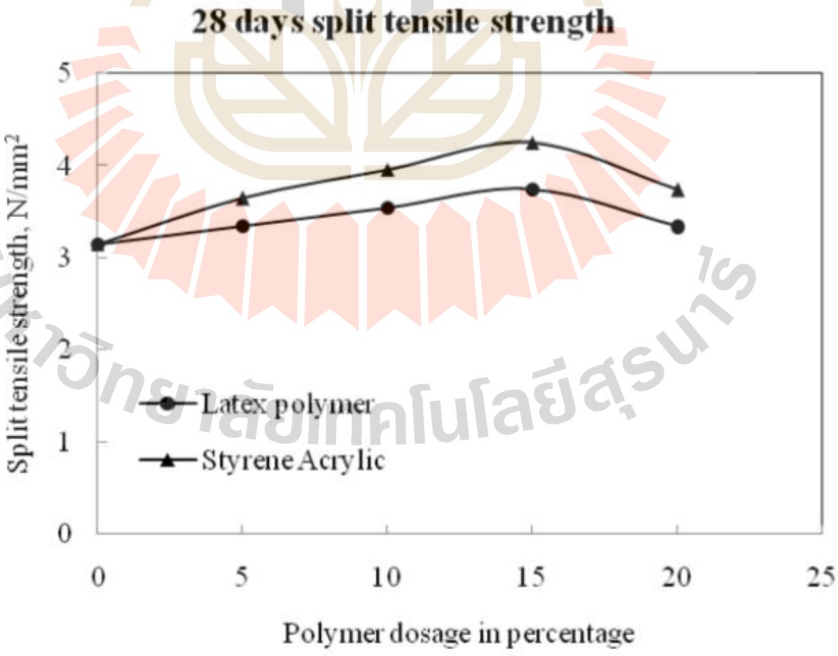

**Figure 2.48** Details of 28days tensile strength

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# CHAPTER III

# COMPRESSIVE AND FLEXURAL STRENGTH OF POLYVINYL ALCOHOL MODIFIED PAVEMENT CONCRETE USING RECYCLED CONCRETE AGGREGATES

## 3.1 Statement of problem

The utilization of waste materials and research on new recycling techniques have been encouraged world widely to promote sustainable practices to reduce the impact of civil engineering construction activities on the environment. Recycled concrete aggregate (RCA) is obtained from the demolition of aged concrete buildings and essentially consists of constituents such as binding materials, water, aggregates and admixtures. The major component is the aggregates, which typically comprises 60–75% of the total concrete volume (Kosmatka et al. 2002). Previous research has shown that RCA could be used sustainably as unbound or stabilized pavement base/subbase materials (Arulrajah et al. 2015; 2016; 2017; 2017; Disfani et al. 2014; Yaghoubi et al. 2017).

RCA can furthermore be used as coarse aggregates in the production of concrete, which would reduce waste concrete stockpiles at landfills and would limit the need for natural aggregate sources (Silva et al. 2014). Reuse of waste materials from demolition activities has numerous environmental and economic benefits.

However, the variable properties of RCA remain the predominant barrier in using RCA for concrete production. Several studies (Behera et al. 2014; Dilbas et al. 2014; Omary et al. 2016; Otsuki et al. 2003) reported that RCA concrete often exhibited low compressive strength, wide variability in quality, high drying shrinkage, large creep and low elastic modulus. Nogchi (2001) and Olorunsogo (2002) indicated that the compressive strength and durability against chloride resistance of RCA concrete gradually decreased as the amount of RCA increased. Silva at el. (2014) suggested that RCA concrete should only be used in non-structural applications such as rigid pavement and canal.

Several researchers have proposed methods to improve the strength and durability of RCA concrete, such as by using the double mixing or two-stage mixing (TSMA) approaches (Otsuki et al. 2003; Tam et al. 2005) or by mixing it with aluminosilicate materials, such as ground Fly Ash, ground bagasse ash, and ground palm oil fuel ash (Kua et al. 2016; Phetchuay et al. 2016; Somna et al. 2012; Tangchirapat et al. 2012; Yoobanpot et al. 2017).

Earlier studies on RCA concrete have focused on the compressive strength properties, while research on the essential flexural strength properties of RCA concrete is limited to date. The flexural strength plays a vital role in the stability of rigid pavement due to its low tensile strength characteristics.

The flexural strength of concrete can be improved by fiber reinforcement (Jamsawang et al. 2015; Sukontasukkul 2004; Sukontasukkul and Jamsawang, 2012). Water-soluble polymers have been also reported to enhance the flexural strength as well as the durability of concrete (Allahverdi et al. 2010; Jaroslav et al. 2015; Viswanath and Thachil, 2008). Approximately 650,000 tons of Polyvinyl alcohol

(PVA) polymer, is produced annually for commercial cement and concrete industries (Rong et al. 2009). Adding PVA into cement paste improves its chemical resistance properties, such as preservation of compressive strength after exposure to chemical attacks (Viswanath and Thachil, 2008). The flexural strength of concrete specimens increases with increasing PVA-to-cement (by weight), p/c ratio due to the significant reduction of both total permeable pore volume and water absorption of the specimens. PVA effectively packs the concrete solid ingredients and results in a dense matrix material (Allahverdi et al. 2010).

To the authors' knowledge, there has been no research undertaken to date on the application of PVA for improving the flexural strength of RCA concrete, which is the prime focus of this research. The RCA concrete specimens were prepared by the TSMA method in this study. The role of the water to cement (w/c) ratio and PVA/cement (p/c) ratio on the compressive and flexural strengths of the RCA-PVA concrete is investigated via macro- and micro-structural testing in this study. The flexural strength improvement of RCA-PVA concrete specimens that meets the compressive strength requirements of the Thailand national road authorities is also reported in this study.

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## 3.2 Material and Methods

### 3.2.1 Materials

Natural river sand with a fineness modulus of 3.74 was used as the fine aggregate for preparing the RCA concrete. The river sand had a specific gravity in saturated surface dry state, water absorption, and percent of voids of 2.58, 3.34%, and

42.5%, respectively. The dry-rodded unit weight of the river sand was 14.7 kN/m$^3$. Particle size distribution of the river sand is shown in **Figure 3.1.**

Recycled concrete aggregate (RCA) specimen had particles with sizes ranging between 4.75 mm and 19 mm. The grain size distribution curve of RCA is shown in **Figure 3.1**. RCA had a fineness modulus and a specific gravity in saturated surface dry state of 1.34 and 2.67, respectively. Its dry-rodded unit weight was 12.1 kN/m$^3$. The water absorption, percent of voids and Los Angeles abrasion loss were, 5.5%, 54% and 41%, respectively. Since the RCA was not scalped to remove the attached mortar, it possessed lower specific gravity and higher water absorption and porosity. Consequently, the RCA was weaker than the natural aggregate (Chen et al. 2003; Salem and Jackson, 2003).

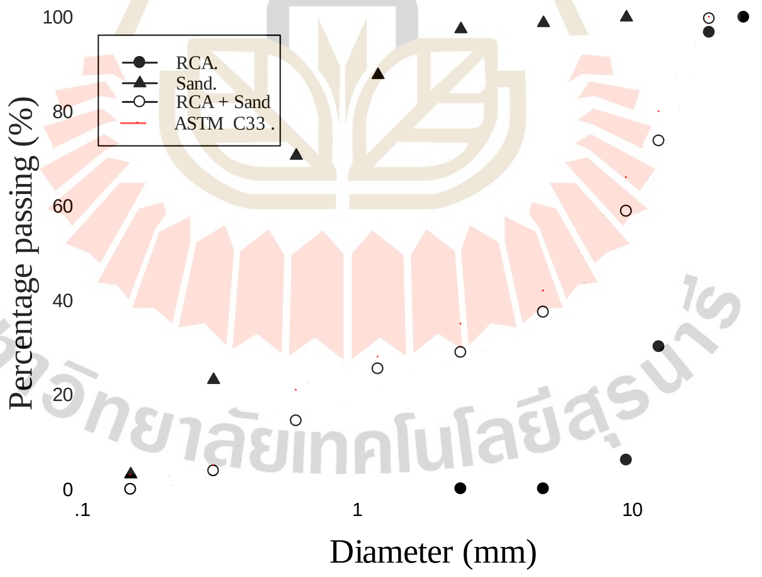

**Figure 3.1**. Particle size distributions of sand, RCA and RCA+Sand.

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Ordinary Portland cement (OPC) was used to make the RCA concrete specimens in this study. OPC had a specific gravity and an average particle size of 3.15 and 14.7 µm, respectively. Chemical compositions of OPC are shown in **Table 3.1**. Polyvinyl alcohol (PVA) was purchased from Chemipan Corporation Co., Ltd, Thailand. It is a synthetic polymer that is achromatic, odorless and soluble water (temperatures of 90～95℃ are generally required for complete solution). PVA had a specific gravity, hydrolyzed, and molecular weight of 1.27-1.31, 87.83%, and 22,000, respectively. PVA has a film forming property, high corrosion resistance to the solvents and lubricating oil and is excellent in adhesion. The flammable properties such as flashpoint and auto-ignition temperatures are above 70℃ and 440℃, respectively, while the combustibility of PVA is very low (Hassan and Peppas, 2000a; 2000b).

**Table 3.1** Chemical compositions of OPC

| Materials | Composition (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $SO_3$ | $Fe_2O_3$ | $Al_2O_3$ | CaO | MgO | LOI |
| Cement | 20.9 | 2.7 | 3.32 | 4.7 | 65.4 | 2.54 | 0.9 |

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### 3.2.2 Specimen Preparation

RCA-PVA concrete specimens were prepared by varying both w/c and p/c ratios. The PVA solution was prepared in five different percentages with respect to the cement weight, viz. 0, 0.5, 1, 1.5, 2.0, representing low to high values for improving workability and water retention abilities of the concrete (Kim and

Robertson, 1998; Kim et al. 1999; Ohama 1998). Four different w/c ratios including 0.3, 0.4, 0.5 and 0.6 were studied. The PVA solutions were prepared by adding PVA powder at a target p/c ratio into 2 liters of boiled water until the PVA was entirely dissolved. The mixture was kept overnight in an open-air atmosphere for allowing to cool down to room temperature before mixing it with cement slurry (Allahverdi et al. 2010; Singh and Rai, 2001; Thong et al. 2016). The 2 liters of water were removed for producing normal concrete and replaced by 2 liters of PVA solution.

The mixing proportions of the RCA concrete specimens are summarized in **Table 3.2**. The RCA was used to fully replace the natural coarse aggregate in the mix proportion. The ratio of fine to coarse aggregates was fixed at 45:55 by volume. The gradation of aggregate (mixture of fine and coarse aggregates) is shown in **Figure 3.1** and compared with upper and lower boundaries suggested by ASTM C33 (2016). It is noted that the gradation of tested aggregates is within the suggested boundary. The slump of the fresh RCA-PVA concrete was controlled in the ranges of 10-30, 20-50, 30-70 and 50-100 mm for w/c ratios of 0.3, 0.4, 0.5 and 0.6, respectively, by varying the amount of type F superplasticizer.

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**Table 3.2** Mix proportions of concretes.

| Mix | Mix Proportion (kg/$m^3$) | | | | | w/c | Slump |
|---|---|---|---|---|---|---|---|
| | Cement | PVA weight. | RCA[a] | Sand | SP[b] | | (mm) |
| W3PVA0 | 417.4 | - | 1193 | 890 | - | 0.3 | 10 |
| W3PVA0.5 | 417.4 | 2.087 | 1189 | 873 | 3.26 | 0.3 | 15 |
| W3PVA1 | 417.4 | 4.174 | 1191 | 874 | 4.35 | 0.3 | 10 |
| W3PVA1.5 | 417.4 | 6.261 | 1182 | 867 | 5.43 | 0.3 | 15 |
| W3PVA2 | 417.4 | 8.348 | 1179 | 864 | 6.52 | 0.3 | 20 |
| W4PVA0 | 417.4 | - | 1189 | 873 | - | 0.4 | 30 |
| W4PVA0.5 | 417.4 | 2.087 | 1194 | 877 | 2.72 | 0.4 | 30 |
| W4PVA1 | 417.4 | 4.174 | 1186 | 870 | 3.26 | 0.4 | 35 |
| W4PVA1.5 | 417.4 | 6.261 | 1173 | 860 | 3.8 | 0.4 | 35 |
| W4PVA2 | 417.4 | 8.348 | 1164 | 852 | 4.35 | 0.4 | 40 |
| W5PVA0 | 417.4 | - | 1174 | 860 | - | 0.5 | 45 |
| W5PVA0.5 | 417.4 | 2.087 | 1187 | 871 | 2.17 | 0.5 | 50 |
| W5PVA1 | 417.4 | 4.174 | 1190 | 873 | 2.39 | 0.5 | 45 |
| W5PVA1.5 | 417.4 | 6.261 | 1176 | 862 | 2.6 | 0.5 | 50 |
| W5PVA2 | 417.4 | 8.348 | 1185 | 869 | 2.82 | 0.5 | 55 |
| W6PVA0 | 417.4 | - | 1168 | 855 | - | 0.6 | 85 |
| W6PVA0.5 | 417.4 | 2.087 | 1195 | 878 | 1.08 | 0.6 | 80 |
| W6PVA1 | 417.4 | 4.174 | 1181 | 866 | 1.3 | 0.6 | 85 |
| W6PVA1.5 | 417.4 | 6.261 | 1166 | 854 | 1.52 | 0.6 | 85 |
| W6PVA2 | 417.4 | 8.348 | 1172 | 859 | 1.73 | 0.6 | 80 |

[a] Recycled coarse aggregate in the saturated surface dry (SSD) state.

[b] Superplasticizer was assumed that it had water 50% by weight.

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In this study, the TSMA method (Tam et al. 2005) was chosen to prepare the RCA-PVA concretes as this method has been proved to reduce the porosity of RCA, in that the produced cement gel fills into the cracks and voids caused during the crushing process of RCA.

### 3.2.3 Initial and Final setting times

The initial and final setting times were investigated for all specimens to explain the effect of PVA content on the hydration process of RCA-PVA concrete specimens by using the Method A-Manual Vicat Needle Apparatus in accordance with the ASTM C191 (2013). The initial setting time is reached when the penetration is 25 mm or less. Setting time ended when the tip of the needle penetrated only 0.5 mm into the cement paste.

### 3.2.4 Compressive and Flexural strengths

Based on ASTM C192 (2016), all of the fresh concrete mixtures were prepared using a rotary drum mixer. For each concrete mix, Ø 100×200 mm cylinders and 100×100×500 mm prismatic specimens were cast. The Ø 100×200 mm cylinders were used to determine the compressive strength according to the ASTM C39 (2016). The 100×100 ×500 mm prismatic specimens were prepared for the flexural strength test with a center-point loading in accordance with the ASTM C293 (2016). The flexural strength of the specimens was determined in accordance with ASTM C 293 using the following equation:

$$\text{Flexural strength} = \frac{3PL}{2bh^2} \tag{3.1}$$

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Where *P* is the maximum applied load, *L* is the span length, *b* and *h* are the average width and depth of the specimens respectively.

All the specimens were cast in steel molds and compacted by a vibrating table. The cylindrical and prismatic concrete specimens were demolded after 24 hours of curing at a room temperature, and then cured in a water-curing tank at 27 ± 2 °C for the designed curing age. The compressive and flexural strengths of RCA concrete were investigated for the curing ages of 7, 14 and 28 days. The mean compressive and flexural strength values were obtained by testing three cylindrical and three prismatic concrete specimens to ensure the consistency of testing.

### 3.2.5 Scanning Electron Microscopy and X-Ray Diffraction

The role of w/c and p/c on the compressive and flexural strengths was examined by scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses. A small specimen was frozen at -195$^{o}$C by immersion in liquid nitrogen and coated with gold before SEM analysis (Sukmak et al. 2013). The specimen was also grinded to fine powder for XRD tests to obtain microstructural information of amorphous and crystalline phases. The XRD scans were performed at 0 – 90$^{o}$2 theta by Bruker D8 ADVANCE device.

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## 3.3 RESULTS

### 3.3.1 Initial and Final Setting Times

**Figure 3.2** shows the initial and final setting times of PVA-cement pastes at various w/c and p/c ratios. The setting time was measured using Vicat apparatus on two representative specimens for each set 15 minutes after preparation time. The PVA influences the hydration process by delaying both initial and final setting times, as compared to the pure cement paste (without PVA) at the same w/c ratios. For instance, at a p/c ratio of 2 and w/c ratios of 0.3, 0.4, 0.5 and 0.6, the initial setting times are delayed by about 44, 54, 43 and 53 minutes, respectively when compared with those of the pure cement pastes. The final setting times are 62, 51, 38 and 44 minutes, respectively longer than those of the pure cement plates, which is similar to the results reported by previous researchers (Jaroslav et al. 2015; Singh and Rai, 2001). It is noted that for the same w/c ratio, the initial and final setting times are longer for higher p/c ratios. For example, at w/c = 0.5, the initial setting times are 215, 225, 229, 235 and 242 minutes for p/c = 0, 0.5, 1.0, 1.5 and 2.0, respectively and the final setting times are 343, 349, 355, 362 and 364 minutes for p/c = 0, 0.5, 1.0, 1.5 and 2.0, respectively.

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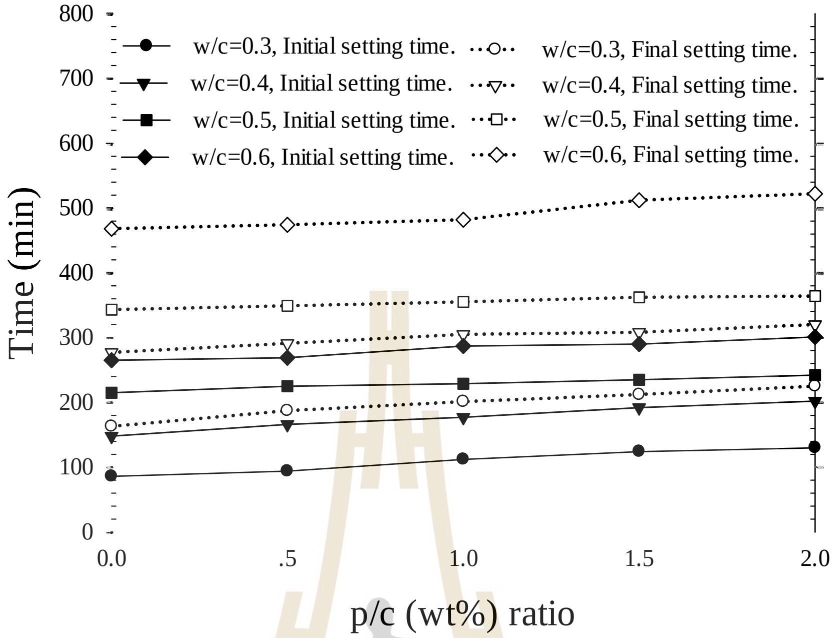

**Figure 3.2**. Initial and final setting times of PVA-cement paste.

### 3.3.2 Compressive Strength of RCA-PVA Concrete

The compressive strength of RCA-PVA concrete specimens at 7, 14 and 28 curing days and different w/c ratios of 0.3, 0.4, 0.5 and 0.6 are shown in **Figure 3.3**. The highest 7-day compressive strength (**Figure 3.3a)** was found at p/c ratio = 0 where the maximum compressive strengths are 29.5, 27.1, 24.7 and 21.2 MPa for w/c ratios of 0.3, 0.4, 0.5 and 0.6, respectively while the minimum 7-day compressive strengths were found at p/c = 2, including 20.6, 15.6, 14.1 and 12.3 MPa for w/c ratios of 0.3, 0.4, 0.5 and 0.6, respectively. This result indicates that the compressive strength reduces with increasing of w/c and p/c ratios. The additional water content (increasing of w/c ratio) leads to coarse pore distribution in concrete specimen and increases its porosity and permeability, hence reduces its compressive strength (Ait-Aider et al. 2007; Albano et al. 2009; Kim et al. 2014; Ma et al. 2014).

Similarly, the maximum 14-day and 28-day compressive strengths were also found at p/c ratio = 0 and w/c = 0.3. At p/c = 0, the 14-day compressive strengths are 33.9, 30.4, 26.9 and 24.3 MPa for w/c ratios of 0.3, 0.4, 0.5 and 0.6, respectively (**Figure 3.3b**) and the 28-day compressive strength are 43.6, 41.1, 38.5 and 32.59 MPa for w/c ratios of 0.3, 0.4, 0.5 and 0.6, respectively (**Figure 3.3c**).

It is evident from the test results that the addition of PVA to the concrete mix not only reduces the compressive strength of the specimen at a particular curing time but also the strength development with time. This is in agreement with the test results of setting times in that the initial and final setting times are longer with increasing of p/c ratio. For instance at w/c = 0.3, 7-day, 14-day and 28-day compressive strengths are 29.5, 33.9 and 43.5 MPa, respectively for p/c = 0; are 24.5, 26.5 and 35.6 MPa, respectively for p/c = 1.0 and are 20.6, 21.1 and 27.4 MPa, respectively for p/c = 2.0.

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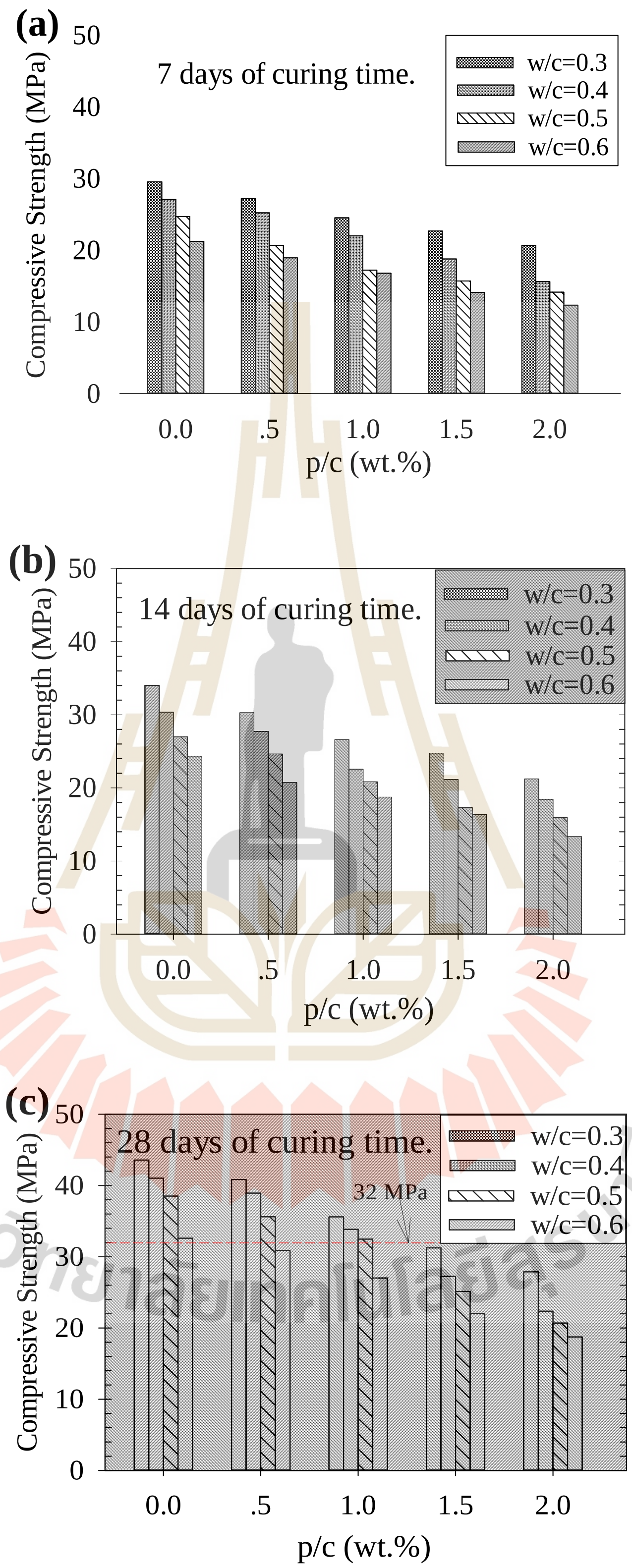

**Figure 3.3** Compressive Strength of RCA-PVA concrete at (a) 7 days, (b) 14 days, (c) 28 days.

### 3.3.3 Flexural Strength of RCA-PVA Concrete

**Figure 3.4** shows the flexural strength of the specimen at various w/c ratios, p/c ratios, and curing times. For low w/c ratios of 0.3 and 0.4, the maximum flexural strength was found at approximately the same p/c ratio of 0.5% at all curing times. The maximum flexural strengths at w/c ratios of 0.3 and 0.4 at 28 days of curing were found to be 6.7 and 5.8 MPa, respectively with an increase of 133% and 139% when compared to RCA concrete specimens at the same w/c ratios. However, the addition of PVA beyond p/c of 0.5% caused a reduction in the flexural strength.

The change in the flexural strength with p/c ratio for higher w/c ratios of 0.5 and 0.6 is also similar to that for w/c = 0.3 and 0.4, where the flexural strength increases to the maximum value at the optimum p/c and then decreases as p/c increases. However, the optimum p/c ratios providing the highest flexural strength are different from those of w/c = 0.3 and 0.4. The optimum p/c ratios were found to be 1.0 and 1.5 for w/c = 0.5 and 0.6, respectively. In other words, the optimum p/c increases with increasing of w/c ratio. At the optimum p/c ratio, the 28-day flexural strengths were 5.35 MPa and 4.93 MPa for w/c = 0.5 and 0.6, respectively. The flexural strength increased by 132% and 129% than those of RCA concrete at the same w/c ratios of 0.5 and 0.6, respectively. Compared with the strength requirement for the rigid pavement by Department of Highways (the 28-day compressive strength > 32 MPa (see Figure 3 (c)), the RCA concrete (without PVA) meets the requirement for all w/c ratios tested. With PVA, the RCA-PVA concretes meet the requirement when w/c ≤ 0.5 and p/c ≤ 1.

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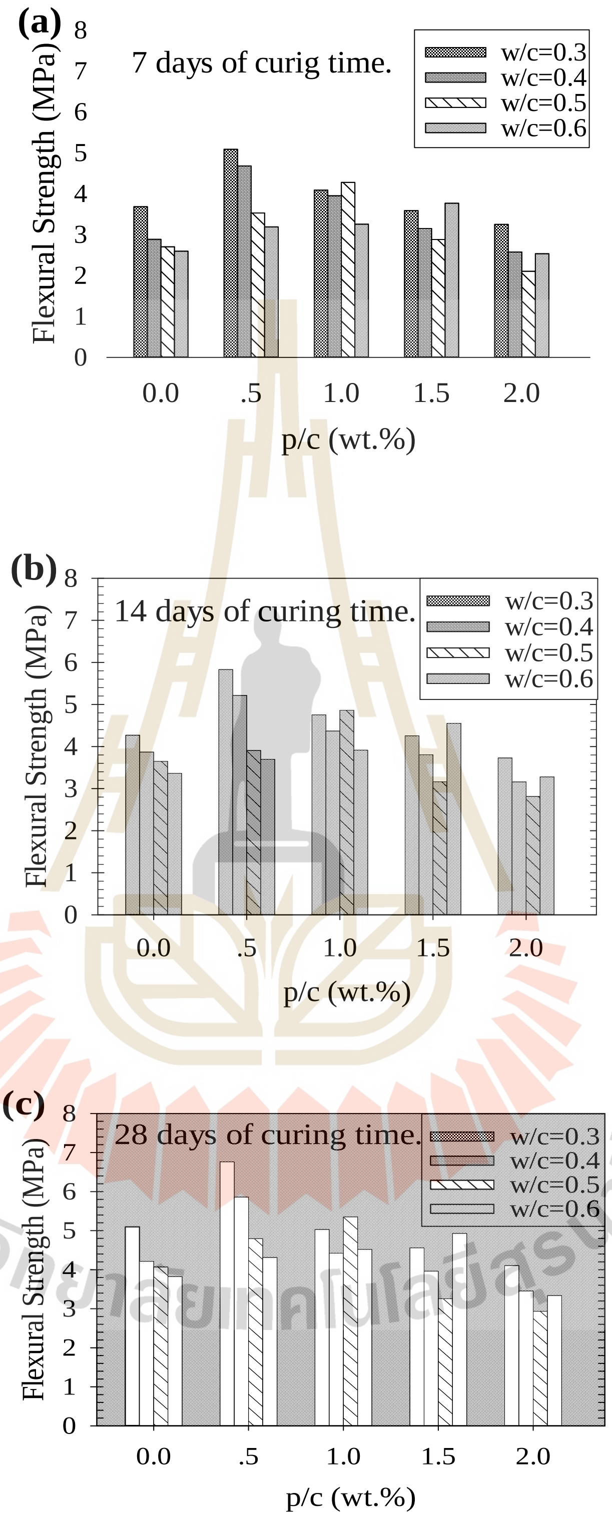

**Figure 3.4** Flexural Strength of RCA-PVA concrete at (a) 7 days, (b) 14 days, (c) 28 days.

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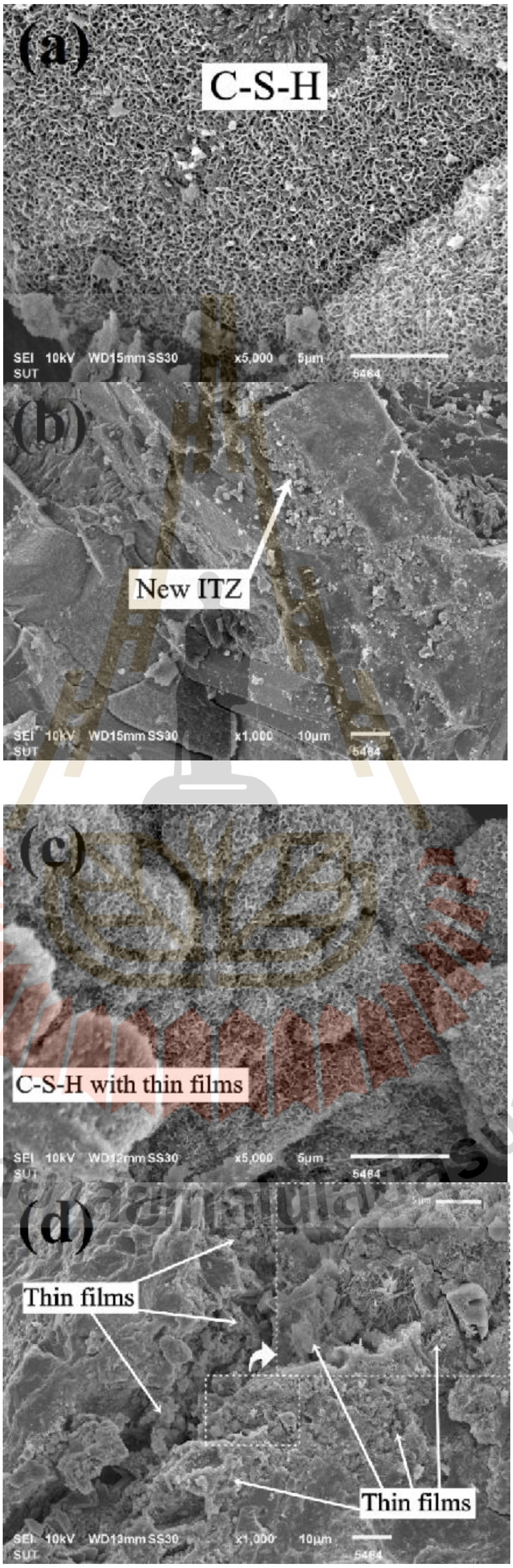
## 3.4 Microstructural Analysis

Scanning electron microscopy (SEM) images of 28 days cured specimens at w/c = 0.5 and p/c = 0, 1 and 2% (W5PVA0, W5PVA1 and W5PVA2) are shown in **Figure 3.5**. For p/c = 0 (**Figures 3.5 a** and **b**), the calcium silicate hydrate (C-S-H) gel is clearly detected, which is the main cementitious product primarily responsible for the strength development in cement based material (Taylor 1986). The same is however not true for the RCA-PVA specimens, films of PVA infiltrate and cover the C-S-H products. At a small amount of p/c = 1.0 (**Figures 3.5c and d**), the thin films of PVA are detected on the C-S-H products while the growth of C-S-H continues and the C-S-H enlarges and penetrates the thin films out to the other matrices. **Figures 3.5e** and **f** indicate the thicker films around C-S-H products for higher p/c of 2%. The films retard the hydration like a huge barrier around the matrix, which prevents water absorption for the hardening and the growth of C-S-H structures. Hence, the growth of C-S-H products in the matrix is prevented, resulting in an extreme reduction of compressive strength.

In addition to the SEM results, the XRD patterns were also examined for the treated specimens to confirm the retardation of cementitious products in RCA-PVA concrete at various p/c ratios. The XRD patterns of specimens at w/c=0.5 with p/c = 0, 1 and 2% (W5PVA0, W5PVA1 and W5PVA2) and cured for 28 days are shown in **Figure 3.6**. The amorphous phase and the board hump (peak) between 17 and 35°2θ are observed, which is similar to previous research works (Abo-El-Enein et al. 2015; Hoy et al. 2016; Kontoleontos et al. 2013; Lothenbach et al. 2011).



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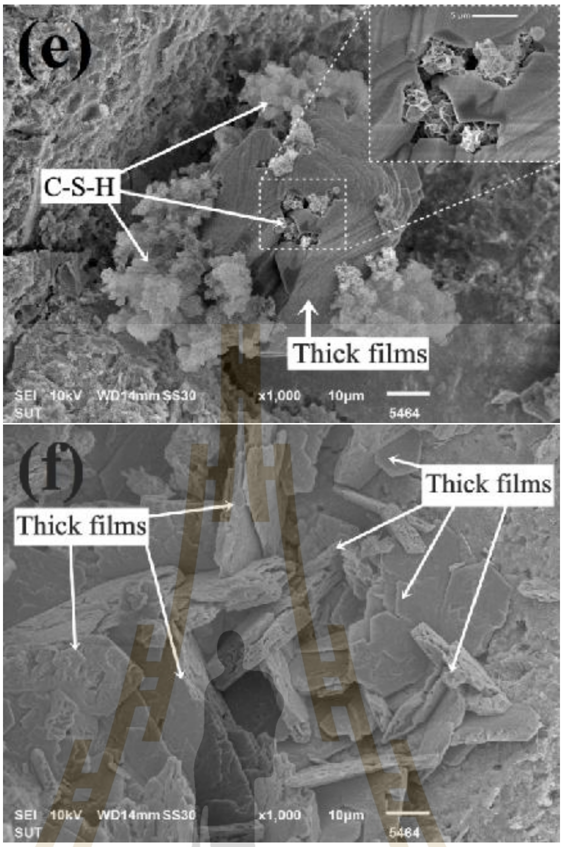

**Figure 3.5** Scanning Electron Microscopy (SEM) images for (a and b) W5PVA0, (c and d) W5PVA1 and (e and f) W5PVA2

The XRD results show the decrease in the Portlandite phase with increasing of p/c ratio, indicating the reduction in hydration products. The presence of the largest amount of calcium silicate hydrate (C-S-H) over-lapped with that of Calcite in W5PVA0 specimens (without PVA) is indicated by the broad hump at about 29.5°2θ in **Figure 3.6(a)**.

For W5PVA1, the broad hump at about 29.5°2θ of C-S-H products (**Figure 3.6(b)**) are less than those in the RCA concrete (W5PVA0). At this state, the thin films of PVA cover and inter woven into cement matrix. The lowest amount of

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cementitious products are observed when p/c = 2.0 as shown in **Figure 3.6(c)** for W5PVA2 specimen.

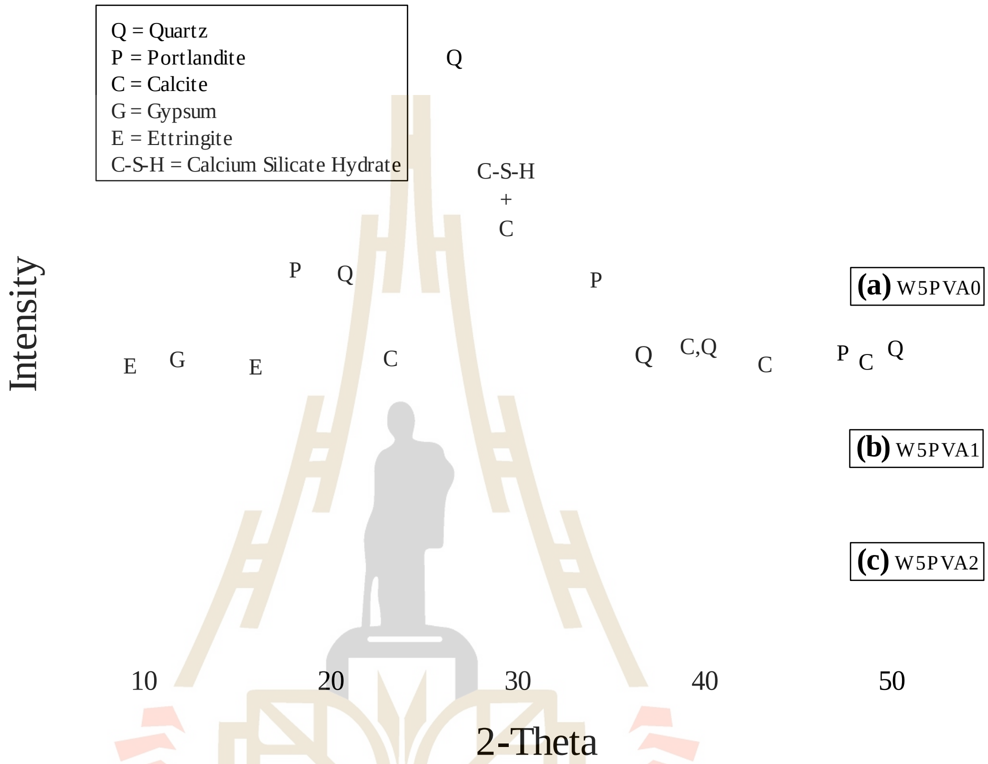

**Figure 3.6** X-ray Diffraction (XRD) pattern of (a) W5PVA0, (b) W5PVA1 and (c) W5PVA2 at 28 days.

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From the SEM images and XRD patterns, it is evident that the addition of PVA into RCA concrete forms a film that creates a barrier around the cement grains and therefore prevents water absorption during the hydration process. The addition of PVA also increases the viscosity of the water solution (Nguyen et al. 2015), causing formation of air bubbles which cannot escape from the RCA-PVA concrete during mixing, and hence an increase in the porosity of the cement matrix (Contrafatto 2013;

Ficker 2011). The addition of PVA therefore leads to a delay in the hydration process of cement-PVA paste, extension of setting time, and reduction in hydration products and the density of the matrix.

Even though the PVA films prevent hydration, the films create linkage among cement matrixes. The flexural strength of RCA concrete is controlled by tensile strength as seen by the crack prorogation from the bottom of prismatic specimens during testing similar to the failure mechanism reported by Jamsawang et al. (2015). The tensile strength of RCA-PVA concrete has contributions from two components: cementation bonds and PVA films. The flexural strength of RCA-PVA concrete specimens increases with p/c ratio up to the maximum value at the optimum p/c ratio where the tensile strength from both components is the highest. The excessive p/c reduces the flexural strength of the RCA-PVA concrete to be even lower than that of the RCA concrete due to significant reduction in cementation bonds.

## 3.5 Conclusions

This research investigates the feasibility of using polyvinyl alcohol (PVA) to improve the flexural strength of recycled concrete aggregate (RCA) concrete to be a sustainable rigid pavement material. The following conclusions can be drawn from this research study:

1. PVA forms a film around cement grains and therefore prevents the water absorption for cement hydration process. Hence, the higher p/c ratio results in the longer initial and final setting times of RCA-cement paste and the lower the compressive strength.

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2. Even though PVA retards hydration, it contributes to improve the tensile strength of the cement matrix and hence results in an increased flexural strength. The flexural strength of RCA-PVA concrete is contributed from cementation bond and PVA film strength. Due to the reduction in cementation bond strength and the increase in tensile strength with increasing p/c ratio, the flexural strength increases with increasing of p/c ratio up to the maximum value at the optimum p/c ratio and then decreases with increasing of p/c ratio.

3. The optimum p/c ratio is dependent upon w/c ratio. The higher w/c ratio results in the higher p/c ratio. The optimum p/c ratio was found to be 0.5, 0.5, 1.0 and 1.5 for w/c = 0.3, 0.4, 0.5 and 0.6, respectively. Based on the national road authority (demanding a minimum 28-day compressive strength of 32 MPa), the w/c ≤ 0.5 and p/c ≤1 was found to be applicable for road construction. At the optimum p/c ratio, the flexural strength of RCA-PVA was approximately 130% higher than that of the RCA concrete.

4. The outcome of this research confirms the viability of using PVA to improve the flexural strength of RCA concrete to be used as an alternative sustainable Rigid Pavement.

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# CHAPTER IV

# RECYCLED CONCRETE AGGREGATE MODIFIED WITH POLYVINYL ALCOHOL AND FLY ASH FOR CONCRETE PAVEMENT APPLICATIONS

## 4.1 Statement of problem

Research on alternative materials derived from construction and industrial wastes has been increasing in recent years, due to the promotion of sustainable practices and the need to reduce negative environmental impacts in civil engineering construction activities. Past studies have shown that construction and demolition (C&D) and industrial wastes such as recycled glass, melamine debris, slag, recycled asphalt pavement can be deemed as suitable road construction materials when stabilized with traditional and nontraditional chemicals (Arulrajah et al. 2017; Donrak et al. 2018; Hoy et al. 2016; Mohammadinia et al., 2018; Muhammad et al. 2018; Latifi et al. 2017, 2018). Recycled Concrete Aggregate (RCA) was also used as an alternative aggregate in asphalt concrete (Paranavithana and Mohajerani, 2006).

Recycled Concrete Aggregate (RCA) is a C&D material, which is obtained from the demolition of aged concrete buildings and reused in the form of aggregates in concrete production. The reuse of RCA would significantly reduce waste stockpiles at landfills and would also limit the need for natural aggregate sources (Silva et al. 2014). Though the use of RCA to replace the natural aggregate in concrete applications is a widespread practice and beneficial to the environment, the aged mortar attached to aggregates and the cracks around aggregates caused by the recycling process results in low mechanical strength properties when compared to conventional concrete (Buck AD 1997; Limbachiya et al. 2000; Mohajerani et al. 2017; Omary et al. 2016). As such, the low mechanical strength properties are a huge barrier for successful RCA utilization.

The usage of RCA affects the ultimate strength of RCA concrete; i.e., decrease in density, modulus of elasticity, compressive and flexural strengths. (Behera et al. 2014; Hansen and Boegh, 1985; Hansen and Narud, 1983; Kheder and Al-Windawi, 2005; Tangchirapat et al. 2010; Tangchirapat et al. 2008). Earlier studies on RCA concrete have focused on the compressive strength improvement to meet pavement strength and design requirements, by introducing the double mixing or two-stage mixing (TSMA) approaches (Otsuki et al. 2003; Tam et al. 2005). Nevertheless, the low flexural strength of RCA concrete is still inferior to that of traditional concrete. The flexural strength is an essential characteristic for rigid pavement design, which controls the thickness and cracks of pavement concrete surface as a consequence of bending stress from traffic loads. Fiber reinforced concrete has been introduced in civil engineering structures which are subjected to substantial bending stresses and has gained popularity due to its superior performance such as hindrance in macro crack propagation, prevention of growth of micro cracks to macroscopic level, enhancement in residual strength after formation of the first crack, improvement in ductility and flexural strength, and high toughness (Abbass et al. 2018; Jamsawang et al. 2015; Sukontasukkul 2004).

Besides fiber reinforcement, water-soluble polymers can also be used to improve the flexural strength of concrete. Water-soluble polymers have chemical

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interactions with the hydration products, resulting in the creation of a film around the cement grains (Gopinathan and Rao, 1992; Kim et al. 1999). Polyvinyl alcohol (PVA), a water-soluble polymer, can efficiently enhance both the conventional and RCA concretes similar to fiber reinforcement (Allahverdi et al. 2010; Jaroslav et al. 2015; Yaowarat et al. 2018). Though the PVA films enhance the tensile strength since the preliminary age, they prevent water absorption in hydration process and retard the growth of C-S-H products, which affect the compressive strength at long-term condition. The optimal proportion of PVA to successfully enhance the flexural strength and with minimal strength reduction in RCA concrete to meet the requirement of Department of Highways, Thailand was recently investigated by Yaowarat et al. (2018).

Replacing Portland cement with industrial pozzolan by-products such as Fly Ash (FA), bagasse ash, and palm oil fuel ash has been found to improve cementation bonding of concrete, moreover, the reuse of by-products has significant environmental and economic benefits (Kua et al. 2016; Phetchuay et al. 2016; Somna et al. 2012; Tangchirapat et al. 2012; Yoobanpot et al. 2017). For example, the compressive strength of both normal and RCA concrete was found to be improved by using FA and ground rice-husk bark ash (Tangchirapat et al. 2010; Tangchirapat et al. 2008). In addition, the use of FA, ground granulated blast furnace slag, and metakaolin to partially replace cement has been found to successfully increase the durability of RCA concrete against chloride penetration (Ann et al. 2008; Kou et al. 2007; Moon and Moon, 2002) which is similar to durability improvement of concrete by adding PVA (Singh and Rai 2001; Viswanath and Thachil 2008).

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To the authors' knowledge, no previous work has been attempted to study the improvement of mechanical properties of RCA concrete with a combination of FA and PVA. Both the compressive and flexural strengths can be improved for RCA-FA-PVA concrete unlike RCA-PVA concrete in which the flexural strength is improved but with a reduction in compressive strength. Therefore, the investigation of the role of influence factors including cement, PVA and FA contents and curing time on mechanical strength improvement is significant and novelty, which is the focus of this research. The mechanical performance was investigated using compressive, flexural and split tensile strength testing on the RCA-PVA-FA concrete at various influence factors. The microstructural analysis via scanning electron microscope (SEM) and energy-dispersive x-ray spectroscopy (EDX) was also carried out to examine the role of influence factors on mechanical strength improvement.

## 4.2 Material and Methods

### 4.2.1 Materials

Natural river sand with a fineness modulus of 3.70 - 3.78 was used as the fine aggregate for preparation of the RCA concrete. The river sand had a specific gravity in saturated surface dry state, percent of voids, and water absorption of 2.56, 40.7%, and 3.11%, respectively. The dry-rodded unit weight of the river sand was 14.7 kN/m$^3$. Particle size distribution of the river sand is shown in **Fig. 4.1**.

The RCA specimens had particle sizes ranging between 4.75 mm and 19 mm. The grain size distribution curve of RCA is shown in **Fig. 4.1**. RCA had a specific gravity and a fineness modulus in saturated surface dry state of 2.71 and 1.37, respectively. Its dry-rodded unit weight was 12.5 kN/m$^3$. The presence of voids, Los

Angeles abrasion loss and water absorption were 56%, 38% and 5.2%, respectively. Since the RCA was not scalped to remove the attached mortar, it possessed lower specific gravity and higher water absorption and porosity. Consequently, the RCA was weaker than the natural aggregate (Chen et al. 2003; Salem and Jackson, 2003).

Ordinary Portland cement (OPC) was used to make the RCA concrete specimens in this study. OPC had a specific gravity and an average particle size of 3.15 and 14.7 µm, respectively. Chemical compositions of OPC are shown in **Table 4.1**

FA was obtained from the Mae Moh power plant in the northern region of Thailand. This is the largest lignite power plant in Thailand and is operated by the Electricity Generating Authority of Thailand (EGAT). **Table 4.1** summarizes the chemical compositions of FA using XRF analysis. **Fig. 4.1** shows the grain size distribution curve of FA, which was obtained by laser particle size analysis. The specific gravity of FA was 2.50.

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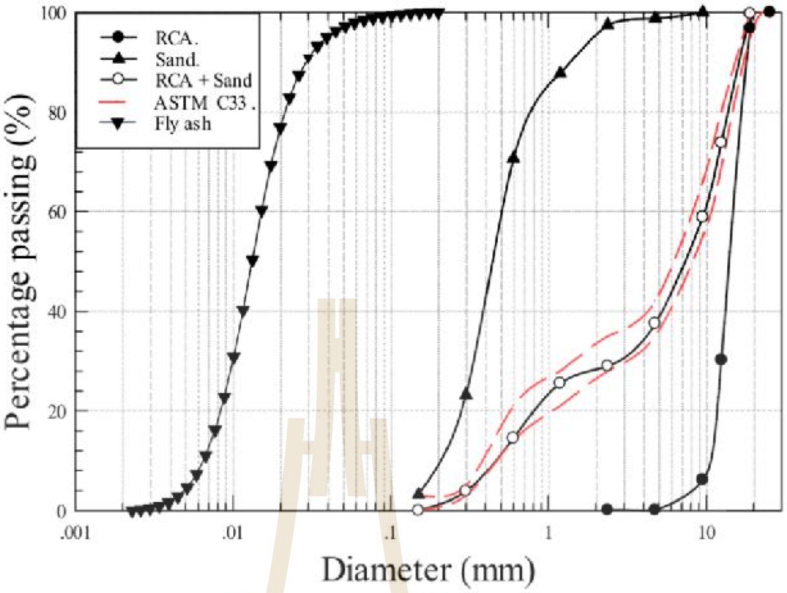

**Figure 4.1** Particle size distributions of sand, RCA, RCA+sand and FA.

Polyvinyl alcohol (PVA) was purchased from Chemipan Corporation Co., Ltd, Bangkok, Thailand. It is a synthetic polymer that is achromatic, odorless and soluble water (temperatures of 90～95℃ are generally required for complete solution). PVA had a specific gravity, hydrolysis (the chemical breakdown of a compound due to reaction with water), and molecular weight of 1.27-1.31, 87.83%, and 22,000 g/mol, respectively. PVA has a film forming property, high corrosion resistance to the solvents and lubricating oil and is excellent in adhesion. The flammable properties such as flashpoint and auto-ignition temperatures are above 70℃ and 440℃, respectively, while the combustibility of PVA is very low (Hassan and Peppas, 2000a; Hassan and Peppas 2000b).

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**Table 4.1** Chemical compositions of OPC and Fly Ash

| Materials | Composition (%) | | | | | | |
|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $SO_3$ | $Fe_2O_3$ | $Al_2O_3$ | CaO | MgO | LOI |
| Cement | 20.9 | 2.7 | 3.32 | 4.7 | 65.4 | 2.54 | 0.9 |
| FA | 39.18 | 4.29 | 15.45 | 22.64 | 11.3 | 1.69 | 1.61 |

### 4.2.2 Specimen Preparation

RCA-PVA-FA concrete specimens were prepared at a fixed w/b = 0.5 with various PVA and FA replacement ratios. The PVA solution was prepared in five different percentages with respect to the binder (cement + FA) weight: 0, 0.5, 1, 1.5, 2.0, representing low to high values for improving workability and water retention abilities of the concrete (Kim and Robertson, 1998; Kim et al. 1999; Ohama 1998). The FA replacement (FA to cement, FA/c) ratios were 10/90, 20/80 and 30/70. The PVA solutions were prepared by adding PVA powder at a target PVA/binder, p/b ratio into 2 liters of boiled water until the PVA was entirely dissolved. 2 liters of water were removed for producing normal concrete and replaced by 2 liters of PVA solution. The mixture was kept overnight in an open-air atmosphere for allowing the temperature of mixture to cool down to room temperature before mixing it with cement slurry (Allahverdi et al. 2010; Singh and Rai, 2001; Thong et al. 2016). The mixing proportions of the RCA concrete specimens are summarized in **Table 4.2**. The RCA was immersed under water for 24 hours, wiped with a towel and then mixed to ensure that the RCA was in the saturated surface dry (SSD) state. The saturated surface dry RCA was used to fully replace the natural coarse aggregates in the mix proportion.

**Table 4.2**. Mix proportions of concretes

| Mix[a] | Mix Proportion (kg/m$^3$) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Cement | Fly Ash | PVA weight. | RCA[b] | Sand | SP[c] | Slump (mm) |
| FA0PVA0 | 417.4 | 0 | - | 1187 | 890 | 0.5 | 95.00 |
| FA0PVA0.5 | 417.4 | 0 | 2.087 | 1185 | 873 | 0.63 | 80.00 |
| FA0PVA1 | 417.4 | 0 | 4.174 | 1191 | 874 | 0.75 | 75.00 |
| FA0PVA1.5 | 417.4 | 0 | 6.261 | 1182 | 867 | 0.94 | 85.00 |
| FA0PVA2 | 417.4 | 0 | 8.348 | 1178 | 864 | 1.25 | 65.00 |
| FA10PVA0 | 375.7 | 41.7 | - | 1185 | 873 | 0.56 | 60.00 |
| FA10PVA0.5 | 375.7 | 41.7 | 2.087 | 1192 | 877 | 0.75 | 85.00 |
| FA10PVA1 | 375.7 | 41.7 | 4.174 | 1187 | 870 | 0.94 | 70.00 |
| FA10PVA1.5 | 375.7 | 41.7 | 6.261 | 1173 | 860 | 1.25 | 80.00 |
| FA10PVA2 | 375.7 | 41.7 | 8.348 | 1175 | 852 | 1.38 | 85.00 |
| FA20PVA0 | 333.9 | 83.5 | - | 1174 | 860 | 1.25 | 65.00 |
| FA20PVA0.5 | 333.9 | 83.5 | 2.087 | 1186 | 871 | 1.38 | 75.00 |
| FA20PVA1 | 333.9 | 83.5 | 4.174 | 1189 | 873 | 1.56 | 85.00 |
| FA20PVA1.5 | 333.9 | 83.5 | 6.261 | 1177 | 862 | 1.69 | 90.00 |
| FA20PVA2 | 333.9 | 83.5 | 8.348 | 1184 | 869 | 1.88 | 85.00 |
| FA30PVA0 | 292.2 | 125.2 | - | 1173 | 855 | 1.44 | 85.00 |
| FA30PVA0.5 | 292.2 | 125.2 | 2.087 | 1193 | 878 | 1.63 | 65.00 |
| FA30PVA1 | 292.2 | 125.2 | 4.174 | 1187 | 866 | 1.81 | 90.00 |
| FA30PVA1.5 | 292.2 | 125.2 | 6.261 | 1169 | 854 | 1.84 | 70.00 |
| FA30PVA2 | 292.2 | 125.2 | 8.348 | 1177 | 859 | 1.94 | 75.00 |

[a] FA0PVA0 is FA/c = 0/100 with p/b (wt.%) = 0, FA30PVA2 is FA/c = 30/70 with p/b (wt.%) = 2.

[b] Recycled coarse aggregate (RCA) in the saturated surface dry (SSD) state.

[c] Superplasticizer (SP) was assumed that it had water 50% by weight.

The ratio of fine to coarse aggregates was fixed at 45:55 by volume. The gradation of aggregate (mixture of fine and coarse aggregates) is shown in **Fig. 4.1** and compared with upper and lower boundaries suggested by ASTM C33 (2016). It should be noted that the gradation of tested aggregates is within the suggested boundary. The slump of the fresh RCA-PVA-FA concrete was limited to 50-100 mm by varying the amount of type F superplasticizer.

In this study, the two-stage mixing approach (TSMA) method (Tam et al. 2005) was chosen to prepare the RCA-PVA-FA concretes as this method has been

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proved to reduce the porosity of RCA, in that the produced cement gel fills into the cracks and voids caused during the crushing process of RCA.

### 4.2.3 Compressive, Flexural and Split tensile Strengths

Based on ASTM C192 (2016), all of the fresh concrete mixtures were prepared using a rotary drum mixer. For each concrete mix, Ø100×200 mm cylindrical and 100×100×500 mm prismatic specimens were cast. The Ø100×200 mm cylinders were used to determine the compressive and split tensile strengths according to the ASTM C39 (2016) and ASTM C496 (2016), respectively, with an average rate of testing of 1 mm/min. The 100×100 ×500 mm prismatic specimens were prepared for the flexural strength test with a center-point loading in accordance with the ASTM C293 (2016) using a rate of 2 mm/min with a span length equal to 350 mm. The flexural strength of the specimens was determined in accordance with ASTM C293 using the following equation:

$$\text{Flexural strength} = \frac{3PL}{2bh^2} \tag{4.1}$$

where $P$ is the maximum applied load, $L$ is the span length, $b$ and $h$ are the average width and depth of the specimens respectively.

The split tensile strength was determined in accordance with ASTM C496 using the following equation:

$$\text{Split tensile strength} = \frac{2P}{\pi l d} \tag{4.2}$$

where $l$ and $d$ are the average length and diameter of the specimens respectively.

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To ensure homogeneity, the OPC and FA were first mixed together for 3 min in the mixer, and then the TSMA method was performed to make RCA-PVA-FA concrete. After mixing, the fresh concrete was immediately cast into steel molds and compacted by steel rods. The cast specimens were covered with plastic to prevent water loss. The cylindrical and prismatic concrete specimens were demolded after 24 hours of curing at a room temperature, and then cured in a water-curing tank at 27 ± 2 °C for the designed curing age. The compressive, flexural and split tensile strengths of RCA-PVA-FA concrete were investigated after 7, 28 and 60 days. The mean compressive, split tensile and flexural strength values were obtained by triple concrete specimens to ensure the consistency of testing. In most cases, the results under the same testing condition were reproducible with low mean standard deviation, SD (SD/$\bar{x}$ < 10%, where $\bar{x}$ is mean strength value).

### 4.2.4 SEM and EDX measurements

The scanning electron microscope (SEM), equipped with an energy dispersive X-ray (EDX) detector, is a highly effective instrument for in-depth analysis of cement and its additives. It is widely used for morphology differentiation and verification of cemented materials. The role of FA/c and p/b ratios and curing time on the compressive, flexural and split tensile strengths was therefore examined by SEM/EDX analysis in this research. Specimens at the ages of 7 and 60 days were broken and the fractions in the middle part of the specimens were used for the analyses. Hydration of the cement paste was stopped by freezing. A small specimen was frozen at -195$^{o}$C by immersion in liquid nitrogen and coated with a layer of gold approximately 20–25 Å thick using a blazer sputtering coater before SEM and EDX analysis (Sukmak et al. 2013), in order to examine its localized morphology and elemental distributions at the microscopic scale. The SEM was used to investigate the effect of p/b and FA/c ratios on the concrete morphology, by collecting data from at least five randomly selected sites from the cement paste. Care was taken to examine only the cement paste, and the sites were randomly selected to avoid overlapping areas and aggregates. The EDX data were obtained using a micro analytical unit that featured the ability to detect the small variations in trace element content. Areas used for EDX analysis corresponded directly to the SEM morphological examination at 2500 magnification.

## 4.3 Mechanical Strength Results

The compressive, flexural and split tensile strengths of RCA-PVA-FA specimens are summarized in **Table 4.3**. The compressive strength of RCA-PVA-FA concrete specimens after 7, 28 and 60 days of curing with the different FA/c ratios 0, 10/90, 20/80 and 30/70 is presented in **Table 4.3** and **Fig. 4.2. Fig. 4.2a** shows that the early 7-day compressive strength reduces with increasing FA/c and p/c ratios. As such, the maximum 7-day compressive strength is found at a group of p/b = 0 whose values are 25.3, 23.0, 19.7 and 16.6 MPa for FA/c = 0/100, 10/90, 20/80 and 30/70, respectively while the minimum 7-day compressive strengths are found at a group p/b = 2 are 14.8, 14.4, 12.7 and 10.6 MPa for FA/c = 0/100, 10/90, 20/80 and 30/70, respectively.

However, the same is not true for long-term conditions (28 and 60 days). **Fig. 4.2b and c** show that the 28-day and 60-day compressive strengths increase with the addition of FA/c ratio from 0/100 till the optimal ratio at 20/80 and subsequently decrease at FA/c = 30/70. The shift of the maximum compressive strength from FA/c = 0/100 for early curing to be 20/80 for long-term curing demonstrates that the

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pozzolanic reaction due to the contribution of FA replacement comes into play at long-term curing.

Similar to the 7-day compressive strength development, the increase of p/b ratio causes a reduction in compressive strength for all FA/c ratios. As such, the maximum 28-day and 60-day compressive strengths are found at a group p/b = 0 and FA/c = 20/80. The dotted line in **Fig. 4.2b** indicates the strength requirement after 28 days of curing for rigid pavement by the Department of Highways, Thailand (DH-S309/2544).

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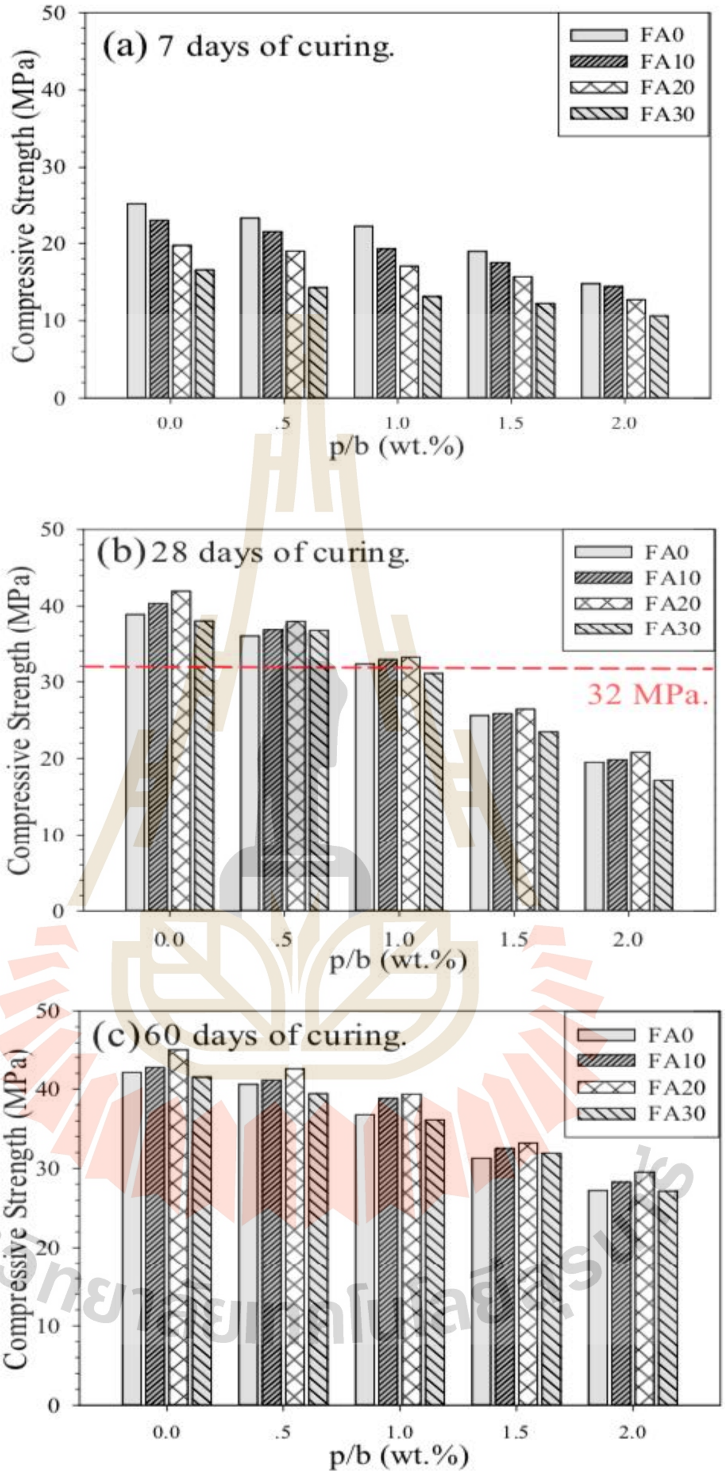

**Figure 4.2** Compressive strength of RCA-PVA-FA concrete at (a) 7 days, (b) 28 days and (c) 60 days.

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**Table 4.3** Compressive, flexural and split tensile strengths.

| Mix | Compressive strength (MPa) | | | Flexural strength (MPa) | | | Split tensile strength (MPa) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 7 days | 28 days | 60 days | 7 days | 28 days | 60 days | 7 days | 28 days | 60 days |
| FA0PVA0 | 25.28 | 38.93 | 42.12 | 2.83 | 4.06 | 5.23 | 1.50 | 1.91 | 2.12 |
| FA0PVA0.5 | 23.28 | 35.97 | 40.61 | 3.61 | 4.78 | 6.14 | 1.57 | 2.03 | 2.27 |
| FA0PVA1 | 22.22 | 32.33 | 36.77 | 4.57 | 5.35 | 7.03 | 1.76 | 2.07 | 2.42 |
| FA0PVA1.5 | 18.98 | 25.61 | 31.29 | 3.01 | 3.29 | 4.86 | 1.73 | 2.12 | 2.55 |
| FA0PVA2 | 14.79 | 19.51 | 27.22 | 2.23 | 2.94 | 3.67 | 1.70 | 2.08 | 2.11 |
| FA10PVA0 | 23.01 | 40.38 | 42.77 | 2.56 | 4.20 | 5.57 | 1.47 | 1.97 | 2.19 |
| FA10PVA0.5 | 21.53 | 36.82 | 41.13 | 3.25 | 4.92 | 6.42 | 1.54 | 2.05 | 2.32 |
| FA10PVA1 | 19.30 | 32.91 | 38.86 | 4.17 | 5.57 | 7.23 | 1.73 | 2.12 | 2.54 |
| FA10PVA1.5 | 17.54 | 25.87 | 32.51 | 2.66 | 3.58 | 5.23 | 1.65 | 2.23 | 2.62 |
| FA10PVA2 | 14.42 | 19.86 | 28.29 | 2.08 | 2.88 | 3.94 | 1.62 | 2.12 | 2.18 |
| FA20PVA0 | 19.74 | 41.96 | 45.12 | 2.24 | 4.33 | 6.08 | 1.45 | 2.07 | 2.33 |
| FA20PVA0.5 | 19.01 | 38.04 | 42.56 | 3.04 | 5.14 | 6.95 | 1.50 | 2.16 | 2.42 |
| FA20PVA1 | 17.07 | 33.21 | 39.38 | 3.81 | 5.65 | 7.86 | 1.72 | 2.24 | 2.64 |
| FA20PVA1.5 | 15.68 | 26.44 | 33.21 | 2.19 | 3.87 | 5.84 | 1.54 | 2.38 | 2.78 |
| FA20PVA2 | 12.73 | 20.82 | 29.54 | 1.81 | 2.96 | 4.67 | 1.54 | 2.22 | 2.31 |
| FA30PVA0 | 16.58 | 38.09 | 41.53 | 1.96 | 3.80 | 5.15 | 1.38 | 1.92 | 2.19 |
| FA30PVA0.5 | 14.29 | 36.71 | 39.42 | 2.62 | 4.59 | 5.92 | 1.45 | 2.02 | 2.25 |
| FA30PVA1 | 13.13 | 31.09 | 36.13 | 3.01 | 4.95 | 6.54 | 1.58 | 2.09 | 2.43 |
| FA30PVA1.5 | 12.25 | 23.48 | 31.93 | 1.51 | 3.22 | 4.76 | 1.51 | 2.15 | 2.53 |
| FA30PVA2 | 10.62 | 17.17 | 27.14 | 1.24 | 2.72 | 3.62 | 1.50 | 2.11 | 2.17 |

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It is noted that the ingredients which meet the strength requirement are FA/c = 0 and p/b = 0, FA/c = 0 and p/b = 0.5, FA/c = 0 and p/b = 1, FA/c = 10 and p/b = 0, FA/c = 10 and p/b = 0.5, FA/c = 10 and p/b = 1, FA/c = 20 and p/b = 0, FA/c = 20 and p/b = 0.5, FA/c = 20 and p/b = 1, FA/c = 30 and p/b = 0, and FA/c = 30 and p/b = 0.5.

**Fig. 4.3** shows the flexural and split tensile strengths of the specimens at various FA/c and p/b ratios and curing times. Unlike compressive strength, the flexural strength at a particular curing time increases with an increase in p/b ratio up to the highest value and then decreases. The p/b ratio providing the maximum flexural strength at a particular FA/c ratio is herein defined as the optimum p/b ratio. The optimum p/b ratio is found to be the same at 1% for all FA/c ratios and curing times tested. The maximum flexural strengths at FA/c = 0/100, 10/90, 20/80 and 30/70 at 28 days of curing are found to be 5.35, 5.57, 5.65 and 4.95 MPa and at 60 days of curing are 7.03, 7.23, 7.86 and 6.54 MPa, respectively with an increase of 34.4%, 29.8%, 29.3% and 26.9% when compared to RCA-FA concrete specimens (without PVA) at the same FA/c ratios. The excessive PVA (p/b > 1%) causes a reduction in the flexural strength, similar to the results reported recently by Yaowarat et al. (2018) for RCA-PVA concrete. FA replacement is found to be useful for the flexural strength improvement of RCA-PVA-FA concrete at long-term curing similar to the increase in compressive strength. The optimal FA/c is found at 20/80, which is the same for compressive strength.

It is evident from **Fig. 4.3** that RCA concrete with and without FA has 28-day flexural strength lower than the requirement specified by Air Force Army (TM 1992) and Virginia Transportation Research Council (Lane 1998) of USA of 4.5 MPa. The PVA of 0.5% and 1.0% can significantly enhance the flexural strength to meet the requirement. The PVA also improves the ductility of RCA-PVA-FA concrete at long-term curing as seen by the relationship between flexural strength versus deflection under flexural beam test on specimens at optimum FA/c = 20/80 in **Fig. 4.4**.

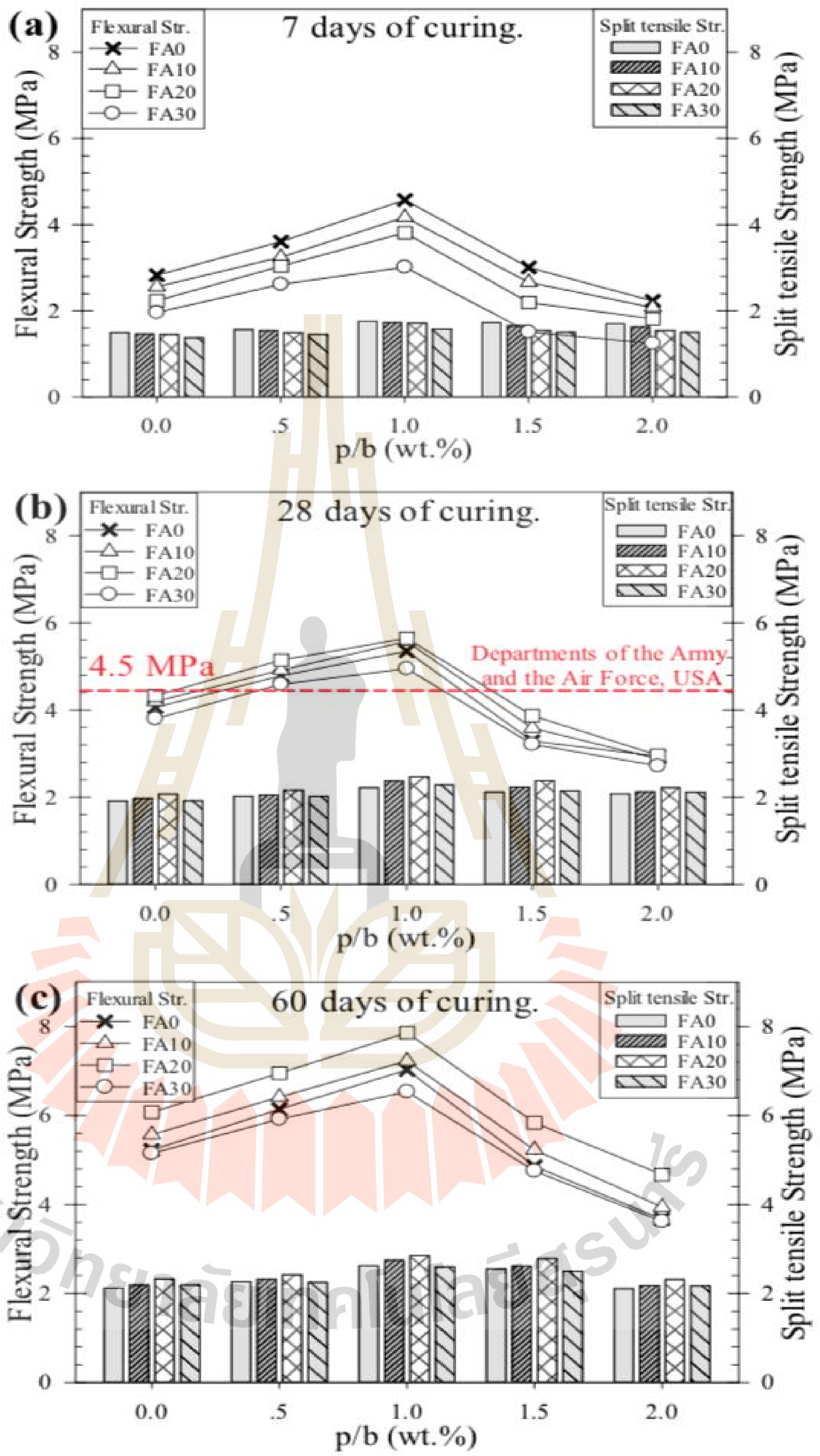

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**Figure 4.3** Flexural and split tensile strength of RCA-PVA-FA concrete at (a) 7 days, (b) 28 days and (c) 60 days.

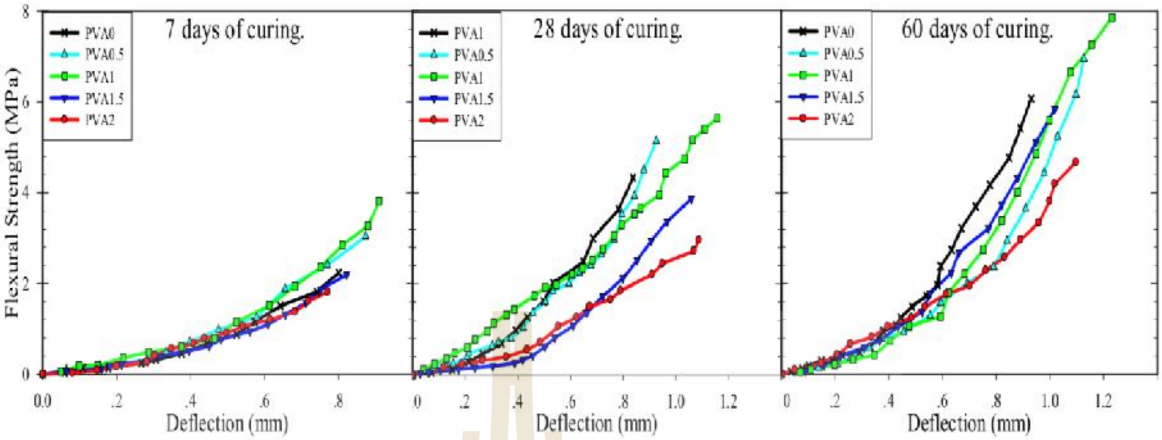

**Figure 4.4** Relationship between flexural strength and deflection of RCA-PVA-FA concrete at FA/c ratio of 20/80 for various curing times.

The stiffness (slope of the relationship) is more or less the same for all p/b ratios at 7 days of curing. While at curing time > 28 days, the stiffness decreases with increasing p/b ratio, showing the more ductile behavior.

Similar to the flexural strength development (**Fig. 4.3**), the optimal p/b and FA/c ratios giving the highest split tensile strength are p/b = 1% and FA/c = 20/80 and the change pattern of tensile strength versus p/b ratio is similar to that of flexural strength versus p/b ratio. This result confirms that the flexural failure is controlled by tensile stress at the base (below neutral axis), not the compressive stress at the surface (above neutral axis) as the concrete is strong in compression compared to tension. The maximum split tensile strengths at p/b = 1% for 60 days are 2.62, 2.75, 2.85 and 2.60 MPa for FA/c of 0/100, 10/90, 20/80 and 30/70, respectively with an increase of 23.6%, 25.5%, 22.3% and 18.7% when compared to RCA-FA concrete specimens (without PVA) at the same FA/c ratios.

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**Fig. 4.5** shows the relationships between flexural and tensile strengths versus compressive strength for 60 days of curing at various cement content, PVA content. As flexural strength is controlled by the tensile strength, the relationships between flexural and tensile strengths versus compressive strength are similar. A linear relationship exists for a set of test data with same p/b ratio even with different FA/c ratios. For different relationships, the higher slope indicates the higher flexural strength for the same compressive strength. It is of interest to note that the slope of the relationship increases with the increase in p/b ratio up to the optimal value of 1%, indicating the role of PVA in the flexural strength.

Compared with the mechanical strength requirement for the rigid pavement (the 28-day compressive and flexural strengths > 32 MPa and > 4.5 MPa, respectively), the RCA-PVA-FA concretes meet the requirement when FA/c ≤ 30/70 for p/b = 0.5% and FA/c ≤ 20/80 for p/b = 1%.

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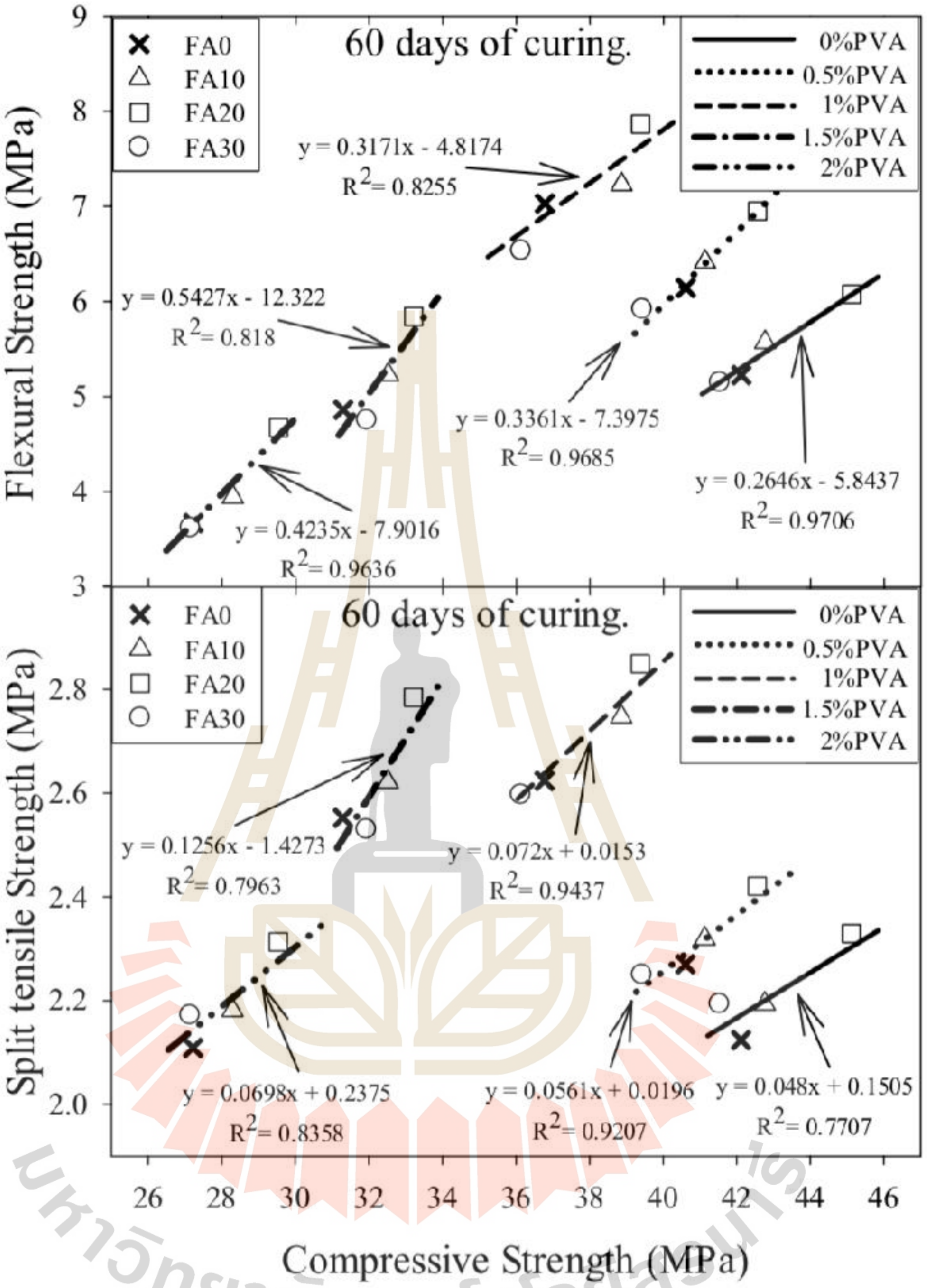

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**Figure 4.5** Relationships between the flexural and split tensile strength versus the compressive strength of RCA-FA concrete at 60 curing days.

## 4.4 Microstructural Analysis

SEM images of 7 and 60 days cured specimens at p/b = 0% with various FA/c = 0/100, 10/90, 20/80 and 30/70 are shown in **Figs. 4.6** through **4.8**. At 7 days and FA/c = 0/100 (**Fig. 4.6a**), the calcium silicate hydrate (C-S-H) matrix is porous with many voids while a denser matrix is clearly detected for 60 days cured specimen (**Fig. 4.6b**). In other words, the porosity reduces considerably with increasing the curing time (Kim et al. 2014). **Fig. 4.6c** presents the EDX data at the locations marked in the SEM images. The major elements present within C-S-H product are Ca and Si but with different atomic Ca/Si ratios for different curing times, the atomic Ca/Si ratios are found to be 2.23 and 1.55 for 7 and 60 days, respectively.

The Ca/Si ratio controls the physical and chemical properties of C-S-H, the Ca/Si ratio of C-S-H decreases over time and generally falls in the range of 1.2–2.3 (Barnes and Bensted, 2002; Richardson and Groves, 1997). As such, 60 days cured specimen (**Fig. 4.6b**) is considered to be the strong C-S-H structure, where the cement paste almost has been fully hydrated. This confirms the growth of C-S-H products with curing time. Therefore, the strength of RCA concrete has gained from C-S-H structure due to the hydration of belite ($C_2S$) and alite ($C_3S$) from cement grain (Mehta et al. 2006; Mindess et al. 2003).

The SEM images of RCA-FA concrete specimens at 7 days (p/b = 0% with FA/c =10/90, 20/80 and 30/70) are shown in **Fig. 4.7a, b** and **c**. It can be seen that the cementitious products on FA surface are little; most of the FA surfaces are smooth for all RCA-FA concrete samples. Ettringite needles are observed in the pores. **Fig. 4.7d** shows EDX results of each specimen at locations close to FA particles, which clearly detect the peaks of aluminium (Al), silica (Si) and calcium (Ca). The products from activation of FA is similar to calcium silicate hydrate gel (C-S-H gel) from Portland cement activation process (Park et al. 2016). Since the pozzolanic reaction of FA in concrete starts after one or more weeks, the increase in the FA additive does not necessarily proportionally increase the early 7-day compressive strength (Arulrajah et al. 2016; Fraay et al. 1989; Sybertz and Wiens, 1991).

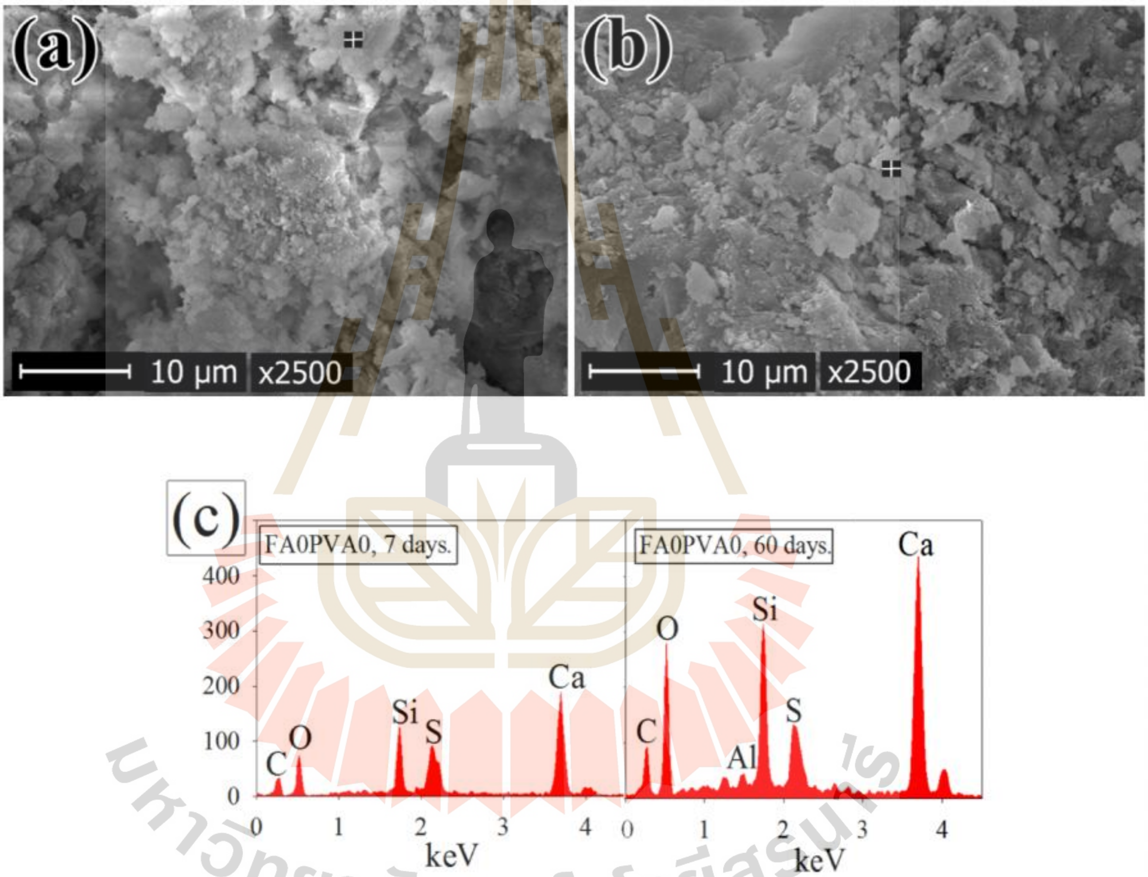

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**Figure 4.6** SEM images for p/b = 0% and FA/c = 0/100 at (a) 7 days, (b) 60 days and (c) EDX.

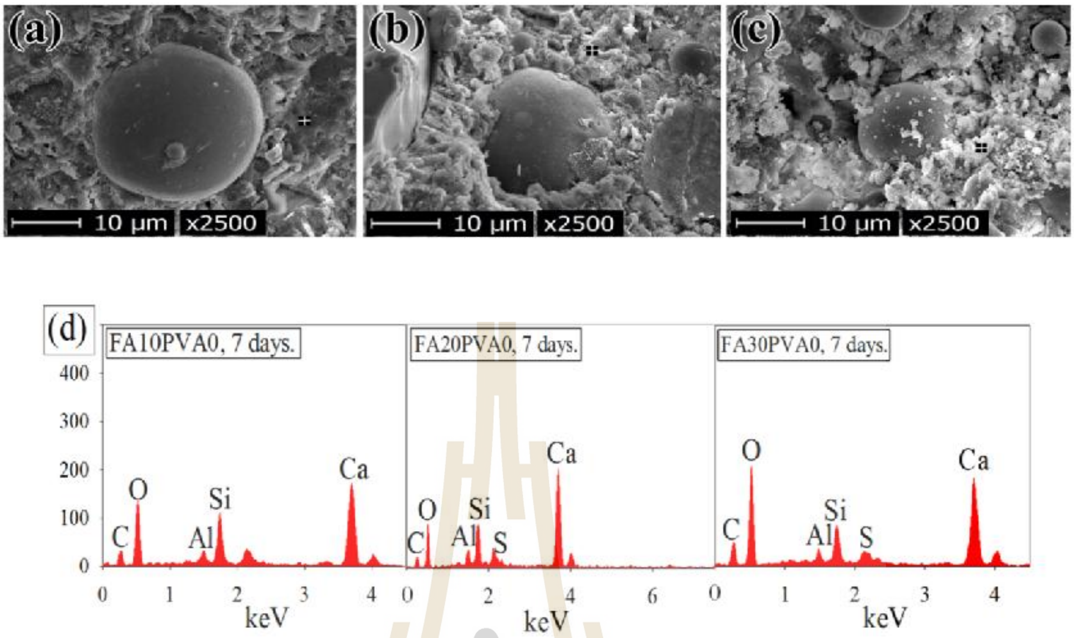

**Figure 4.7** SEM images at 7 days for p/b = 0% and FA/c = (a) 10/90, (b) 20/80, (c) 30/70 and (d) EDX.

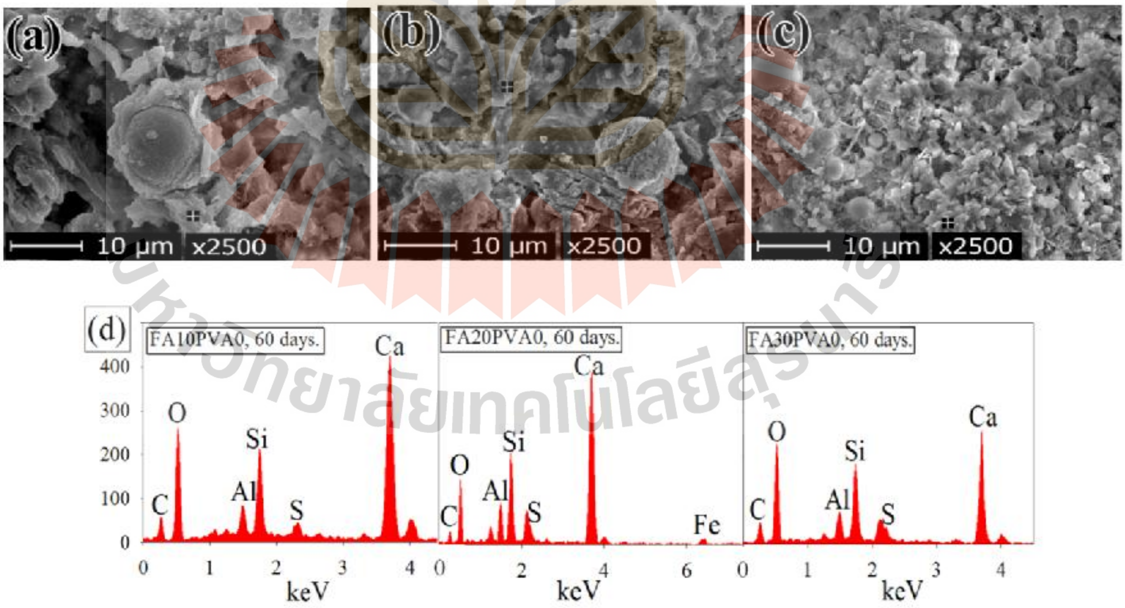

**Figure 4.8** SEM images at 60 days for p/b = 0% and FA/c = (a) 10/90, (b) 20/80, (c) 30/70 and (d) EDX.

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Activation of FA at 60 days of curing is observed in **Fig. 4.8**. For FA/c = 10/90 (**Fig. 4.8a**), FA particles have signs of etching on their surface indicating the precipitation in the pozzolanic reaction (Berry et al. 1994; Fraay et al. 1989; Xu and Sarkar, 1994). The more cementitious products are found for FA/c = 20/80 (**Fig. 4.8b**); the SEM image shows denser structure and the more FA particles in the matrixes compared to FA/c = 10/90. Since the pozzolanic reaction is caused by FA activated by $Ca(OH)_2$ (Lee 1970; Taylor 1997), the Si and Al in FA are consumed to develop C–S–H and C-A–S–H. Therefore, the FA surface is covered with the C–S–H gel and other hydration products (Berry et al. 1994; Xu et al. 1993; Xu and Sarkar, 1994). As the process continues, the C–S–H gel layer on the FA grain thickens, fills the voids between FA and cement grains, and afterwards heavily precipitates throughout the matrix, hence increased long-term compressive strength (Jitchaiyaphum et al. 2013).

For FA/c = 30/70 and 60 days (**Fig. 4.8c**), many FA particles still have smooth surfaces while some FA particles have dissolving surfaces, suggesting that most of them are unreacted or acted as an inert material serving as a precipitation nucleus for $Ca(OH)_2$ and C–S–H gel to increase the packing effect (Fraay et al. 1989). Although the FA/c = 30/70 increases Si and Al contents, FA particles mostly stay in the amorphous shape causing in accumulation of unreacted FA particles and do not form any cementitious bond (Arulrajah et al. 2016). Overall, the morphology in **Fig. 4.8c** indicates the lower precipitation in the pozzolanic reaction when compared to FA/c = 20/80.

The EDX analysis of RCA-FA concrete is presented in **Fig. 4.8d**, which indicates Ca/Si ratios of 1.77, 1.89 and 1.87 for FA/c = 10/90, 20/80 and 30/70, respectively. The major elements such as Si, Ca and Al, with some amount of sulphur

(S) and ferrite (Fe) are present in RCA-FA concrete, indicating the presence of calcium aluminosilicate hydrate (C-A-S-H) products (Garcia et al. 2016). Comparing FA/c = 10/90 with FA/c = 20/80, the FA particles in the concrete matrix is fewer and the peak of Al is lower for FA/c = 10/90, which leads to the low amount of precipitation nucleus for $Ca(OH)_2$ and hence lower cementitious products. However, the increase in FA/c to 30/70 causes lower cementitious products in mixture when compared to the FA/c = 20/80 and hence C-S-H and $Ca(OH)_2$ from the hydration reaction are reduced. The lower $Ca(OH)_2$ results in the lower degree of pozzolanic reaction. The decrease in the cementitious products from $Ca(OH)_2$ and FA reaction is illustrated by the lowest peaks of Ca, Si and Al in EDX of FA/c = 30/70.

The RCA-PVA-FA concrete at 60 days of curing with p/b = 1% and 2% are shown in **Figs. 4.9** and **4.10**, respectively. For the RCA-PVA-FA specimens, at a small amount of p/b = 1%, the thin films of PVA are detected on the cementitious products for FA/c = 0/100, 10/90, 20/80 and 30/70 (**Fig. 4.9a-d**), PVA films infiltrate to and cover cementitious matrixes. Over the time, the cementitious products grow continuously and penetrate the thin films. As such, these films reinforce cementitious matrixes and enhance the tensile strength among matrixes. The thicker films around the cementitious products are observed for higher p/b = 2% (compare **Figs. 4.9** to **4.10**). Even though the thicker film enhances the reinforcing ability, meanwhile it retards the hydration and pozzolanic reaction like a large barrier around the matrix, which prevents water absorption for the hardening and the growth of C-S-H structures (Yaowarat et al. 2018).

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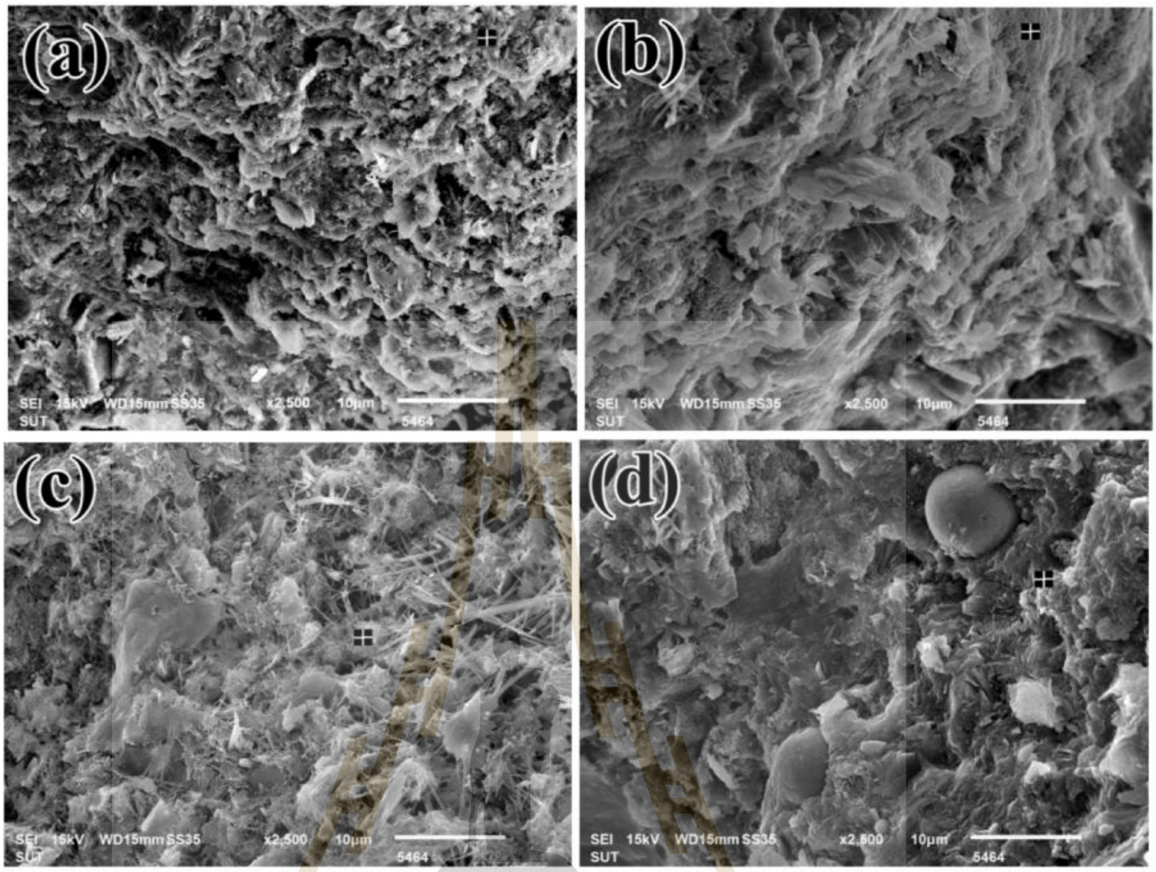

**Figure 4.9** SEM images at 60 days for p/b = 1% and FA/c = (a) 0/100, (b) 10/90, (c) 20/80 and (d) 30/70.

Consequently, the growth of C-S-H in the matrix is prevented, resulting in an extreme reduction of compressive strength as demonstrated in **Fig. 4.10e**. The EDX result of RCA-PVA-FA concrete at p/b = 2% also revealed that the amount of major components such as Ca, Si and Al are lower than p/b = 0%, which confirms the effect of retardation in the hydration and pozzolanic reaction caused by exceeding p/b ratio (Contrafatto 2013; Yaowarat et al. 2018).

It is evident that the FA and PVA improve both microstructure and mechanical strengths of RCA-PVA-FA concrete. The pozzolanic reaction due to additional FA at optimum FA/c = 20/80 is clearly observed by the etching on FA surface, the growth of

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C-S-H and the dense structure, which results in the enhanced long term mechanical strengths (> 28 days). The thin films of PVA at optimum p/b = 1% reinforce the cementitious matrix and hence enhance the tensile and flexural strengths in both short and long term curing.

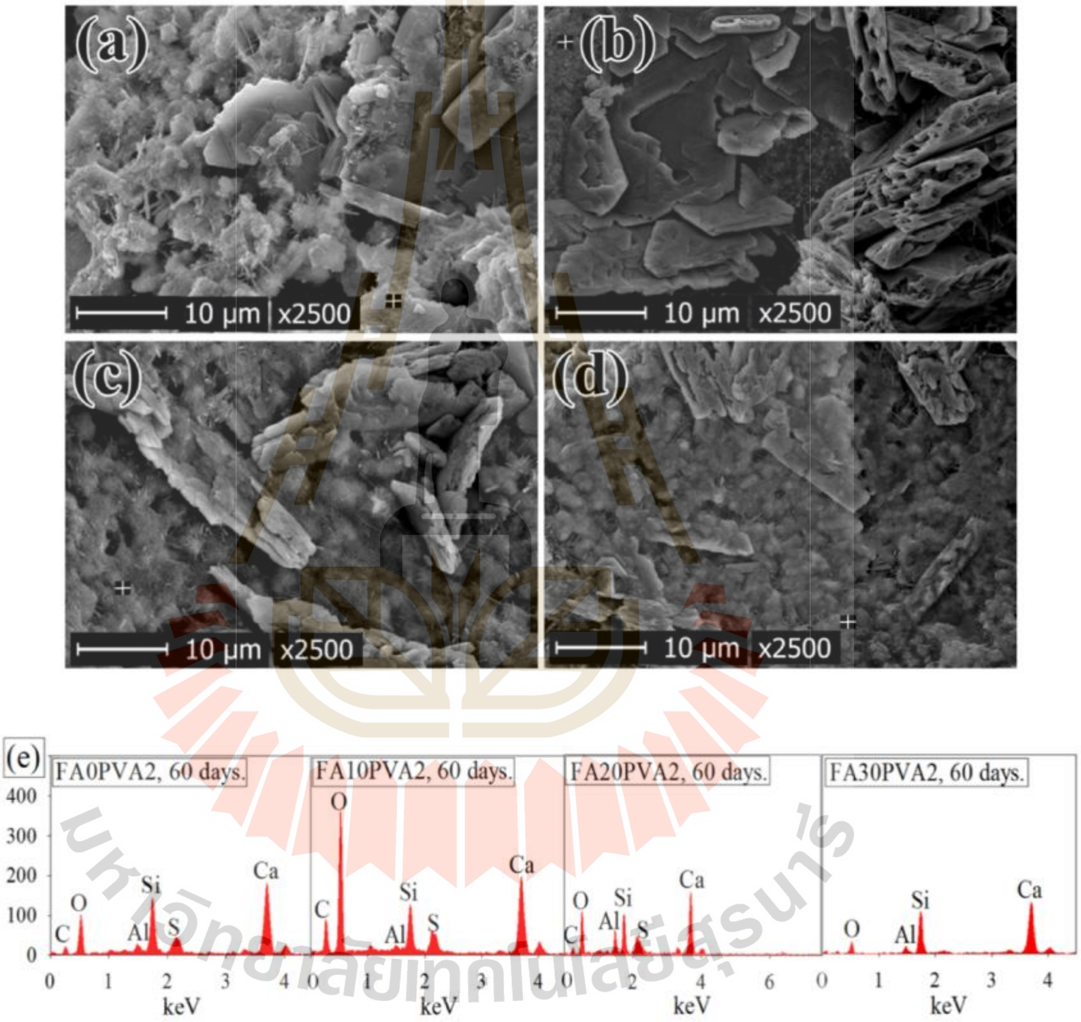

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**Figure 4.10** SEM images at 60 days for p/b = 2% and FA/c = (a) 0/100, (b) 10/90, (c) 20/80, (d) 30/70 and (e) EDX

## 4.5 Conclusions

This research investigated the possibility of using polyvinyl alcohol (PVA) and Fly Ash (FA) to improve the properties of Recycled Concrete Aggregate (RCA) concrete as an alternative material for rigid pavements. The result of RCA-PVA-FA concrete revealed that, for short-term (7 days) the compressive strength decreased with increasing FA/c ratio, while for long-term (> 28 days) FA/c = 20/80 was an appropriate proportion to achieve maximum compressive strength indicating that the pozzolanic reaction comes into play at long-term curing. The SEM image showed that growth of C–S–H and C-A–S–H on FA surface and in the matrix with increasing FA/c and the maximum cementitious products was found at FA/c = 20/80. Unreacted FA particles with relatively low cementitious products were found at higher FA/c ratios. , Consequently, the optimum FA/c providing the highest long term compressive strength was at 20/80.

The additional PVA caused the reduction in compressive strengths at all curing times but at the same time improved tensile strength; i.e., the PVA films reinforced the cementitious matrix. The p/b = 1% provided the maximum flexural and split tensile strengths for all FA/c ratios and curing times. For p/b > 1%, the excess PVA films covered cement grains and therefore prevented the water absorption for cement hydration and pozzolanic reaction, resulting in lower cementation bonding strength and hence the lower flexural and tensile strengths. The contribution from cementation bond strength on the flexural and tensile strengths could be improved with the addition of FA. The optimum FA/c ratio was found to be 20/80 whereby the maximum C-S-H was developed. The possibility of using other types of pozzolanic materials such as bagasse ash, palm oil fuel ash, rice-husk ash and slag together with various natural

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and synthetic polymers in rigid pavement applications is recommended for future study.

Based on the specifications of the Department of Highways, Thailand and the Army and the Air Force, USA (minimum 28-day compressive and flexural strengths of 32 MPa and 4.5 MPa, respectively), the FA/c ≤ 30/70 with p/b = 0.5% and FA/c ≤ 20/80 with p/b = 1% were found to be applicable for roads, streets, walks and open storage areas. The outcome of this research confirms the viability of using PVA and FA to improve the flexural and split tensile strength of RCA concrete to be used as an alternative sustainable rigid pavement.

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# CHAPTER V

# EFFECT OF CEMENT STABILIZATION OF RECYCLED CONCRETE AGGREGATES MODIFIED WITH POLYVINYL ALCOHOL: MECHANICAL AND MICRO-SCALE PROPERTIES

## 5.1 Statement of problem

Research on recycled construction and demolition (C&D) materials in civil engineering construction activities is increasingly gaining popularity during the past few decades due to the predicament of a lack of quarry-produced materials from natural resources. Developing and developed countries alike have aimed to reuse the C&D wastes in the infrastructure construction, which is a more sustainable way compared to stockpiling or sending them to landfills (Wu et al. 2016). To date, with an increasing impetus from state government sustainability initiatives, several research projects have reported that C&D and waste materials may be used sustainably as valuable resources in civil engineering infrastructure applications (Arulrajah et al. 2018; Mirzababaei et al. 2018b; Yaghoubi et al. 2017; Mirzababaei et al. 2017b; Arulrajah et al. 2017; Arulrajah et al. 2016; Hoy et al. 2016; Arulrajah et al. 2015).

Recycled Concrete Aggregate (RCA) is a well-known and well-accepted C&D material available in the market, which is obtained from the demolition of old buildings (Arulrajah et al. 2014a; Rahman et al. 2014; Arulrajah et al. 2012). Reuse of RCA has numerous environmental benefits, which would reduce waste concrete stockpiles and would also limit the need for natural aggregate sources. In order to reuse the RCA in better applications such as pavement base/subbase, the research on the stabilization of RCA with different additives (such as cement, lime, Fly Ash, geopolymer, etc.) to improve its mechanical properties has been conducted (Donrak et al. 2018; Sun and Li 2018; Yaghoubi et al. 2018; Mohammadinia et al. 2017). Among all these stabilizers, cement is widely used to improve the strength properties (Jin et al. 2018; Rao et al. 2001). Although cement stabilization is a good option for road bases/subbases, cement-stabilized RCA exhibits a brittle behavior under compression and flexural loading (Onyejekwe and Ghataora 2014; Sukontasukkul and Jamsawang 2012). Moreover, there are some discussions that using cement in a pavement base/subbase structure may be considered as the source of shrinkage cracking and such cracks tend to propagate through the overlaying asphalt layer (Xuan et al. 2016; George 1968). These issues need to be taken into consideration because the cracks appear to be propagated under the cyclic load and finally fail the overlaying pavement surface which results in a low service life (Chini et al. 2001; Petrarca and Galdiero 1984). Therefore, the ductile behavior and toughness of pavement materials need to be improved to prevent the sudden failure due to traffic loads (Disfani et al. 2014).

In an attempt to improve the ductile behaviour of subbase /base materials, past studies have reported on the use of traditional binders in combination with various kind of fibers in several geotechnical engineering applications ( Festugato et al. 2017; Kumar and Gupta 2016; Anggraini et al. 2015; Estabragh et al. 2012; Cai et al. 2006). The results concluded that in fiber-reinforced samples, a uniform distribution of fibers developed resisting forces throughout the structure of sample, hence resulting in an increase in energy absorption capacity (Mirzababaei et al. 2013). However, fibers are easily entangled and therefore the distribution of fibers cannot be accurately determined; i.e., the samples are reinforced by randomly distributed fibers (Kravchenko et al. 2018; Li et al. 2018).

In addition to fiber-reinforced soil and base/subbase materials, polymer-stabilization techniques have become progressively popular for soil improvement projects (Santoni et al. 2002). There are many polymeric binders that have been proven to be effective as potential particle binders for soil stabilization (Onyejekwe and Ghataora 2015). Polyvinyl alcohol (PVA) is a polymer, which is recognized as an eco–friendly, odorless, water-soluble, non–ionic and hydrophilic polymer with an excellent film forming potential (Ding et al. 2002). Brown et al. (2004) investigated the effect of PVA-stabilized soil and the results indicated that PVA acts as a polymeric binder by entwining within the soil particles and thus stabilizing the loose soil into a relatively firm mass. PVA has also been reported to enhance the ductility as well as the toughness of clay similar to the fiber reinforcement (Mirzababaei et al. 2018a; Mirzababaei et al. 2017a). Moreover, PVA solutions can be prepared easily by dissolving PVA in water (Çay and Miraftab 2013), which can potentially be used to stabilize RCA particles and the distribution of PVA solution can be precisely determined more than the fibers.

To the best of the authors' knowledge, there has been no work published on the use of PVA for stabilizing the cement-stabilized RCA, hence this research on the combined effects of cement and PVA on the mechanical responses of RCA is novel. There is currently a lack of comprehensive study in the literature to investigate the influence of the PVA on unconfined compressive strength (UCS), California bearing ratio (CBR) and repeated load triaxial (RLT) of cement-stabilized RCA, which this research study seeks to address. This research study reports on a comprehensive investigation conducted on the performance of PVA with cement stabilized RCA as a material for pavement base/subbase applications. A systematic experimental program was conducted by varying the percentage of PVA combined with cement and comparing to the unbound-RCA sample.

## 5.2 Material and Methods

### 5.2.1 Materials

Samples of Recycled Concrete Aggregate (RCA) were collected from a recycling site located in the city of Melbourne, Australia. RCA used in this study is typically comprised of graded aggregates up to 20 mm in dimension. The geotechnical properties of RCA as determined from the basic laboratory testing are summarized in **Table 5.1**. The maximum Los Angeles (LA) abrasion value of 40 is normally accepted by Victorian state road authority for pavement base/subbase materials (VicRoads 1998). General Portland (GP) cement was used to stabilize RCA in 3% by weight of the dry RCA (i.e. 3 g GP cement was added to 100 g of dry RCA).

**Table 5.1.** Geotechnical properties of RCA.

| Geotechnical properties | Test standards | RCA |
|---|---|---|
| Bulk density – coarse (kg/m$^3$) | ASTM C29 (2017) | 1422.89 |
| Bulk density – fine (kg/m$^3$) | ASTM C29 (2017) | 1417.86 |
| Water absorption – coarse (%) | ASTM C127 (2015) | 6.45 |
| Water absorption – fine (%) | ASTM C128 (2015) | 8.50 |
| Bulk Specific Gravity – coarse | ASTM C127 (2015) | 2.28 |
| Bulk Specific Gravity – fine | ASTM C128 (2015) | 2.19 |
| Organic content (%) | ASTM D2974 (2014) | 2.7 |
| pH | AS 1289.4.3.1 (1997) | 10.9 |
| Flakiness index | BS 812-105.1 (1989) | 15.8 |
| Los Angeles abrasion loss | ASTM C131 (2006) | 33.7 |

Polyvinyl alcohol (PVA) in dry form was purchased from Chemipan Corporation Co., Ltd, Bangkok, Thailand. It is a synthetic polymer that is achromatic, odorless and water soluble (a temperature range of 90~95°C is generally required for a complete solution). PVA had a specific gravity, hydrolysis, and molecular weight of 1.27-1.31, 87.83%, and 22,000 g/mol, respectively, while the viscosity of 4% PVA in $H_2O$ at 20°C is 24.6 mPa.s.

### 5.2.2 Sample Preparation and Experimental program

The laboratory evaluation was conducted to determine the engineering properties of blends including particle size distribution, modified Proctor compaction, California bearing ratio (CBR), unconfined compressive strength (UCS) test, repeated load triaxial (RLT) test as well as scanning electron microscopy (SEM).

Particle size distribution test consisting of sieve analysis and hydrometer test was performed on RCA aggregates based on ASTM D422 (ASTM 2007c). **Fig. 5.1** shows the particle size distribution curve of RCA compared to the requirements of the local road authorities (VicRoads 2011). The gradation plot showed that RCA is a well-graded gravel with silt and sand according to Unified Soil Classification System (USCS) and entirely conforms to the requirements suitable for usage in pavement-base/subbase applications. Modified Proctor compaction tests were carried out on unbound RCA and 3% cement-stabilized RCA to determine the maximum dry density (MDD) and optimum moisture content (OMC) according to ASTM D1557 (ASTM 2009).

The compaction curve of unbound RCA and 3% GP cement-stabilized RCA are provided in **Fig. 5.2**. RCA stabilized with 3% GP cement is significantly deviated the MDD and OMC of RCA similar to previous research (Arulrajah et al.

2017). Therefore, the selected MDD and OMC values on the modified Proctor compaction curve of the RCA with 3% GP cement binder as illustrated in **Fig. 5.2** were used for sample preparation of PVA-cement-stabilized RCA.

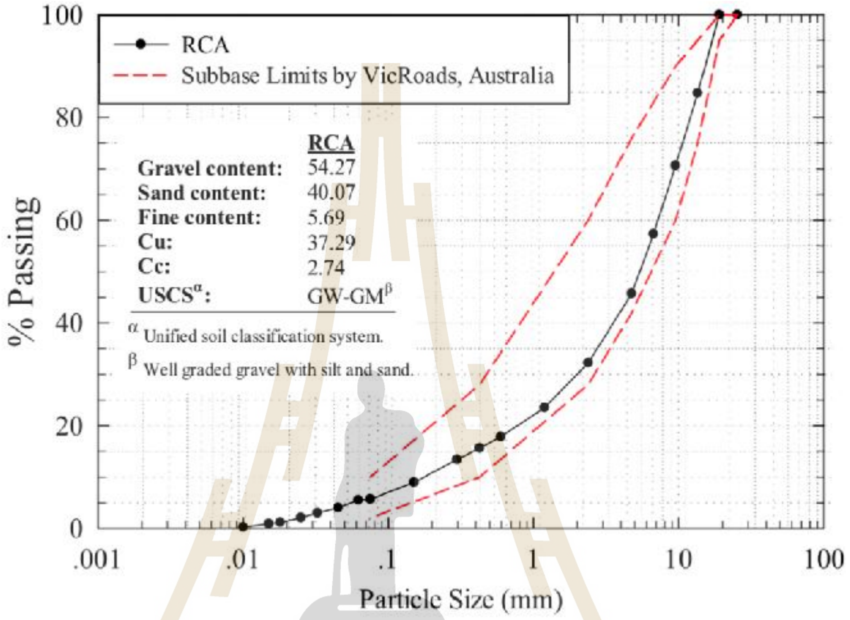

**Figure 5.1** Particle size distribution of RCA materials

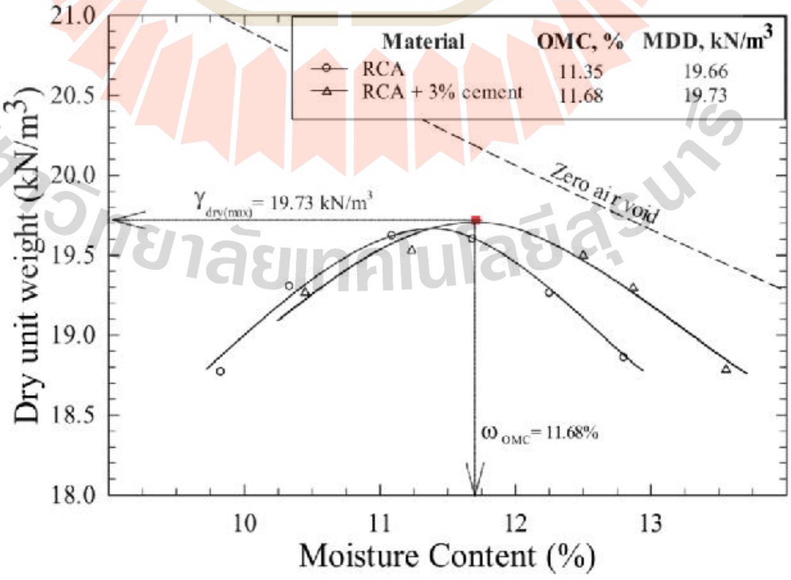

**Figure 5.2** Compaction curves of unbound RCA and 3% cement stabilized RCA Materials

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The four PVA percentages by dry weight of RCA which were evaluated were with 0.5%, 1%. 1.5% and 2% dosages. The predetermined amount of PVA in powder form was mixed in distilled water. The amount of distilled water was calculated from the OMC from the compaction curve of the RCA with 3% GP cement. PVA was dissolved in the distilled water elevated to 95 °C using a magnetic stirrer hot-plate for a minimum period of 1 h until a clear solution was achieved. The PVA-solution was stored in a glass bottle and kept overnight to cool down to the room temperature. As an example, 1% PVA by weight of 1000 g RCA is 10 g; the OMC of the cement-stabilized RCA is 11.68% or water 116.8 ml per 1000 g of RCA. Then the PVA-solution was prepared by mixing 10 g PVA powder into 116.8 ml of distilled water for RCA 1000 g.

Due to relatively high water absorption of the materials, RCA aggregates were mixed with the PVA-solution at OMC obtained from the compaction test 2–3 h prior to compaction and then GP cement was added to the wet mix just prior to compaction. GP cement and RCA with PVA-solution were thoroughly mixed together by hand for 10 minutes to ensure a homogeneous mixture and thereafter the compaction was begun. The samples were removed from the mold and consequently wrapped in a vinyl cling and kept in a curing box for a curing period of 7 and 28 days. All the samples were compacted to the target density of 100% MDD and target moisture content of 100% OMC, the moisture content of each sample was determined using remaining materials from each blend. Once the curing period reached, the weight of the sample was checked to determine any possible loss of the moisture content during the curing period. However, due to the use of the cling layer around the sample, no noticeable moisture loss was observed.

Soaked CBR tests were performed on samples prepared at their optimum conditions (OMC and MDD) and tested upon completion of four days soaking condition with a surcharge mass of 4.5 kg on top. The soaked CBR test is commonly required for pavement materials, to simulate the worst in-service case scenario for a pavement (Arulrajah et al. 2014b). A metal tripod to support the dial gauge was placed on the edge of the CBR mold for measuring the amount of swell during soaking in accordance with ASTM D1883 (ASTM 2007b).

UCS and RLT test samples were prepared using split molds to ensure the samples are not disturbed during the removal and parallel end faces are maintained. A total of 8 samples (4 samples for 7 days of curing and 4 samples for 28 days on curing) were prepared for each blend and were compacted using modified compactive effort energy (ASTM 2009) in cylindrical molds with a diameter of 100 ± 1 mm and the height of 200 ± 1 mm (a height to diameter ratio of larger than or equal to 2 according to ASTM D1632 (ASTM 2007a)) in 8 layers with the application of 25 blows per layer. Three samples were tested to determine the UCS value of the stabilized RCA and an average value has been reported. One sample was prepared for RLT testing to determine the Resilient Modulus ($M_R$) in accordance with the procedure described in AASHTO (2007) for base/subbase materials.

Scanning Electron Microscopy (SEM) was used to investigate the effect of PVA on the cement stabilized RCA morphology at the microscopic scale. Samples at the ages of 7 and 28 days were broken and the used for the analyses by collecting data from at least five randomly selected sites from the sample.

## 5.3 Results and Discussion

The average UCS for different mixture contents at 7 and 28 curing days compared with the minimum 7-day required strength for subbase materials (Texas Department of Transportation, 2013) are presented in **Fig. 5.3a.** At 7-day, the UCS of unbound RCA and 3% cement-stabilized RCA are 0.72 and 2.11 MPa, respectively; in other words, the UCS of RCA increases by almost 3-fold with added 3% cement. However, the decrease in strength and subsequently increases up until reaching a maximum value can be found by the addition of PVA into the 3% cement-stabilized RCA samples. The UCS values of PVA-cement-stabilized RCA are 0.69, 0.94, 2.28 and 3.74 MPa for 3% cement-stabilized RCA with PVA dosages of 0.5%, 1%, 1.5% and 2%, respectively. It is evident from the test results that the addition of 0.5% and 1% PVA into 3% cement-stabilized RCA reduces the UCS, which resulted in 205.8% and 124.5% deterioration in the 7-day UCS of the samples, respectively. While the UCS values of 1.5% and 2% PVA-cement stabilized RCA were improved 8.1% and 77.3%, respectively, when compared to the 3% cement-stabilized RCA without PVA. Based on the 7-day UCS requirement for subbase materials, both the 3% cement-stabilized RCA (without PVA) as well as the 3% cement-stabilized RCA with 1.5% and 2% of PVA meet the requirements.

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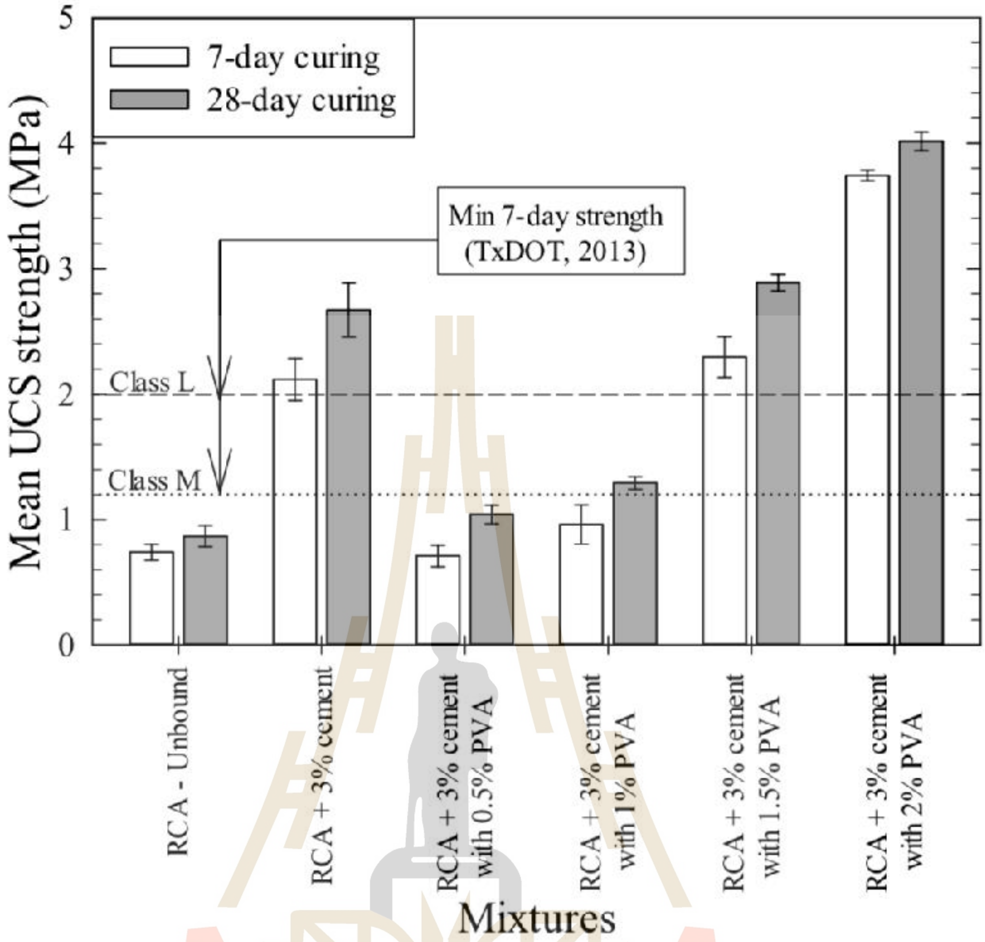

**Figure 5.3** (a) Variation of UCS of Unbound-RCA and 3% cement stabilized RCA with and without PVA.

Similarly, the PVA was found to affect the 28-day UCS value for all blends and has the same trend as of 7-day UCS. The increase in the UCS value of each blend due to further curing is expected due to the growth of cementitious products. **Fig. 5.3b** shows the stress-strain relationship of 3% cement-stabilized RC with and without PVA. For PVA > 1.0%, the strain at failure increases with increasing PVA percentage. The cement-stabilized RCA with PVA has higher UCS and strain values at the failure that are higher than those of the cement-stabilized RCA without PVA.

The toughness is defined as the required energy to deform the sample to a strain level equivalent to the peak stress and is calculated from the area under the stress-strain curve up to the selected strain value (Maher and Ho 1994; Mirzababaei et al. 2013). Therefore, the combined addition of cement and 1.5% or 2% PVA shows a larger under-graph area, which demonstrates a more ductile behavior of the sample when compared to the sample without PVA. The maximum UCS was also found for 3% cement-stabilized RCA with 2% PVA sample with the largest failure strain value (i.e., 4.48%).

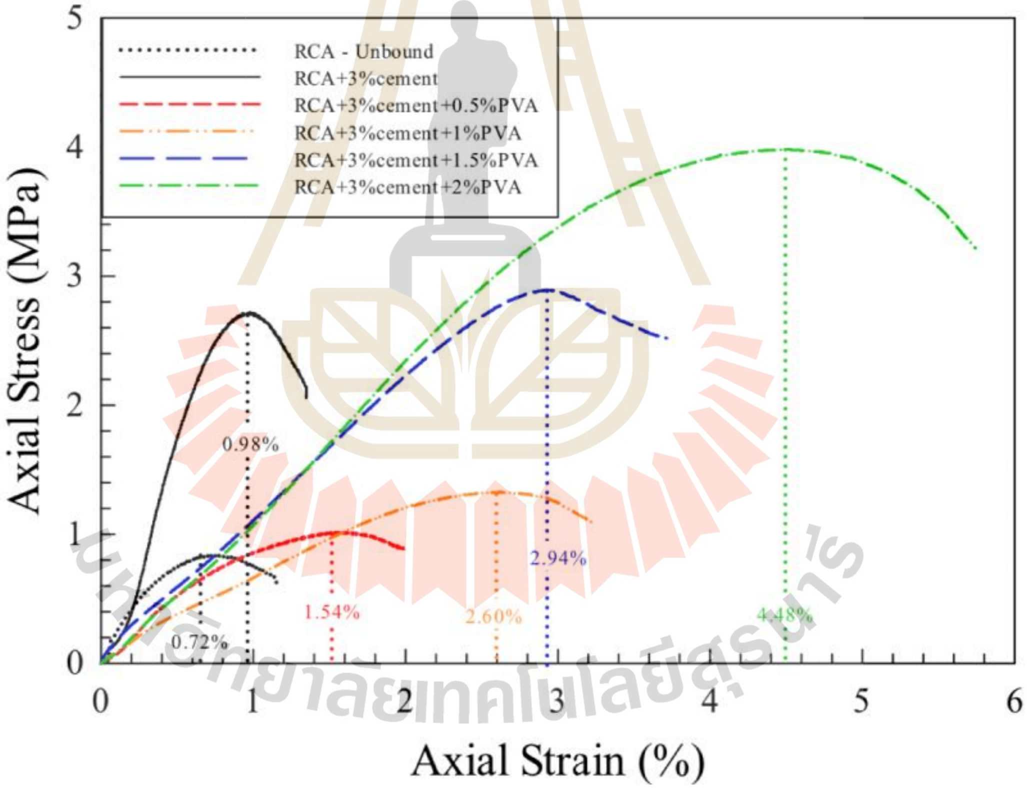

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**Figure 5.3** (b) Stress–strain behavior of selected 28-day UCS samples.

**Fig. 5.4** presents the soaked CBR test results of unbound-RCA and 3% cement-stabilized RCA with and without PVA. The CBR value of RCA increases and reaches the highest value for cement stabilized samples without PVA. Concurrently, the swelling value is reduced, which is a similar trend to that reported previously (Arulrajah et al. 2014a; Disfani et al. 2014). Improvements in UCS and CBR values and decrease in the swelling can be attributed to the cementitious products in the samples, as 3% of GP cement was added as a stabilizer (Puppala et al. 2011). However, the addition of PVA to the 3% cement-stabilized RCA samples results in the decrease of CBR values, whilst, increasing the swelling value.

This result confirms the high dilapidated rate in the strength of PVA-cement-stabilized RCA in soaked conditions since the PVA is recognized as a hydrophilic polymer and is still vulnerable to water (Mirzababaei et al. 2018a; Mirzababaei et al. 2017a). Although PVA bonds the RCA particles together for enhanced UCS and toughness, it hinders the hardening of cement leading to a reduced stiffness (Yaowarat et al. 2018a; 2018b). Although the addition of 2% PVA has the most improving effect on the UCS of the RCA aggregates, it absorbs the water into the matrix during the soaking resulting in an increased swelling and therefore, weakened adherence and chaining ability and reduced CBR value. Even though CBR values for RCA were reduced, the minimum 80% CBR requirement for typical quarry materials in base/subbase application was still met (Maghool et al. 2017).

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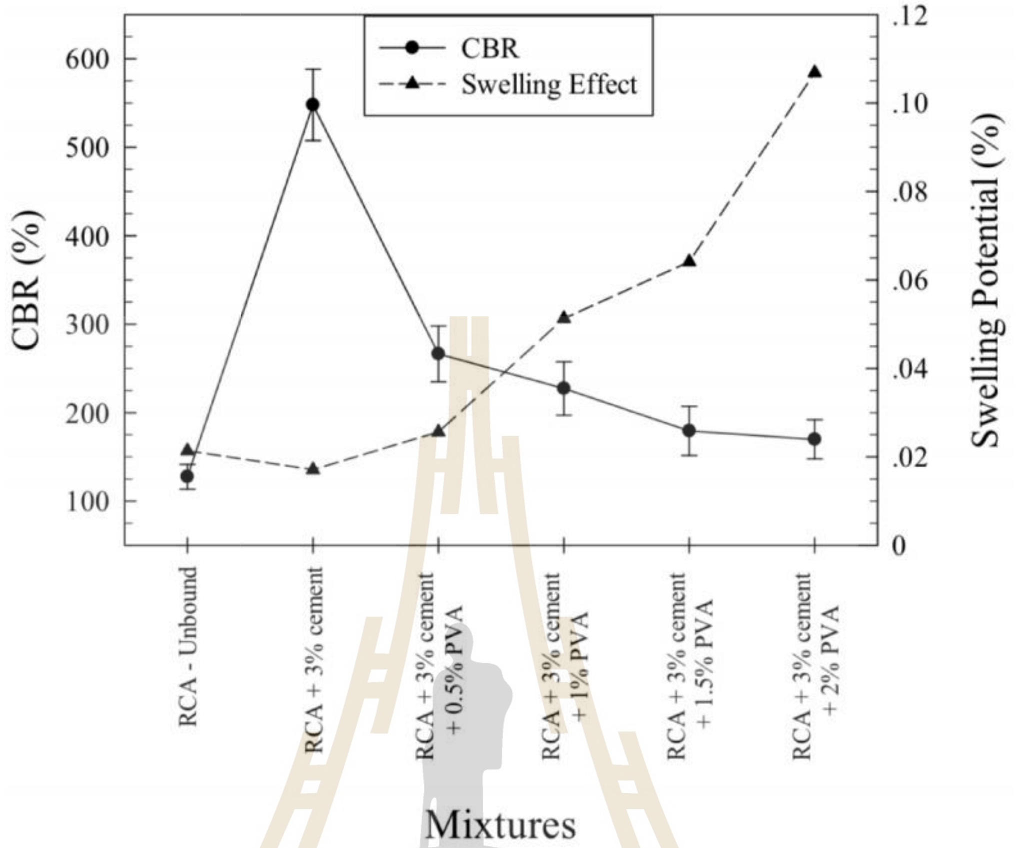

**Figure 5.4** CBR results of Unbound-RCA and 3% cement stabilized RCA with and without PVA.

The resilient modulus for pavement construction materials, is defined as a ratio of deviator stress to the resilient strain ($M_R = \sigma_d/\varepsilon_r$) experienced by the material under repeated loading simulating traffic load (Saberian and Li 2018). The resilient modulus ($M_R$) of stabilized RCA aggregates at 7 and 28 curing days is presented in **Fig. 5.5**. The $M_R$ was determined under a combination of 15 loading stages at five confining pressures on six RCA mixtures. **Fig. 5.5** illustrates that the $M_R$ values for 7 and 28-day cured samples increased when either the confining pressure or the deviator stress was increased. This behavior can be attributed to the fact that materials tend to get denser and stronger with higher confining pressure and also get stiffer with higher

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deviator loading (Maghool et al. 2016; Puppala et al. 2011; Arulrajah et al. 2015). The sample at 7-day curing has a lower $M_R$ value when compared to $M_R$ value obtained by the sample with 28 days of curing, which are similarly supported by the UCS test results.

For each curing period, the 3% cement-stabilized RCA sample without PVA showed a higher $M_R$ when compared to the same sample stabilized with PVA while the unbound-RCA samples generate the minimum $M_R$. The $M_R$ of 3% cement-stabilized RCA sample was noticeably higher than the combinations of 3% cement with 1.5% PVA as well as 3% cement with 2% PVA-stabilized RCA while the later blends have higher UCS values. This is due to the fact that the cementation bonds improve the strength and stiffness of the samples, hence, the rigidity increases, and the resilient deformation reduces which results in a subsequent rise in resilient modulus. On the other hand, the addition of PVA into the 3% cement-stabilized RCA sample causes a reduction in stiffness, but PVA is transformed to improve the shear strength and toughness of the samples (i.e. PVA increases the shear strength and toughness more than it increases the rigidity of the material). This suggests that only cement mixed RCA performs more successfully than the combination of cement and PVA in sustaining dynamic resilient loads at lower stress levels. However, based on the recommended range of the $M_R$ values for pavement materials (AASHTO 1993) which are 79-329 MPa and 42-228 MPa for the base and subbase layers, respectively, the $M_R$ of all samples are higher than the minimum recommended values.

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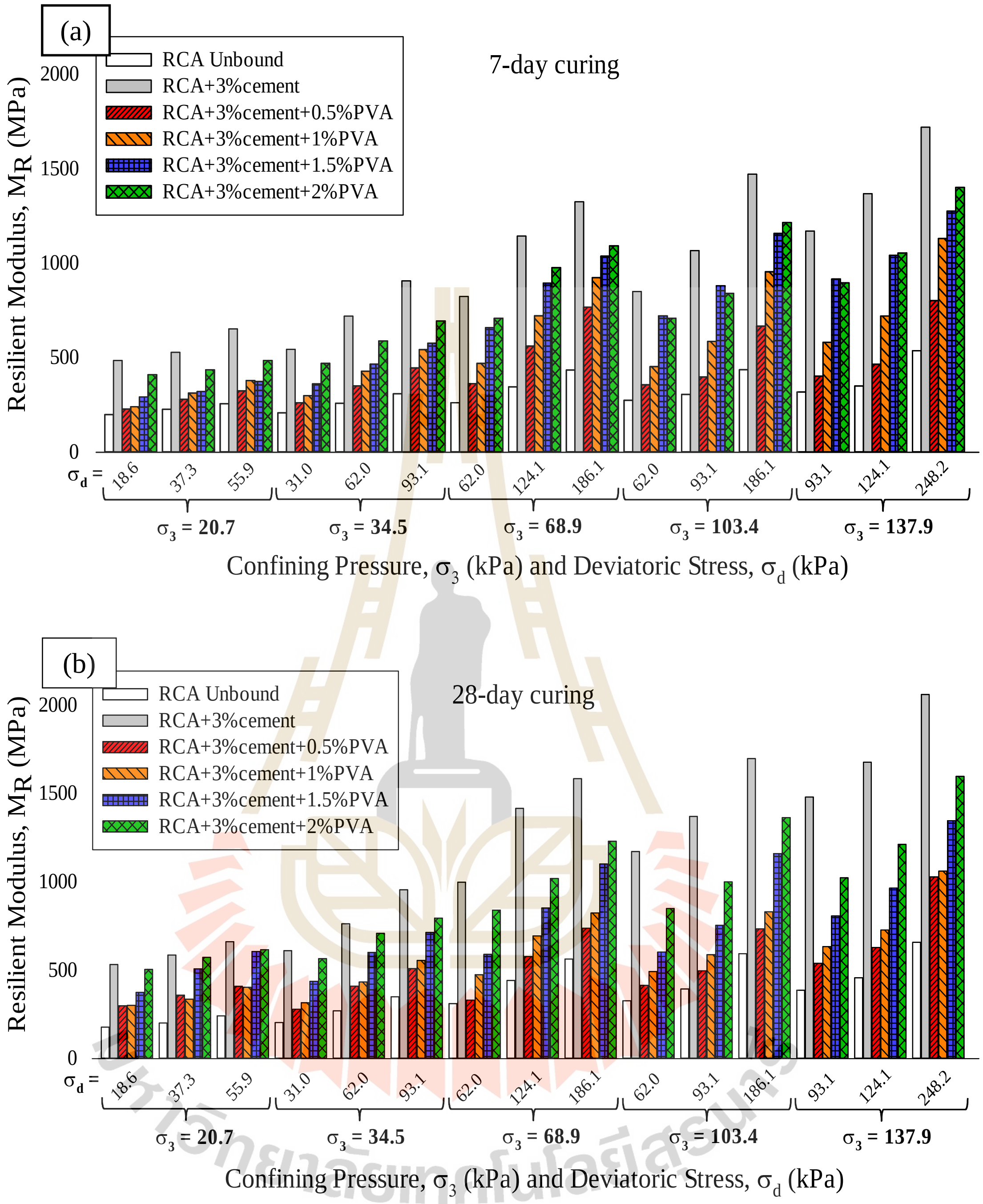

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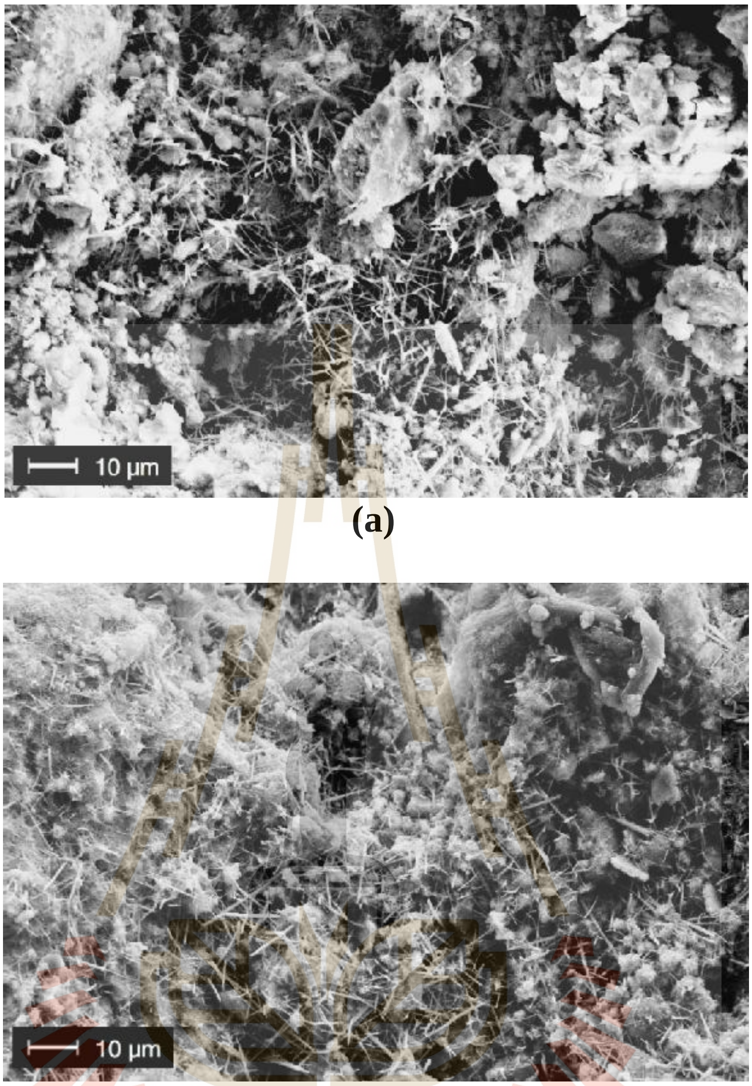
**Figure 5.5** RLT Resilient modulus values of the samples at (a) 7 and (b) 28 days

To investigate the microstructural development of cementation in binding the material’s matrix, SEM technique was implemented. The texture of hydration product of the cement-blended RCA is shown in **Fig. 5.6** for RCA stabilized with 3% cement at 7 and 28 days of curing. **Fig. 5.6a** shows the SEM image at an early condition, and the sample is porous and has many voids; the cementitious products such as ettringite is abundantly formed in between RCA particles while Calcium Silicate Hydrate (C-S-H) is slightly germinated. As a result of further curing, a denser matrix is clearly detected for 28 days cured specimen (**Fig. 5.6b**), the C-S-H gel and ettringite products are enormously grown-up and the surface appeared relatively uniform with less voids. Therefore, the formation of hydration products has resulted in strength and stiffness improvement of the RCA sample stabilized with 3% cement (Sun et al. 2015).

The SEM images of RCA samples with combinations of 3% cement with various PVA percentages at 28 days of curing are presented in **Fig.5.7**. The cementitious products of the sample mixed with 0.5% PVA are extremely disappeared (**Fig. 5.7a**) when compared to the sample without PVA at the same curing age (**Fig. 5.6b**). The PVA films gain thickness and entwine the RCA particles together and in the meanwhile; the amount of hydration products further decreased and were rarely found when the PVA percentage increased (**Fig. 5.7b-d**), similar to that reported earlier (Yaowarat et al. 2018a; Yaowarat et al. 2018b). This confirms that PVA films retard the hydration reaction and the hardening action of cement, causing the reduction in stiffness and rigidity. However, the thicker film enhances the attachment ability between RCA particles along with the reduction in extent and number of inter pore-spaces. This leads to the formation of larger aggregates that contribute well to withstand the stresses and isolation at the interface of solid-void part of the RCA sample skeleton, and hence further contributions are made to shear strength improvement and toughness of RCA as demonstrated in **Fig. 7d.**



(a)

(b)

**Figure 5.6** SEM image of 3% cement-stabilized RCA materials at (a) 7 and (b) 28 days

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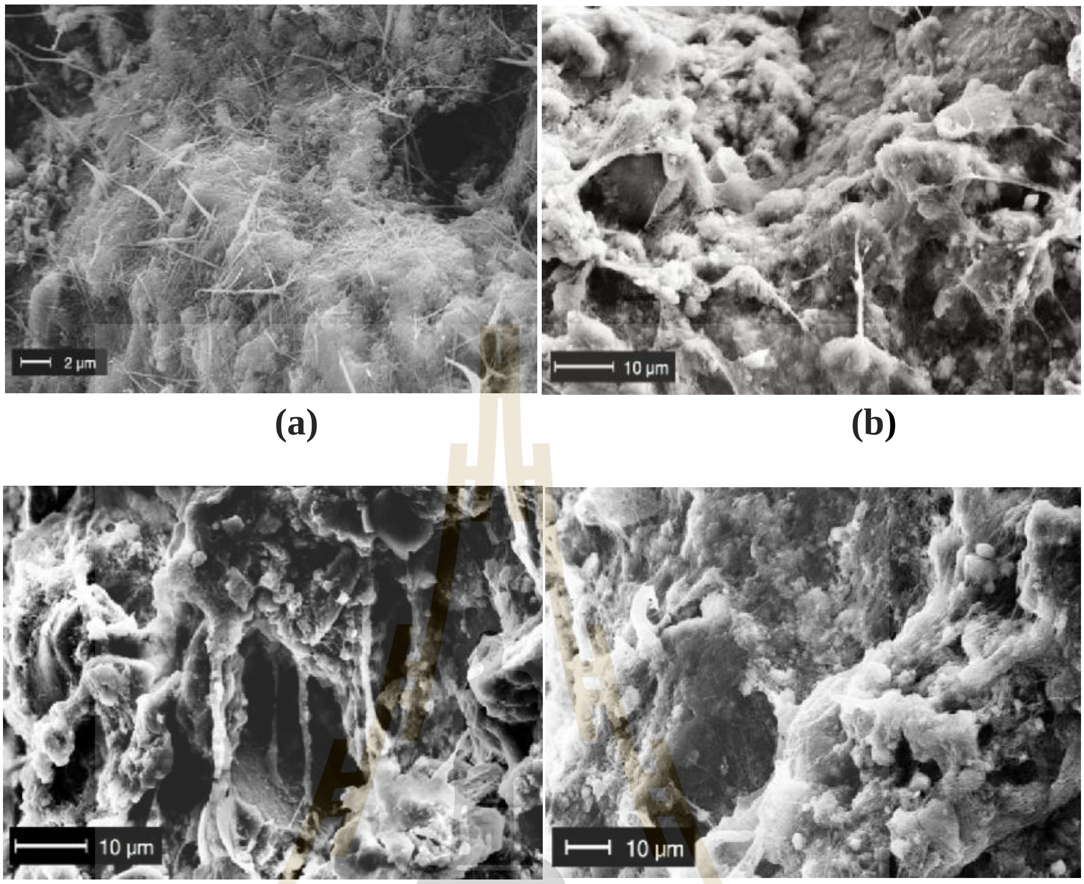

(a) (b)

(c) (d)

**Figure 5.7** SEM image of 3% cement-stabilized RCA with (a) 0.5%PVA, (b) 1%PVA, (c) 1.5%PVA and (d) 2%PVA at 28 days

## 5.4 Conclusions

This research study investigated the strength improvement behavior of cement-stabilized RCA using polyvinyl alcohol (PVA) solution. The effect of cement and PVA on the strength behavior at a wide range of PVA contents (0.5-2%) and fixed 3% cement contents is discussed and presented. The following conclusions arising from this research can be drawn:

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1. Mean UCS value of RCA increased by mixing 3% cement. Moreover, a considerably higher UCS and toughness observed in the combined addition of 3% cement with 1.5% or 2% PVA. The 3% cement-stabilized RCA with 1.5% or 2% PVA and without PVA met the strength requirements for class M and L subbase application. An increase of 26% in UCS was observed for 28-day cured 3%cement-0%PVA sample while the 28-day UCS of 3%cement-2%PVA slightly increased by 8% compared to the similar 7-day cured samples. The notable increase in strength after 28 days of curing compared to just 7 days of curing is as expected.

2. Because the PVA is recognized as a water-soluble and hydrophilic polymer, it absorbed the water during the soaking and caused the increased swelling and losing of the attachment ability. Hence, CBR value reduced with increasing the PVA content.

3. PVA films retard the hydration and hardening processes of cement and therefore, samples stabilized with 3% cement and 0.5% PVA experienced a significant drop in UCS and $M_R$ due to a reduction in strength and stiffness. However, the addition of PVA resulted in a higher polymeric binder in the soil matrix which enhanced the shear strength and attachment ability between RCA particles. It was found to be more effective for the UCS improvement and the sample demonstrated a more ductile behavior with increasing PVA content.

4. Even though the UCS and toughness modulus increased with adding PVA to the cement, the $M_R$ of cement-PVA-stabilized RCA was still lower than that of the sample without PVA. In other words, the polymeric binder improves the shear strength and ductility rather than rigidity. Even with the reduction in $M_R$, all cement-stabilized RCA with PVA have $M_r$ higher the minimum recommended values.

5. SEM analysis of the PVA and cement stabilized RCA showed that the thickness of PVA films increased with increasing PVA content. This causes uniform matrices of aggregated particles with less inter pore-spaces, resulting in a strength increase along with a toughened behavior.

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# CHAPTER VI

# CONCLUSIONS AND RECOMMENDATIONS

## 6.1 Summary and conclusions

This thesis consists of three main objectives. The first is to investigate the possibility of using the polyvinyl alcohol (PVA), a water-soluble polymer and cement as a raw material to develop the flexural strength of RCA-PVA concretes. The Recycled Concrete Aggregate (RCA) is used as coarse aggregates and river sand is used as a fine aggregates. A water-to-cement ratios, w/c is a mixture of water and cement. A PVA-to-cement ratios, (p/c) is mixture of polyvinyl alcohol (PVA) and cement. The second is to develop the strength of RCA-PVA concrete with Fly Ash (FA). The influence of FA-to-cement ratios (FA/c), PVA-to-binder ratios (p/b) and curing time on the mechanical strength of RCA-PVA-FA concrete was assessed by compressive, split tensile and flexural strength tests. The third is to investigate the usage of PVA and c for improving the mechanical strengths of RCA to be used as an alternative material in pavement base/subbase applications. The RCA is used as coarse and fine aggregates. The laboratory evaluation was comprised of California bearing ratio, modified Proctor compaction, repeated load triaxial test, unconfined compressive strength (UCS) and scanning electron microscope. The conclusions can be drawn as follows:

### 6.1.1 Chapter 3: Compressive and Flexural Strength of Polyvinyl Alcohol Modified Pavement Concrete Using Recycled Concrete Aggregates

This chapter illustrates the possibility of using PVA and c as a main material to develop a RCA-PVA concrete at varying w/c ratio of 0.3-0.6. The optimum p/c ratio providing the highest flexural strength is dependent on w/c ratio. The flexural strength increased with increasing p/c ratios up to an optimum p/c ratio that provided the highest flexural strength, followed by a subsequent decrease beyond this peak value. This is because the films create linkage among cement matrices and enhance the tensile strength among particles. The optimum p/c ratio was found to be 0.5 for w/c = 0.3 and 0.4, and 1.0 and 1.5 for w/c = 0.5 and 0.6, respectively. Based on the Thailand Department of Highways (demanding a minimum 28-day compressive strength of 32 MPa), the w/c ≤ 0.5 and p/c ≤ 1 was found to be applicable for road construction. In case of exceeding the optimal p/c ratio at each w/c ratios, the thick PVA films retard the hydration like a barrier around the matrix, which prevent water absorption for the hardening and the growth of C-S-H structures. Hence, the growth of C-S-H products in the matrix is prevented, resulting in an extreme reduction of compressive strength.

### 6.1.2 Chapter 4: Recycled Concrete Aggregate Modified with Polyvinyl Alcohol and Fly Ash for Concrete Pavement Applications

The strength development with influential factors for the manufacturing of RCA-PVA-FA concrete is presented in this chapter. The studied factors are FA/c ratio, p/b ratio and curing time duration with w/c = 0.5. The optimum FA/c ratio for manufacturing RCA-PVA-FA is 0/100 for short-term curing (7 days). However, the optimal FA/c ratio that achieved the highest long-term (> 28 days) compressive strength was 20/80 indicating that the pozzolanic reaction comes into play at long-term curing. The SEM image showed that growth of C–S–H and C-A–S–H on FA surface and in the matrix with increasing FA/c and the maximum cementitious products was found at FA/c = 20/80. For all FA/c ratios tested, the additional p/b ratio caused the reduction in compressive strengths but at the same time PVA improved tensile strength, the highest flexural and split tensile strengths were found at the optimal p/b ratio of 1%. At the optimal PVA content, the PVA films infiltrated into cementitious matrixes and enhanced the reinforcing ability within the matrixes. However, the excess PVA content retarded the hydration and caused the reduction in cementitious tensile bonding.

### 6.1.3 Chapter 5: Effect of Cement Stabilization of Recycled Concrete Aggregates Modified with Polyvinyl Alcohol: Mechanical and Micro-Scale Properties

This chapter investigates the possible ability of using PVA and cement to stabilize RCA as an alternative material in pavement base/subbase applications. The UCS of RCA increases by almost 3-fold with added 3% cement, mixing PVA > 1.5% into the cement-stabilized RCA has a vital role in improving the compressive strength along with gaining a higher modulus of toughness. The UCS value of stabilized RCA with 3% cement and RCA with 3% cement and 1.5% or 2% PVA met the minimum requirement for 7 days of curing. The addition of PVA reduced the resilient modulus (MR); however, the MR value of all blends was still higher than the minimum recommended value. The CBR value and swelling in soaked condition increased with increasing the PVA content. SEM analysis of the PVA and cement

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stabilized RCA showed that the thickness of PVA films increased with increasing PVA content. This causes uniform matrices of aggregated particles with less inter pore-spaces, resulting in a strength increase along with a toughened behavior. Overall, the stabilized RCA with 3% cement and 1.5% and 2% PVA showed better properties of the UCS and toughness than cement mixtures.

## 6.2 Recommendations for future work

- This study used only polyvinyl alcohol (PVA) to modify cement-based material. The other polymer materials such as poly(vinyl acetate-vinyl carboxylate), poly(ethylene-vinyl acetate) and styrene-butadiene rubber latex can be considered for further study.
- FA was used as a pozzolanic material in this study. Further work can be done using other pozzolanic materials such as rice husk ash, bagasse ash, metakaolin.
- It would be useful to study the sulphate and acid resistance of RCA-PVA-FA concrete since PVA is good in chemical resistance.
- This thesis only investigates the stabilization of RCA by using PVA with cement. The use of natural rubber alternative to PVA can be considered for further study.

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# APPENDIX A

# PUBLICATIONS

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# List of Publications

## INTERNATIONAL CONFERENCE PAPERS

Yaowarat, T., Horpibulsuk, S., Arulrajah, A. (2018) **Strength Development of Polyvinyl Alcohol (PVA) Modified Concrete Using Recycled Concrete Aggregates as Coarse Aggregate,** the 11th SEATUC Symposium at Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam on 13th – 14th March 2017

## INTERNATIONAL JOURNAL PAPERS

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Mirzababaei, M., and Rashid, A. S. A. (2018). "**Compressive and Flexural Strength of Polyvinyl Alcohol Modified Pavement Concrete Using Recycled Concrete Aggregates.**" Journal of  Materials in Civil Engineering., 30(4), 04018046.

Yaowarat, T., Horpibulsuk, S., Arulrajah, A., Mohammadinia, A., and Chinkulkijniwat A. (2018). "**Recycled Concrete Aggregate Modified with Polyvinyl Alcohol and Fly Ash for Concrete Pavement Applications.**" Journal of Materials in Civil Engineering., 31(7), 04019103.

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# Compressive and Flexural Strength of Polyvinyl Alcohol–Modified Pavement Concrete Using Recycled Concrete Aggregates

Teerasak Yaowarat[1]; Suksun Horpibulsuk, Ph.D.[2]; Arul Arulrajah, Ph.D.[3];
Mehdi Mirzababaei, Ph.D.[4]; and Ahmad Safuan A Rashid[5]

**Abstract:** Research on the utilization of recycled concrete aggregate (RCA) in civil engineering applications is gaining popularity worldwide due to the increased efforts to promote preservation of the environment and sustainable development. Recycled concrete aggregate concrete is, however, presently still limited to nonstructural applications. Recycled concrete aggregate concrete can still be considered as a rigid pavement material when its flexural strength is improved adequately to sustain future traffic loads. In this study, polyvinyl alcohol (PVA), a water-soluble polymer, was used to improve the flexural strength of RCA concrete. The influence of PVA-to-cement ($p/c$) and water-to-cement ($w/c$) ratios on the compressive and flexural strengths of RCA-PVA concrete was investigated via scanning electron microscopy (SEM) and X-ray diffraction (XRD). Polyvinyl alcohol films were found to retard the hydration process, resulting in the delay in initial and final setting times of cement-PVA paste, therefore reducing the compressive strength of RCA-PVA concrete. For all the $w/c$ ratios tested, the flexural strength increased with increasing $p/c$ ratios up to an optimum $p/c$ ratio that provided the highest flexural strength, followed by a subsequent decrease beyond this peak value. The optimum $p/c$ ratio tended to increase with an increase in $w/c$ ratio, being 0.5, 0.5, 1.0, and 1.5 for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively. Based on the requirements of the Department of Highways, Thailand, the $p/c \leq 1$ at $w/c \leq 0.5$ was found to be suitable for developing RCA-PVA concrete for rigid pavements. The outcome of this research confirms the viability of using PVA to improve the flexural strength of RCA concrete for usage as a sustainable rigid pavement material. **DOI: 10.1061/(ASCE)MT.1943-5533.0002233.** © *2018 American Society of Civil Engineers.*

**Author keywords:** Polyvinyl alcohol; Recycled concrete aggregate; Flexural strength; Compressive strength; Microstructure; Pavement.

## Introduction

The utilization of waste materials and research on new recycling techniques have been encouraged worldwide to promote sustainable practices to reduce the effect of civil engineering construction activities on the environment. Recycled concrete aggregate (RCA) is obtained from the demolition of aged concrete buildings and essentially consists of constituents such as binding materials, water, aggregates, and admixtures. The major component is the aggregates, which comprise 60–75% of the total concrete volume (Kosmatka et al. 2002). Previous research has shown that RCA could be used sustainably as unbound or stabilized pavement base and subbase materials (Arulrajah et al. 2015, 2016a, b, 2017; Disfani et al. 2014; Yaghoubi et al. 2017).

Recycled concrete aggregate can furthermore be used as coarse aggregates in the production of concrete, which would reduce waste concrete stockpiles at landfills and would limit the need for natural aggregate sources (Silva et al. 2014). Reuse of waste materials from demolition activities has numerous environmental and economic benefits. However, the variable properties of RCA remain the predominant barrier in using RCA for concrete production. Several studies (Behera et al. 2014; Dilbas et al. 2014; Omary et al. 2016; Otsuki et al. 2003) reported that RCA concrete often exhibited low compressive strength, wide variability in quality, high drying shrinkage, large creep, and low elastic modulus. Nogchi (2001) and Olorunsogo and Padayachee (2002) indicated that the compressive strength and durability against chloride resistance of RCA concrete gradually decreased as the amount of RCA increased. Silva et al. (2014) recommended that RCA concrete should only be used in nonstructural applications, such as in rigid pavements and canal linings.

Several researchers have proposed methods to improve the strength and durability of RCA concrete, such as by using the double mixing approach or two-stage mixing approach (TSMA) (Otsuki et al. 2003; Tam et al. 2005) or by mixing it with aluminosilicate materials, such as ground fly ash, ground bagasse ash, and ground palm oil fuel ash (Kua et al. 2016; Phetchuay et al. 2016; Somna et al. 2012; Tangchirapat et al. 2012; Yoobanpot et al. 2017).

Earlier studies on RCA concrete focused on the compressive strength properties. The compressive strength of RCA can be improved by both nontraditional and traditional chemicals

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[1] Ph.D. Scholar, School of Civil Engineering, Suranaree Univ. of Technology, 111 University Ave., Muang District, Nakhon Ratchasima 30000, Thailand. E-mail: teerasakyaowarat@gmail.com

[2] Professor, School of Civil Engineering; Director, Center of Excellence in Innovation for Sustainable Infrastructure Development, Suranaree Univ. of Technology, 111 University Ave., Muang District, Nakhon Ratchasima 30000, Thailand (corresponding author). E-mail: suksun@g.sut.ac.th

[3] Professor, Dept. of Civil and Construction Engineering, Swinburne Univ. of Technology, Melbourne, VIC 3122, Australia. E-mail: aarulrajah@swin.edu.au

[4] Lecturer, School of Engineering and Technology, Central Queensland Univ., Melbourne, VIC 3000, Australia. E-mail: m.mirzababaei@cqu.edu.au

[5] Senior Lecturer and Fellow, Faculty of Civil Engineering, Centre of Tropical Geoengineering (GEOTROPIK), Universiti Teknologi Malaysia, 81310 UTM Skudai, Malaysia. E-mail: ahmadsafuan@utm.my

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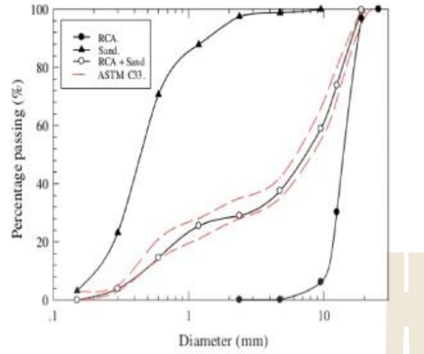

**Fig. 1.** Particle size distributions of sand, RCA, and RCA + sand

(Chinkulkijniwat and Horpibulsuk 2012; Latifi et al. 2015, 2016, 2017; Hoy et al. 2017; Horpibulsuk et al. 2006). Research on the essential flexural strength properties of RCA concrete is, however, still limited to date. The flexural strength plays a vital role in the stability of rigid pavement due to its low tensile strength characteristics (Deshpande et al. 2012; Kumutha and Vijai 2008).

The flexural strength of concrete can be improved by fiber reinforcement (Jamsawang et al. 2015; Sukontasukkul 2004; Sukontasukkul and Jamsawang 2012). Water-soluble polymers have also been reported to enhance the flexural strength as well as the durability of concrete (Allahverdi et al. 2010; Jaroslav et al. 2015; Viswanath and Thachil 2008). Approximately 650,000 t of polyvinyl alcohol (PVA) polymer are produced annually for the commercial cement and concrete industries (Rong et al. 2009). Adding PVA into cement pastes improves its chemical resistance properties, such as preservation of compressive strength after exposure to chemical attacks (Viswanath and Thachil 2008). The flexural strength of concrete specimens increases with increasing PVA-to-cement (by weight) ($p/c$) ratio due to the significant reduction of both total permeable pore volume and water absorption of the specimens. Polyvinyl alcohol effectively packs the concrete solid ingredients and results in a dense matrix material (Allahverdi et al. 2010).

To the best of the authors' knowledge, there has been no research undertaken to date on the application of PVA for improving the flexural strength of RCA concrete, which is the prime focus of this research. The RCA concrete specimens were prepared by the TSMA method in this study. The role of the water-to-cement ($w/c$) ratio and $p/c$ ratio on the compressive and flexural strengths of the RCA-PVA concrete is investigated via macrostructural and microstructural testing in this study. The flexural strength improvement of RCA-PVA concrete specimens that meets the compressive strength requirements of the Thailand national road authorities is also reported in this study.

## Materials and Methods

### *Materials*

Natural river sand with a fineness modulus of 3.74 was used as the fine aggregate for preparing the RCA concrete. The river sand had a specific gravity in the saturated surface dry state, water absorption, and percent of voids of 2.58, 3.34, and 42.5%, respectively. The dry-rodded unit weight of the river sand was 14.7 kN/m$^3$. Particle size distribution of the river sand is shown in Fig. 1.

**Table 1.** Chemical Compositions of OPC

| Composition | Content (%) |
|---|---|
| $SiO_2$ | 20.9 |
| $SO_3$ | 2.7 |
| $Fe_2O_3$ | 3.32 |
| $Al_2O_3$ | 4.7 |
| CaO | 65.4 |
| MgO | 2.54 |
| Loss on ignition | 0.9 |

Recycled concrete aggregate specimens had particles with sizes ranging between 4.75 and 19 mm. The grain size distribution curve of RCA is shown in Fig. 1. Recycled concrete aggregate had a fineness modulus and a specific gravity in the saturated surface dry state of 1.34 and 2.67, respectively. Its dry-rodded unit weight was 12.1 kN/m$^3$. The water absorption, percent of voids, and Los Angeles abrasion loss were 5.5, 54, and 41%, respectively. Because the RCA was not scalped to remove the attached mortar, it possessed lower specific gravity and higher water absorption and porosity. Consequently, the RCA was weaker than the natural aggregate (Chen et al. 2003; Salem and Jackson 2003).

Ordinary portland cement (OPC) was used to make the RCA concrete specimens in this study. Ordinary portland cement had a specific gravity and an average particle size of 3.15 and 14.7 $\mu$m, respectively. Chemical compositions of OPC are shown in Table 1. Polyvinyl alcohol was purchased from Chemipan Corporation, Bangkok, Thailand. It is a synthetic polymer that is achromatic, odorless and soluble in water (temperatures of 90–95°C are generally required for complete solution). Polyvinyl alcohol had a specific gravity, hydrolyzed, and molecular weight of 1.27–1.31, 87.83%, and 22,000 g/mol, respectively. Polyvinyl alcohol has a film-forming property, high corrosion resistance to the solvents and lubricating oil, and is excellent in adhesion. The flammable properties such as flashpoint and autoignition temperatures are more than 70 and 440°C, respectively, while the combustibility of PVA is very low (Hassan and Peppas 2000a, b).

### *Specimen Preparation*

Recycled concrete aggregate PVA concrete specimens were prepared by varying both $w/c$ and $p/c$ ratios. The PVA solution was prepared in five different percentages with respect to the cement weight: 0, 0.5, 1, 1.5, and 2.0, representing low to high values for improving workability and water retention abilities of the concrete (Kim and Robertson 1998; Kim et al. 1999; Ohama 1998). Four different $w/c$ ratios, 0.3, 0.4, 0.5, and 0.6 were studied. The PVA solutions were prepared by adding PVA powder at a target $p/c$ ratio into 2 L of boiled water until the PVA was entirely dissolved. In this research, 2 L of water were removed for producing normal concrete and replaced by 2 L of PVA solution. The mixture was kept overnight in an open-air atmosphere to allow it to cool down to room temperature before mixing it with cement slurry (Allahverdi et al. 2010; Singh and Rai 2001; Thong et al. 2016).

The mixing proportions of the RCA concrete specimens are summarized in Table 2. The RCA was used to fully replace the natural coarse aggregate in the mix proportion. The ratio of fine to coarse aggregates was fixed at 45:55 by volume. The gradation of aggregates (mixture of fine and coarse aggregates) is shown in Fig. 1 and compared with upper and lower boundaries suggested by ASTM C33 (ASTM 2016b). The gradation of tested aggregates is within the suggested boundary. The slump of the fresh RCA-PVA

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**Table 2.** Mixing Proportions of Concretes

| Mix | Mixing proportion (kg/m$^3$) | | | | | $w/c$ | Slump (mm) |
|---|---|---|---|---|---|---|---|
| | Cement | PVA weight | RCA[a] | Sand | SP[b] | | |
| W3PVA0 | 417.4 | — | 1,193 | 890 | — | 0.3 | 10 |
| W3PVA0.5 | 417.4 | 2.087 | 1,189 | 873 | 3.26 | 0.3 | 15 |
| W3PVA1 | 417.4 | 4.174 | 1,191 | 874 | 4.35 | 0.3 | 10 |
| W3PVA1.5 | 417.4 | 6.261 | 1,182 | 867 | 5.43 | 0.3 | 15 |
| W3PVA2 | 417.4 | 8.348 | 1,179 | 864 | 6.52 | 0.3 | 20 |
| W4PVA0 | 417.4 | — | 1,189 | 873 | — | 0.4 | 30 |
| W4PVA0.5 | 417.4 | 2.087 | 1,194 | 877 | 2.72 | 0.4 | 30 |
| W4PVA1 | 417.4 | 4.174 | 1,186 | 870 | 3.26 | 0.4 | 35 |
| W4PVA1.5 | 417.4 | 6.261 | 1,173 | 860 | 3.8 | 0.4 | 35 |
| W4PVA2 | 417.4 | 8.348 | 1,164 | 852 | 4.35 | 0.4 | 40 |
| W5PVA0 | 417.4 | — | 1,174 | 860 | — | 0.5 | 45 |
| W5PVA0.5 | 417.4 | 2.087 | 1,187 | 871 | 2.17 | 0.5 | 50 |
| W5PVA1 | 417.4 | 4.174 | 1,190 | 873 | 2.39 | 0.5 | 45 |
| W5PVA1.5 | 417.4 | 6.261 | 1,176 | 862 | 2.6 | 0.5 | 50 |
| W5PVA2 | 417.4 | 8.348 | 1,185 | 869 | 2.82 | 0.5 | 55 |
| W6PVA0 | 417.4 | — | 1,168 | 855 | — | 0.6 | 85 |
| W6PVA0.5 | 417.4 | 2.087 | 1,195 | 878 | 1.08 | 0.6 | 80 |
| W6PVA1 | 417.4 | 4.174 | 1,181 | 866 | 1.3 | 0.6 | 85 |
| W6PVA1.5 | 417.4 | 6.261 | 1,166 | 854 | 1.52 | 0.6 | 85 |
| W6PVA2 | 417.4 | 8.348 | 1,172 | 859 | 1.73 | 0.6 | 80 |

[a] Recycled coarse aggregate in the saturated surface dry (SSD) state.
[b] SP = superplasticizer, which was assumed to have 50% water by weight.

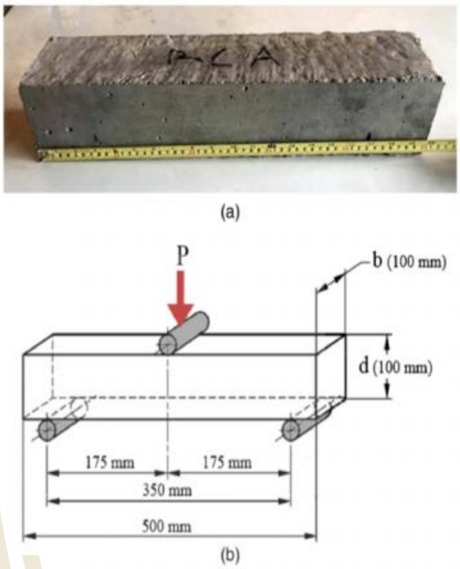

**Fig. 2.** (a) Specimen; (b) schematic of the dimensions for flexural tests

concrete was controlled in the ranges of 10–30, 20–50, 30–70, and 50–100 mm for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively, by varying the amount of Type F superplasticizer.

In this study, the TSMA method (Tam et al. 2005) was chosen to prepare the RCA-PVA concretes because this method has been proven to reduce the porosity of RCA, in that the produced cement gel fills into the cracks and voids caused during the crushing process of RCA.

### *Initial and Final Setting Times*

The initial and final setting times were investigated for all specimens to explain the effect of PVA content on the hydration process of RCA-PVA concrete specimens by using Method A, manual Vicat needle apparatus, in accordance with ASTM C191 (ASTM 2013). The initial setting time is reached when the penetration is 25 mm or less. Setting time ended when the tip of the needle penetrated only 0.5 mm into the cement paste.

### *Compressive and Flexural Strengths*

Based on ASTM C192 (ASTM 2016a), all of the fresh concrete mixtures were prepared using a rotary drum mixer. For each concrete mix, Ø100 × 200 mm cylinders and 100 × 100 × 500 mm prismatic specimens were cast. The Ø100 × 200 mm cylinders were used to determine the compressive strength according to ASTM C39 (ASTM 2016c). The 100 × 100 × 500 mm prismatic specimens were prepared for the flexural strength test with a center-point loading in accordance with ASTM C293 (ASTM 2016d). The flexural strength of the specimens was determined in accordance with ASTM C293 using the following equation:

$$\text{Flexurl strength} = \frac{3PL}{2bd^2} \tag{1}$$

where $P$ = maximum applied load; $L$ = span length; and $b$ and $d$ = average width and depth of the specimens, respectively. The schematic diagram showing the test specimen and setting is given in Fig. 2.

All the specimens were cast in steel molds and compacted by a vibrating table. The cylindrical and prismatic concrete specimens were demolded after 24 h of curing at room temperature, and then cured in a water-curing tank at 27 ± 2°C for the designed curing age. The compressive and flexural strengths of RCA concrete were investigated for the curing ages of 7, 14, and 28 days. The mean compressive and flexural strength values were obtained by testing three cylindrical and three prismatic concrete specimens to ensure the consistency of testing. In most cases, the results under the same testing condition were reproducible with low mean standard deviation (SD) ($\mathrm{SD}/\bar{x} < 10\%$, where $\bar{x}$ is mean strength value).

### *Scanning Electron Microscopy and X-Ray Diffraction*

The role of $w/c$ and $p/c$ ratios on the compressive and flexural strengths was examined by scanning electron microscopy (SEM) and X-ray diffraction (XRD) analyses. A small specimen was frozen at −195°C by immersion in liquid nitrogen and coated with gold before SEM analysis (Sukmak et al. 2013). The specimen was also ground to fine powder for XRD tests to obtain microstructural information of amorphous and crystalline phases. The XRD scans were performed at 0–90° $2\theta$ by a Bruker D8 ADVANCE device (United States).

## Results

### *Initial and Final Setting Times*

Fig. 3 shows the initial and final setting times of PVA-cement pastes at various $w/c$ and $p/c$ ratios. The setting time was measured using a Vicat apparatus on two representative specimens for each set 15 min after preparation time. The PVA influences

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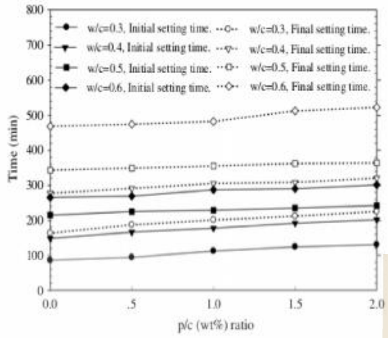

**Fig. 3.** Initial and final setting times of PVA-cement paste

the hydration process by delaying both initial and final setting times, as compared with the pure cement paste (without PVA) at the same $w/c$ ratios. For instance, at a $p/c$ ratio of 2 and $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, the initial setting times are delayed by approximately 44, 54, 43, and 53 min, respectively, when compared with those of the pure cement pastes. The final setting times are 62, 51, 38, and 44 min, respectively, longer than those of the pure cement plates, which is similar to the results reported by previous researchers (Jaroslav et al. 2015; Singh and Rai 2001). For the same $w/c$ ratio, the initial and final setting times are longer for higher $p/c$ ratios. For example, at $w/c = 0.5$, the initial setting times are 215, 225, 229, 235, and 242 min for $p/c = 0$, 0.5, 1.0, 1.5, and 2.0, respectively, and the final setting times are 343, 349, 355, 362, and 364 min for $p/c = 0$, 0.5, 1.0, 1.5, and 2.0, respectively.

### Compressive Strength of RCA-PVA Concrete

The compressive strength of RCA-PVA concrete specimens at 7, 14, and 28 curing days and different $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6 are shown in Fig. 4. The highest 7-day compressive strength [Fig. 4(a)] was found at $p/c$ ratio = 0, where the maximum compressive strengths are 29.5, 27.1, 24.7, and 21.2 MPa for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively, while the minimum 7-day compressive strengths were found at $p/c = 2$, including 20.6, 15.6, 14.1, and 12.3 MPa for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively. This result indicates that the compressive strength reduces with increasing of $w/c$ and $p/c$ ratios. The additional water content (increasing of $w/c$ ratio) leads to coarse pore distribution in the concrete specimen and increases its porosity and permeability, hence reducing its compressive strength (Ait-Aider et al. 2007; Albano et al. 2009; Kim et al. 2014; Ma et al. 2014).

Similarly, the maximum 14- and 28-day compressive strengths were also found at $p/c$ ratio = 0 and $w/c = 0.3$. At $p/c = 0$, the 14-day compressive strengths are 33.9, 30.4, 26.9, and 24.3 MPa for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively [Fig. 4(b)] and the 28-day compressive strengths are 43.6, 41.1, 38.5, and 32.59 MPa for $w/c$ ratios of 0.3, 0.4, 0.5, and 0.6, respectively [Fig. 4(c)]. The dotted line in Fig. 4(c) indicates the strength requirement for rigid pavement by the Thailand Department of Highways [DH-S309/2544 (Thailand Department of Highways 1996)].

It is evident from the test results that the addition of PVA to the concrete mix not only reduces the compressive strength of the specimen at a particular curing time but also the strength development with time (Fig. 4). This is in agreement with the test results of setting times in that the initial and final setting times are longer with increasing of $p/c$ ratio. For instance, at $w/c = 0.3$-, 7-, 14-, and 28-day compressive strengths are 29.5, 33.9, and 43.5 MPa, respectively, for $p/c = 0$; while these values decrease to 24.5, 26.5, and 35.6 MPa, respectively, for $p/c = 1.0$, and to 20.6, 21.1, and 27.4 MPa, respectively, for $p/c = 2.0$.

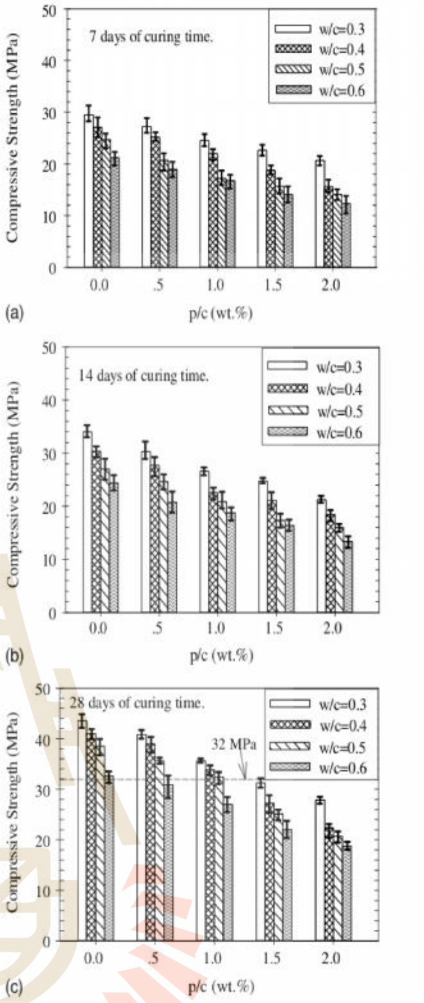

**Fig. 4.** Compressive strength of RCA-PVA concrete at (a) 7 days; (b) 14 days; (c) 28 days

### Flexural Strength of RCA-PVA Concrete

Fig. 5 shows the flexural strength of the specimens at various $w/c$ ratios, $p/c$ ratios, and curing times. The change of the highest strengths for each $w/c$ ratio at various curing times is shown by the dotted lines. The $p/c$ ratio providing the highest flexural strength at a particular $w/c$ ratio is herein defined as the optimum $p/c$ ratio. The optimum $p/c$ ratio was found at approximately the same $p/c$

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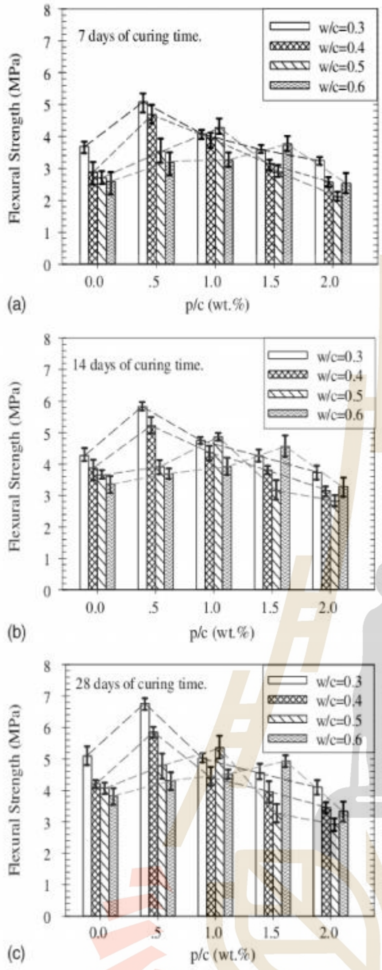

**Fig. 5.** Flexural strength of RCA-PVA concrete at (a) 7 days; (b) 14 days; (c) 28 days

ratio of 0.5% at all curing times for low $w/c$ ratios of 0.3 and 0.4. The maximum flexural strengths at $w/c$ ratios of 0.3 and 0.4 at 28 days of curing were found to be 6.7 and 5.8 MPa, respectively, with an increase of 33 and 39% when compared with RCA concrete specimens at the same $w/c$ ratios. However, the addition of PVA beyond $p/c$ of 0.5% causes a reduction in the flexural strength.

The change in the flexural strength with $p/c$ ratio for higher $w/c$ ratios of 0.5 and 0.6 is also similar to that for $w/c = 0.3$ and 0.4, where the flexural strength increases to the maximum value at the optimum $p/c$ and then decreases as $p/c$ increases. However, the optimum $p/c$ ratios are different from those of $w/c = 0.3$ and 0.4. The optimum $p/c$ ratios were found to be 1.0 and 1.5 for $w/c = 0.5$ and 0.6, respectively. In other words, the optimum $p/c$ increases with increasing $w/c$ ratio. At the optimum $p/c$ ratio, the 28-day flexural strengths are 5.35 and 4.93 MPa for $w/c = 0.5$ and 0.6, respectively. The flexural strength increases by 32 and 29% compared with those of RCA concrete at the same $w/c$ ratios of 0.5 and 0.6, respectively. Compared with the strength requirement for the rigid pavement by the Thailand Department of Highways (the 28-day compressive strength >32 MPa [Fig. 3(c)], the RCA concrete (without PVA) meets the requirement for all $w/c$ ratios tested. With PVA, the RCA-PVA concretes meet the requirement when $w/c \leq 0.5$ and $p/c \leq 1$.

### *Microstructural Analysis*

Scanning electron microscopy images of 28 days cured specimens at $w/c = 0.5$ and $p/c = 0$, 1, and 2% (W5PVA0, W5PVA1, and W5PVA2) are shown in Fig. 6. For $p/c = 0$ [Figs. 6(a and b)], the calcium silicate hydrate (C—S—H) gel is clearly detected, which is the main cementitious product primarily responsible for the strength development in cement-based material (Taylor 1986). Strong interfacial transition zones (ITZs) between RCA and the mortar matrix caused due to TSMA are clearly observed in Fig. 6(b); i.e., a thin layer of cement slurry on the surface of RCA at the first stage of mixing permeated into the existing pores of the cement mortar and filled up the existing cracks and voids.

However, the same is not true for the RCA-PVA specimens, films of PVA infiltrate in the pores of RCA-PVA specimens and cover the C—S—H products. At a small amount of $p/c = 1.0$ [Figs. 6(c and d)], the thin films of PVA are detected on the C—S—H products, while the growth of C—S—H continues and the C—S—H enlarges and penetrates the thin films out to the other matrices. Figs. 6(e and f) indicate the thicker films around C—S—H products for higher $p/c$ ratio of 2%. The films retard the hydration like a barrier around the matrix, which prevents water absorption for the hardening and the growth of C—S—H structures. Hence, the growth of C—S—H products in the matrix is prevented, resulting in an extreme reduction of compressive strength.

In addition to the SEM results, the XRD patterns were also examined for the treated specimens to confirm the retardation of cementitious products in RCA-PVA concrete at various $p/c$ ratios. The XRD patterns of specimens at $w/c = 0.5$ with $p/c = 0$, 1, and 2% (W5PVA0, W5PVA1, and W5PVA2) and cured for 28 days are shown in Fig. 7. The amorphous phase and the board hump (peak) between 17 and 35°$2\theta$ are observed, which is similar to previous research (Abo-El-Enein et al. 2015; Hoy et al. 2016; Kontoleontos et al. 2013; Lothenbach et al. 2011). The XRD results show the decrease in the portlandite phase with increasing $p/c$ ratio, indicating the reduction in hydration products. The presence of the largest amount of C—S—H overlapped with that of calcite in W5PVA0 specimens (without PVA) is indicated by the broad hump at approximately 29.5°$2\theta$ in Fig. 7(a).

For W5PVA1, the broad hump at approximately 29.5°$2\theta$ of C—S—H products [Fig. 7(b)] is less than that in the RCA concrete (W5PVA0). At this state, the thin films of PVA cover and interweave into the cement matrix. The lowest amount of cementitious products are observed when $p/c = 2.0$ as shown in Fig. 7(c) for the W5PVA2 specimen.

From the SEM images and XRD patterns, it is evident that the addition of PVA into RCA concrete forms a film that creates a barrier around the cement grains and therefore prevents water absorption during the hydration process. The addition of PVA also increases the viscosity of the water solution (Nguyen et al. 2015), resulting in the formation of air bubbles, which are trapped in the RCA-PVA concrete during the mixing process, and hence increasing the porosity of the cement matrix (Contrafatto 2013; Ficker 2011). The addition of PVA leads to a delay in the hydration process of cement-PVA paste, an extension of both the initial and final

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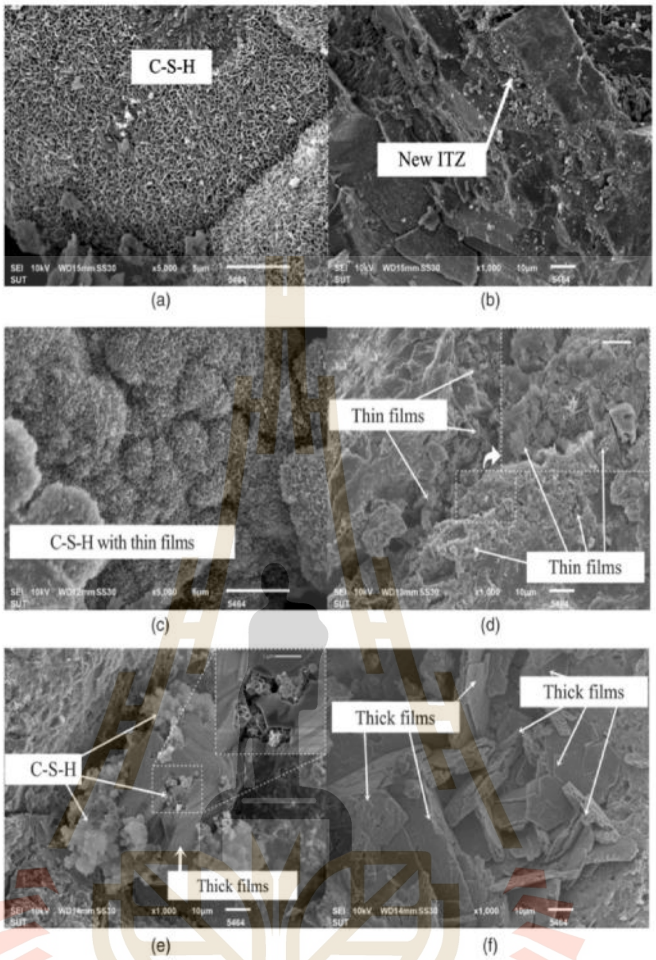

**Fig. 6.** Scanning electron microscopy images for (a and b) W5PVA0; (c and d) W5PVA1; (e and f) W5PVA2

setting times, and a reduction in hydration products, as well as a reduction in the density of the matrix.

Even though the PVA films delay hydration, the films create linkage among cement matrixes and enhance the tensile strength among particles. The flexural strength of RCA concrete is controlled by tensile strength as seen by the crack propagation from the bottom of prismatic specimens during testing (Fig. 8) similar to the failure mechanism reported by Jamsawang et al. (2015). The flexural strength of RCA-PVA concrete specimens increases with $p/c$ ratio up to the maximum value at the optimum $p/c$ ratio, where the highest tensile strength exists. The excessive $p/c$ ratio reduces the flexural strength of the RCA-PVA concrete to be even lower than that of the RCA concrete.

The $w/c = 0.5$ at various $p/c$ ratios was chosen for the microstructural analysis to explain the change in compressive and flexural strength, where $p/c = 1.0$ is the optimum ratio. Similar microstructural analysis results should be obtained where the optimum $p/c$ ratio will be at 0.5 for $w/c = 0.3$ and 0.4 and at 1.5 for $w/c = 0.6$.

## Conclusions

This research investigates the feasibility of using PVA to improve the flexural strength of RCA concrete to be a sustainable rigid pavement material. Polyvinyl alcohol forms a film around cement grains and therefore prevents the water absorption for the cement hydration process. The higher $p/c$ ratio therefore results in longer initial and final setting times of RCA-cement paste and lower compressive strength.

Even though PVA retards hydration, it contributes to improve the flexural strength. The optimum $p/c$ ratio providing the highest flexural strength is dependent on $w/c$ ratio. The optimum $p/c$ ratio was found to be 0.5 for $w/c = 0.3$ and 0.4, and 1.0 and 1.5 for $w/c = 0.5$ and 0.6, respectively. Based on the Thailand Department of Highways (demanding a minimum 28-day compressive strength of 32 MPa), the $w/c \leq 0.5$ and $p/c \leq 1$ was found to be applicable for road construction. At the optimum $p/c$ ratio, the flexural strength of RCA-PVA was approximately 30% higher than that

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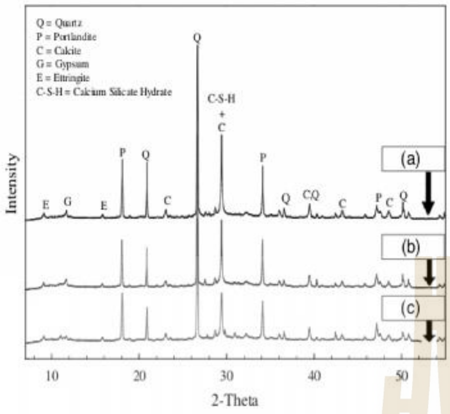

**Fig. 7.** X-ray diffraction pattern of (a) W5PVA0; (b) W5PVA1; (c) W5PVA2 at 28 days

**Fig. 8.** Specimen after being tested for flexural strength

of the RCA concrete. The outcome of this research confirms the viability of using PVA to improve the flexural strength of RCA concrete to be used as an alternative sustainable rigid pavement.

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วิทยาลัยเทคโนโลยีสุรน

# BIOGRAPHY

Mr. Teerasak Yaowarat was born in June 1992 in Nakhon Ratchasima, Thailand. He obtained his Bachelor’s degree in Civil Engineering from the School of Civil Engineering, Suranaree University of Technology in 2014. Then, he has been awarded a Royal Golden Jubilee (RGJ) Ph.D. Program Scholarship from the Thailand Research Fund (TRF) in 2014 for his Ph.D. study in the School of Civil Engineering, Suranaree University of Technology. During his Ph.D. study (2014-2019), he has worked as a teaching assistant for Surveying Laboratory and Hydraulics Laboratory. He has visited the Faculty of Science, Engineering and Technology, Swinburne University of Technology, Melbourne, Australia for his oversea research under the supervision of Prof. Arul Arulrajah from April 30, 2018 to April 20, 2019. He has published 2 international ISI journal papers and 1 keynote lecture in 11th SEATUC Symposium at Ho Chi Minh City University of Technology (HCMUT), Ho Chi Minh City, Vietnam

มหาวิทยาลัยเทคโนโลยีสุรนารี