

UNIVERSITI TEKNOLOGI MARA

**PHYSICAL, MECHANICAL AND
MICROSCOPIC INVESTIGATION
ON SELF-CURED CONCRETE
CONTAINING GREEN ARTIFICIAL
AGGREGATE (GAA)**

NORHALIZA BINTI HAMZAH

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NORHALIZA BINTI HAMZAH

Thesis submitted in fulfilment
of the requirements for the degree of
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ABSTRACT

Lightweight aggregates replacing natural aggregate act as internal water reservoirs, mitigating shrinkage, improving hydration, and reducing evaporation while addressing environmental and economic challenges of water-intensive curing. However, there is limited study available on using Green Artificial Aggregate (GAA), a sustainable lightweight aggregate manufactured from waste material specifically ceramic waste, bottom ash and fly ash as self-curing agent in concrete. The present study aims to examine the potential of GAA as a self-curing agent in concrete while evaluating its effects on strength and durability performance compared to conventional concrete with curing and without curing process. The Design of Experiments (DOE) method was adopted for the mix design to produce concrete Grade 30 with the water cement ratio used was 0.53. The aggregates condition used in the concrete mixes was divided into air-dry (AD) and saturated-surface-dry (SSD). Two types of curing regimes were used namely water- curing and air-curing. Normal concrete was also prepared as a control specimen. Various tests were carried out to determine the characteristics of the aggregates including specific gravity, water absorption, water desorption, surface texture, aggregate crushing value, porosity, x-ray fluorescence and sieve analysis. The performance of self-cured concrete was determined through compressive strength, ultrasonic-pulse velocity, density, flexural strength, modified compressive strength, shrinkage, expansion and initial surface absorption. Furthermore, various techniques including scanning electron microscopy (SEM) with energy dispersive X-ray (EDX) Analysis, X-ray diffraction (XRD) and mercury intrusion porosimetry (MIP) were used to study the microstructure of the self-cured concrete. The experimental results showed that that GAA possesses significantly higher water absorption (10.6%) compared to granite (0.32%), enabling it to function effectively as an internal water reservoir. Control concrete exhibited superior compressive strength, though self-cured concrete demonstrated enhanced strength development. The performance differential between control and GAA concrete is attributed to GAA's porosity. Statistical analyses confirmed aggregate type and curing regimes significantly influence mechanical properties. GAA's porosity facilitates internal water reservation for hydration. SSD and AD GAA showed comparable compressive strength, indicating pre-soaking is unnecessary for effective internal curing. Self-cured specimens performed optimally with delayed demoulding under air-curing, while conventional concrete maximized strength with early demoulding in water-curing. Statistical analyses revealed demoulding timing negligibly affects compressive strength, suggesting expedited formwork removal enhances construction efficiency without compromising structural integrity. Microstructural analysis revealed elevated calcium concentrations in self-cured concrete relative to controls indicate enhanced hydration, improved C-S-H formation, and denser microstructure from internal curing. SSD GAA concrete exhibited superior pore refinement notably a 27% diameter reduction in air-cured specimens enhancing durability and reducing permeability. Overall test results together with microstructure study showed that GAA can be used as self-curing agent in the concrete. This research contributes to United Nations Sustainable Development Goals (UN SDGs) 9, 11, 12, and 13 by transforming industrial and construction waste into valuable construction materials, thereby reducing water consumption and natural resource extraction while promoting sustainable infrastructure and climate action.

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TABLE OF CONTENTS

	Page
CONFIRMATION BY PANEL OF EXAMINERS	ii
AUTHOR'S DECLARATION	iii
ABSTRACT	iv
ACKNOWLEDGEMENT	v
TABLE OF CONTENTS	vi
LIST OF TABLES	xi
LIST OF FIGURES	xiii
LIST OF ABBREVIATIONS	xviii
LIST OF NOMENCLATURES	xx
CHAPTER 1 INTRODUCTION	1
1.1 Background of Study	1
1.2 Problem Statement	2
1.3 Objectives of Study	4
1.4 Scope of Work and Limitations	5
1.5 Significance of Study	8
CHAPTER 2 LITERATURE REVIEW	10
2.1 Introduction	10
2.2 Mechanism of Hydration for Conventional Concrete	11
2.3 Mechanism of Self-Curing Concrete	13
2.4 Types of Curing Agent in Self-Curing Concrete	16
2.4.1 Artificial Lightweight Aggregate (LWA)	16
2.4.2 Porous Superfine Powders	18
2.4.3 Superabsorbent Polymer (SAP)	19
2.4.4 Polyethylene Glycol (PEG)	21
2.4.5 Natural Fibers	22
2.4.6 Artificial Normal Weight Aggregate (ANWA)	23
2.5 Advantages of LWA on Concrete	25

2.6	Physical Properties of LWA as Self-Curing Agent	26
2.6.1	Water Absorption	26
2.6.2	Water Desorption	27
2.6.3	Shape and Surface Texture	27
2.7	Effects of LWA as Self-Curing Agent in Performance of Concrete	28
2.7.1	Physical Properties	28
2.7.1.1	<i>Workability</i>	28
2.7.1.2	<i>Density</i>	29
2.7.2	Mechanical Properties of Self-Cured Concrete	30
2.7.2.1	<i>Compressive Strength</i>	30
2.7.2.2	<i>Splitting Tensile and Flexural Strength</i>	35
2.7.2.3	<i>Shrinkage</i>	38
2.7.3	Microstructure Examination of Self-Cured Concrete	41
2.7.3.1	<i>Scanning Electron Microscopy (SEM)</i>	42
2.7.3.2	<i>X-Ray Diffraction</i>	43
2.8	Artificial Aggregate as Self-Curing Concrete Agent	47
2.9	Summary of Literature Review	49
CHAPTER 3 RESEARCH METHODOLOGY		51
3.1	Introduction	51
3.2	Preparation of Materials	55
3.2.1	Ordinary Portland Cement (OPC)	55
3.2.2	Fine Aggregates	56
3.2.3	Coarse Aggregate	57
3.2.4	Water	59
3.3	Characterisation of Coarse Aggregates	60
3.3.1	Sieve Analysis of Coarse Aggregates	60
3.3.2	Specific Gravity of Coarse Aggregate	61
3.3.3	Absorption Capacity of Coarse Aggregate	62
3.3.4	Desorption of Coarse Aggregate	63
3.3.5	Aggregate Crushing Value	64
3.4	Determination of Mix Proportion	66
3.5	Casting and Preparation of Concrete Specimens	67
3.5.1	Preparation of Mould	67

3.5.2	Preparation of Concrete Specimens	68
3.5.3	Determination of Fresh State of Concrete Mixes	70
3.6	Curing Conditions	71
3.7	Testing on Hardened Concrete Specimen	72
3.7.1	Apparent Density	72
3.7.2	Ultra-Pulse Velocity (UPV)	72
3.7.3	Initial Surface Absorption Test	75
3.7.4	Compressive Strength Test	75
3.7.5	Flexural Strength Test	76
3.7.6	Modified Compressive Strength Test	78
3.7.7	Expansion and Drying Shrinkage	79
3.7.8	Mode of Failure	80
3.8	Microstructure Examination	81
3.9	X-Ray Fluorescence (XRF)	83
3.10	X-Ray Diffraction (XRD)	84
3.11	Mercury Intrusion Porosimetry (MIP)	85
3.12	Stereo Microscope	86
3.13	Data Collection and Analysis	88

CHAPTER 4 CHARACTERISATION OF MATERIALS AND INITIAL PERFORMANCE OF CONCRETE CONTAINING GREEN ARTIFICIAL AGGREGATE (GAA) 90

4.1	Introduction	90
4.2	Characteristics of Coarse Aggregates	90
4.2.1	Specific Gravity	91
4.2.2	Water Absorption	91
4.2.3	Aggregate Crushing Value (ACV)	92
4.2.4	Water Desorption	93
4.3	Morphology and Microstructure of Aggregates	95
4.3.1	Stereo Microscope	95
4.3.2	Mercury Intrusion Porosimetry (MIP)	96
4.4	Workability of Concrete With and Without GAA	97
4.5	Compressive Strength of Concrete With and Without GAA	99
4.6	Ultrasonic Pulse Velocity (UPV) of Concrete With and Without GAA	107

4.7	Density	111
4.8	Summary of Statistical Analysis for Concrete Properties	115
4.9	Finalisation of Mix Design for Self-Cured Concrete	118
4.10	Summary	118

CHAPTER 5 MECHANICAL PROPERTIES OF SELF-CURED SPECIMENS CONTAINING GREEN ARTIFICIAL AGGREGATE (GAA)

121

5.1	Introduction	121
5.2	Compressive Strength of Self-cured Concrete	122
5.3	Ultra-Pulse Velocity (UPV) of Self-cured Concrete	126
5.4	Density of Hardened Self- Cured Concrete	130
5.5	Flexural Strength	133
5.6	Modified Compressive Strength	135
5.7	Summary of Statistical Analysis for Self-cured Properties	136
5.8	Expansion and Shrinkage	140
5.9	Initial Surface Absorption (ISAT)	142
5.10	Summary	144

CHAPTER 6 MICROSTRUCTURE, CHEMICAL COMPOSITION AND POROSITY OF SELF-CURED CONCRETE

146

6.1	Introduction	146
6.2	Scanning Electron Microscope (SEM)	147
6.3	Energy-Dispersive X-Ray (EDX)	150
6.4	X-Ray Diffraction (XRD)	155
6.5	Mercury Intrusion Porosimetry (MIP)	159
6.6	Summary	162

CHAPTER 7 CONCLUSION DAN RECOMMENDATION

164

7.1	Introduction	164
7.2	Conclusions	165
7.3	Future Recommendations	169

REFERENCES	170
APPENDICES	202
AUTHOR'S PROFILE	212

LIST OF TABLES

Tables	Title	Page
Table 2.1	Compressive Strength Reduction of Concrete Due to LWA Addition as Compared to Control at Age 28 Days	31
Table 2.2	Use of Artificial Aggregate as Self-Curing Agent in Concrete Reported in Previous Resaerchers	48
Table 3.1	Composition of Cement, Determined by XRF	56
Table 3.2	Chemical Properties of GAA and NA (% weight) Extracted from Literature	59
Table 3.3	Specific Gravity of Coarse Aggregate	62
Table 3.4	Aqueous Salt Solutions and Associated Equilibrium RH Prepared for Desorption of Coarse Aggregate	63
Table 3.5	Mix Design for Concrete Mixes	67
Table 3.6	UPV Test Results Classification	73
Table 4.1	Physical and Mechanical Properties of Coarse Aggregate Used in the Present Study	91
Table 4.2	The Compressive Strength and Percentage of Increase for Concrete Specimens at 3 Days, 7 Days, and 28 Days of Age Cured in Water	100
Table 4.3	The Compressive Strength and Percentage of Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Air	101
Table 4.4	The Compressive Strength and Ratio of Percentage Increased for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air	103
Table 4.5	The UPV and Percentage of Increase Measured at 3 Days to 7 Days and 28 Days of Concrete Specimens Containing AD GAA, SSD GAA and Control Concrete (CTR) Cured in Water	108
Table 4.6	The UPV and Percentage of Increase from 3 Days to 7 Days and 28 Days of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Air	109

Table 4.7	The UPV and Ratio of Percentage Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air	110
Table 4.8	The Density and Percentage of Increase from 3 Days to 7 Days and 28 Days of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Water	112
Table 4.9	The Density and Percentage of Increased from 3 Days to 7 Days and 28 Days Of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Air	113
Table 4.10	The Density and Ratio of Percentage Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air	114
Table 4.11	Summary of Statistical Analysis for Concrete Properties	116
Table 4.12	Mix Design for Control and Self-Cured Concrete	118
Table 5.1	The Compressive Strength and Ratio of Increase Concrete Strength from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Different Water and Air Curing Conditions	124
Table 5.2	The UPV and ratio of increase in UPV from 3 days to 7 days, 7 days to 28 days and 28 days to 56 days cured in water and air curing	128
Table 5.3	The density and ratio of increase in density for control and GAA concrete specimens from 3 to 7 days, 7 days to 28 days and 28 days to 56 days cured in water and air curing	131
Table 5.4	Flexural Strength of Control Concrete and GAA Concrete at 28 Days Cured in Water and Air	134
Table 5.5	Modified Compressive for Prism Control and GAA (Self-Cured) Specimens at 28 Days Cured in Water and Air	136
Table 5.6	The Summary of Statistical Analysis for Experimental Variables Tested on GAA Concrete (Self-Cured)	137
Table 6.1	Compound and Index Name of Chemical and Mineral Composition in Concrete Recognised by X-pert Pro Software	155
Table 6.2	The Total Porosity (%) and Average Pore Diameter (μm) for Self-Cured and Control Concrete Samples Taken at the Age of 28 Days	160

LIST OF FIGURES

Figures	Title	Page
Figure 2.1	Hydration Process Flow for Conventional Concrete	12
Figure 2.2	Electron Microscopic Image of Hardened Cement Paste after Hydration	13
Figure 2.3	Illustration of the differences between self-curing and external curing	14
Figure 2.4	The Mechanism of Self-Curing Concrete	15
Figure 2.5	The Contact Zone Under Internal Curing and Normal Curing	16
Figure 2.6	Model Moving of Water in Concrete Incorporate Self-Curing with $r(t) < R_a$	18
Figure 2.7	Microstructure of Cenopheres Under SEM Observation	19
Figure 2.8	Process of Water Uptake to SAP	20
Figure 2.9	Hydrogen Bonds Between Water Molecules and An –OH Group on a Polymer Molecule	22
Figure 2.10	Free and Bound Water in Wood	23
Figure 2.11	Compressive Strength at 7 and 28 Days	32
Figure 2.12	Compressive Strength of UHPC: (a) at 7, 28, and 56 Days of Curing	35
Figure 2.13	Effect of Autogenous Shrinkage of Concrete with Air-Dry (AD) and Saturated-Surface-Dry (SSD) Lightweight Coarse Aggregate	39
Figure 2.14	Autogenous Shrinkage (In Micron) of UPHC Made of Different Contents of LWA	41
Figure 2.15	Normal-Bonded (Left) and Well-Bonded AAC-LWA (Right) on Interfacial Transition Zone (ITZ) of Cement Paste	43
Figure 2.16	X-ray Diffraction Peaks of Self-Compacting Concrete (SCC) Subjected to Different Curing Regimes at $27 \pm 2^\circ\text{C}$	44
Figure 2.17	X-ray Diffraction Analysis of Cement Paste for Both the LWAC and Normal Concete (NC) Specimens	44
Figure 2.18	XRD Spectra of UHPC Samples Contained: (a) LW0, (b) LW15 and, (c) LW30	46

Figure 3.1	Experimental Programme in the Present Research Work	53
Figure 3.2	Ordinary Portland Cement (OPC) Used in the Present Investigation	55
Figure 3.3	Grading Curve of Fine Aggregate Used in the Present Investigation	57
Figure 3.4	Natural Aggregate (NA) of 10 mm Size Crushed Granite	57
Figure 3.5	Green Artificial Aggregate (GAA) of 10 mm Size Used for Replacing NA	58
Figure 3.6	Sieve Shaker Used to Determine the Particle Size Distribution of Aggregates	60
Figure 3.7	Grading Curve for Two (2) Types Coarse Aggregate Used in the Present Study	61
Figure 3.8	Test Procedures of Desorption of Coarse Aggregate	64
Figure 3.9	Aggregate Crushing Value (ACV) Test Apparatus	65
Figure 3.10	Test Procedures for Determining ACV for the Aggregates	66
Figure 3.11	Steel Moulds that Ready for Casting	68
Figure 3.12	Mechanical Mixer	69
Figure 3.13	Vibrating Table	69
Figure 3.14	Process to Produce SSD Condition of Coarse Aggregates (a) Immerse the Aggregate in the Water for 24 hours and (b) Rolling up the Aggregate into the Towel	70
Figure 3.15	Slump Measurement of Fresh Concrete	71
Figure 3.16	Test Procedures of UPV Test	74
Figure 3.17	ISAT Test Setup	75
Figure 3.18	Universal Testing Machine for Compressive Strength Test	76
Figure 3.19	Arrangement for the Flexural Strength Test Setup of Two-Point Loadings	77
Figure 3.20	Flexural Test Machine	78
Figure 3.21	The Broken Prism Specimens and the Set Up For Modified Compression Test	78
Figure 3.22	Expansion and Drying Shrinkage Test Apparatus	80
Figure 3.23	Test Procedures of Drying Shrinkage and Expansion Test	80
Figure 3.24	Failure Pattern of Cube Concrete	81

Figure 3.25	The Coated Concrete Sample Before Placing in the SEM Machine	82
Figure 3.26	The Workstation for SEM Examination	83
Figure 3.27	Preparation Sample into Powdered Form for XRF Analysis	83
Figure 3.28	XRF Equipment Used to Determine the Chemical Composition of Cement and GAA	84
Figure 3.29	Ultima IV X-Ray Diffractometer	85
Figure 3.30	Test Procedure for XRD Test	85
Figure 3.31	Micromeritics AutoPore IV Equipment Used for Pore Analysis of the Concrete Powder Samples	86
Figure 3.32	The Procedures for Colour Propagation Test Using Stereo Microscope	87
Figure 3.33	The Workstation for Stereo Microscope Used for Observing Morphological Structure of Aggregates and Water Movement from Aggregates to Cement Paste	87
Figure 4.1	Water Absorption of GAA after 24 Hours Soaked in Pigmented Water	92
Figure 4.2	The Water Movement in the Concrete Specimen Containing GAA Shows From Pre-Wetted GAA to Cement Paste	94
Figure 4.3	Water Desorption Properties of Pre-Wetted GAA at Different RH	94
Figure 4.4	The Model Illustrating the Movement of Water from Pre-Wetted GAA to Cement Paste	95
Figure 4.5	Image of (a) GAA and (b) Granite (Magnification 0.67x~4.5x)	96
Figure 4.6	Pore Size Distribution of GAA	97
Figure 4.7	Pore Size Distribution of Granite	97
Figure 4.8	Slump (in mm) of Fresh Concrete Containing 50% and 100% GAA Which Prior to That are in SSD and AD Conditions	98
Figure 4.9	Ratio of Percentage Increment of Compressive Strength From 3 to 7 Days and 7 to 28 Days Cured in Water and Air	104
Figure 4.10	Failure Pattern of Concrete Cube Made of Granite, AD and SSD GAA Cured in Water After Compression Test at Age of 28 Days	105

Figure 4.11	Failure Pattern of Concrete Made of Granite, AD and SSD GAA Cured in Air After Compression Test at Age of 28 Days	106
Figure 4.12	Ratio of Percentage Increment of UPV From 3 to 7 Days and 7 To 28 Days Cured in Water and Air	111
Figure 4.13	Ratio of Percentage Increment of Density From 3 to 7 Days And 7 To 28 Days Cured in Water and Air	115
Figure 5.1	Ratio of Increased Concrete Strength from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing at Different Time Demoulding	126
Figure 5.2	Ratio of Increase in UPV for Control and GAA Concrete Specimens from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing at Different Time Demoulding	129
Figure 5.3	Ratio of Increase in Density from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing Conditions at Different Time Demoulding	132
Figure 5.4	Expansion and Shrinkage Values of Self-Cured (GAA) and Control Concrete Up to 28 Days	142
Figure 5.5	ISAT for All Series of Control and GAA Concrete Specimens at 28 Days	143
Figure 6.1	Scanning Electron Micrograph of (a) Control Concrete (b) Concrete Containing GAA at Low Magnification of 150x at the Age of 7, and 28 Days, Cured in Air	148
Figure 6.2	Scanning Electron Micrograph of (a) Control Concrete (b) Concrete Containing GAA at Low Magnification of 150x at the Age of 7, and 28 Days, Cured in Water	149
Figure 6.3(a)	EDX Spectra and Maps of Control Concrete (CTR-1D-AD-AC) at 28 Days of Age, Cured in Air	151
Figure 6.3(b)	EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-AD-AC) at 28 Days of Age, Cured in Air	151
Figure 6.3(c)	EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-SSD-AC) at 28 Days of Age, Cured in Air	152
Figure 6.4(a)	EDX Spectra and Maps of Control Concrete (CTR-1D-AD-WC) at 28 Days, Cured in Water-Curing Condition	153

Figure 6.4(b)	EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-AD-WC) at 28 days, Cured in Water-Curing Condition	154
Figure 6.4(c)	EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-SSD-WC) at 28 Days, Cured in Water-Curing Condition	154
Figure 6.5	X-Ray Diffraction (XRD) Spectra of Control Concrete and Self-Cured Concrete at 7 Days Cured in Air	156
Figure 6.6	X-Ray (XRD) Diffractogram of Control Concrete and Self-Cured Concrete at 28 Days Cured in Air	157
Figure 6.7	X-Ray Diffraction (XRD) of Control Concrete and Self-Cured Concrete at 7 Days Cured in Water	158
Figure 6.9	Pore Size Cumulative Distribution Of A) Water-Cured And B) Air-Cured GAA And Control Concrete At Age Of 28 Days	161

LIST OF ABBREVIATIONS

Abbreviations

AAC-LWA	Autoclaved Aerated Concrete Lightweight Aggregate
AC	Air Curing
ACV	Aggregate Crushing Value
AD	Air-Dry
AI	Artificial Intelligence
ANWA	Artificial Normal Weight Aggregate
ASTM	American Society for Testing and Materials
BS	British Standard
Ca(OH) ₂	Calcium Hydroxide (Portlandite)
CH	Calcium Hydroxide
C-S-H	Calcium Silicate Hydrate
CTR	Control Concrete
EDX	Energy Dispersive X-ray
FA	Fly Ash
GAA	Green Artificial Aggregate
HPC	High-Performance Concrete
ITZ	Interfacial Transition Zone
LECA	Lightweight Expanded Clay Aggregate
LWA	Lightweight Aggregate
LWAC	Lightweight Aggregate Concrete
MIP	Mercury Intrusion Porosimetry
NA	Natural Aggregate/Not Applicable
OPC	Ordinary Portland Cement
PEG	Polyethylene Glycol
RH	Relative Humidity
SAP	Superabsorbent Polymer
SEM	Scanning Electron Microscopy
SPSS	Statistical Package for the Social Sciences
SSD	Saturated Surface-Dry
UHPC	Ultra-High-Performance Concrete
UPV	Ultrasonic Pulse Velocity

WC	Water Curing
XRD	X-Ray Diffraction
XRF	X-Ray Fluorescence

LIST OF NOMENCLATURES

Nomenclatures

A	Area (mm^2)
d	Lateral dimensions of the specimen in mm (for flexural strength calculation)
F	Maximum load in N (for flexural strength calculation)
ε	Strain (Microstrain)
$f_{(y)}$	Flexural strength in MPa
l	Distance between the supporting roller (mm)
L	Length as measured during or after cure (mm)
L_0	Original length (mm)
M_1	Mass of oven-dry test sample in air (g)
M_2	Mass of SSD test sample in air (g)
M_0^D	Mass of the oven-dry sample (g)
$M_{(rh)}$	Equilibrium mass of RH (g)
$M_{(SSD)}$	Mass of SSD condition samples (g)
P	Load (kN)
$r(t)$	Radius of pores in cement paste
R_a	Radius of pores in LWA
$\rho(C)$	Apparent density (kg/m^3)
$M_{(C)}$	Mass of cured concrete (kg)
$V_{(C)}$	Volume of cured concrete (m^3)
SF	Strain factor (0.796×10^{-5})
t	Transit time (s)
V	Pulse velocity (km/s)
$W_{(LWA)}$	Water released at different RH
W_0	Oven-dry samples weight (kg)
$W_{(SSD)}$	Weight of aggregate in condition of SSD (kg)
$W_{(W)}$	Weight of aggregate while submerged in water (kg)
Δt	Transit time (s)
$\sigma_{(C)}$	Compressive strength (MPa)

CHAPTER 1

INTRODUCTION

1.1 Background of Study

Concrete is the most used construction material worldwide, comprises of Portland cement, water and aggregates. Fine aggregates, water and cement blended together to form a paste which coating all the individual pieces of coarse aggregate, thereby results in a plastic mixture. A chemical reaction called hydration occurs between water and cement. A concrete turn to a solid state from a plastic approximately two (2) hours and it continues to gain its strength as it cures. Curing of concrete is an important process in construction to gain optimal performance in any environment or application. Curing is the process of controlling the rate, extent of moisture loss and temperature in concrete during cement hydration process (James *et al.*, 2011; Neville, 2011; Nahata *et al.*, 2014; Shaikh *et al.*, 2017). Proper curing of concrete is important to ensure that it achieves its intended performance and durability. There are several methods of conventional curing that are commonly used in the construction industry. One of the most common methods is wet curing, which involves keeping the surface of the concrete moist by applying a continuous moist of water or covering it with wet burlap or other similar materials (Bandara *et al.*, 2019; Gereziher & Zhutovsky, 2022). Another method is steam curing, which involves applying heat and moisture to the concrete using steam (Mei *et al.*, 2018; Uygunoğlu & Hocaoglu, 2018; Zou *et al.*, 2018).

It has typically been common to remove formwork within 24 or 48 hours of concreting on-site, which is subsequently aided by conventional curing methods to further develop the desired properties of concrete. Throughout the building, concrete is cast in a variety of shapes and locations. Continuous curing is challenging for concrete applied at heights, vertical members, sloped roofs and concrete with a wide thickness (Chand *et al.*, 2015; Nduka *et al.*, 2018; Rodríguez-Torres & Torres-Castellanos, 2019). Many researchers have studied self-curing concrete using different materials that have potential as self-curing agents such as expanded shale, clay and slate, pumice and bottom ash (Zhutovsky *et al.*, 2002; Zhutovsky & Kovler, 2017; Akhnoukh, 2017; Kevern & Nowasell, 2018; Zou D. *et al.*, 2018; Kim & Lee, 2018; Vázquez-Rodríguez

et al., 2020), superabsorbent polymers (Riyazi *et al.*, 2017; Almeida & Klemm, 2018; Kang *et al.*, 2018; Oh & Cheol, 2018; Woyciechowski & Kalinowski, 2018; Liu *et al.*, 2021), polyethylene glycol (Bashandy, 2016; Madduru *et al.*, 2016; Sarbapalli *et al.*, 2017; Madduru *et al.*, 2018; Amin *et al.*, 2021), natural fibres (Kawashima & Shah, 2011; Zadeh & Bobko, 2014; Jongvisuttisun *et al.*, 2018; Dávila-Pompermayer, *et al.* 2020) and artificial normal weight aggregate such as ceramic and recycle concrete waste (Aslam *et al.*, 2016; Gonzalez-Corominas & Etxeberria, 2016; Shigeta *et al.*, 2018; Etxeberria, 2020).

In this present study, the type of aggregate used is artificial aggregate produced from several waste materials which was supplied by Active Pozzolan Technology Sdn. Bhd in Pasir Gudang, Johor. Throughout this study, the aggregate was called green artificial aggregate (GAA) due to its production from combination of wastes. The selection of GAA is based upon its affordable price and availability. The component of GAA is ceramic waste, bottom ash and fly ash. GAA The intention to determine the influence of GAA as self-curing agent to concrete properties, the mechanism under proper and improper curing process is the main interest in this study. Within the knowledge of the author, the application of artificial aggregate produced from combination of wastes to be used as self-curing agent in concrete has not been reported elsewhere. Therefore, it is the purpose of the present study to explore the utilisation of GAA as self-curing agent in concrete.

1.2 Problem Statement

The construction industry reliance on water-intensive external curing methods for concrete poses significant environmental and economic challenges. External curing addresses proper hydration of the concrete. If the concrete is not properly cured, then the surface layer, about 30 to 50 mm (Gowripalan *et al.*, 1990; Neville, 2011; Taylor, 2014), will be affected due to the potential evaporation of water from the concrete surface. Thus, the moisture loss leads to lower degree of cement hydration and a porous zone between the aggregates and cement paste, resulting in undesirable concrete properties such as decreased compressive strength and increased porosity (Sathanandham *et al.*, 2013; Nduka *et al.*, 2018; Bandara *et al.*, 2019). Therefore, several researchers introduced the concept of self-curing concrete (Dhir *et al.*, 1994; 1995,1996; Reinhardt & Weber, 1998). The concept of self-curing concrete is

introduced to mitigate the process of water evaporation in concrete and hence increase the capacity of water retention in concrete compared to that of conventional curing concrete (Reinhardt & Weber, 1998; Bentz *et al.*, 2005; El-Dieb, 2007; Zhutovsky *et al.*, 2011; Thrinath & Kuma, 2017; Vázquez-Rodríguez *et al.*, 2020). Therefore, the technique in which water-filled internal curing agents react as reservoirs are added to concrete mixture which can gradually release its water during hydration and evaporation process (Jongvisuttisun *et al.*, 2018; Sastry & Kumar, 2018; Mrad & Chehab, 2019; De Meyst *et al.*, 2020). Previous researchers reported various type of lightweight aggregates (LWAs) replacing natural aggregate to act as water reservoirs in concrete due to their water absorption ability, subsequently provide additional water for shrinkage mitigation, improve hydration and decrease the process of water evaporation in concrete (Jensen & Kovler, 2007; Liu *et al.*, 2017; Zou D *et al.*, 2018). Expanded shale (Henkensiefken *et al.*, 2010; Browning *et al.*, 2011; Henkensiefken *et al.*, 2011), expanded clay (Liu & Zhang, 2010; Paul and Lopez, 2011; Ghourchian *et al.*, 2013; Zhang & Poon, 2017; Pradeep & Beena, 2020; Vázquez-Rodríguez *et al.*, 2020), bottom ash (Kim *et al.*, 2014; Wyrzykowski *et al.*, 2016; Kim and Lee, 2018; Balapour *et al.*, 2020; Rodríguez-Álvaro *et al.*, 2020) and pumice (Zhutovsky *et al.*, 2002b; Akcay & Tasdemir, 2010; Zhutovsky & Kovler, 2017; Vázquez-Rodríguez *et al.*, 2020) are most common LWAs used as self-curing agents.

However, the various self-curing agents studied by previous researchers present limitations. Expanded shale and expanded clay (LECA), while capable as internal water reservoirs, suffer from substantial strength reduction issues due to their inherently lower strength. The magnitude of this strength reduction correlates directly with the percentage of lightweight aggregate (LWA) replacement and can compromise structural integrity when used as partial replacement for conventional aggregates. Additionally, these natural resource-based materials are expensive to produce. The reliance on natural resources for LWA production raises serious environmental concerns, as it contributes to the environmental degradation. Meanwhile, superabsorbent polymers (SAP) effectively absorb and gradually release water, however, create problematic voids after water depletion thereby resulting in decreasing concrete strength, making them impractical for large-scale construction project. These limitations highlight the need for developing improved self-curing solutions that provide the minimal impact on mechanical properties, and enhanced durability under varying environmental conditions when it fully replacement with the natural or conventional aggregate.

Most studies have focused on partial replacement by LWA as a self-curing agent to evaluate the performance of the concrete. There is limited research on the performance of concrete with 100% replacement by LWA. Therefore, to further assess the concept of self-curing in concrete using full replacement of GAA as a curing agent was investigated in the present study. The effects of GAA in concrete were investigated through its physical, mechanical and microstructure properties to confirm whether it can be used as self-curing agent and capable of maintaining the strength performance of normal-strength concrete. Few studies have provided insights into the microstructure and mineralogical development of high-performance concrete (HPC) containing LWA as a curing agent (Tuan *et al.*, 2011; Suwan & Wattanachai, 2017; Kim & Lee, 2018). However, the previous works have not well explained on comprehensive scientific evidence demonstrating how LWA influences the microstructure and mineralogical development of normal-strength concrete under proper curing and improper curing process. These studies were used as references for this present study. Therefore, it drives the author to investigate the microstructure and mineralogical development of normal-strength concrete containing GAA as a curing agent.

There were three research questions in this study, first, can GAAs act as a self-curing agent in concrete; secondly, can the inclusion of GAA maintain the strength of self-cured concrete when replacing 100% conventional aggregate with external and without external curing process; and thirdly, how the GAA action as a self-curing agent can be proven in terms of microstructural aspects in normal-strength concrete.

1.3 Objectives of Study

The objectives of this research are as follows;

- a) To characterise the physical, mechanical and microstructure properties of GAA as a self-curing agent in concrete.
- b) To evaluate strength and durability performance of normal-strength concrete containing GAA as a curing agent in comparison with conventional concrete with curing and without curing process.
- c) To examine the microstructure and mineralogical development of normal-strength concrete containing GAA as a curing agent in comparison with those made of conventional concrete with curing and without curing process.

- d) To confirm and verify the change in microstructure and mineralogical of concrete mixes due to self-curing actions.

1.4 Scope of Work and Limitations

The green artificial coarse aggregates, which consists of ceramic waste, bottom ash and fly ash were obtained from only one source from Active Pozzolan Technology Sdn. Bhd, located in Pasir Gudang, Johor. Three (3) major stages of activities were performed and it was further described in Chapter 3. The first stage represents the activities involved in determining the GAA properties. The physical properties of GAAs were tested, namely sieve analysis, which conducted as according to ASTM C136 (2019), density and specific gravity which conducted as according to ASTM C127 (2015). Subsequently, aggregate absorption and desorption testing were conducted based on ASTM C127 (2015) and ASTM C1498 (2016), respectively, to confirm whether the GAAs can store water and release the absorbed water in the concrete mix. Aggregate crushing value (ACV) was carried out according to BS 812-110 1990 to determine the strength of aggregate. Meanwhile, the microstructure of GAA was examined using Stereo Microscope to determine the shape and texture. Mercury intrusion porosimetry (MIP) was conducted to determine the porosity of the GAA, which influences the capability of aggregate as a self-curing agent. For comparison, all the tests carried out to GAA were tested for granite as well.

The second stage encompasses the activities that determined the initial performance of the concrete strength replaced by 50% and 100% with GAA. Fully replacement of granite with green artificial coarse aggregate is determined at this stage, as the objective is to produce normal strength self-cured concrete. The 50% replacement level was selected to provide a comparative baseline for evaluating the performance characteristics of GAA-incorporated concrete against conventional concrete. This intermediate replacement level allows for the assessment of how partial integration of GAA influences the concrete's mechanical, physical, and microstructural properties, while also examining the transition in self-curing effectiveness. The 100% replacement level represents the primary objective of this research, which is to completely replace conventional granite aggregate with GAA, thereby maximizing the self-curing potential and sustainability benefits of waste-derived artificial aggregate in concrete production. The aggregates were soaked for 24 hours before mixing to get the saturated-surface-dry

(SSD) aggregate condition. Nevertheless, air-dry aggregates (AD) condition was also prepared to suit in-field application as comparison. The water cement ratio used was 0.53 and kept constant for all series concrete specimens according to Building Research Establishment (Teychenné *et al.*, 1997) method for grade 30. The aggregate conditions used in the concrete mixes were divided into air-dry (AD) and saturated-surface-dry (SSD). There are six (6) designation mixes of concrete in this stage as follows:

- 1) concrete containing 100% AD granite as control concrete (CTR 100%-AD);
- 2) concrete containing 100% SSD granite as control concrete (CTR 100%-SSD);
- 3) concrete containing 50% AD GAA (GAA 50% -AD);
- 4) concrete containing 50% SSD GAA (GAA 50%- SSD);
- 5) concrete containing 100% AD GAA (GAA 100%- AD); and
- 6) concrete containing 100% SSD GAA (GAA 100%- SSD).

The workability of the fresh concrete mixes was performed based on. The specimen size 100 mm x100 mm x100 mm cubes were used. The specimens were demoulded after 24 hours and were cured in water-curing (WC) at ages 3, 7, and 28 days before testing. Air-curing (AC) was also adopted to simulate improper curing. The testing for compressive strength and ultrasonic pulse velocity (UPV) were conducted based on BS 12390-3:2009 and ASTM C597 2016 respectively.

The final stage involved the tests on the concrete specimens incorporating GAA. Only the concrete specimens containing GAA was tested at this stage based on the results obtained from the second stage. The one containing 100% granite acts as control concrete. The aggregate conditions used in the concrete mixes were divided into air-dry (AD) and saturated-surface-dry (SSD). There are four (4) mixes of concrete at this stage as follows;

- 1) concrete containing 100% AD granite as control concrete (CTR 100%-AD);
- 2) concrete containing 100% SSD granite as control concrete (CTR 100%-SSD);
- 3) concrete containing 100% AD GAA (GAA 100%- AD); and
- 4) concrete containing 100% SSD GAA (GAA 100%-SSD).

The specimen size 10 mm x100 mm x100 mm cubes and 100 mm x100 mm x500 mm prism moulds were used. For determining the effect of the improper curing conditions, the specimens were cured under six (6) types of curing as follows:

- 1) curing in water after 24 hours demoulding (1D-WC);
- 2) curing in laboratory environment after 24 hours demoulding (1D-AC);
- 3) curing in water after 3 days demoulding (3D-WC);
- 4) curing in laboratory environment after 3 days demoulding (3D-AC);
- 5) curing in water after 7 days demoulding (7D-WC); and
- 6) curing in laboratory environment after 7 days demoulding (7D-AC)

The six curing conditions were designed to systematically evaluate the effect of delayed curing on concrete performance. Two variables were incorporated: the demoulding delay period (1, 3, and 7 days) and the subsequent curing environment (water curing versus air curing). This approach enabled comprehensive assessment of how extended ambient exposure before proper curing affects concrete properties. By comparing these conditions, the progressive deterioration in concrete performance with increasing curing delay could be quantified, and the ability of GAA concrete's self-curing mechanism to mitigate the detrimental effects of improper curing practises could be determined. The compressive and flexural strength test were carried out in accordance with BS12390-3:2009, while, mode of failure was performed based on BS 12390-3(2009). Ultrasonic pulse velocity (UPV), shrinkage and expansion, initial surface absorption tests were conducted in accordance with ASTM C597, (2016), BS-812-120 (1990) and BS 1881-208:1996 respectively. The scanning electron microscopy (SEM) examination and energy dispersive X-ray (EDX) were used to assess the feature of the interfacial transition zone (ITZ) in self-cured concrete. Further investigation was carried out in determining the characteristic of self-cured concrete in terms of formation cement hydration products through X-Ray Diffraction (XRD).

The physical and mechanical characteristics and the microscopic properties of GAA as potential self-curing agent in the concrete and the initial performance of normal-strength concrete containing 50% and 100% of AD and SSD GAA cured in water and air in terms of its mechanical properties are presented in Chapter 4. Meanwhile, the performance of self-cured concrete containing full replacement of AD and SSD GAA as self-curing agent, the influence of demoulding time effect on the self-

curing mechanisms and the practical implications of using GAA as a 100% replacement for conventional aggregate in self-curing concrete applications is presented in Chapter 5. Finally, the microstructure and the mineralogical development of self-cured concrete containing of AD and SSD GAA as self-curing agent are presented in Chapter 6.

1.5 Significance of Study

The outcome of this study will be used as reference to develop self-curing concrete by using sustainable material instead of chemical materials and material from natural resources. GAA is aggregate produced from the combination of industrial wastes such as ceramic, bottom, and fly ash. The use of GAA as a self-curing agent in the concrete by completely replacing granite aggregate is considered a step toward reducing carbon emissions. The significance of this research in self-curing concrete aspect lies in the development of GAA as an internal curing agent. This eliminates the dependency on external water supply for curing process. The self-curing mechanism provides continuous moisture internally throughout the concrete matrix. This ensures optimal hydration even in water-scarce conditions or difficult-to-access structural elements. The GAA stores water during mixing and gradually releases it during hydration process. This approach addresses the common problem of inadequate curing in construction sites. Consequently, the concrete achieves improved strength and durability without external intervention. This study also contributes to new knowledge in concrete technology and structural engineering by providing sustainable concrete solutions that enhance building durability and reduce construction material costs. The implementation of self-curing technique has been demonstrated to enhance the service life of building structures (Cusson et al., 2010; Vosoughi et al., 2017), which would consequently reduce the maintenance costs over the structure's lifecycle compared to conventional non-cured concrete.

This research significantly contributes to the United Nations Sustainable Development Goals (SDGs). The study directly aligns with multiple SDG targets through its innovative approach to concrete technology. In relation to SDG 9: Industry, Innovation and Infrastructure, the development of GAA from industrial waste materials promotes sustainable industrialization. This research introduces innovative construction materials that enhance infrastructure resilience. The use of waste-derived aggregates demonstrates circular economy principles in construction sector. GAA-incorporated

concrete provides durable infrastructure with reduced environmental impact. This aligns with SDG 9.4 target to upgrade infrastructure and retrofit industries for sustainability. Regarding SDG 11: Sustainable Cities and Communities, the research contributes to building sustainable and resilient cities. Self-curing concrete reduces water consumption during construction activities. This is particularly significant for urban areas facing water scarcity. The enhanced durability of structures reduces the need for frequent repairs and renovations. This minimizes construction waste generation in urban environments. The study supports SDG 11.6 target to reduce adverse environmental impact of cities. In terms of SDG 12: Responsible Consumption and Production, this study promotes sustainable management of natural resources. The utilization of ceramic waste, bottom ash, and fly ash reduces landfill dependency. Industrial waste materials are transformed into valuable construction resources. This reduces the extraction of natural granite aggregates from quarries. The research demonstrates waste valorisation in concrete production. This directly supports SDG 12.5 target to substantially reduce waste generation through prevention, reduction, recycling and reuse.

Concerning SDG 13: Climate Action, the replacement of natural aggregates with waste-derived GAA reduces carbon footprint. Granite extraction and processing require significant energy consumption. The use of industrial waste reduces the need for raw material extraction. This contributes to lower greenhouse gas emissions in construction industry. The research supports climate change mitigation through sustainable material development. This aligns with SDG 13.2 target to integrate climate change measures into policies and planning. Overall, this research provides a holistic approach to sustainable concrete technology. The findings offer practical solutions for construction industry to achieve environmental sustainability. The study bridges the gap between waste management and sustainable construction practices. The outcomes contribute to global efforts in achieving sustainable development while maintaining structural performance requirements.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Curing is the process of controlling the rate, extent of moisture loss and temperature in concrete during cement hydration and reduce water evaporation. The process of curing allows continuous hydration of cement until it achieves its potential strength and durability. It is crucial to ensure the condition moisture is proper otherwise the hydration of cement virtually ceases due to relative humidity within the capillaries drops below 80%. If hydration stopped, sufficient calcium silicate hydrate (C-S-H) cannot be developed. This would disrupt the development of dense microstructure and refined pore structure within the cement matrices. The disruption prevents the formation of dense microstructure and refined pore allowing ingress of deleterious agents into concrete. Thus, leads to the bad quality of concrete such as plastic shrinkage cracks, poorly formed hydrated products, finishing problems and other surface defects. Previous studies have reported various methods to prevent the loss of moisture during concreting like spraying or fogging the surface of new cast concrete with water, using wet surface covering and water ponding which is suitable for horizontal surfaces. Other methods include membrane curing which keeps the water within the concrete to maximise the potential hydration, steam and leaving formwork in place. The accelerated curing method such as microwave curing, direct electric curing and infrared curing are used through the application of heat on fresh concrete to promote rapid cement hydration by gaining the early-age strength of concrete. However, a common feature of all the existing curing techniques is often applied to the surface of the concrete. If proper curing process is not provided it will affect the compressive strength and durability of the hardened concrete. Therefore, a new approach of self-curing concrete has been introduced. Self-curing concrete or internal curing can be defined as concrete that can cure itself without the need for external curing for the hydration process. The practice of self-curing is a technique that can supply more water to concrete for more effective cement hydration and decreased self-desiccation. This chapter discusses the mechanism of self-curing concrete, types of curing agents and previous studies related to the

influence of curing agents in the self-curing cement-based system. Generally, all types of self-curing agents have shown promising results in the self-curing cement-based systems and have the potential to extend to new studies. Their influences in self-curing cement-based system are explained in the following sections and sub-sections.

2.2 Mechanism of Hydration for Conventional Concrete

The addition of water to Ordinary Portland Cement (OPC) powder initiates the cement hydration reactions instantly. This chemical reaction leads to the cement paste setting and hardening. Within a few minutes, needle-like crystals of calcium sulfoaluminate hydrate, notably ettringite, develop. After a period of time, ettringite converts into monosulfate hydrate. Two (2) hours after the hydration process begins, large prismatic crystals of calcium hydroxide (CH) and tiny calcium silicate hydrates (C–S–H) fill the voids formerly filled by water and hydrated cement particles. Therefore, calcium silicate hydrate, calcium hydroxide, and calcium sulfoaluminate are the three (3) primary components of hydrated cement paste (Saleh & Eskander, 2020). Calcium silicate hydrate is the primary hydration product, contributing to almost 60% of the volume of solids. It is composed of a layer of sponge-like structures with a large surface area ($500 \text{ m}^2/\text{g}$). The ultimate strength of the product is largely owing to the development of C–S–H and is principally due to van der Waals physical adhesion forces. Van der Waals forces are weak intermolecular attractions between C–S–H gel layers that accumulate across the large surface area ($500 \text{ m}^2/\text{g}$), through which cohesive bonds are created that are translated into macroscopic strength gain as hydration progresses. (Esteves et al., 2007). Calcium hydroxide is the second most prevalent component, contributing to approximately 25% of the total. Compared to C–S–H, calcium hydroxide composed of massive plate-like crystals with a lower surface area. It contributes to the reduction of van der Waal forces and is relatively soluble in comparison to C–S–H, making the concrete reactive to acidic solutions. Calcium sulfoaluminate plays a small part in the cementitious structure properties by almost 15% solid volume. Chemical resistance of the cementitious final product to sulfate attack is an issue, owing to the existence of the monosulfate hydrate (Saleh & Eskander, 2020).

The summarise of the mechanism of hydration for conventional concrete can be refer to Figure 2.1. The hydration process is exothermic, releasing heat that can affect the rate of reactions and the final properties of the concrete, especially in mass concrete

applications. The water-to-cement ratio (w/c) is another critical factor influencing the hydration mechanism. A lower w/c ratio results in a denser microstructure with less porosity, leading to higher strength and durability. However, sufficient water is necessary for complete hydration.

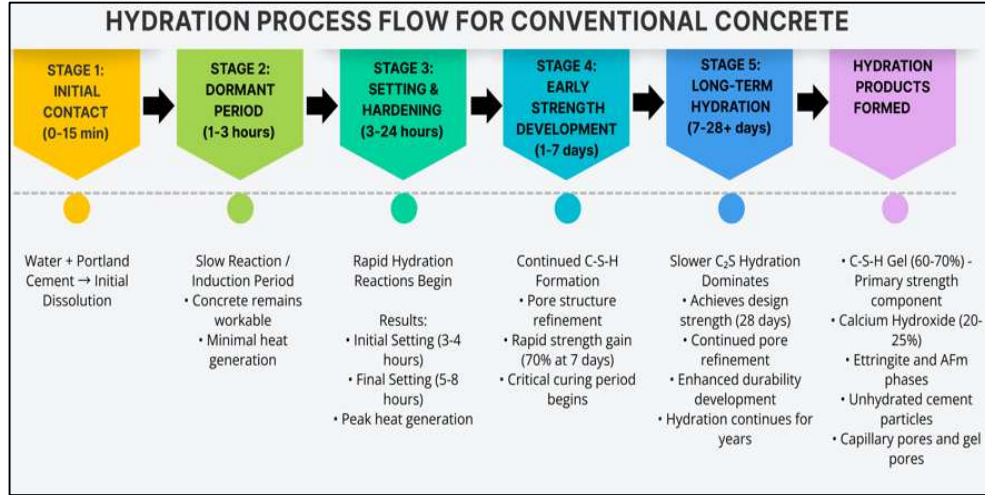
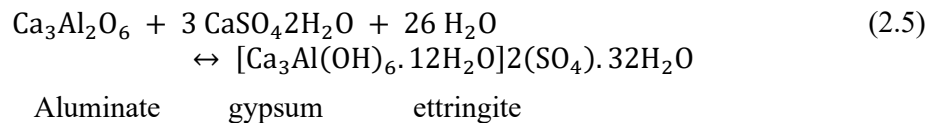
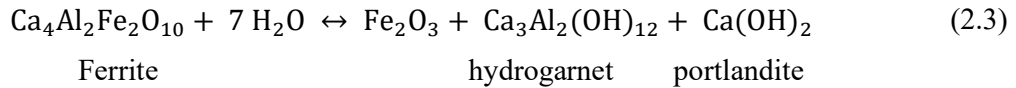
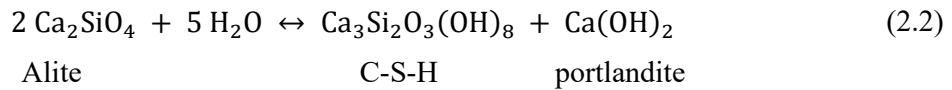
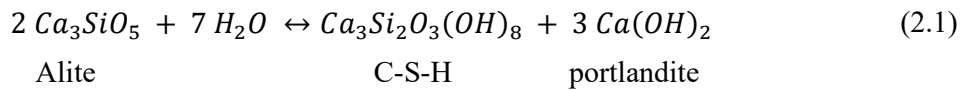


Figure 2.1 Hydration Process Flow for Conventional Concrete

Figure 2.2 shows electron microscopic images of hardened cement paste after hydration. The main reactions that occur between mixing water and Portland cement powder are given by García (2004). Equations 2.1 to 2.6 show the chemical reactions during the hydration process of cement.



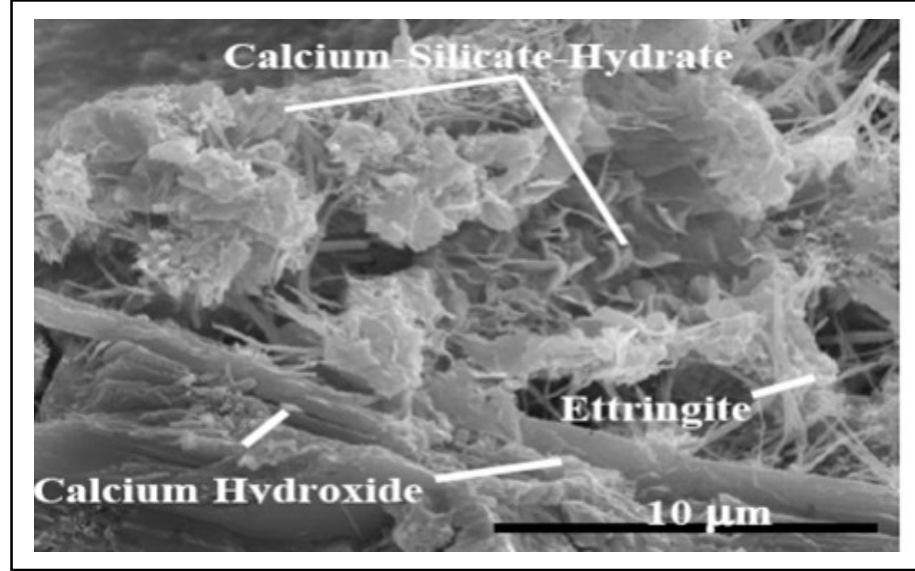
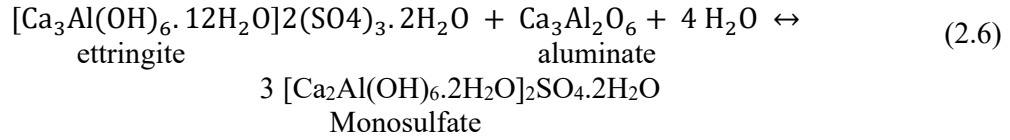


Figure 2.2 Electron Microscopic Image of Hardened Cement Paste after Hydration

Source: (Soler, 2007)

The following sections present a review and explain the mechanism of self-cured concrete in gaining its strength.

2.3 Mechanism of Self-Curing Concrete

Self-curing technology or internal curing has gained popularity within concrete research community. The concept of self-curing concrete is to mitigate water evaporation in concrete and hence increase the capacity of water retention in concrete (Wang *et al.*, 1994; Dhir *et al.*, 1998; Bentz *et al.*, 2005; El-Dieb, 2007; Bora *et al.*, 2017; Akeed *et al.*, 2022). The technique has been introduced whereby water-filled internal curing agents acting as reservoirs are added to concrete mixture which can gradually release its water during hydration and evaporation process as illustrated in Figure 2.3 (Bentz & Weiss, 2011; Liu *et al.*, 2017; Jongvisuttisun *et al.*, 2018; Sastry & Kumar, 2018; Yang *et al.*, 2022). The concept of self-curing was initially developed to address durability issues in high-performance concrete (HPC) mixtures that utilise low water-cementitious (w/c) material ratios (less than 0.42), chemical admixtures, and

supplementary cementitious materials (Hoff, 2002; Babcock & Taylor, 2015; Akeed *et al.*, 2022). In these low w/c ratio mixtures, the cement cannot be fully hydrated due to insufficient water availability (Neville, 2011). However, the challenge of achieving complete hydration through adequate curing is not limited to HPC alone. Normal strength concrete also suffers from inadequate hydration when external curing is insufficient or impractical, particularly in construction sites with limited water access or difficult-to-reach structural elements (Meeks & Carino, 1999). Therefore, the self-curing approach, which provides internal water reservoirs through porous aggregates, offers benefits across the full spectrum of concrete strengths by ensuring continuous moisture availability during cement hydration, regardless of external curing conditions.

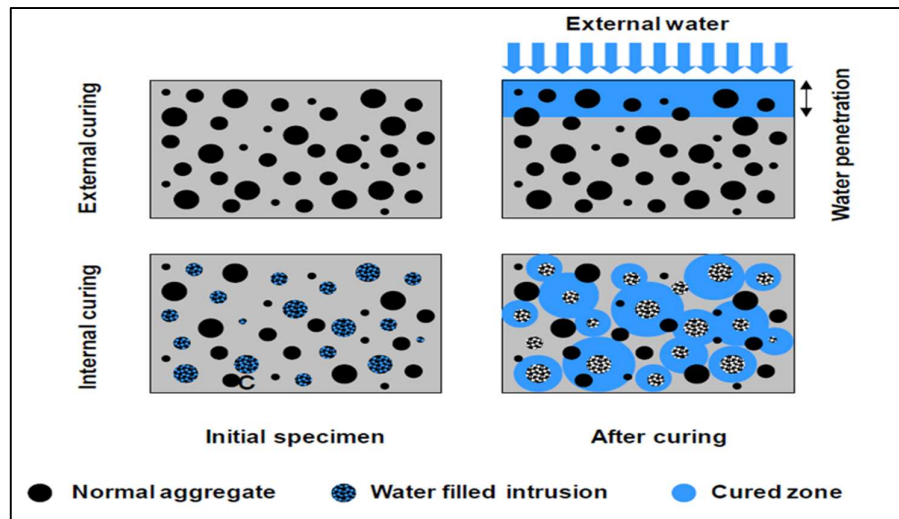


Figure 2.3 Illustration of the differences between self-curing and external curing

Source: (Bentz & Weiss, 2011)

Porous aggregate is frequently associated with poor concrete quality. However, when utilised in wet conditions, the aggregate might benefit the concrete since the water absorbed by the aggregate is slowly released into the already-hardened cement paste, continuing the hydration process (Sampebulu', 2012). As a result, concrete properties will be improved such as increased strength and decreased drying shrinkage. The water movement is caused by the humidity gradient between the aggregate that is high and the cement paste that is low. The culmination of this process results in the formation of high-density hydration products at the aggregate-paste interface, substantially enhancing the bond strength between these components. This mechanism yields multiple benefits including increased compressive and tensile strengths, reduced drying

shrinkage, and improved performance in elevated temperatures. Schematic diagram of the mechanism of self-curing concrete depicted in Figure 2.4. (Sampebulu', 2012). Self-curing, also known as autogenous curing or internal curing, enables curing "from the inside out", which is achieved by introducing a pre-saturated component as an internal curing agent (Han *et al.*, 2017). The curing agent is spread uniformly throughout the matrix and acts as a reservoir for internal water. The water within the curing agent has not involved in the chemical reaction until a humidity gradient forms during an initial hydration phase. Han *et al.*, (2017) illustrates the self-curing process occurs as shown in Figure 2.5. Han *et al.*, (2017) found that as initial cement hydration occurs, a humidity gradient develops, triggering the release of water from these agents. Water is transported from the curing agent to unhydrated cement by the driving forces of capillary suction, vapor diffusion, and capillary condensation for supporting continuous hydration. As result, the self-curing process effectively mitigates autogenous shrinkage by filling pores created by shrinkage and increasing the overall degree of hydration. This gradual internal water release contributes to developing a denser, more uniform microstructure, particularly in the interfacial transition zone between cement paste and aggregates. Consequently, self-curing concrete exhibits improved durability and potentially enhanced mechanical properties. However, the efficacy of this process is contingent upon optimising the type and quantity of self-curing agents to balance the benefits of additional hydration against the potential adverse effects of excess water.

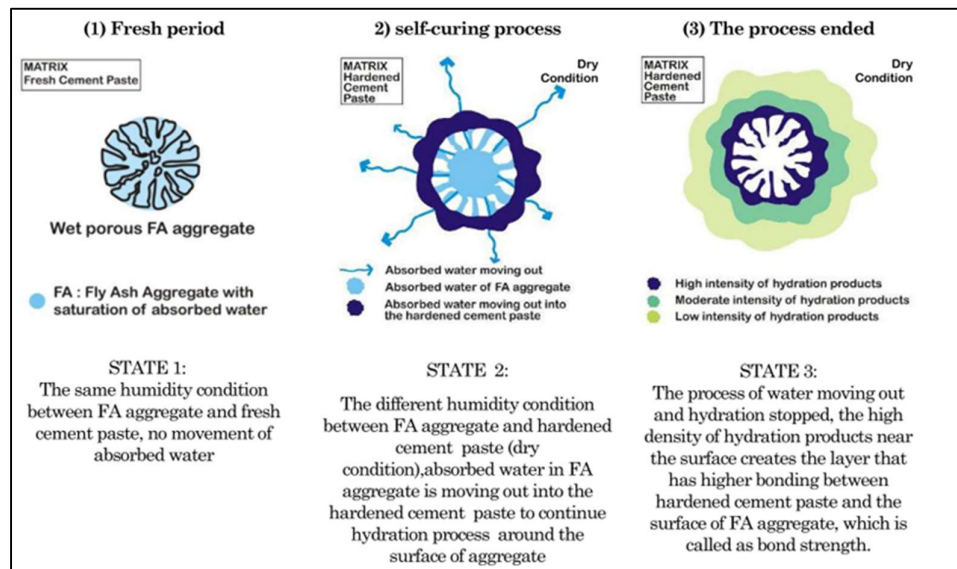


Figure 2.4 The Mechanism of Self-Curing Concrete
Source: (Sampebulu', 2012)

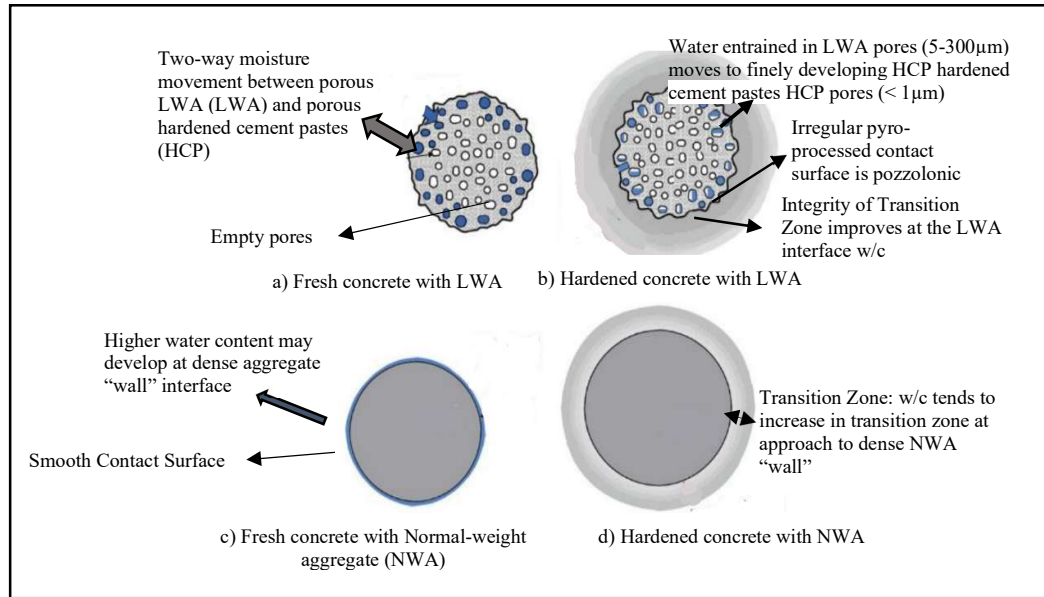


Figure 2.5 The Contact Zone Under Internal Curing and Normal Curing

Source: (Han *et al.*, 2017)

2.4 Types of Curing Agent in Self-Curing Concrete

There are a lot of techniques and materials that have been studied in self-curing concrete by using different materials of curing agent. The techniques are namely using lightweight aggregate (LWA), porous superfine powders, superabsorbent polymers (SAP), polyethylene glycol (PEG), natural fibres and normal weight aggregate have also been looked into as curing agents. The description for each curing agent and their mechanisms lies behind in self-curing concrete is reviewed in the following sub-sections.

2.4.1 Artificial Lightweight Aggregate (LWA)

The most widely utilised self-curing agent in self-curing concrete is LWA. It is light, solid, and porous material, which normally being used as a lightweight concrete for instance wall panels of non-load bearing and low-strength applications (Abutaha *et al.*, 2016; Ibrahim & Abdul Razak, 2016; Herki, 2020). Therefore, LWAs were investigated in this present study as a self-curing agent. The features found in LWA are have high porosity and absorption capacity that have the beneficial effect of supplying additional water internally (Paul & Lopez, 2011; Sensale & Goncalves, 2014;

Akhnoukh, 2017; Bari *et al.*, 2021). Due to its high of porosity, the density of LWAs is lesser than normal-weight aggregates. The saturated-surface dried density of LWAs are reported below than 2000 kg/m^3 (Zhutovsky *et al.*, 2002a; Akcay & Tasdemir, 2010; Paul & Lopez, 2011; Kim *et al.*, 2016; Zhang & Poon, 2017; Zou D *et al.*, 2018). Water absorption of porous LWAs depending on pore structures. The minimum water absorption is above 5% by mass of LWA is required as recommended by ASTM C1761 /C1761M (Castro *et al.*, 2011; Lura *et al.*, 2014; ASTM C1761, 2017). LWA can be in the form of coarse or fine aggregate. The most common LWA used as curing agent in self-curing concrete from natural-based are expanded shale (Zou & Weiss, 2014; Yang & Wang, 2017; Yang *et al.*, 2022), expanded clay (LECA) (Paul & Lopez, 2011; Ghourchian *et al.*, 2013; Mousa *et al.*, 2015a; Akhnoukh, 2017; Zhang & Poon, 2017; Kamal *et al.*, 2018; Al Saffar *et al.*, 2019; Agrawal *et al.*, 2021) and pumice (Zhutovsky *et al.*, 2002a; Mustafa *et al.*, 2009; Akcay & Tasdemir, 2010; Abadel, 2023). Meanwhile, curing agent from by-product materials which often studied in concrete by several researchers are bottom ash (Kim *et al.*, 2014; Kim *et al.*, 2016; Wyrzykowski *et al.*, 2016; Mohamad *et al.*, 2017; Zhang & Poon, 2017; Kim & Lee, 2018; Nguyen *et al.*, 2019), lightweight concrete waste (Suwan & Wattanachai, 2017; Abate *et al.* 2018), and brick chips (Iffat *et al.*, 2017; Manzur *et al.*, 2019; Bandara *et al.*, 2019).

Pre-wet LWAs which have been immersed in fresh water at least for 1 hour is used as internal reservoirs. A system of capillary pores is formed during hydration. As soon as the relative humidity (RH) decreases (due to hydration and drying), a humidity gradient develops (Hoff, 2002; Grasley *et al.*, 2006; Zhang *et al.*, 2012; Yadav *et al.*, 2017). Based on the law of fluid flow and the system's law of capillary attraction, the migration of the water in concrete is illustrated in Figure 2.6. The radius (R_a) of pores in cement paste ($r(t)$) are very small than the pores in LWA (R_a). The pores of the cement paste by capillary suction absorb the water from the LWA due to difference in vapor pressure and move the water to the drier cement paste, where a reaction with the un-hydrated cement occurs (Weber & Reinhardt, 1997; Hoff, 2002; Yadav *et al.*, 2017; Nguyen & Le, 2018). The un-hydrated cement particles, hydrated to form hydration products reduces the size of the pores in the hydrated cement, as well as enabling the pores to continue to absorb the water from the LWA. This process continues until all the water from LWA has been transported to the cement paste creating self-curing mechanism.

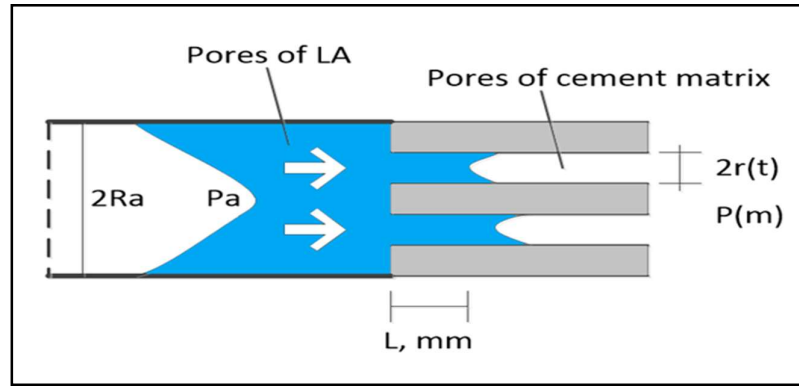


Figure 2.6 Model Moving of Water in Concrete Incorporate Self-Curing with $r(t) < R_a$

Source: (Nguyen & Le, 2018)

2.4.2 Porous Superfine Powders

Porous superfine powders primary features are small particle size materials with big specific surface area, mesoporous structure and able to absorb the aqueous phase whereby enable to supply the water for further hydration process in cementitious material (Rahmasari *et al.*, 2019; Liu *et al.*, 2017). Porous superfine powders possess nanometre-size of pores for instance cenosphere (Wang and Liu, 2016; Liu *et al.*, 2017; Chen P *et al.*, 2019; Liu *et al.*, 2019), rice husk ash (Tuan *et al.*, 2011; Ye *et al.*, 2013; Van *et al.*, 2014; Amin *et al.*, 2019), and biochar (Gupta & Kua, 2018; Mrad & Chehab, 2019). In general, the particle size of porous superfine powders ranges from $5\mu\text{m}$ to $10\mu\text{m}$ as illustrated in Figure 2.7, which is much smaller than that of Super Absorbent Polymer (SAP) particles and LWAs. Only if the pore sizes of cement paste smaller than superfine powders pore size, the water would be released into cement paste whereby the hydration process occurs. Besides, the application of porous superfine powders able to slow down the reduction of the internal self-desiccation of Ultra-High Performance Concrete (UPHC), thus strongly decreasing its autogenous shrinkage (de Sensale *et al.*, 2008; Van *et al.*, 2014; Liu *et al.*, 2017). Referring to Kelvin equation (Lura *et al.*, 2003), the water saturation capacity would react to the humidity change between 75 and 98%, while the size range of pore corresponds to the change of RH from around 75 to 98%. This presumed the absorbed water in the mesopores will gradually release its water when the internal RH in concrete drops below 98% to compensate for the self-desiccation during hydration.

By using the concept of protected paste volume, Bentz and Snyder (1999) revealed that cement paste should be closed to the internal curing water reservoir so that the absorbed water could be penetrated. Hence, cement paste is secured by absorbed water from self-desiccation. To achieve this, the curing agent particle size should be as small as possible (Zhutovsky *et al.*, 2011; Liu *et al.*, 2017). Previous studies found that smaller internal curing agent particles show better result than larger one (Lura & Breugel, 2000). Zhutovsky *et al.*, (2004a) also revealed that decreasing the internal curing particle size down from 4 to 2mm would able to improve the efficiency of curing.

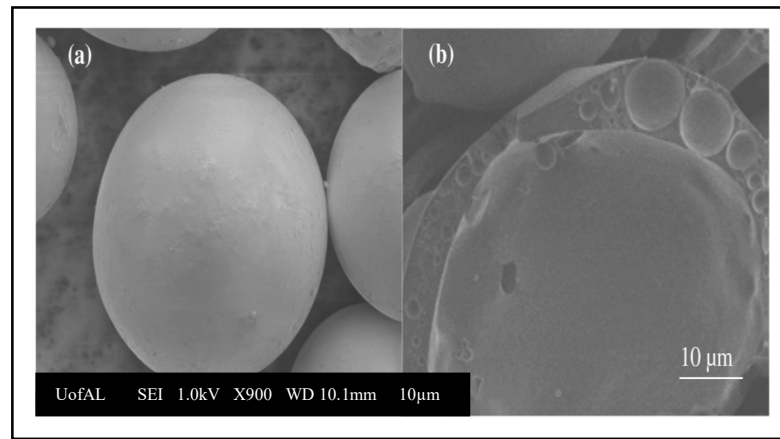


Figure 2.7 Microstructure of Cenopheres Under SEM Observation

Source: (Liu *et al.*, 2017)

2.4.3 Superabsorbent Polymer (SAP)

Superabsorbent polymers (SAP), recognised as hydrogels, are three-dimensional cross-link network structure that have capability to absorb a certain large amount of liquid compared to their own mass without dissolving due to osmotic pressure, and swell to form an insoluble gel (Jensen & Hansen, 2001a; Kim & Schlangen, 2010; Ding *et al.*, 2017; Wong, 2017). However, when SAP was applied in a cement-based system to entrain water, it can substantially decrease the extension of absorption due to the high pH environment of the concrete mixture compared to freshwater (Liu *et al.*, 2017). Nevertheless, the SAP able to absorb much more water than LWA to be used as a curing agent in self-curing concrete. Chemical reaction will occur when SAP is exposed to an aqueous solution leading to swelling of the SAP. Absorption of SAP driven by osmotic pressure as illustrated in Figure 2.8, then develops

the space between cross-links and polymer chains. Meanwhile, the presence of osmotic pressure is from a concentration gradient of moveable ions between the gel and solution (Mechtcherine & Reinhardt, 2012; Wang *et al.*, 2015; Snoeck *et al.*, 2017; Wong, 2017). The swollen SAPs react as water reservoirs in concrete. However, due to humidity decreasing in concrete, the absorbed water is drawn back into the cement paste capillary pores. This results led to the SAPs gradually releases the absorbed water and leave the voids (Lee *et al.*, 2010, 2016; Wong, 2017).

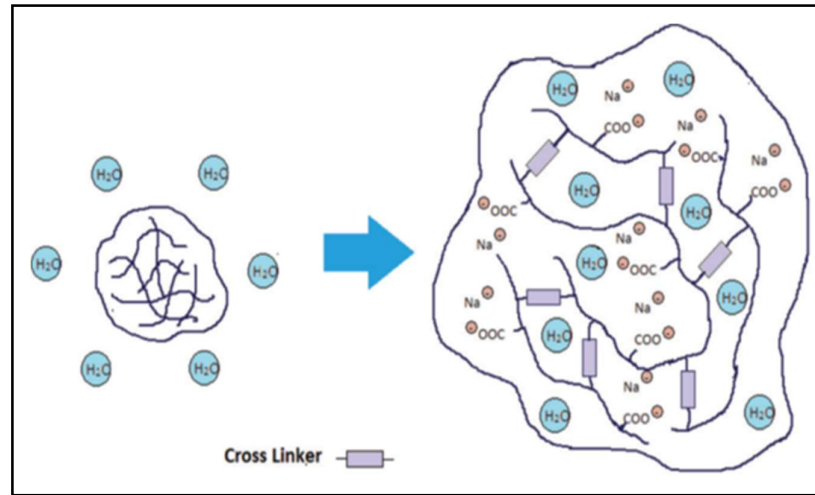


Figure 2.8 Process of Water Uptake to SAP
Source: (Mechtcherine & Reinhardt, 2012)

SAP was developed in the 1980s and widely used in forestry, agriculture, health supplies and other fields because of their potential as water reservoir, expand and water retention (Buchholz & Graham, 1998; Jensen & Hansen, 2001a; Esteves *et al.*, 2007; Siramanont *et al.*, 2010; Mechtcherine & Reinhardt, 2012; Dang *et al.*, 2017). SAP was used with cementitious materials in concrete to mitigate shrinkage (autogenous and drying) via self-curing (Jensen & Hansen, 2001b; Mechtcherine *et al.*, 2009; Craeye *et al.*, 2011; Snoeck *et al.*, 2015; Wehbe & Ghahremaninezhad, 2017; Tu *et al.*, 2019) to enhance the durability towards freeze and thaw deterioration (Mönnig & Lura, 2007; Mechtcherine & Reinhardt, 2012; Wong, 2017). Researchers from previous studies reported that the dosage of SAP (Jensen & Hansen, 2002; Esteves, 2009; Liu *et al.*, 2017), types (Snoeck *et al.*, 2014; Liu *et al.*, 2017), particle size whereby SAP with bigger size will effect of absorb water (Jensen & Hansen, 2002; Esteves, 2009). Water-saturated state of SAP will act as important role on effectiveness on self-curing process

(Igarashi & Watanabe, 2006; Liu *et al.*, 2017). SAPs were also found to improve autogenous healing (Kim & Schlangen, 2010; Wong, 2017) and creep (Assmann & Reinhardt, 2014; Shen *et al.*, 2016; Wong, 2017; Xin *et al.*, 2018). Changing the rheology of the fresh concrete is another SAP characteristic (Mönnig, 2009; Esteves, 2010; Mechtcherine & Reinhardt, 2012; Mechtcherine *et al.*, 2015; Wong, 2017). Dudziak and Mechtcherine (2010) reported that the workability of concrete containing SAP was decreased due to extra internal curing water absorbed by the SAP and these studies were supported by Schröfl (2012).

2.4.4 Polyethylene Glycol (PEG)

Polyethylene-glycol is a condensation polymer of ethylene oxide and water with the general formula $H(OCH_2CH_2)_nOH$, where n is the average number of repeating ox ethylene groups typically from 4 to about 180 (Dhir, *et al.*, 1994). The most effective molecular weights for self-curing purposes typically range between 200 to 6000 g/mol, with different applications favouring specific weights. According to Raoult's Law, when the vapour pressure of the solute is less than the vapour pressure of the solvent, it is apparent that theoretically, by the addition of chemical would head to a decreasing in the vapour pressure of water thus reducing the rate of evaporation process above the concrete surface (Dhir *et al.*, 1994, 1998; Madduru *et al.*, 2016; Sarbapalli *et al.*, 2017; Sastry & Kumar, 2018). Therefore, the application of water soluble polymers for instant polyethylene glycol (PEG) as self-curing in concrete has been observed to be efficient in retaining water, reduces the water surface tension and enhancing in hydration process (El-Dieb, 2007; El-Dieb *et al.*, 2012; Mousa *et al.*, 2015a; 2015b; Sarbapalli *et al.*, 2017; Madduru *et al.*, 2018; El Wakkad *et al.*, 2019; Sastry & Kumar, 2018). Upon with water molecules, polymeric chains created by hydrophilic units form hydrogen bonds. A hydrogen bond is a frail bond whereby formed between hydrogen atoms in a compound and strongly electronegative atoms in other molecules (Alberty & Daniels, 1975; Dhir *et al.*, 1994). The existence of a positive charge at the hydrogen atom cause of being attracted to the electronegative atom via electrostatically as illustrated in Figure 2.9. For this purpose, water soluble polymers with either hydroxyl (-OH-) or ether (-O-) functional groups were used as the chemical to lower the self-desiccation effect in concrete (Alberty & Daniels, 1975; Dhir *et al.*, 1994). These bonds are strong enough to retain water within the concrete but weak enough to allow gradual release for

continued cement hydration. For most applications, dosages between 0.5-2% of cement weight provide optimal results, with diminishing returns or even negative effects at higher concentrations (El Wakkad et al., 2019; Madduru *et al.*, 2018; Sastry & Kumar, 2018).

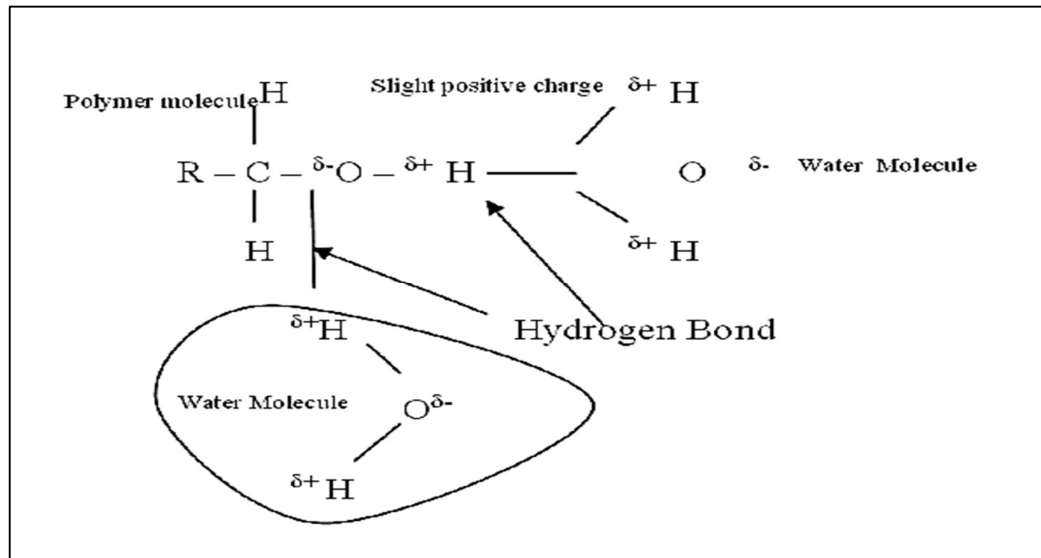


Figure 2.9 Hydrogen Bonds Between Water Molecules and An –OH Group on a Polymer Molecule

Source: (Dhir et al., 1994)

2.4.5 Natural Fibers

Previous researchers have investigated that wood-derived fibres and powder are potentially can be used as self-curing agents in cement-based material due to the capability to absorb and retain water as well as gradually released the absorbed water (Mohr, 2005; Elsaid *et al.*, 2011; Kawashima & Shah, 2011; Mezencevova *et al.*, 2011; Zadeh & Bobko, 2014; Jongvisuttisun *et al.*, 2018). The example of wood-derived fibres used as self-curing agent in concrete are eucalyptus pulp (Jongvisuttisun *et al.*, 2018), kenaf fibers (Zadeh & Bobko, 2014), and cellulose fibers (Kawashima & Shah, 2011). Wood-derived fibres are hygroscopic materials and the movement of water via the pulps depending on concentration gradient (diffusion) by capillary draw, and also by osmotic pressure effect (Wu *et al.*, 2009; Mezencevova *et al.*, 2011; Jongvisuttisun *et al.*, 2018). Moavenzadeh (1990), Elsaid *et al.*, (2011) and Jongvisuttisun *et al.* (2018) explained that wood-derived fibres consist of two pores namely larger pore (e.g lumen) comprises of free water and smaller pore as illustrated in Figure 2.10. Both pores play a role as

moisture transport, from wood pulps to nearby hydrating cement. Furthermore, pore solution in cement-based material is an alkaline. Therefore, it influences the characteristic of wood pulps to swell or shrink as well as changing the effective size of the porous space (Lindstroem & Carlsson, 1982; Scallan, 1983; Bendzalova *et al.*, 1996; Jongvisuttisun *et al.*, 2018), and hence can affect the water transport. Besides, free water in the lumen and weakly bound water may be released into the surrounding whereby the cement matrix may be self-desiccating over time. These provide relief from self-desiccation and subsequent autogenous shrinkage.

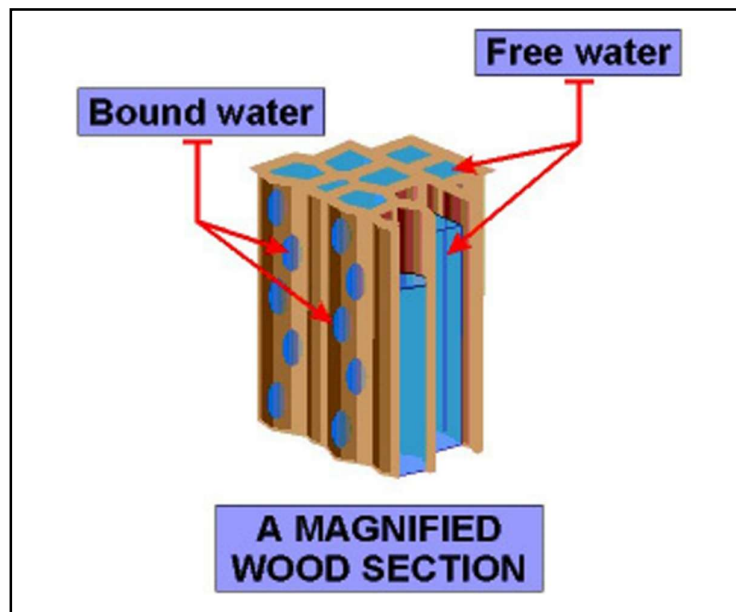


Figure 2.10 Free and Bound Water in Wood

Source: (Ahmed, 2006)

2.4.6 Artificial Normal Weight Aggregate (ANWA)

The permeability and durability of concrete mixtures containing ANWA is determined by the ANWA properties (Mechtcherine and Reinhardt, 2012; Bogas and Gomes, 2013; Yang & Wang, 2017). Both application of SAP and LWA in self-curing concrete technique will cause porosity in concrete. It is also stated that self-curing design can lead to a compromise on the properties of certain materials (Piérard *et al.* 2006; Savva & Petrou, 2018). Therefore, it is understandable that both techniques have some drawbacks that affecting the mechanical or durability properties of concrete. Construction industry waste material such as ceramic (Suzuki *et al.*, 2009; Sato *et al.*,

2011; Shigeta *et al.*, 2018) and recycled concrete waste (Corinaldesi & Moriconi, 2010; Silva *et al.*, 2015; Jørgensen, 2016; Suwan & Wattanachai, 2017) have potential as water reservoirs in self-curing concrete. This is attributed by their ability in absorbing water due to its porosity.

Suzuki *et al.* (2009) and Meddah and Sato (2010) mentioned that saturated surface dry (SSD) density of crushed waste ceramic was 2480 kg/m^3 , whereby the value is almost same with natural normal fine aggregate. This statement is further supported by Shigeta *et al.* (2018), who reported that SSD density of waste ceramic coarse aggregate is 2260 kg/m^3 while natural normal coarse aggregate is 2620 kg/m^3 . Thus, it provides good effects on the strength of the concrete containing crushed waste ceramic compared to that plain concrete due to its porous nature which enables internal curing through water absorption and gradual release during cement hydration, while also promoting better mechanical interlocking between the aggregate and cement paste at the interfacial transition zone. Moreover, water absorption of waste ceramic coarse aggregate is 9% compared to natural normal aggregate which recorded 0.67% water absorption. Similarly, Suzuki *et al.* (2009) revealed that water absorption of waste ceramic coarse aggregate also is 9% and crushing value is 21.4% almost same as reported by Sato *et al.* (2011). The capability of water absorption in ceramic waste aggregates will help in the hydration process of the concrete.

Among the crucial properties that differentiate LWA from ANWA are their water absorption capacity and specific gravity characteristics. Following section presents a review on advantages of LWA on concrete. LWAs exhibit remarkably higher water absorption rates, typically more than 10% by mass, compared to ANWA which generally show water absorption rates less than 10% (Shigeta *et al.* 2018; Suwan & Wattanachai, 2017). This difference in water absorption capacity is attributed to the porous internal structure of LWA, which is deliberately created during the manufacturing process to achieve specific performance characteristics. The density characteristics of these aggregates also demonstrate substantial variations that influence concrete properties. LWAs typically have densities ranging from 1000 to 2000 kg/m^3 (Zhang & Poon, 2017; Zou D *et al.*, 2018), while ANWA show higher densities between 2400 to 2800 kg/m^3 . This distinction influences the mechanical properties of concrete. The lower density of LWA, combined with its higher water absorption capacity, makes it particularly suitable for internal curing applications, as it can store and gradually release water during the cement hydration process. In contrast, ANWA, despite its

higher density and superior mechanical strength, offers limited internal curing capabilities due to its lower water absorption capacity. These fundamental differences in water absorption and density significantly impact the self-curing efficiency and overall performance of concrete, making the choice between LWA and ANWA crucial for specific construction applications. The following section present a review on advantage of incorporating LWA in concrete.

2.5 Advantages of LWA on Concrete

Globally, aggregate resources are the most utilised natural resources. To achieve sustainable development in the building industry, it is crucial to identify alternative aggregates for concrete production. Artificial light weight aggregate is manufactured from waste materials like as fly ash, expanded clay, slate, shale and bottom ash. The problem of disposing of industrial by-products, such as fly ash, silica fume, and bottom ash grows daily. As an environmentally friendly material for the construction industry, the ideal LWA should have a sintered core with a nearly spherical shape (diameter in the range of 4–14 mm) and a rough surface that is impervious to water, as well as good features such as low porosity and water absorption (Wang *et al.*, 2020). Typically, the density of concrete ranges from 2200 to 2600 kg/m³. Due to the effect of seismic forces worldwide, the demand for lightweight structural design is increasing, as it minimises the self-weight of the structural element (Agrawal *et al.*, 2021). Besides, application of LWA in concrete will enhance thermal insulation characteristics, decrease structural dead load, allowing larger structures to be built with the same foundation size, and lead to lower CO₂ emissions (Eziefula *et al.*, 2018; Ayati *et al.*, 2019; Hao *et al.*, 2022). It has been shown that LWA plays a crucial role in the production of lightweight concrete by reducing greenhouse gas emissions in buildings and the self-weight of the structure (Hao *et al.*, 2022; Kwek & Awang, 2021). In addition, LWA can be used as self-curing agent in the concrete as reported by Balapour *et al.*, (2020), Pradeep and Beena, (2020) and Ma *et al.*, (2019). The following section presents a review on physical properties of LWA that can act as self-curing agent.

2.6 Physical Properties of LWA as Self-Curing Agent

Three (3) main properties of LWA as self-curing agent namely water absorption, water desorption, and shape and surface are further discussed in the following sub-sections. These properties affect the characteristic and contribute to function as self-curing agent.

2.6.1 Water Absorption

Water absorption of porous aggregate is strongly related to its pore size distribution and porosity. The large pores in porous aggregate are rapidly saturated, especially larger than 1 μm pores, but have very poor capacity for water retention and will reduce the efficiency of internal curing (Ma *et al.*, 2019; Zou D *et al.*, 2018). Besides, with declining pore size, water absorption becomes difficult. Even if a very small pore can absorb water in a vacuum, it is difficult to release water. It is assumed that 100 nm of pore size is a vital value for internal curing (Mechtcherine and Reinhardt, 2012; Ma *et al.*, 2019). Increasing the number of open pores is also very helpful for water absorption and internal curing in concrete. Usually, the high-strength of porous aggregate water absorption at a 1-hour soak in water is less than 10%, but ordinary porous aggregate water absorption is around 15-20% (Wei *et al.*, 2010). The explanation is possibly that cement particle blocked the pores of porous aggregate (Henkensiefken, 2008).

If air-dry porous aggregate is applied, water from the cement paste starts to be absorbed. Golias *et al.* (2012) discovered that oven-dry porous aggregate absorbed water from cement paste up to initial set, but its absorption of water is lower compared with that if immerses in water. Castro *et al.* (2012) further discovered that 55% of the 24 hours pre-wetting quantity was absorbed by porous aggregate but amount would be increased up to 70-75% if it was firstly soaked for a few minutes in the water. Therefore, the pre-saturation is necessary for porous aggregate. More water is absorbed when the volume of porous aggregate is higher and the internal curing effect is therefore more noticeable. However, higher amount of porous aggregate will obviously reduce the strength of concrete due to its porous structure.

2.6.2 Water Desorption

The water desorption process is related to the pore size of porous aggregate and internal relative humidity (RH) of concrete. Only water in pores larger than a certain size (critical pore) is released at constant RH (Nguyen & Le, 2018; Henkensiefken, 2008), thereby, the pores smaller than critical pore are still saturated. The effectiveness of internal curing depends on water desorption process of porous aggregate. Trtik *et al.* (2011) thought that three (3) things should first be addressed in order to achieve a successful curing effect: (1) when the water is released by the self-curing agent, (2) how much water can be released, (3) how far the internal curing water in hardened paste can go. The best curing efficiency can be achieved if internal curing water can be released when concrete needs and adequate water can spread where it is required. A majority of water in the pores of porous aggregate is released at high RH (>96%) (Henkensiefken, 2008). When RH is reduced to 92%, almost all the water in the pores is released.

2.6.3 Shape and Surface Texture

The shape and texture of an aggregate have a more significant effect on the qualities of freshly mixed concrete than on hardened concrete. Elongated, angular, and rough surface textured aggregates require significantly more water to form workable concrete than rounded, smooth, and compact aggregates (Jagadish & Jagadeesan, 2015; Kosmatka & Wilson, 2011). As a result, angular aggregate particles require additional cement to retain the same water ratio to cementing materials. However, with up to standard gradation, both crushed and uncrushed aggregates (of the same aggregate type) often provide the same strength for the same cement factor. The amount of water and cement required for mixing tends to increase as the void content of the aggregate increases (C. Tang *et al.*, 2017). Besides, voids between aggregate particles increase with aggregate angularity (Kosmatka & Wilson, 2011). The binding between cement pastes and a particular aggregate often increases as the particles get rougher and more angular. This increase in bond is considered when aggregates for concrete that require strong flexural strength or compressive strength. This finding was supported by Yehia *et al.* (2014), who reported that flexural strength improved by around 80%, attributed to the enhanced bond between the aggregate and cement paste caused by the angular particle shape and roughed surface.

Aggregate particles that are flat or elongated should be avoided or limited to no more than 15% of the total aggregate mass. According to ASTM D4791 (2010), flat and elongated particles are defined as those coarse aggregate particles that have a ratio of length to thickness equal to or greater than a specified value such as 5:1. Due to the increased mixing water required by such aggregate particles, the strength of concrete, particularly in flexure, may be compromised if the water-cement ratio is not adjusted (Kosmatka *et al.*, 2002). The following section presents the effects of LWA as self-curing agent towards the performance of concrete.

2.7 Effects of LWA as Self-Curing Agent in Performance of Concrete

This section discusses the findings reported in previous studies related to the use of LWA as self-curing agent in cementitious material (Akhnoukh, 2017; Alaskar *et al.*, 2021; Gopi & Revathi, 2021; Khan *et al.*, 2016; Suwan & Wattanachai, 2017). However, research to self-curing concrete containing LWA as self-curing agents is still lacking, especially in air-dry curing conditions. Therefore, the outcomes from the previous studies are discussed and presented in the following sub-sections. Three (3) aspects are reviewed in this section which are physical properties, mechanical properties and microstructure examination of self-cured concrete made of LWA as self-curing agent.

2.7.1 Physical Properties

Two (2) aspects are reviewed in this sub-section which are the workability of fresh concrete and the density of hardened concrete as presented in the following sub-sections.

2.7.1.1 Workability

Concrete has usually been coveted for its good strength development and good workability. However, it is frequently challenging to address both issues simultaneously when employing the traditional water-to-cement ratio. Increases in water-to-cement ratio improve the workability of concrete but have the negative effect on strength. Reducing the water-to-cement ratio of concrete to enhance its strength properties while

keeping high workability is hard to achieve unless water-reducing admixtures are added to the mix. Several researchers have studied on the workability of mortar or concrete by using LWA as conventional aggregate replacement material. The porous, water-absorbing lightweight particles can impair the workability of the concrete and the effective water/binder ratio during the mixing stage (Neville, 2011; Nguyen *et al.*, 2019; Al-Ani *et al.*, 2020). As the LWA content increased, the workability started to decrease (Al-Ani *et al.*, 2020; Chinnu *et al.*, 2021). Khan *et al.* (2016) indicated that increasing oil palm shell (OPS) content as aggregate replacement material increased the slump value up to a replacement level of 20%. Beyond that, the slump value of the concrete started to decrease. The slump value decreased by 46% at a replacement level of 40% compared to that of control concrete attributed to the porous structure and higher water absorption of the OPS than granite aggregates. Additionally, the decline in the workability of the concrete is also due to the shape of the LWA (Fanijo *et al.*, 2020; Okorafor *et al.*, 2019).

The reduced workability in concrete can be effectively compensated by the use of pre-saturated LWAs. When the LWA was used in saturated-surface dry (SSD) condition as a result, part of the moisture near the surface of LWA may contribute actively to its workability. Therefore, the workability of concrete containing porous aggregate gave the same workability as conventional concrete. In this case, excess mixing water absorbed by porous aggregate does not affect the value of the effective water-cement ratio and does not reduce the strength of concrete (Zaichenko *et al.*, 2015). Water is often retained in LWAs via holes that are bigger than those found in a hydrating cement paste (Dayalan & Buellah, 2007). Pre-mixing of LWA and water for a few minutes is also considered (Ma *et al.*, 2019).

2.7.1.2 Density

The replacement of LWA for conventional coarse aggregates such as granite or limestone typically reduces concrete density. The porous nature of LWA enables them to function as internal water storage units, promoting the self-curing mechanism. When LWA are used instead of traditional aggregates such as granite or limestone, they create a network of pores filled with water throughout the material. The water is slowly released throughout the process of cement hydration, which helps to maintain a continual curing process within the concrete. Shafigh *et al.* (2018) investigated the

characteristics of fresh and hardened concrete utilising lightweight expanded clay aggregate as a partial substitute for granite aggregate. When granite aggregates were replaced entirely with lightweight expanded clay aggregate, the density decreased from 2294 kg/m³ to 1507 kg/m³ due to the lower specific gravity of lightweight expanded clay aggregate. A similar result was found by Shivashankar and Chetan (2018), which carried out different replacement levels. At replacement levels of 25% and 50%, the density was reduced by 24.4 % and 48.8 %, respectively, compared to those of control concrete. A study conducted by Khan *et al.*, (2016) revealed that an increase of oil coconut shells as LWA in concrete decreased concrete density and compressive strength. This is because oil palm shells aggregates have a lower specific gravity and crushing strength than those of granite aggregates. After reaching a replacement level of 40%, a density reduction of approximately 16.5 % was achieved compared to the control concrete. Concrete weight reduction is beneficial in construction because it reduces the dead loads on structural elements. Therefore, the optimal use of LWA as a self-curing agent involves finding a balance that maximises internal curing benefits while maintaining adequate strength and achieving the desired density reduction.

2.7.2 Mechanical Properties of Self-Cured Concrete

This sub-section examines three (3) crucial aspects of concrete performance when LWA are employed as self-curing agents, namely compressive strength, split tensile and flexural strength, and shrinkage behaviour. This review explores how the incorporation of LWA improved mechanical performance through effective self-curing mechanisms.

2.7.2.1 Compressive Strength

Akhnoukh (2017) studied the influence of LWA addition to the compressive strength of normal strength concrete. The amount replacement of LWA which is expanded shale with the water absorption of 15% and specific gravity of 1.25 are 10%, 20% and 30%. Meanwhile replacement using lightweight expanded clay aggregates (LECA) with water absorption 12.9% and specific gravity 1.41 at percentage 12.5%, 25%, 37.5% and 50%. The compressive strength for self-curing concrete with LWA as self-curing agent were compared to those of control concrete. Compressive strength test

was performed at age of 1, 7 and 28 days. It can be said that, the lower compressive strength was recorded by concrete containing LECA compared to the control concrete. However, this initial strength decrease is often outweighed by the benefits of improved hydration and reduced shrinkage. The reduced compressive strength did not violate the minimum strength required. The slow release of water from pre-soaked LWAs ensure the continuation of cement hydration process. This is especially important in mixes that have low water-to-cement ratio. This internal moisture source slows down autogenous shrinkage, which lowers the risk of early-age cracking that could damage the structure. Table 2.1 shows the summary of percentage reduction of compressive strength for 28 days when LECA was used in concrete as self-curing agent reported by Akhnoukh (2017). LWA can successfully replace up to 50% of normal-weight coarse aggregates without substantial compromise to compressive strength. While the immediate impact on compressive strength may appear negative, the enhanced durability and reduced shrinkage due to self-curing mechanism contribute to better long-term performance of concrete. This nuanced interplay between initial strength, continued hydration, and long-term durability underscores the importance of optimising LWA content to balance immediate strength requirements with the long-term benefits of internal curing.

Table 2.1
Compressive Strength Reduction of Concrete Due to LWA Addition as Compared to Control at Age 28 Days

Types of mixes	LWA percentage replacement	Compressive Strength
Expanded shale 1	10%	8%< control
Expanded shale 2	20%	9%< control
Expanded shale 3	30%	18%< control
Expanded clay 1	12.5%	22%< control
Expanded clay 1	25%	24%< control
Expanded clay 1	37.5%	27%< control
Expanded clay 1	50%	29%< control

Source: (Akhnoukh, 2017)

A similar results was found by Gopi and Revathi (2021) who used LECA and fly ash aggregates (FAA) as self-curing agent in high-performance concrete. The fine aggregate was replaced by LECA/FAA under saturated surface dry condition by 0% to 20% at a 5% interval. The compressive strength was obtained at 7 and 28 days. It was

observed that, compressive strength increased with an increase in LECA aggregate content up to 15% but started to decrease when the replacement beyond 15%. The maximum compressive strength of about 45 MPa was achieved by a mix containing 15% LECA (L₁₅) in the self-curing concrete mix, as shown in Figure 2.11. It was discovered that 15% LECA was found to be optimum to develop self-curing concrete. This strength enhancement is attributed to the self-curing mechanism, where saturated LWA act as internal water reservoirs, gradually releasing moisture to support continued hydration. Interestingly, while initial strength at 7 days was lower for LWA mixes, the continued internal curing led to significant strength gain by 28 days. This phenomenon underscores the importance of sustained hydration in strength development, facilitated by the self-curing mechanism of LWA. Similar observations have been made by several researchers in which the optimum use of LECA in self-curing concrete as 15% (Famili *et al.*, 2012; Maghsoudi *et al.*, 2011; Paul & Lopez, 2011). The study also demonstrated that self-curing through LWA not only impacts compressive strength but also enhances other mechanical properties such as flexural strength, ductility and energy absorption capacity, highlighting the comprehensive benefits of this innovative curing approach in concrete development.

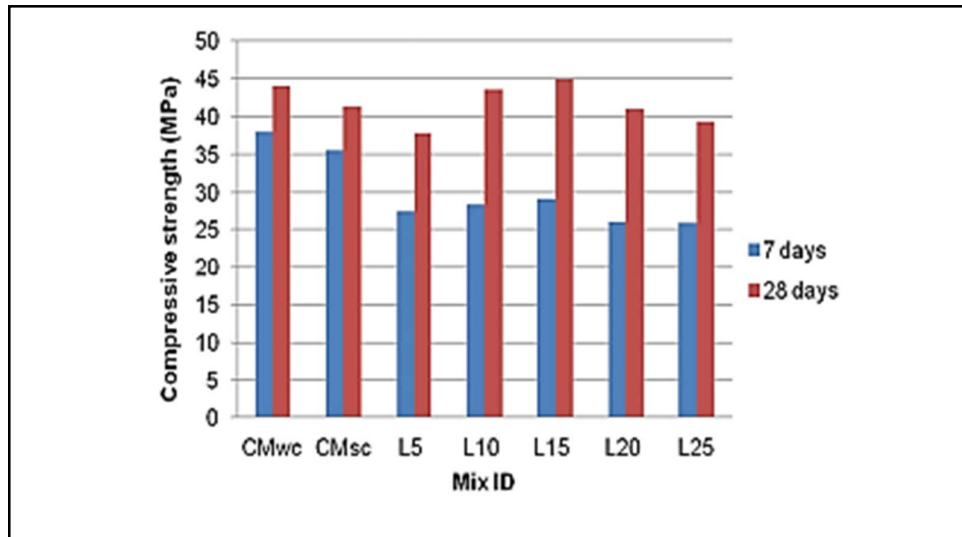


Figure 2.11 Compressive Strength at 7 and 28 Days

Source: (Gopi & Revathi, 2021)

A research study by Alaskar *et al.* (2021) on the effect of volcanic tuff as natural LWA towards the compressive strength of high-performance concrete revealed that with the addition and increase in the natural LWA content, the compressive strength of

concrete decreased. Compressive strength of 86 MPa was recorded at 28 days for the control mix without natural LWA. However, compressive strength of 84, 77, and 70 MPa were obtained for concrete containing 5%, 10%, and 20% coarse LWA, respectively. The results indicated that the use of coarse LWA at replacement levels of 5, 10, and 20% reduced the strength by about 2.3, 10.5, and 18.6% of the control concrete, respectively. This strength retention, despite increased porosity from LWAs, is attributed to the self-curing mechanism. LWAs act as internal water reservoirs, gradually releasing moisture to support continued hydration, particularly beneficial in low water-cement ratio mixes. This process ensures more complete cement hydration and improved microstructure development, partially offsetting the strength reduction from increased porosity.

Suwan and Wattanachai (2017) studied on recycled autoclaved aerated lightweight concrete (ACC- LWA) as aggregate. They suggested that 20% to 40% of LWA replacement level can be an optimum for internal curing of high-strength concrete. The amount replacement of coarse LWA at percentage 20%, 40% and 60% with specific gravity of the LWA was 1.06, 30% water absorption and water cement ratio was 0.35. Compressive strength test was carried out at age of 1, 3, 7 and 28 days. While the overall compressive strength decreased with increasing LWA content, the study demonstrated that optimal replacement levels of 20% to 40% (LWA20 and LWA40) achieved superior strength compared to those of normal concrete. This strength enhancement is attributed to the internal curing effect of AAC-LWA, which acts as a water reservoir, gradually releasing moisture to support continued cement hydration. The porous nature of LWA, with pore sizes of 50-100 μm compared to the cement paste pores of 1-100 nm, facilitates capillary suction, transferring water from larger AAC pores to smaller cement paste pores. This process promotes continued calcium silicates hydrates (C-S-H) formation and improves the interfacial transition zone between aggregate and paste. Paul and Lopez, (2011) and Lura and Bisschop, (2004) mentioned, the use of an aggregate with a lower intrinsic strength than conventional aggregate could restrict the strength of the concrete achieved. The studies indicated that the compressive strength decreased as the LWA content increased, despite the fact that the hydration and microstructure in the areas adjacent to AAC-LWA was enhanced. This compromise necessitates of meticulous consideration in practical applications, as structural integrity cannot be sacrificed in exchange for internal curing benefits.

A research conducted by Yew *et al.* (2020) indicated that as LECA replacement increased from 50% to 90%, compressive strength decreased from 34.11 MPa to 25.46 MPa at age 28 days cured in water, while density reduced from 1983 kg/m³ to 1736 kg/m³. This inverse relationship between LECA content and strength in lightweight concrete is primarily attributed to the low particle strength of LECA and the higher void content compared to those of normal aggregates. However, the study indirectly suggested a self-curing mechanism through the water absorption property in LECA. The high-water absorption capacity of LECA (42.53%) indicated its potential as an internal water reservoir, gradually releasing moisture for continued hydration. This self-curing effect may explain the relatively high strength retention despite significant LWA inclusion. Although the study offers vital insights into the impact of LECA on concrete qualities, it does not directly investigate the self-curing mechanism. The absence of shrinkage measurements and microstructural analysis limits understanding of how LECA contributes to internal curing. In addition, the study did not investigate the long-term improvement in strength or the durability elements, which are essential for evaluating the complete capabilities of LECA in sustainable concrete applications.

Abadel (2023) studied the compressive strength of Ultra High-Performance Concrete (UHPC) with varying proportions of LWAs at the curing of 7, 28, and 56 days. The test findings indicated that as LWA content increased from 0% to 30%, compressive strength generally decreased, with 56-day strength reducing from 120 MPa to 92.5 MPa as shown in Figure 2.12. The UPHC mixes were designated as LW5, LW10, LW15, LW20, LW25 and LW30 to reflect the replacement levels of 5%, 10%, 15%, 20%, 25% and 30% LWA for replacing normal aggregate respectively. However, the UHPC made of 5% and 10% LWA showed slight strength increases of 4% and 1.31% respectively, suggesting an optimal range for LWA inclusion. The microstructural examination clearly demonstrated the self-curing action of LWAs, as the specimens containing 30% LWAs showed denser microstructures. This can be attributed to the constant hydration process enabled by the water held within the LWAs. This internal curing mechanism partially offsets the strength reduction caused by the weaker LWAs. The research however does not thoroughly investigate the long-term strength growth and addresses durability issues. The apparent contradiction between reduced overall strength and improved microstructure with a higher LWA content warrants further investigation.

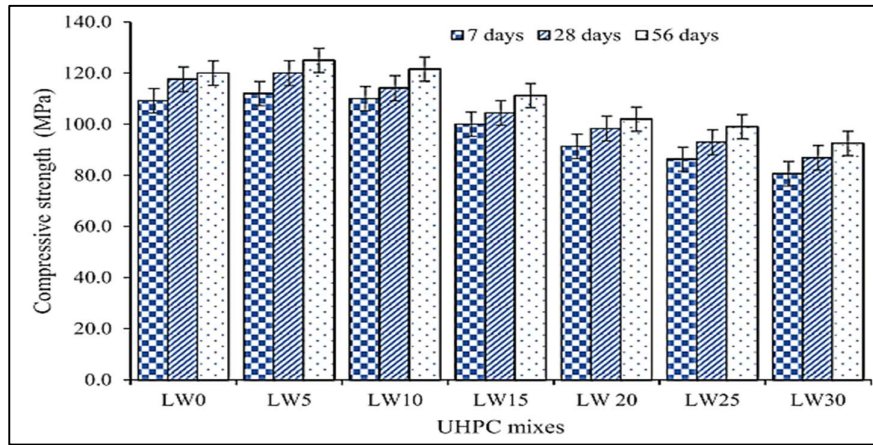


Figure 2.12 Compressive Strength of UHPC: (a) at 7, 28, and 56 Days of Curing

Source: (Abadel, 2023)

2.7.2.2 Splitting Tensile and Flexural Strength

Several previous studies reported the effect of internal curing on the splitting tensile strength of high-performance concrete. Francis *et al.* (2017) reported that partial replacement of fine aggregate with LWA up to 30% enhanced split tensile strength, with a peak value of 3.97 MPa compared to 3.89 MPa for conventional concrete. Similarly, when 1% polyethylene glycol with an average molecular weight of 400 daltons (PEG-400) was added to 25% LWA, the resulting self-curing specimens exhibited a split tensile strength of 3.87 MPa, which was very close to the strength of water-cured samples (3.96 MPa). These improvements can be attributed to the internal curing mechanism provided by LWA and PEG, which ensures continuous hydration by releasing water gradually. Other study reported that flexural and splitting tensile strength has similar behaviour as compressive strength, in which decreases as the replacement of LWA increased (Hoff, 2002). According to Kockal and Ozturan (2011), the minimum 28 days splitting tensile strength required for structural lightweight concrete to be used in structural element is 2.0 MPa. The flexural strength of normal weight concrete with a compressive strength of 34 to 55 MPa is in the range of 5 to 6 MPa with a flexural/compressive strength ratio of 11.6 to 13.5 % (Mehta & Monteiro, 2014). Zhutovsky and Kovler (2017) mentioned that internal curing of concrete made of the water to cement ratios of 0.33, 0.25 and 0.21 had a detrimental influence on splitting tensile strength. The reduction of splitting tensile strength is considerable at an early age. The results indicated that at the age of one day, the reduction percentages

were 20%, 20%, and 27% for those made of water to cement ratios of 0.25, 0.21, and 0.33, respectively. On the other hand, the splitting tensile strength was comparable to that of the reference cured concrete.

Pradeep *et al.* (2019) studied on effect of pre-soaked LECA on strength, durability and flexural behaviour of high-performance concrete. They found that the compressive strength increased by 17.5% at 28 days for the optimal 15% LECA replacement. Meanwhile, split tensile strength slightly decreased by 2.4%. Conversely, flexural strength showed modest improvement of 3.5% and 4.2% for plain and reinforced concrete beams, respectively when 15% LECA was included in the concrete mix. These findings suggest that the self-curing mechanism provided by the pre-soaked LECA enhances the overall concrete strength, likely due to improved hydration and a denser microstructure. However, the difference in the increase in compressive and tensile strength emphasises the intricate relationship between internal curing and the characteristics of the aggregate. The slight reduction in split tensile strength may be attributed to the porous nature of LECA, which could facilitate crack propagation under tensile loads. However, the lack of long-term strength data and detailed microstructural analysis limits the understanding of the ongoing internal curing process.

Mousa *et al.* (2015b) investigated the mechanical properties of self-curing concrete. They found that the use of saturated LECA in the different ratios in concrete mixes allows internal curing for the concrete by providing continual hydration, which increased the tensile strength of concrete. The results indicated that the self-curing agents improve these properties compared to that of conventional concrete. At 28 days, the optimal 15% LECA replacement increased split tensile strength by 7.4% and flexural strength by 7.2%. These enhancements are attributed to the self-curing mechanism, which provides internal water reservoirs for continued hydration, resulting in a denser microstructure and stronger aggregate-paste interfaces. Critically, while this research provides valuable insights into the relationship between self-curing and mechanical properties, it has several limitations. The lack of microstructural analysis and long-term strength data limits the understanding of the ongoing self-curing process. Flexural strength rose gradually at 28 days, with increment percentages of 1.6%, 7.2%, and 3.4% for 10%, 15%, and 20% of LECA, respectively. The results of this experiment indicated that the tensile strength of all self-curing concrete was between 6.4 and 8.5% higher in comparison with those without LECA.

Studies by Zou D *et al.* (2018) on flexural strength of plain and internally cured mortar containing shale and coal bottom ash were revealed that the flexural strength of internally cured mortar is lower than that of the plain one. It is possible to conclude that aggregate strength has higher influence on the flexural strength. The efficiency of internal curing becomes evident at later ages, with some internally cured mixtures surpassing the plain mortar in flexural strength at 7 and 28 days. This improvement is attributed to the enhanced hydration facilitated by the water released from LWAs, leading to a denser paste microstructure. The study highlighted that the internal curing

efficiency is influenced by both the pore structure and the surface area to water content ratio of the LWAs. Larger pores in LWAs promote more efficient water release, while a higher surface area to water content ratio facilitates better water distribution in the cement matrix. However, the research falls short in providing a comprehensive analysis of split tensile strength development, which is crucial for understanding the tensile behaviour of internally cured concrete.

According to Abadel (2023), the flexural strength of UHPC specimens with different amounts of LWA after being cured for 7, 28, and 56 days shows that when the LWA percentage increased from 0% to 30%, there is a consistent decrease in flexural strength at each curing age. The decrease in flexural strength of the UHPC with 0% to 30% lightweight pumice aggregates after 7, 28, and 56 days of curing may be due to many variables. Firstly, LWA have poorer mechanical properties compared to those of traditional aggregates (Li *et al.* 2018). Secondly, the reduced adhesion between the cement matrix and the LWA can lead to a decrease in the binding strength at the interface between the aggregates and the cement paste (Zhuang *et al.*, 2016). Thirdly, in comparison to conventional aggregates, the lighter aggregates have a greater porosity and a reduced surface area, both of which may result in a weakened bond between the LWAs and the cement matrix. As a consequence, the flexural rigidity of the UHPC may be diminished. Nevertheless, an intriguing phenomenon was observed when specimens were subjected to elevated temperatures: Compared to those specimens exposed to ambient conditions, those containing LWA exhibited a higher flexural strength. For instance, at 30% LWA replacement (LW30), the specimens exposed to 200°C showed a 10.2% increase in flexural strength compared to those exposed to ambient conditions. This enhancement can be attributed to the self-curing mechanism provided by LWAs, which release internal moisture during heating, promoting continued hydration and densification of the cement matrix. However, the research does not include

measurements of split tensile strength, a crucial factor in comprehending the tensile characteristics of concrete. Additionally, the limited range of LWA percentages and types may not capture the full spectrum of the outcomes related to the self-curing mechanisms.

2.7.2.3 Shrinkage

A common occurrence in cement-based materials, cracking has a detrimental effect on the structural integrity of the concrete. Generally, it is believed to be related to shrinkage. Chemical shrinkage and autogenous shrinkage are reported to be responsible for the cracking of high-performance cement-based materials (Craeye *et al.*, 2011; Cusson and Hoogeveen, 2008). Additionally, the capillary porosity created by chemical shrinkage is requisite for autogenous shrinkage (Lura *et al.*, 2003). During the hardening process in concrete, both autogenous shrinkage and chemical shrinkage occur due to cement hydration. The absolute volume change corresponds to the chemical shrinkage, whereas the apparent volume change corresponds to the autogenous shrinkage during cement hydration (Jensen & Hansen, 2001a). Deformation of cement-based materials caused by the loss of capillary water is referred to as drying shrinkage. In order to mitigate autogenous shrinkage caused by chemical shrinkage pores, additional water must be introduced to fill the capillary porosity created by the chemical shrinkage (Ma *et al.*, 2015).

Bentur *et al.*, (2001) discovered that when the amount of fine LWA replacement for normal-weight aggregate reached 25%, autogenous shrinkage of high-performance concrete could be eliminated. However, Geiker *et al.* (2004) reported that the value to be 20% for LWA replacement to eliminate autogenous shrinkage. The amount of LWA that must be replaced is determined by the pore structure and water absorption rate of the LWA. These values must be known to confirm the amount of LWA required to mitigate autogenous shrinkage. For instance, vacuum-saturated LWA significantly reduces autogenous shrinkage compared to those of oven-dry LWA as depicted in Figure 2.13. This is because dry LWA is incapable of absorbing sufficient additional water from concrete during the plastic stage. The plastic stage of concrete is relatively short, typically lasting only a few hours. This limited timeframe is often insufficient for dry LWAs to fully saturate, especially for larger aggregate particles or those with a less interconnected pore structure (Castro *et al.*, 2012). If dry LWA absorbs the required

amount of internal curing water from the concrete mixture, it is similar to the action performed by pre-wetted LWA (Golias *et al.*, 2012). By optimising the LWA porosity and particle size, it is possible to achieve an effective internal curing condition while using the least LWA (Kovler *et al.*, 2004; Zhutovsky *et al.*, 2002). Zhutovsky *et al.* (2004b) reported that using fine LWA was more effective than coarse LWA at ensuring adequate distribution of internal curing water in concrete. When the particle size of LWA was reduced, it will be distributed more uniformly in the matrix and improved the internal curing action of the cement paste. Besides, the amount of internal water absorbed by LWA and the desorption process of LWA effect on shrinkage of high-performance cement-based materials. In general, pre-wetting LWA for 24 hours significantly reduces and even eliminates autogenous shrinkage (Akçay & Tasdemir, 2010). Furthermore, the type of LWA used can have an effect on its effectiveness, suppose the water to cement ratio is maintained constant. In that case, the LWA with lower strength and a high-water absorption rate has better inhibitory effect on autogenous shrinkage in pre-wetted conditions. In contrast, LWA with higher strength and low-water absorption rate performed better when added in the dry state (Zhuang *et al.*, 2016).

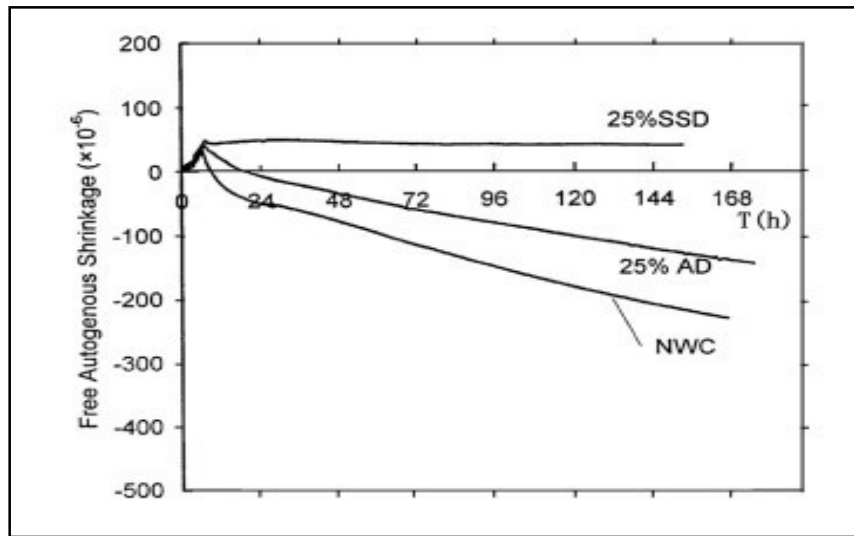


Figure 2.13 Effect of Autogenous Shrinkage of Concrete with Air-Dry (AD) and Saturated-Surface-Dry (SSD) Lightweight Coarse Aggregate

Source: (Bentur *et al.*, 2001)

Dong *et al.* (2009) reported that increasing the moisture content of expanded shale may slow the shrinkage. However, drying shrinkage cannot be completely avoided by increasing the amount of LWA. In contrast, Deboodt *et al.* (2016) believed that fine LWA had little benefit in reducing drying shrinkage, especially when an external wet curing period of three days or longer was used. When the environment is dry, a noticeable moisture gradient in the concrete and the drying of the concrete surface may occur (Han *et al.* 2013). The underlying reason for shrinkage during the plastic stage is the rapid loss of water from the concrete surface due to evaporation and the physical process of capillary pressure build-up (Boshoff & Combrinck, 2013; Cohen *et al.* 1990). While the mechanism of drying shrinkage is similar to that of plastic shrinkage, the former is believed to occur more frequently during the hardening stage. Autogenous shrinkage of high-performance cement-based materials occurs due to the effect of a significant decrease in relative humidity within the pore system and an increase in capillary stress (Ghafari *et al.*, 2016). Depending on the water content of the system and the pore size distribution caused by hydration and chemical shrinkage, in which the volume of the hydration products, is less than the sum of the volumes of the unhydrated cement and water that reacted is transformed into autogenous shrinkage (Mechtcherine & Reinhardt, 2012).

Abadel (2023) discovered that increasing the percentage of LWAs reduced the shrinkage of the UHPC. Several factors contributed to the decrease in autogenous shrinkage of ultra-high-performance concrete as the proportion of LWAs increased. Additionally, the incorporation of LWAs into the UHPC mixture improves internal drainage, allowing excess water to flee more rapidly and thereby decreasing the concrete's overall shrinkage. The enhanced drainage is attributable to the larger pore size of the LWA, which facilitates more efficient conveyance of excess water compared to the smaller pore size of the cement paste. By means of improved drainage, the quantity of internal moisture accessible for self-desiccation can be further diminished, thereby mitigating the potential for fractures (Akeed *et al.*, 2022). The findings of the study indicated that the sample with no LWA experienced the highest shrinkage (2100 microns) throughout all curing ages. In contrast, the sample containing 30% LWA exhibited the least shrinkage (958 microns) throughout all curing ages as shown in Figure 2.14. This demonstrates the advantageous impact of LWAs on the autogenous shrinkage of UHPC and offers significant insights into the potential use of LWAs as a partial replacement for fine aggregates in UHPC in order to enhance its characteristics.

LW5, LW10, LW15, LW20, LW25 and LW30 represent the UPHC specimens amended with 5%, 10%, 15%, 20%, 25%, and 30% LWA for replacing normal aggregate respectively.

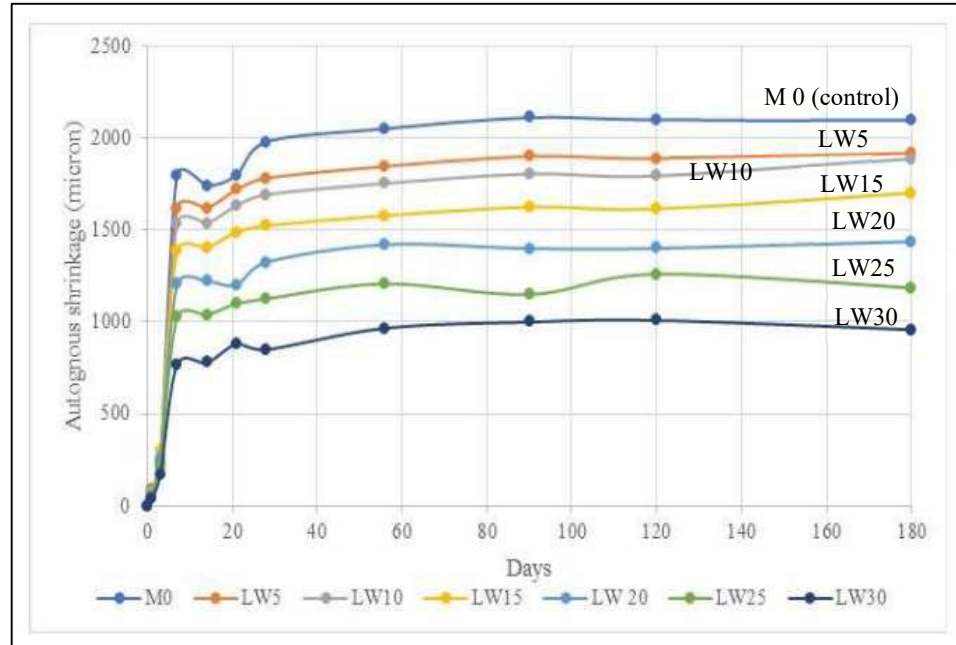


Figure 2.14 Autogenous Shrinkage (In Micron) of UPHC Made of Different Contents of LWA

Source: (Abadel, 2023)

2.7.3 Microstructure Examination of Self-Cured Concrete

The effect of aggregate particles on concrete and mortar microstructure continues to be of significant interest to researchers, as it influences the mechanical strength and durability of the structure (Wong & Buenfeld, 2006). The bond strength between the aggregates and the cement paste matrix, a zone called the interfacial transition zone (ITZ), which affected by the morphology of the aggregates, including the size, texture, shape, roughness, and porosity of the aggregates (Hilal, 2016). Between cement paste and conventional aggregate, ITZ has a higher porosity and contains more calcium hydroxide ($\text{Ca}(\text{OH})_2$) and ettringite (Mehta & Monteiro, 2001). However, a thin and denser ITZ was formed between porous aggregate and cement paste matrix (Elsharief *et al.* 2005; Liu *et al.* 2011; Liu *et al.*, 2019). In addition, the formation of calcium silicate hydrate (C-S-H) in high quantities (Suzuki *et al.*, 2009; Agostini *et al.*, 2010; Suwan and Wattanachai, 2017; Al Saffar *et al.*, 2019) and the

homogeneous hydration product (Zhang & Gjerv, 1990; Larbi, 1993) are also improved in ITZ. Thus, enhance the strength of internally curing concrete and establishes a well-bonding between porous aggregate and cement paste at ITZ. Several techniques were employed to verify the mineralogical change in self-curing concrete that shows the formation of calcium silicate hydrate as discussed in the following sub-sections.

2.7.3.1 Scanning Electron Microscopy (SEM)

Along with the physical and mechanical properties, a study of the microstructure of the morphology of the phase using a scanning electron microscope (SEM) is required to determine the type, amount, size, shape, and distribution of phases present in a solid concrete formed under different curing conditions (Madduru *et al.*, 2018). The ITZ of concrete samples was examined to determine the distribution of atomic ratios in aggregates and hydrated phases of ITZ. Limited research was done on the effect of microstructure examination on the concrete containing LWA as a self-curing agent. The investigation was carried out by Suwan and Wattanachai (2017) using SEM to verify the improvement of strength in hardened concrete and aggregate-cement bonding. It was observed a well bonded between Autoclaved Aerated Concrete LWA (AAC-LWA) and ITZ whereby LWA replaced 20% to 40% of conventional aggregate as shown in Figure 2.15. It can be explained that by the suitable amount of LWA, it served the additional of water for internal curing whereby extra water in aggregates transferred to the cement paste across ITZ. As a result, it increases hydration level to the cement binders and the uniformity in ITZ. Additionally, these factors were the key reasons that strengthened the concrete. Sun *et al.* (2015) applied SEM examination to compute ITZ microstructure in cement mortar containing LWA with 0.35 water to cement ratio and 50% aggregate volume fraction. The microstructure of lightweight aggregate (LWA) is much more porous than those made of natural aggregate, but the boundaries of LWA are relatively difficult to distinguish and the cement paste is more uniformly distributed with less unhydrated particles, even in the ITZ. In contrast, the boundaries between natural aggregates and the cement matrix are sharp, and their ITZ contains more unhydrated cement particles and apparent pores. The results indicated that the internal curing reduces the permeability of the ITZ section due to less percolated porosity and smaller pore sizes compared with the samples without internal curing mechanism.

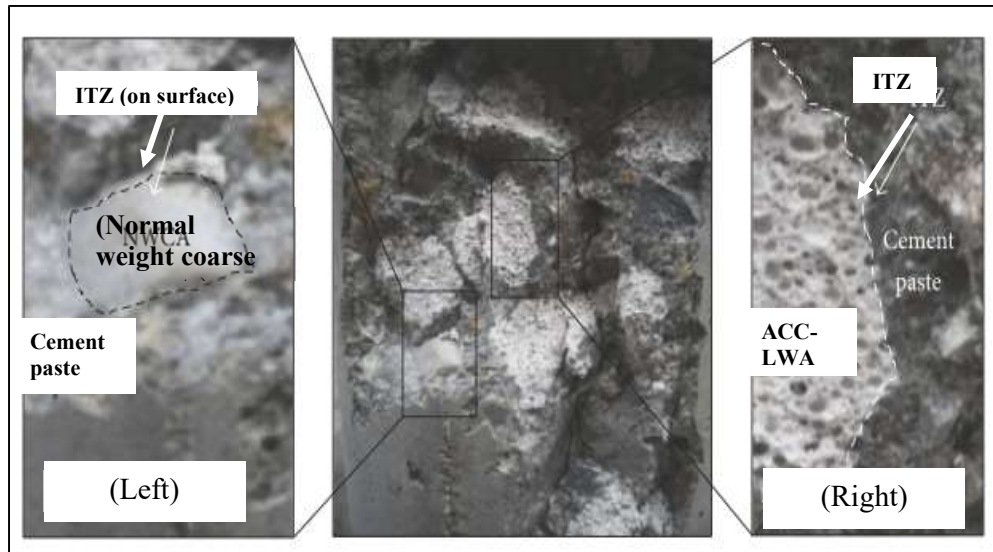


Figure 2.15 Normal-Bonded (Left) and Well-Bonded AAC-LWA (Right) on Interfacial Transition Zone (ITZ) of Cement Paste

Source: (Suwan & Wattanachai, 2017)

2.7.3.2 X-Ray Diffraction

Madduru *et al.* (2018) investigated chemical curing agent compounds to improve the curing efficiency in concrete in terms of performance and microstructure. It was revealed that the use of hydrophilic and hydrophobic chemicals resulted in a dense microstructure. This is an indication of stable C-S-H gel formation compared to no cured specimens as shown in Figure 2.16. While no cured specimens exhibited poor microstructure with interlinking of micro cracks and ettringite formation. Tang (2017) reported that the calcium hydroxide (CH) content of concrete containing oven dried LWA was the lowest. This is due to the water absorption characteristic of the oven dried LWA, resulting in free water reduction and lower rate of hydration. As for concrete containing with LWA pre-soaked in water for 1 hour, its CH content is higher than that of concrete containing oven dried LWA as shown in Figure 2.17. The evolution of CH (calcium hydroxide) peaks across curing ages demonstrates the self-curing mechanism, where pre-soaked lightweight aggregates (LWA) act as internal water reservoirs, enabling more complete hydration compared to oven-dried LWA samples. The relatively higher and more pronounced CH peaks in samples with pre-soaked LWA (especially visible at 14 and 28 days) indicate more effective self-curing, as the stored

water in the LWA supports continued cement hydration, leading to greater CH formation compared to samples with oven-dried LWA.

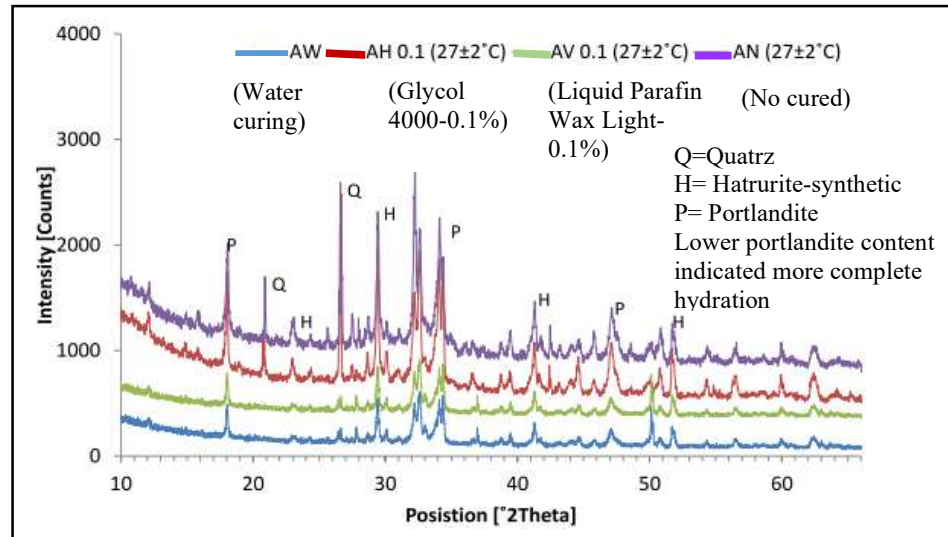


Figure 2.16 X-ray Diffraction Peaks of Self-Compacting Concrete (SCC) Subjected to Different Curing Regimes at $27\pm 2^{\circ}\text{C}$

Source: (Madduru *et al.*, 2018)

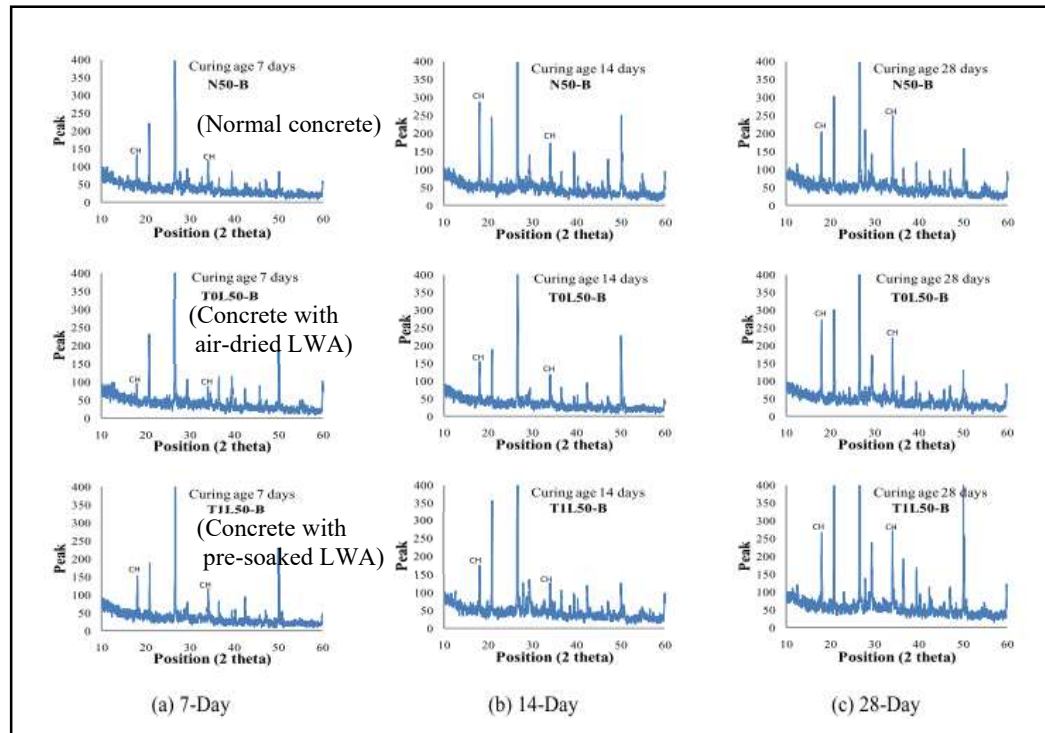


Figure 2.17 X-ray Diffraction Analysis of Cement Paste for Both the LWAC and Normal Concete (NC) Specimens

Source: (Tang, 2017)

Abadel (2023) discovered the first XRD spectrum as depicted in Figure 2.18. The UHPC sample without pumice replacement revealed high peaks of portlandite ($\text{Ca}(\text{OH})_2$), calcium-silicate-hydrate (C-S-H) and ettringite. It appears that the UHPC sample without fine aggregate replacement has higher crystallinity. Sharp, powerful spectrum peaks may suggest highly crystalline phases like portlandite, a common cement-based phase (Lim *et al.*, 2019). The UHPC sample with 15% pumice replacement of fine aggregates showed reduced peak portlandite, C-S-H and ettringite intensities in the second XRD spectrum. Pumice replacing fine aggregates may have reduced UHPC crystallinity. Some of the same peaks as the first spectrum suggest that the UHPC sample containing 15% pumice exhibited similarity of crystalline phases as that control sample. Portlandite, calcium-silicate-hydrate, and ettringite intensities are considerably lower in the third XRD spectrum, which represents the UHPC sample with 30% pumice replacement of fine particles. Replacing fine particles with pumice may have further reduced UHPC crystallinity. Pumice, being a natural pozzolan, reacts with calcium hydroxide produced during cement hydration to form additional calcium silicate hydrate (C-S-H) gel, which is amorphous in nature. This pozzolanic reaction not only increases the amount of amorphous material but also consumes crystalline calcium hydroxide, thereby reducing overall crystallinity (Akeed *et al.*, 2022). By replacing fine cement particles with pumice, the total amount of cement available to form crystalline hydration products is reduced. The water retention properties of pumice can alter water availability for cement hydration, affecting the formation of crystalline structures. This reduction in crystallinity, while potentially beneficial for strength and durability due to the formation of additional C-S-H gel and a more refined pore structure, highlights the complex interplay between material composition and microstructural development in UHPC.

The progressive decrease in $\text{Ca}(\text{OH})_2$ (portlandite) peaks from LW0 to LW30 indicates active internal curing, as the pumice is likely providing stored water that enables continued hydration reactions, while its pozzolanic nature consumes the portlandite to form additional C-S-H. The C-S-H peak variations across the three (3) spectra suggest that the pumice is serving a dual role in self-curing: first as a water reservoir that releases moisture gradually for continued hydration, and second as a pozzolanic material that reacts with portlandite to create more of the beneficial but less crystalline C-S-H gel. The overall reduction in peak intensities and crystallinity from LW0 to LW30 reflects more complete and sustained hydration processes enabled by the

pumice's water retention and release properties - a key mechanism of self-curing that promotes the formation of amorphous C-S-H over crystalline phases.

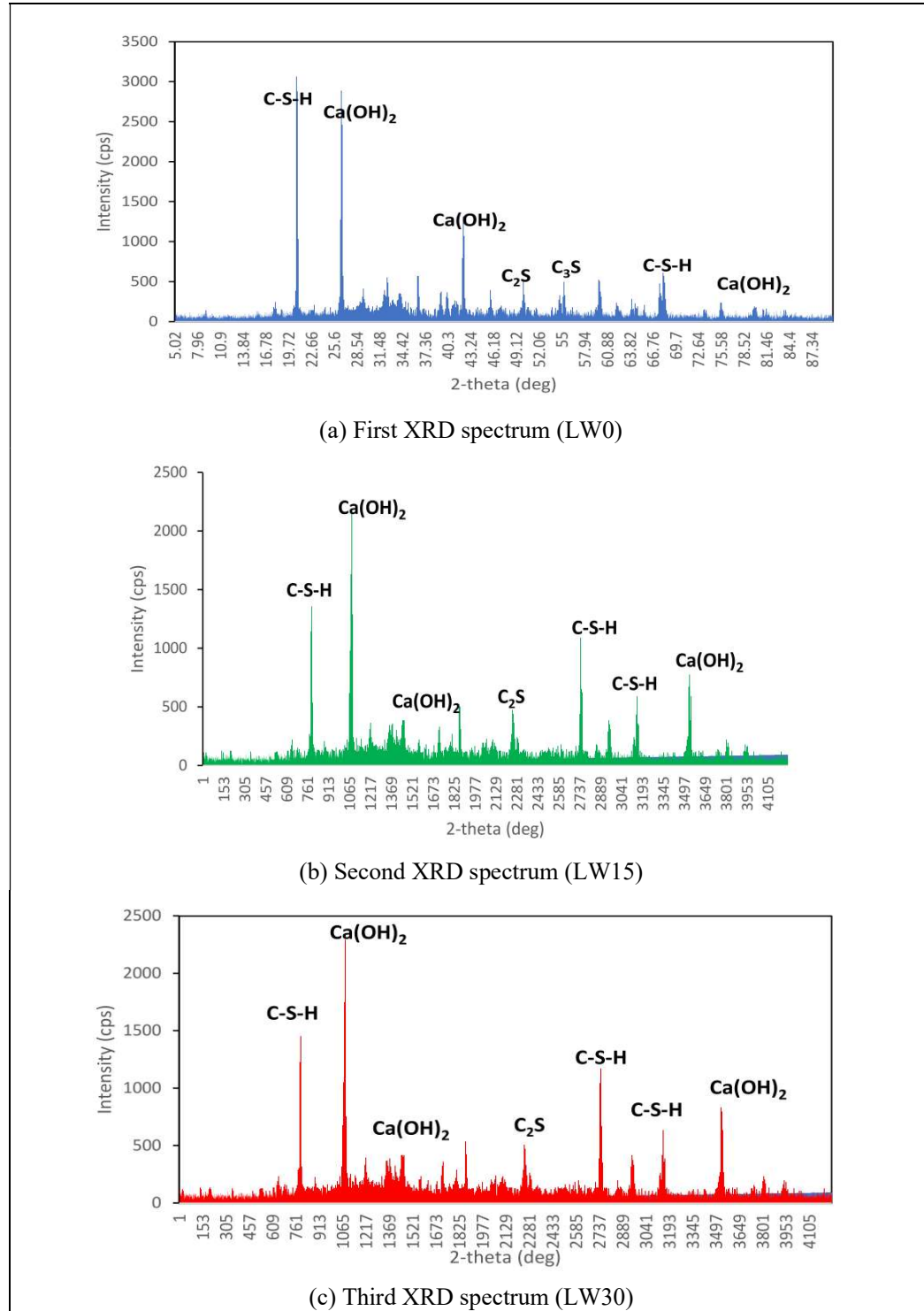


Figure 2.18 XRD Spectra of UHPC Samples Contained: (a) LW0, (b) LW15 and, (c) LW30

Source: (Abadel, 2023)

2.8 Artificial Aggregate as Self-Curing Concrete Agent

Artificial aggregates have been increasingly used in the construction of infrastructure as a replacement for natural aggregates. Most artificial aggregates are produced from waste and by-products (Tabsh & Abdelfatah, 2009; Xiao *et al.*, 2012; Safiuddin *et al.*, 2013; Liu *et al.*, 2017) and their unique properties, such as porosity and absorption capacity, have the added benefits of supplying water internally for self-curing concrete (Shigeta *et al.*, 2018; Wyrzykowski *et al.*, 2016; Mousa *et al.*, 2015a). Also, using large quantities of industrial waste can help to reduce suspension in natural aggregates (He *et al.*, 2020; Shafigh *et al.*, 2014). Furthermore, it is seen as an effective process to convert waste or by-products into useful building materials. Thus, this leads to beneficial performance for the economy whereby it produces cheaper mortar and concrete materials for low-cost construction (Al Saffar *et al.*, 2019). The use and application of using artificial aggregates produced from waste materials will also aid in the reduction and utilisation of materials produced from chemical resources as curing agents in concrete. Lastly, it positively contributes to safeguarding and protecting the environment leading to sustainable development and reduces carbon emission (He *et al.*, 2020). Besides, waste material as a curing agent replacing natural aggregates in concrete will lead to the reduction in landfill and preserve natural resources such as the flora and fauna from being destroyed (Rasheed & Abdulrasool, 2020). The water retention and release mechanisms of artificial aggregates also provide more controlled and sustained internal curing compared to chemical agents. While SAPs can cause excessive early-age expansion and potential cracking, porous artificial aggregates demonstrate more gradual water release patterns that better match the hydration of concrete requirements (Babcock & Taylor, 2015; Lv *et al.*, 2015). Research indicated that some chemical agents may leach out over time or undergo degradation, potentially affecting the concrete's long-term performance. In contrast, artificial aggregates remain stable within the concrete matrix, providing continuous benefits throughout the service life of the structure (Wang *et al.*, 2024). Moreover, artificial aggregates offer greater versatility in terms of source materials and properties customisation. Their characteristics can be tailored through processing parameters to optimise water retention, release rates, and mechanical properties for specific applications. This adaptability is not readily achievable with chemical curing agents, which typically have fixed properties.

Table 2.2 tabulates the use of artificial aggregates as self-curing agents in concrete that have been reported in previous researchers to address the gap. From the previous studies, extensive researches have been conducted on self-curing concrete using natural and commercial lightweight aggregates, leaving a critical gap in understanding the potential of artificial aggregates produced from waste materials as internal curing agents. Specifically, the combination of ceramic waste, bottom ash, and fly ash as artificial aggregates has not been thoroughly investigated for self-curing applications. This innovative approach not only advances the field of self-curing concrete technology but also provides a sustainable solution for utilising multiple waste streams in concrete production. Furthermore, existing literature lacks comprehensive studies related to replacement of natural aggregates with artificial alternatives as a self-curing agent, particularly regarding their microstructural development and long-term performance in normal strength concrete. This innovative research direction contributes to both sustainable concrete technology and practical construction methodologies.

Table 2.2
Use of Artificial Aggregate as Self-Curing Agent in Concrete Reported in Previous Researchers

Artificial aggregates that have been used as self-curing agent	Resources	Researchers
LECA	Natural Resources	(Pradeep <i>et al.</i> , 2019), (Zhuang <i>et al.</i> , 2016) (Mousa <i>et al.</i> , 2015a; 2015b), (Zhang & Poon, 2017)
LECA and Expanded shale	Natural Resources	(Akhnoukh, 2017), (Wu <i>et al.</i> , 2019)
Expanded shale	Natural Resources	(Aghaee & Khayat, 2023), (Zou D <i>et al.</i> , 2018)
LECA and Fly Ash (FA)	Natural Resources & by-product	(Gopi & Revathi, 2021), (Pradeep & Beena, 2020), (Kadhar <i>et al.</i> , 2023)
LECA and Polyethylene Glycol (PEG)	Natural & Chemical Resources	(Mousa <i>et al.</i> , 2015a; 2015b), (Kamal <i>et al.</i> , 2018)
Ceramic	Waste material	(Sato <i>et al.</i> , 2011), (Shigeta <i>et al.</i> , 2018)
Recycle Concrete/ Brick Aggregate	Waste material	(Suwan & Wattanachai, 2017), (Afifi & Abou-Zeid, 2016), (Chen <i>et al.</i> , 2019), (Manzur <i>et al.</i> , 2019)
Natural Fibre	Natural Resources	(Zadeh & Bobko, 2014), (Jongvisuttisun <i>et al.</i> , 2018)
Volcanic	Natural Resources	(Alaskar <i>et al.</i> , 2021), (Abadel, 2023), (Zhutovsky & Kovler, 2017)

Artificial aggregates that have been used as self-curing agent	Resources	Researchers
Bottom ash	By-product	(Kim, & Lee, 2018) , (Balapour <i>et al.</i> , 2020), (Wyrzykowski <i>et al.</i> , 2016), (Zou D <i>et al.</i> , 2018)
Biochar	Waste material	(Mrad & Chehab, 2019)
Present study, GAA= combination of ceramic waste, bottom ash, and fly ash	Waste material & by-product	None of the researchers have studied the application of GAA as a self-curing agent, therefore the present study was prompted.

2.9 Summary of Literature Review

Extensive literature has examined the efficacy of lightweight aggregates (LWA) as internal curing agents and their impact on the mechanical and microstructural properties of high-performance concrete. Research consistently demonstrates that LWA can effectively function as a self-curing agent when substituted for conventional aggregates in concrete mixtures. However, this substitution presents notable trade-offs in mechanical properties. Studies indicate that incorporating LWA as a self-curing agent generally results in decreased compressive strength, reduced split tensile strength, and diminished flexural strength compared to conventional concrete. The magnitude of these strength reductions correlates directly with the percentage of LWA replacement. Despite these mechanical limitations, the internal curing mechanism facilitated by LWAs offers significant advantages, particularly in terms of reduced shrinkage and enhanced durability characteristics. These findings underscore the necessity for further research into alternative aggregate materials that can maintain optimal mechanical properties while providing effective self-curing capabilities, both in properly cured conditions and in scenarios where conventional curing processes are impractical or unavailable.

Moreover, with the growing demand from the construction industry for development, more affordable and environmentally acceptable materials are required. Consequently, the generation of industrial waste in commercial quantity has prompted research in that direction. The use of alternative aggregate made from industrial waste as a self-curing agent for construction materials can improve the overall performance of self-cured concrete as the waste is available in large quantities, and the overall process is cheaper than conventional production. From the literature review, it is noted

that mostly LWAs from natural resources and polymers from chemical resources were used as self-curing agents. The literature review shows that the artificial aggregate produced from a combination of waste material and by-products, such as ceramic waste, bottom ash, and fly ash, has never been used as curing agent. Studies on the influence of replacing natural aggregates with 100% of artificial aggregate as curing agent and microstructural examination in normal strength concrete were undertaken in this present work to fill the gaps.

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

This chapter explains the methods undertaken along with guidelines and literature review in Chapter 2 to achieve the objectives of the study. The present works are primarily consisting of experimental works conducted at Universiti Teknologi Malaysia (UTM), Johor Bahru, Johor and Universiti Teknologi MARA (UiTM), Shah Alam, Selangor. Most of the testing methods and procedures followed the Standard Method of American Society Testing Method (ASTM) and British Standard (BS). Laboratory tests were carried out to collect data for analysis, and the test results were compared to those from earlier studies. Additionally, this chapter uses brief graphics, figures, diagrams, pictures, tables, and charts to analyse the data and conclude the findings.

The experimental programme of this study was divided into three (3) stages and statistical analysis was employed. The first stage is identification and characterisation of aggregates in order to determine the capabilities of the aggregate as an internal water reservoir in concrete. The tests conducted were sieve analysis, specific gravity, water absorption, water desorption, surface texture, aggregate crushing value, X-ray Fluorescence (XRF) and Mercury Intrusion Porosimetry (MIP). In this study, granite aggregate was replaced with 100% green artificial aggregate (GAA) by volume. However, to determine the initial performance of concrete strength, 50% replacement of GAA was used in concrete mix proportion. The tests involved in the second stage were compressive strength test, ultrasonic pulse velocity (UPV), and density tests for control concrete and concrete containing GAA. The final stage determines the performance of concrete containing 100% GAA, and the GAA acted as a self-curing agent. The tests involved are the compressive strength, UPV, density, flexural strength, modified compressive strength, initial surface absorption, shrinkage and expansion properties. The compressive strength, UPV, and density were conducted at the age of 3, 7, 28, and 56 days, while flexural strength, and modified compressive strength was conducted at the age of 28 days. Shrinkage and expansion of concrete were tested every

day until 28 days, meanwhile, initial surface absorption was conducted at the age of 3, 7, and 28 days. The UPV and density tests were performed prior to the compressive strength. Shrinkage and expansion tests were conducted before the flexural strength was performed, whereas modified compressive strength was conducted after flexural strength test. Furthermore, the internal structure of concrete was performed by using Scanning Electron Microscopy (SEM), energy dispersive x-ray (EDX), X-Ray Diffraction (XRD), and Mercury Intrusion Porosimetry (MIP) on crushed of concrete specimens obtained from compressive strength testing. All tests were performed on control concrete and concrete containing GAA which consist of three (3) identical specimens for 3, 7, 28, and 56 days. The data acquired from the compressive strength, UPV, density, flexural strength and modified compressive strength test were then analysed statistically with Statistical Package for the Social Sciences (SPSS) to determine whether observed differences are statistically significant or merely due to random variation. Figure 3.1 shows the experimental programme which consists of three (3) stages in the research work.

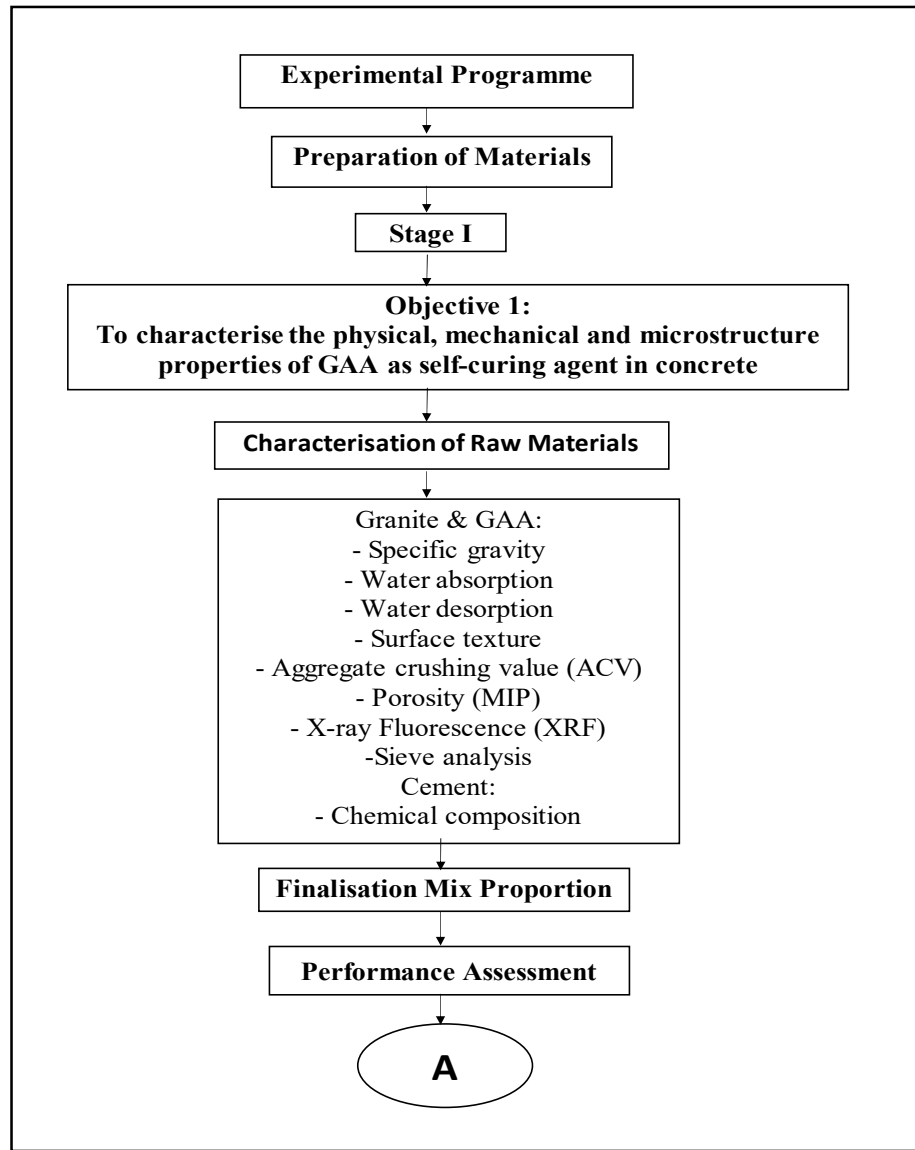


Figure 3.1 Experimental Programme in the Present Research Work

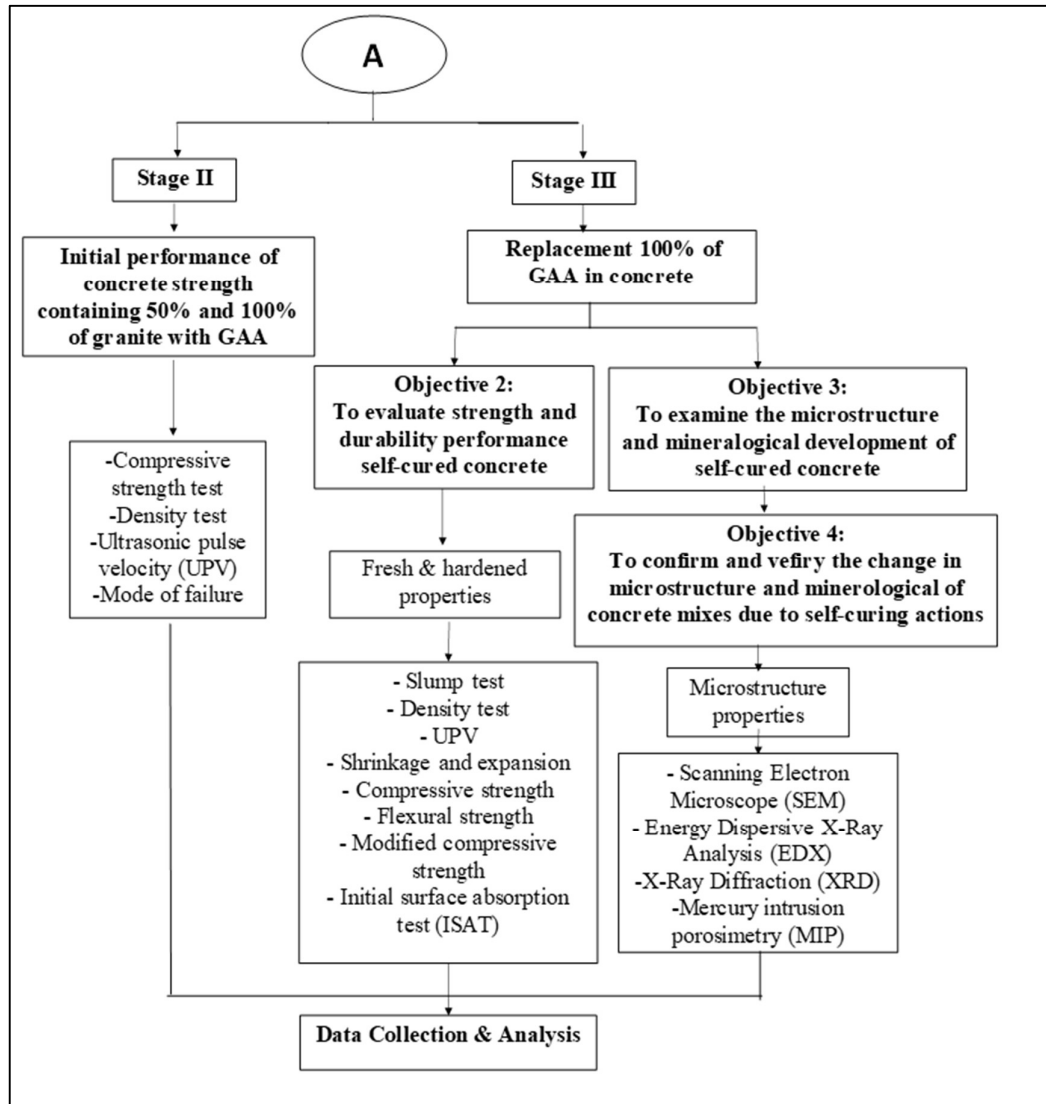


Figure 3.1 Experimental Programme in the Present Research Work (Continued)

The following sections present the procedures and steps in the preparation of materials, characterisation of raw materials, finalisation mix proportion, performance assessment, data collection and analysis.

3.2 Preparation of Materials

The materials used to produce concrete in this study are mainly Ordinary Portland Cement (OPC), fine aggregate, coarse aggregate and water. The materials used are in good condition and the details of the materials used are discussed in the following sub-sections.

3.2.1 Ordinary Portland Cement (OPC)

Cement is the main component in the concrete that binds the materials together. The cement used in this study was ordinary Portland cement (OPC) acquired from YTL Cement Manufacturing Company of Malaysia, conforming to ASTM C150, (2007) Type I specification. The use of cement was important in concrete in order to produce cement hydration product namely calcium silicate hydrates (C-S-H). The OPC used during the entire experimental work is shown in Figure 3.2.



Figure 3.2 Ordinary Portland Cement (OPC) Used in the Present Investigation

The samples of cement were determined using Rigaku X-ray Fluorescence Spectrophotometer (XRF) to analyse its chemical composition. The chemical composition of OPC used in this study are shown in Table 3.1.

Table 3.1
Composition of Cement, Determined by XRF

Compound	% Weight
Calcium oxide (CaO)	68.9
Silico oxide (SiO)	17.9
Sulfur trioxide (SO ₃)	4.09
Aluminium oxide (Al ₂ O ₃)	3.41
Iron oxide (Fe ₂ O ₃)	2.98
Magnesium oxide (MgO)	1.7
Potassium oxide (K ₂ O)	0.879

3.2.2 Fine Aggregates

In this study, local river fine aggregates as provided in Structure and Materials Laboratory, UTM with the specific gravity of 2.62 and fineness modulus of 2.91 was used. A sieve analysis or gradation test was conducted in accordance with ASTM C33 (2018) to evaluate the particle size distribution of a granular material. The separation sizes of aggregates was performed using mechanical sieve shaker compliance to ASTM C136 (2019). In sieving the fine aggregate, one (1) kg of aggregate was placed into the sieve whereby the sieve size at the top was 9.5 mm and end up with the small size of sieve, 150 μ m. The cumulative passing (37%) in 600 μ m pan was selected to use in the designation of mix for concrete. Fine modulus (FM) of fine aggregate used was 2.91 based on the calculation of summation value of cumulative percentage retained above 150 μ m and dividing with 100. The value of FM was obtained according to a specified limit between 2.3 and 3.1 as stipulated in ASTM C136 (2019). The gradation curve of fine aggregate is shown in Figure 3.3 with the minimum and maximum values in accordance with ASTM C33 (2018).

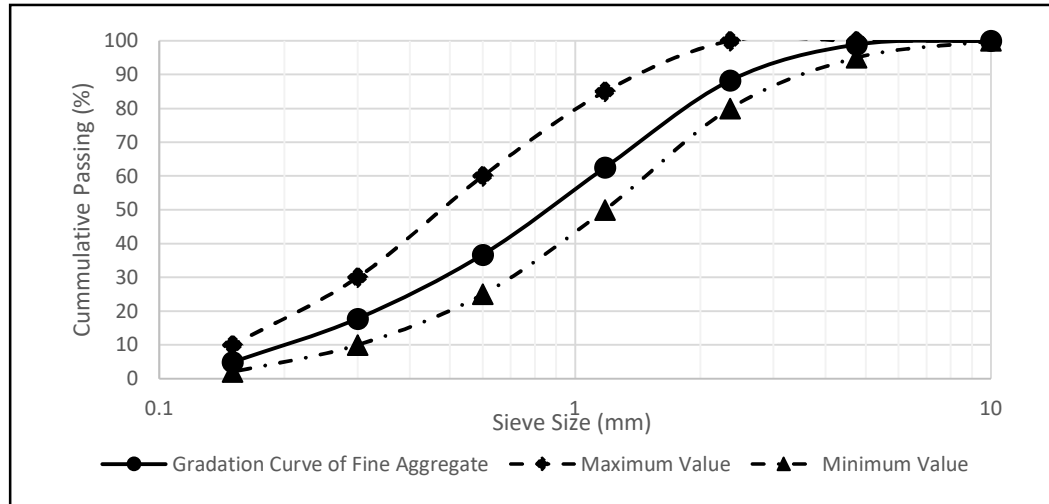


Figure 3.3 Grading Curve of Fine Aggregate Used in the Present Investigation

3.2.3 Coarse Aggregate

Two (2) types of coarse aggregates were used: namely, natural aggregate and green artificial aggregate (GAA). Both aggregates comply with the general grading requirement specified in BS EN 12620 (2002). The following paragraphs explain the appearance and characteristics for natural aggregate (NA) and green artificial aggregate (GAA) employed in the present study. The utilised NA consists of crushed granite with angular shape. The NA samples retained in 10 mm stack were collected to be used for casting of specimens. Figure 3.4 presents the NA samples used in the present study. Incorporating clean aggregate into the mix is crucial as it has the potential to impact the strength and durability of the concrete.



Figure 3.4 Natural Aggregate (NA) of 10 mm Size Crushed Granite

The GAA samples were supplied by Active Pozzolan Technology Sdn. Bhd. in Pasir Gudang, Johor. The components of GAA are made from ceramic waste, bottom ash, and fly ash with a rounded shape, as depicted in Figure 3.5. The maximum size of the GAA employed in the present study was 10 mm. The use of 10mm nominal maximum aggregate size for GAA in this study was justified by several factors. First, 10mm aggregate size has been successfully employed in numerous previous studies on self-curing concrete using lightweight aggregates and artificial aggregates, with its effectiveness for internal curing mechanisms having been demonstrated (Al Saffar et al., 2019; Bentur et al., 2001; Suzuki et al., 2009). Second, a larger surface area-to-volume ratio is provided by smaller aggregate sizes, which is beneficial for self-curing applications as the water absorption and desorption characteristics of the aggregate are enhanced.



Figure 3.5 Green Artificial Aggregate (GAA) of 10 mm Size Used for Replacing NA

The samples of GAA were tested for its chemical composition. The samples were determined by X-ray Fluorescence (XRF), and chemical composition of granite is extracted from literatures as shown in Table 3.2. The coarse aggregate samples passing 10 mm sieve were collected to be used for casting of specimen. As shown in Table 3.2, the major constituents of granite according to previous researchers consist of 70 to 75% silica, 14 to 16% alumina, 2 to 6% potassium oxide, 1 to 3% total iron, and less than 1% magnesia and titania. Meanwhile, as compared to GAA used in this study, similar constituents with value of 61.6%, 14.3%, 2.48%, 2.44%, 0.6%, and 0.3% respectively were observed. From this result, it can be concluded that the dominant component is silico oxide (SiO_2) at 61.6%, which originates primarily from ceramic waste and coal combustion ashes. Ceramic materials are characterised by high silica content, while fly

ash and bottom ash from coal combustion typically contain 40-60% SiO₂ as their major component. The substantial aluminium oxide (Al₂O₃) content of 14.3% is contributed by all three constituent materials, as both fly ash and ceramic waste are recognised as alumino-silicate materials (Mathew et al., 2023). The relatively high calcium oxide (CaO) content of 13.3% in GAA distinguishes it from conventional granite aggregate, and can be attributed to the presence of ceramic waste and bottom ash, in which calcium-bearing compounds from the combustion process are commonly contained (Vosoughi et al., 2017). The iron oxide (Fe₂O₃) content of 2.44% originates from both the ceramic raw materials and the mineral matter in coal ash. The combination of these oxides, particularly the high SiO₂ and Al₂O₃ content, provides GAA with pozzolanic characteristics through which contribution to the hydration process in concrete can be made. Therefore, the chemical composition of GAA represents a synergistic blend of its constituent waste materials, in which the silica-alumina framework from ceramics is combined with the reactive oxides from combustion ashes to create an artificial aggregate with unique properties suitable for self-curing applications

Table 3.2
Chemical Properties of GAA and NA (% weight) Extracted from Literature

Compound	GAA Present study	Granite (Othman <i>et al.</i> , 2010)	Granite (Kim et al., 2019)	Granite (Pradesh, 2016)
Silico oxide (SiO)	61.6	70	75	72.04
Aluminium oxide (Al ₂ O ₃)	14.3	16	15.24	14.42
Calcium oxide (CaO)	13.3	2.2	0.98	1.82
Iron (III) oxide (Fe ₂ O ₃)	2.44	2.3	2.44	1.22
Sodium Oxide (Na ₂ O)	2.98	1.9	1.57	3.69
Potassium oxide (K ₂ O)	2.48	6.1	2.49	4.12
Titanium dioxide (TiO ₂)	0.331	0.30	0.03	-
Magnesium oxide (MgO)	0.622	0.88	0.09	0.71
Sulfur trioxide (SO ₃)	0.517	0.12	0.23	-
Barium oxide (BaO)	0.307	0.049	0.09	-

3.2.4 Water

The chemical reaction between the compound of cement and water yields products. Hence, the water must not contain any substance that might affect the

chemical reaction between compounds of cement and water. Municipal tap water available in concrete laboratory was used throughout the study in mixing, curing and other purposes.

3.3 Characterisation of Coarse Aggregates

The characterisation of coarse aggregates is a crucial step in understanding their properties and potential performance in concrete. Key parameters examined in the present study include particle size distribution, specific gravity, water absorption and desorption, and resistance to crushing. The details of the tests are discussed in the following sub-sections.

3.3.1 Sieve Analysis of Coarse Aggregates

Sieve analysis represents a fundamental procedure in materials characterisation, particularly for coarse aggregates utilised in concrete production. A sieve analysis or gradation test was conducted in accordance with ASTM C33-18 (ASTM C33, 2018) to evaluate the particle size distribution of a granular material. The sieve pan size of 14 mm until 2.36 mm was used. The weight of the coarse aggregate sample was two (2) kg according to ASTM C136-19 (ASTM C136, 2019) is a minimum weight of aggregate samples to be placed into the sieve shaker as shown in Figure 3.6. The minimum and maximum cumulative percentage passing as stipulated in ASTM C33-18 (ASTM C33, 2018) is plotted in Figure 3.7 along with the particle distribution of coarse aggregate (natural) used in this study.



Figure 3.6 Sieve Shaker Used to Determine the Particle Size Distribution of Aggregates

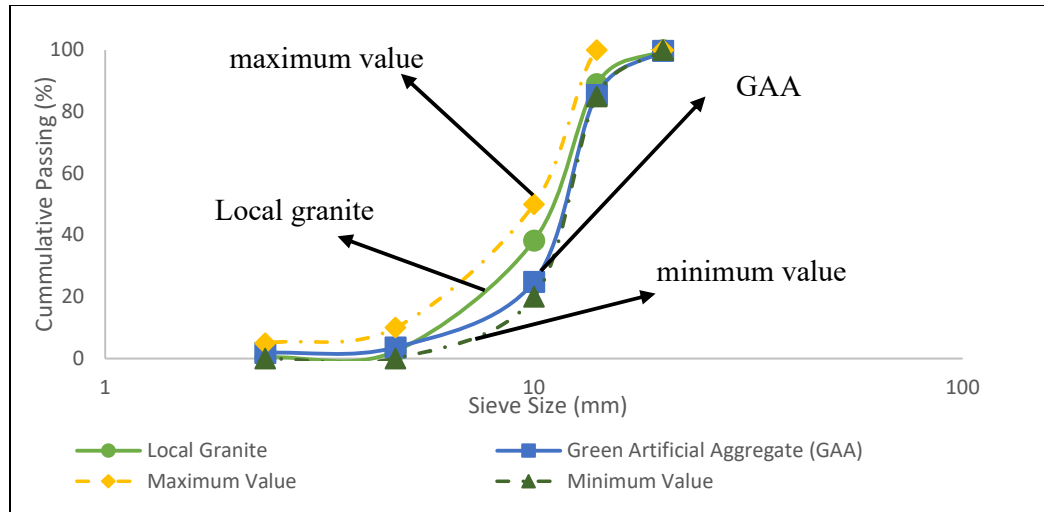


Figure 3.7 Grading Curve for Two (2) Types Coarse Aggregate Used in the Present Study

3.3.2 Specific Gravity of Coarse Aggregate

Specific gravity is also referred to as relative density which was defined as the ratio of the aggregate weight of totally dried to the saturated surface dry weight. The test was performed in accordance with ASTM C127-15 (ASTM C127, 2015). Firstly, two (2) kg of coarse aggregate samples were collected from aggregate retained at a sieve of 4.75mm and dried in the oven for two (2) hours at temperature 110 °C. The same samples were soaked in water for 20 hours after being cooled at room temperature to ensure the water-filled the pores in the aggregate. Upon the completion of water immersion, the excess of water in the aggregate surface was wiped using a towel prior to the determination of mass aggregate and recorded as saturated surface dry (SSD) weight, W_{SSD} . The SSD samples were then put in a wire basket and immersed in water at the temperature of 23°C. These samples were weighed while hanging in the wire basket and recorded as the weight of aggregate submerged in water, W_w . Finally, the samples were dried again in oven for two (2) hours and the weight of oven-dry samples, W_o was weighed. The average weight of three (3) different conditions is tabulated in Table 3.3.

Table 3.3
Specific Gravity of Coarse Aggregate

Aggregate	Granite	GAA
Undisturbed samples weight (kg)	2.1	2.1
Oven-dry samples weight, W_o (kg)	2.088	1.997
Weight of aggregate in condition of SSD, W_{SSD} (kg)	2.095	2.244
Weight of aggregate while submerged in water, W_w (kg)	1.291	1.193
Specific Gravity, $\frac{W_o}{W_{SSD} - W_w}$	2.6	1.9

3.3.3 Absorption Capacity of Coarse Aggregate

The absorption capacity of aggregate indicates the amount of water absorbed by the pore within this aggregate when soaked in water. The test was performed in accordance with ASTM C127-15 (ASTM C127, 2015) to determine absorption capacity. It can be calculated from Equation 3.1. Absorption capacity of granite was found as 0.34 % while GAA was found to be 12.4%. The absorption capacity of granite is relatively low as compared to GAA. It shows that granite itself is dense and non-porous structure while GAA, made from waste materials exhibits much higher absorption capacity.

$$Absorption (\%) = \frac{(M_2 - M_1)}{M_1} \times 100 \quad (3.1)$$

where,

M_2 = Mass of SSD test sample in air (g)(W_{SSD}); and

M_1 = Mass of oven-dry test sample in air (g)(W_o).

3.3.4 Desorption of Coarse Aggregate

For this research, the desorption isotherms for the materials was tested according to ASTM C1498 (ASTM C1498, 2016). This technique provides a wider assessment of the materials' desorption behaviour whereby could provide insight into the materials' viability in terms of internal curing benefits. Using saturated salt solutions, four (4) specific Relative Humidity (RH) were created. A summary of the saturated salt solutions and the RH environments are presented in Table 3.4. The production of saturated salt solutions was prepared according to ASTM E104-20a (ASTM E104, 2020). The calculation for mass of water released at different RH is expressed as in Equation 3.2 (ASTM C1761, 2017). The details of test procedures are as shown in Figure 3.8.

$$W_{LWA} = \frac{M_{SD} - M_{RH}}{M_{OD}} \quad (3.2)$$

where,

- M_{SD} = Mass of SSD condition samples (g);
- M_{RH} = Equilibrium mass of RH (g); and
- M_{OD} = Mass of the oven-dry sample (g).

Table 3.4
Aqueous Salt Solutions and Associated Equilibrium RH Prepared for Desorption of Coarse Aggregate

Saturated Aqueous Salt Solution	Equilibrium RH (at 20 0 C)
Potassium Sulphate, K ₂ SO ₄	97.6 ± 0.6%
Potassium Chloride, KCl	85.1 ± 0.3%
Sodium Chloride, NaCl	75.5 ± 0.2%
Sodium Bromide, NaBr	59 ± 0.1 %



Step 1: The granite and GAA were soaked in water for 24 hours. After saturation, the aggregates were removed from the water. The aggregates were rolled up into the absorbent towel and then the aggregates were shaken and rolled from side to side. Then, the samples were weighed to obtain the mass of SSD (M_{SD}).



Step 2: The saturated salt solution was prepared in air-tight containers to maintain the required RH before appropriate amount of SSD conditioned aggregate samples were inserted and placed in a perforated holder. The holder is suspended above the saturated salt solution in the container.



Step 3: Then, the container with the SSD-conditioned aggregates and salt solution (from Step 2) is placed inside the temperature-controlled cabinet to keep the temperature at 20 °C.



Step 4: The aggregate samples were taken out and weighed every 24 hours to determine mass losses (due to water loss) (M_{RH}). An electric balance with accuracy to 0.01 g was used in the test. Finally, the samples were oven-dried to determine the dry weight (M_{OD}).

Figure 3.8 Test Procedures of Desorption of Coarse Aggregate

3.3.5 Aggregate Crushing Value

The British Standard BS 812-110: 1990 (BS 812-110, 1990) was applied to determine the aggregate crushing value (ACV) of the aggregate. This method was used to assess the compressive strength of loose aggregates. The test measures an aggregate's resistance to crushing under gradually applied compressive load. The test comprises of open-ended steel cylinder, 150 mm internal diameter with 152 mm exterior diameter of

steel plunger. The wall thickness of the cylinder is 16mm with a 10 mm thick steel base. The apparatus come with a steel rod to attain the appropriate volume of coarse aggregate. Figure 3.9 illustrates the test apparatus to determine the ACV for the aggregates. The test requires to be compacted and the aggregate samples were crushed in the steel cylinder by applying a constant load via the plunger. The test procedures are as shown in Figure 3.10. The total percent mass of the material passing is represented as the ACV analogous to Equation 3.3. The ACV of the granite was found as 17.56 % while GAA was found as 24.35%. The ACV of granite being 17.56% indicates that the granite aggregate has relatively good strength and resistance to crushing. The ACV of GAA being 24.35% indicates that the GAA has lower strength and higher susceptibility to crushing compared to granite.

$$ACV (\%) = \frac{M_2}{M_1} \times 100 \quad (3.3)$$

where,

- M2 = Mass of the material passing the 2.36 mm test sieve (g); and
M1 = Mass of the test specimen (g)



Figure 3.9 Aggregate Crushing Value (ACV) Test Apparatus



Step 1: The mass of the aggregate sample was measured using a calibrated electronic balance (M_1).



Step 2: The aggregate samples are filled in three layers inside the steel cylinder. Each layer being subjected to 25 strokes from the tamping rod.



Step 3: Then, the aggregate samples are placed in the plunger and removed to testing machine and load is applied reaches 400 kN in 10 min $\pm$ 30s.



Step 4: Then, the crushed aggregate samples were collected in sieving to determine the extent of crushing. The amount of crushed particles passing a 2.36 mm sieve, then it was weighed (M_2).

Figure 3.10 Test Procedures for Determining ACV for the Aggregates

3.4 Determination of Mix Proportion

The proportion of the mix design is critical for concrete to perform the required properties. The design process allows for the development of parameters such as workability, compressive strength and durability. The design mix of self-curing concrete was carried out similarly to that of plain normal strength concrete. The method of mix design applied is in accordance with the BRE mix design method (Teychenne *et*

al., 1997), formerly known as the DoE method. According to ASTM C138-17 (ASTM C138, 2017), modifications were made to the mix proportion of self-curing concrete using GAA to gain concrete within required properties. The design concrete strength is 30 MPa at the age of 28 days, the water-cement ratio is 0.53, and the design slump of 60-180mm with nominal aggregates sizes of 10 mm for all mixes. In this experiment, granite was subsequently replaced by GAA at 50% and 100% by volume. Table 3.5 shows the details of the mix proportion used throughout the experiment.

Table 3.5
Mix Design for Concrete Mixes

Mix	Cement (kg/m ³)	Water (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate	
				Granite (kg/m ³)	GAA (kg/m ³)
Control (CTR)	470	250	930	700	0
Mix 1 (50% GAA)	470	250	930	350	260
Mix 2 (100% GAA)	470	250	930	0	515

* GAA = Green Artificial Aggregate

3.5 Casting and Preparation of Concrete Specimens

The preparation of concrete specimens can be divided into three (3) steps as follows.

- i. Preparation of mould;
- ii. Preparation of concrete specimens and
- iii. Determination fresh state of concrete mixes.

The steps are elaborated in the following sub-sections.

3.5.1 Preparation of Mould

The required numbers of 100 mm x 100 mm x 100 mm cube moulds for compressive strength test and 100 mm x 100 mm x 500 mm prism moulds for flexural strength test were provided. Firstly, the mould was cleaned of any debris and concrete remnants from the previous casting operation. Then, the joints were properly tightened to prevent water from leaking out and keep them from dislocating during the vibration

operation. A layer of grease was applied to the surface of the internal mould before pouring the concrete to prevent the hardened concrete from sticking to the mould. Figure 3.11 shows the moulds that were applied with grease.



Figure 3.11 Steel Moulds that Ready for Casting

3.5.2 Preparation of Concrete Specimens

A mechanical mixer with 20 litre capacity and a rotating speed of 80 rpm as shown in Figure 3.12 was used for mixing process. The mixing process means blending all aggregates with cement into a paste and uniform mass. The weighed materials from the design calculation were mixed together for up to five (5) minutes except water to achieve uniformity. Finally, water was added incrementally during mixing to adjust to the desired slump. The fresh concrete was placed into the mould in two (2) layers and compacted using the vibrating table as shown in Figure 3.13 for each layer in accordance with ASTM C192-19 (ASTM C192, 2019). The objective of using the vibrating table is to ensure that all samples are subjected to a constant compaction effect and to eliminate any embedded air bubbles in the concrete. In the end, by using a trowel, the top surface of the mould was then levelled up. To assess the workability of fresh concrete, the drop measurement was taken from the top of slump cone to the slumped of fresh concrete in compliance with BS EN 12350-2 (2019).



Figure 3.12 Mechanical Mixer



Figure 3.13 Vibrating Table

In this experiment, two (2) conditions of coarse aggregate were prepared, namely saturated-surface-dry condition (SSD) and air-dry condition (AD). The technique to produce SSD condition of coarse aggregates is by immersing the aggregates in municipal tap water for 24 hours. Then, the aggregate was filtered using filter equipment before the excessive of water were removed by using a towel in accordance with ASTM C127-15 (ASTM C127, 2015) as shown in Figure 3.14. The aggregates in SSD condition were required to minimise the water evaporation that can affect the workability of the fresh concrete. Besides, it is also required to avoid insufficient water for support proper cement hydration. There are six (6) designation mixes of concrete in second stage: concrete containing 100% AD granite as control concrete, concrete containing 100% SSD granite as control concrete, concrete containing 50% AD GAA, concrete containing 50% SSD GAA, concrete containing 100% AD GAA and concrete containing 100% SSD GAA. While four (4) mixes of concrete at third stage: control concrete with 100% of SSD granite, control concrete with 100% of AD granite, self-cured concrete with 100% of SSD GAA and self-cured concrete with 100% of AD GAA. Total of three hundred ninety-six (396) cube specimens of 100 mm x 100 mm x 100 mm and twenty-four (24) prism specimens of 100 mm x 100 mm x 500 mm were produced for tests. All the specimens were subjected to water and air curing for 3, 7, 28, and 56 days. The selection of 56 days as the maximum curing period for this study was based on technical and practical considerations. Extended hydration characteristics are exhibited by self-curing concrete compared to conventional concrete due to the continuous internal water supply from

porous aggregates. While most strength is typically achieved by standard concrete by 28 days, strength development continues to be shown by self-curing concrete between 28 and 56 days as stored water is gradually released by the internal curing agent to sustain hydration (Meng et al., 2018). This extended hydration period is particularly important for the long-term benefits of the self-curing mechanism to be demonstrated.



Figure 3.14 Process to Produce SSD Condition of Coarse Aggregates (a) Immerse the Aggregate in the Water for 24 hours and (b) Rolling up the Aggregate into the Towel

3.5.3 Determination of Fresh State of Concrete Mixes

The assessment of the fresh properties of concrete in term of workability was determined by slump test. The slump test was a widely adopted method due to its simplicity and practicality in both laboratory and field conditions. The slump test for workability measurement was conducted in accordance with ASTM C143 (ASTM C143, 2020). the metal slump cone with dimensions of 300 mm height, 200 mm base diameter, and 100 mm top diameter was placed on a flat, non-absorbent surface before being filled with concrete. A sample of freshly mixed concrete was placed into the mould in three (3) equal volume lifts. Then, a steel tamping rod was used to apply 25 blows over the surface of each layer. The surface of the concrete was levelled by the rod. Once the top was levelled, the mould was removed from the concrete before the wet concrete is allowed to subside approximately 5 seconds. The vertical distance between the original and displaced position of the centre of the top surface of the

concrete was measured and reported as the slump of the concrete as shown in Figure 3.15.



Figure 3.15 Slump Measurement of Fresh Concrete

3.6 Curing Conditions

The curing process is one of the essential processes for controlling the rate and extent of moisture in concrete during the hydration process. A proper curing process was undertaken to ensure that it achieves its intended strength and durability. The specimens were cured under six (6) types of curing condition as follows

- i) curing in water after 24 hours demoulding (1D-WC);
- ii) curing in laboratory environment after 24 hours demoulding (1D-AC);
- iii) curing in water after 3 days demoulding (3D-WC);
- iv) curing in laboratory environment after 3 days demoulding (3D-AC);
- v) curing in water after 7 days demoulding (7D-WC) and
- vi) curing in laboratory environment after 7 days demoulding (7D-AC).

As for comparison, concrete with normal aggregate (granite) was cast and went through the same curing process. The objective of assessing the difference in demoulding time in concrete incorporating GAA is to determine the effect of the improper curing conditions by early removal of formwork on the concrete strength.

3.7 Testing on Hardened Concrete Specimen

In this study, various physical and mechanical properties of concrete were conducted. The tests for hardened concrete include apparent density, ultra-pulse velocity (UPV), initial surface absorption, compressive strength, flexural strength, modified compression, expansion and shrinkage. The tests are described in the following sub-sections.

3.7.1 Apparent Density

Apparent density can be defined as mass per volume. The mass of self-cured concrete was measured by using digital weighing scale. Apparent density for self-cured concrete is fundamental parameter to be measured before carrying out any destructive test. Monitoring on the consistency of self-cured concrete production can be done via the basic apparent density and it can be calculated from Equation 3.4 as follows:

$$\rho_c = \frac{M_c}{V_c} \quad (3.4)$$

where,

$$\begin{aligned} \rho_c &= \text{Apparent density (kg/ m}^3\text{);} \\ M_c &= \text{Mass of cured concrete (kg); and} \\ V_c &= \text{Volume of cured concrete (m}^3\text{).} \end{aligned}$$

3.7.2 Ultra-Pulse Velocity (UPV)

Ultrasonic pulse velocity (UPV) test is a common non-destructive test used to determine the quality and the homogeneity of concrete according to ASTM C597 (ASTM C597, 2016). UPV measurements can also be correlated with mechanical properties like compressive strength and density when proper calibration curves are established. The UPV test technique uses the ultrasonic waves passing through the concrete. The apparatus was equipped with a pair of transducers and an electronic timing device for measuring transit time, t in length path, L . To obtain more accurate results, UPV readings were taken from each surface of the concrete cube for every

batch. Figure 3.16 shows the procedure for conducting UPV test. The UPV results, which was obtained in terms of velocity were then compared with the classification presented in Table 3.6 to determine the concrete quality.

Table 3.6
UPV Test Results Classification

Pulse Velocity (m/s)	Concrete Quality
> 4500	Excellent
3500 – 4500	Good (slight porosity may exist)
3000 – 3500	Medium (loss of integrity may suspected)
<3000	Poor (loss of integrity exist)

Source: (Neville, 2011)

The velocity was calculated by using formula in Equation 3.5 as follows:

$$V = \frac{L}{\Delta t} \quad (3.5)$$

where,

V = Pulse velocity (km/s);

L = Distance between centers of transducer faces (km); and

Δt = Transit time (s)



Step 1: A thin, uniform layer of grease is applied onto both transmitting and receiving transducers before it measures between two (2) locations of transducers on the concrete surface. The grease is applied to ensure proper acoustic contact between the transducers and the concrete surface.



Step 2: The pulse generator is calibrated by using calibration rod (reference bar) before the test. This calibration step is essential because the accuracy of UPV measurements depends directly on precise time measurements. Even small timing errors can significantly affect calculated velocities and subsequent concrete quality assessments.



Step 3: Then, the transmitter is placed on the surface of the concrete while the receiver is set on the opposite side. Finally, the transit and pulse velocities are recorded. Velocity was calculated using Equation 3.5

Figure 3.16 Test Procedures of UPV Test

3.7.3 Initial Surface Absorption Test

The objective of the test was to measure the rate of water absorbed into the surface of the concrete. Initial surface absorption test (ISAT) was conducted in accordance with BS 1881: Part 208 (BS 1881-208, 1996) using 100 mm concrete cube. The concrete specimens were prepared in accordance with the procedure outlined in the compressive strength test specimens, with the mixture proportion analogous to those in Table 3.5. Before the test begins, the specimens were oven-dried at 105 °C until a constant weight was recorded. The tap from the reservoir was closed and the reservoir is filled with water. Then, the tap was opened to allow the water to run into the cap and capillary tube. The air was flushed from the cap through the capillary tube. Figure 3.17 shows the set up for ISAT.

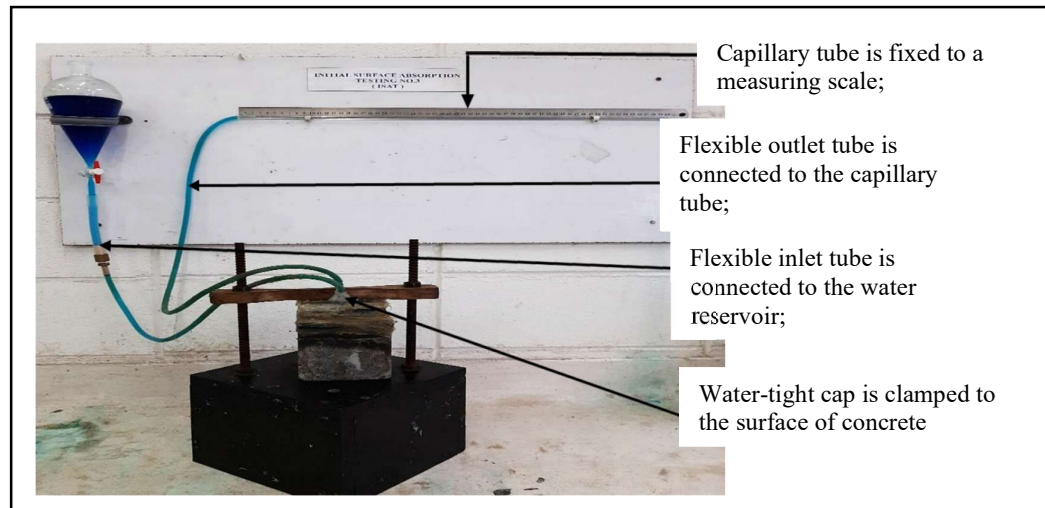


Figure 3.17 ISAT Test Setup

3.7.4 Compressive Strength Test

Compressive strength test was conducted in accordance with BS 12390-3 (2009) stipulation. Compressive strength denotes the ability of a structure or material to withstand under compression. The specimens were prepared before testing. The loading machine was cleaned, and the digital unit of the machine was programmed with the desired sample information. A constant loading rate was set up and applied to the specimens until failed. A typical testing operation is depicted in Figure 3.18. The mode

of failure of the specimen was observed. The compressive strength of the concrete cubes was calculated using Equation 3.6.

$$\sigma_c = \frac{P}{A} \quad (3.6)$$

where,

σ_c = Compressive strength (MPa);

P = load (kN); and

A = area (mm²).



Figure 3.18 Universal Testing Machine for Compressive Strength Test

3.7.5 Flexural Strength Test

Flexural strength was conducted using British Standard specification of BS 12390-5 (2009). This technique is commonly known as the modulus of rupture and applied to measure its resistance against failure in bending. A total of 24 specimens (prism) size 100 mm x 100 mm x 500 mm including control specimens were prepared. The arrangement of loading and support roller was fixed as illustrated in Figure 3.19. The marked prism was placed in the testing machine and placed with the longitudinal axis of the specimen at right angles to the rollers. The maximum load carried by the

specimen was recorded prior to the final breakdown as shown in Figure 3.20. The flexural strength, f_{cf} can be calculated using Equation 3.7 as follows:

$$f_{cf} = \frac{Fl}{d_1 d_2^2} \quad (3.7)$$

where,

- f_{cf} = Flexural strength in MPa;
- F = Maximum load in N;
- l = Distance between the supporting roller in mm; and
- d = Lateral dimensions of the specimen in mm (see Figure 3.19).

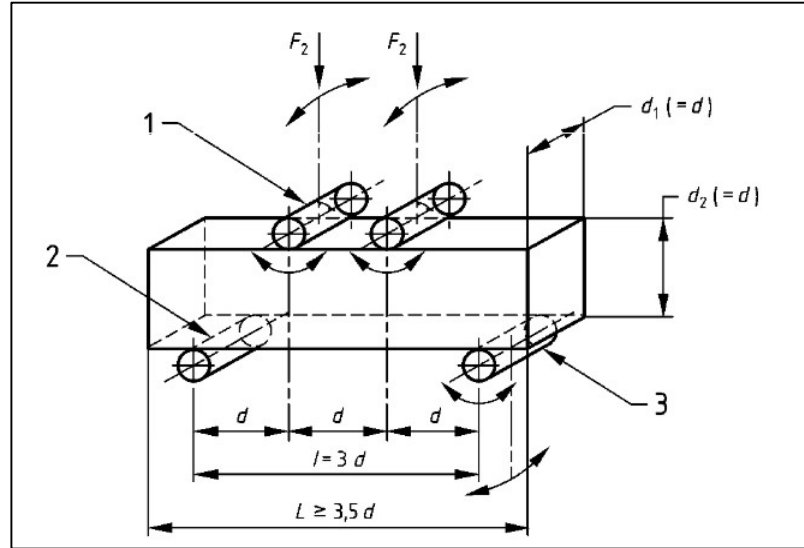


Figure 3.19 Arrangement for the Flexural Strength Test Setup of Two-Point Loadings



Figure 3.20 Flexural Test Machine

3.7.6 Modified Compressive Strength Test

The modified compression test was carried out after the flexural test was conducted by using the broken parts of the prism from the flexural test. The objective of the test was to determine the compressive strength of the prism specimens and compared it with the results of the cube's compressive strength. The test was carried out by the compression machine the one used for compressive strength test explained in Sub-Section in 3.7.4. Two (2) steel plate size 100 mm x 100 mm each were positioned in parallel on top and below of the prism sample. The purpose of the steel plates was to apply the loading of the compression machine to the broken prism sample. Figure 3.21 shows the set-up of modified compression test.



Figure 3.21 The Broken Prism Specimens and the Set Up For Modified Compression Test

3.7.7 Expansion and Drying Shrinkage

Expansion and drying shrinkage represent opposing microscopic dimensional changes in concrete that significantly impact its long-term performance and durability. Drying shrinkage strain is related to moisture losses due to water evaporation or hydration process of cement from concrete while expansion specimens are water-cured to simulate maximum moisture exposure, allowing measurement of these opposing dimensional behaviours under extreme conditions. The test was conducted under BS-812-120 (1990). For expansion and drying shrinkage test, a total of 24 specimens (prism) with a size 100 mm x 100 mm x 500 mm including the control specimens were prepared. For the drying shrinkage test, the concrete specimens were cured in the air environment while the expansion test, the specimens were cured in water tank. Figure 3.22 illustrates the test apparatus for expansion and drying shrinkage test. The details of the test procedure are as shown in Figure 3.23. The strain of each specimen was calculated based on the Equations 3.8 and 3.9.

$$\varepsilon = (\text{Demec reading} - \text{Demec Datum}) \times \text{SF} \quad (3.8)$$

where,

$$\begin{aligned} \varepsilon &= \text{Strain (Microstrain); and} \\ \text{SF} &= \text{Strain factor } (0.796 \times 10^{-5}) \end{aligned}$$

$$\text{Percentage of shrinkage or expansion} = \frac{L_0 - L}{L} \times 100 \quad (3.9)$$

where,

$$\begin{aligned} L_0 &= \text{Original length (mm); and} \\ L &= \text{Length as measured during or after cure (mm)} \end{aligned}$$

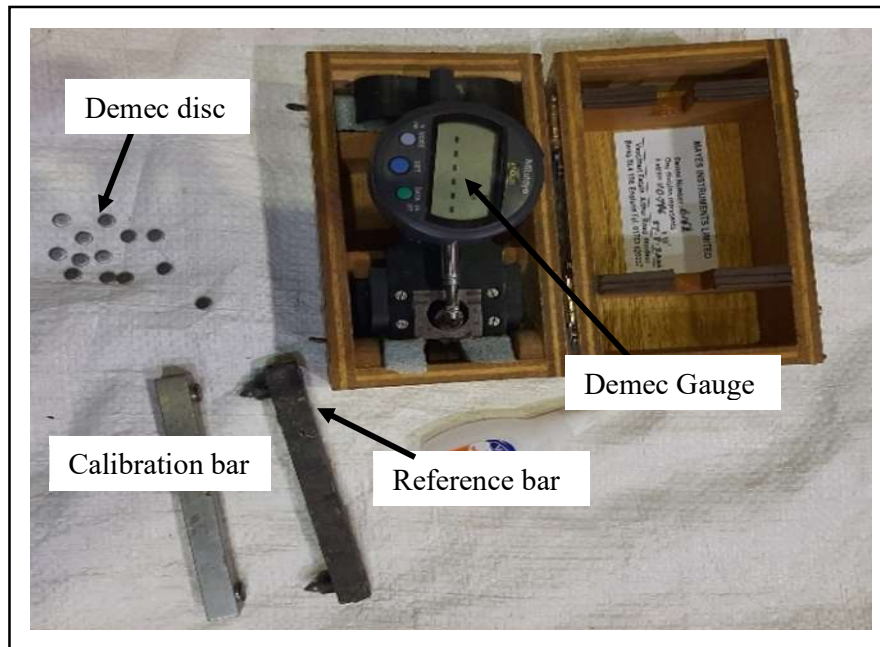


Figure 3.22 Expansion and Drying Shrinkage Test Apparatus

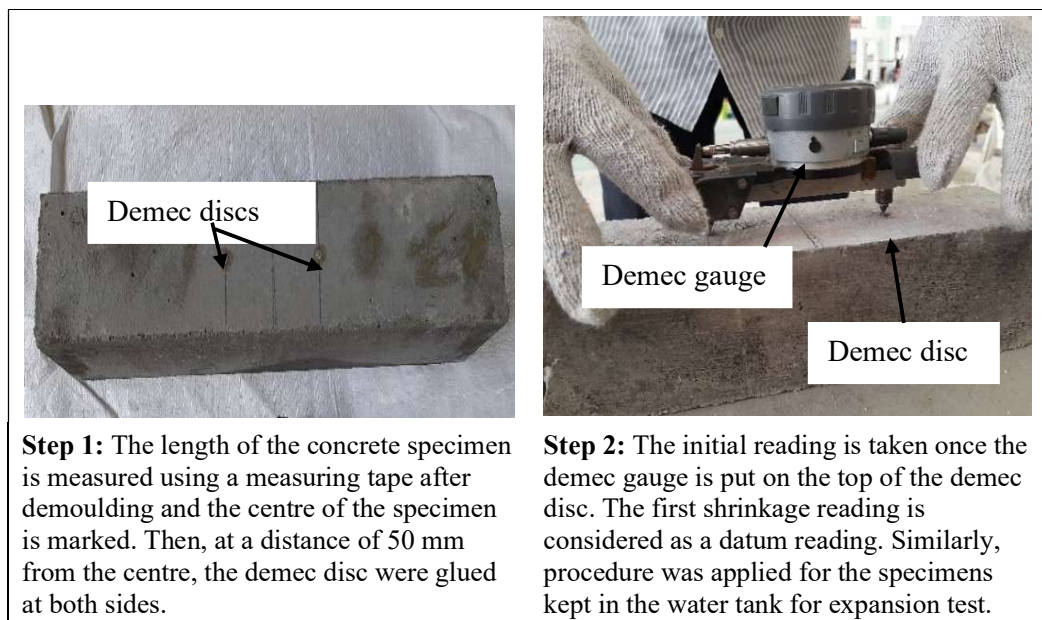


Figure 3.23 Test Procedures of Drying Shrinkage and Expansion Test

3.7.8 Mode of Failure

The mode of failure of the crushed concrete specimens was observed in accordance with BS 12390-3(2009). The test was performed at the age of 3, 7, and 28 days using 100 mm x 100 mm x 100 mm cube and 100 mm x 100 mm x 500 mm prism

specimens for compressive strength and flexural strength, respectively. The mode of failure of the concrete specimens was last observed after the specimen was completely tested under compressive strength test or flexural test. The objective of the test was to observe the breakdown bonding between the binder and the coarse aggregates. The concrete specimens that have undergone compressive strength test, were placed again in the compression test machine. Then, the load was applied at a constant rate until the cracks on the specimen able to form the failure pattern as presented in Figure 3.24.



Figure 3.24 Failure Pattern of Cube Concrete

3.8 Microstructure Examination

The study of the microstructure is essential as it provides a clear view of the bonding between cement matrix and aggregate inside the specimen. In addition, a microstructure study was carried out to understand the mechanisms leading to the degradation of cementitious materials whereby important for proper guide for the development of durable concrete. Microstructure property of concrete in this study was obtained under Scanning Electron Microscopy (SEM). The details of the microstructure examination are explained in the following paragraph.

The microstructure examination was conducted at School of Mechanical Engineering, Universiti Teknologi MARA (UiTM), Shah Alam, Selangor by using Hitachi Model SU3500 Variable Pressure Scanning Electron Microscope. The objective of this test is to visualise the image of micrograph between cement paste and coarse aggregate to correlate the strength of concrete, which is obtained from the compressive

strength test. This can be done by examining the internal microstructure with the use of image analysis. Before conducting the test, the control concrete and concrete samples containing GAA at days 3, 7, and 28 were crushed into small pieces around 5 mm to 10 mm size. After that, the sample was put in the oven at 100⁰ C to remove unnecessary liquid in order to stop the reaction inside the sample for 24 hours. Then, the concrete samples were coated and placed to sample holder prior to SEM analysis as shown in Figure 3.25.

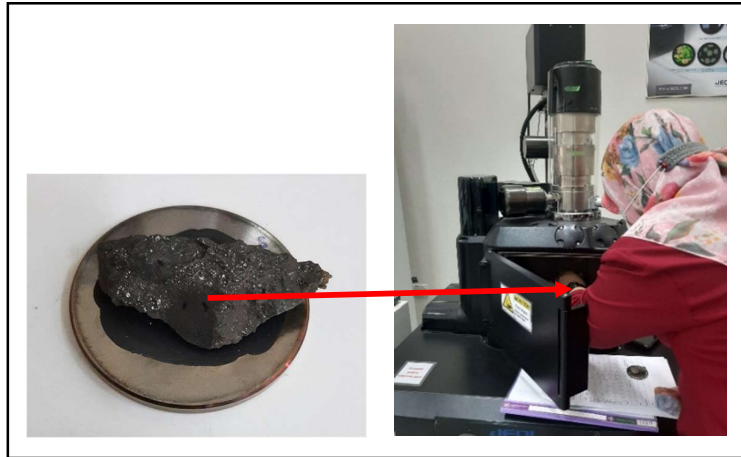


Figure 3.25 The Coated Concrete Sample Before Placing in the SEM Machine

This instrument was also equipped with an Energy Dispersive X-rays Detector (EDX) to verify the chemical compositions of a crushed sample by focusing at the desired spot. The EDX spectrum formed from the x-ray energy level which is capable to measure the concentration ions of chemical composition of cement paste such as calcium (Ca), aluminium (Al), sulfur (S), magnesium (Mg), and silica (Si). The highest concentration of ions emerged as the peak on the graph. The workstation of SEM used in the present study is shown in Figure 3.26.



Figure 3.26 The Workstation for SEM Examination

3.9 X-Ray Fluorescence (XRF)

X-Ray Fluorescence (XRF) is a non-destructive analytical technique that determines the elemental composition of materials by measuring the fluorescent X-rays emitted when a sample is excited by a primary X-ray source. The cement and GAA were also tested for its chemical composition by using NEX CG X-Ray Fluorescence. The aim of this test is to identify the chemical composition of cement and GAA namely as SiO_2 , CaO , Al_2O_3 and Fe_2O_3 in the sample. Firstly, the samples were crushed by using pestle and mortar into powdered form and passed through 150 μm sieve at about 100g as depicted in Figure 3.27. Then, the sample was put in the oven at 100°C to remove unnecessary liquid in order to stop the reaction inside the sample for 24 hours before tested in the in XRF equipment. Figure 3.28 shows the XRF equipment which was used in this study.

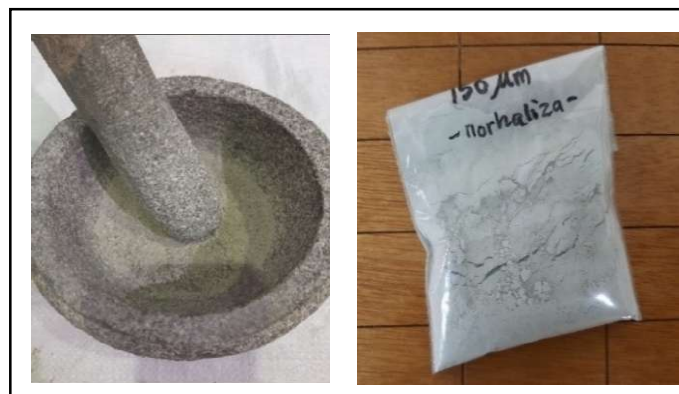


Figure 3.27 Preparation Sample into Powdered Form for XRF Analysis



Figure 3.28 XRF Equipment Used to Determine the Chemical Composition of Cement and GAA

3.10 X-Ray Diffraction (XRD)

The test was carried out at School of Mechanical Engineering, UiTM, Shah Alam, Selangor by using Ultima IV X-ray diffractometer as shown in Figure 3.29. Operating conditions of Ultima IV X-ray diffractometer using copper ($\text{Cu-K}\alpha$) radiation was used in this study. The scale of the usual XRD pattern on the x-axis (diffraction angle) indicates the crystal lattice spacing, while the y-axis scale (peak height) indicates the diffraction ray intensity. The scan step was 0.02° using a scanning rate of $5^\circ/\text{min}$ and in the range 2-theta-scale from 6° to 80° . The samples were tested for 3, 7-, and 28-days curing periods for each required batch.

By recognising the X-ray pattern, the XRD test is capable of identifying polycrystalline phases in materials by measuring how X-rays are diffracted by their atomic lattice structure. The test was carried out on concrete specimens to detect the effect of GAA inclusion as curing agent to the cement hydration product such as portlandite ($\text{Ca}(\text{OH})_2$), calcite (CaCO_3), vaterite (CaCO_3) and cristobalite (SiO_2). Generally, the crystals of these four (4) major compounds may contribute to the strength development and hydration of cement. Details of test procedure is as shown in Figure 3.30.



Figure 3.29 Ultima IV X-Ray Diffractometer

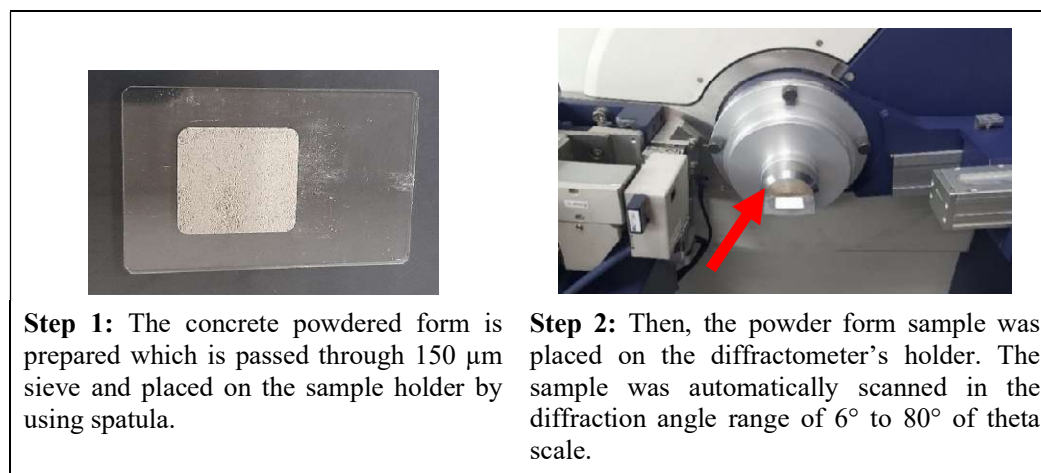


Figure 3.30 Test Procedure for XRD Test

3.11 Mercury Intrusion Porosimetry (MIP)

The test was performed at Multipurpose Laboratory, School of Chemical Engineering, UiTM, Shah Alam, Selangor by using Micromeritics AutoPore IV version. MIP is a specialised technique that characterises porous materials by forcing liquid mercury into pores under precisely controlled pressure. The instrument has one (1) high-pressure port with two (2) low-pressure analysis ports, as shown in Figure 3.31. It is able to determine the pore volume, pore size distribution, bulk density and apparent density of cement-based specimens which directly correlate with mechanical properties and durability characteristics. The test was conducted by a laboratory technician due to the presence of the element mercury. Miniature of the sample approximately 5 mm thick and between 5 g was prepared and added to the sample container called dilatometer.

The instrument of Micromeritics was operated in Microsoft Window XP environment. The analysis was conducted by graphing the curve corresponding to the volume of intruded mercury in mm^3/g versus the applied pressure in MPa. The high pressure can be up to 400 MPa. The particle size was calculated directly from intrusion pressure using the Mayer-Stowe calculation model by plotting the fraction of particles versus the particle size. The resulting pressure-volume curves yield detailed insights into the microstructural development of cementitious materials that directly influence the material's strength, permeability, and long-term durability.

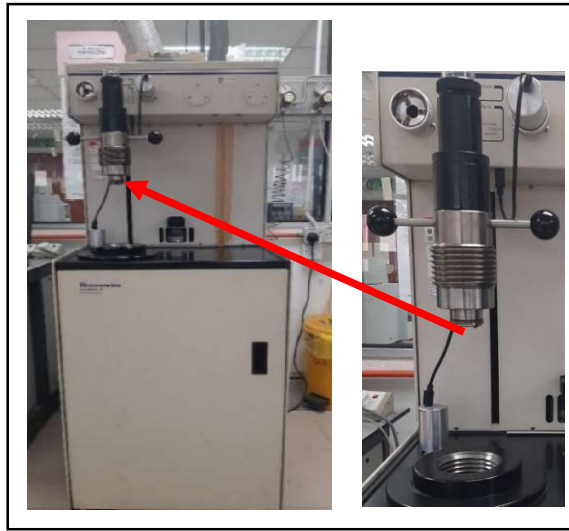


Figure 3.31 Micromeritics AutoPore IV Equipment Used for Pore Analysis of the Concrete Powder Samples

3.12 Stereo Microscope

The test was conducted by using Stereo microscope HSZ600. The purpose of this test is to observe water movement from GAA particles to the surrounding hydrating cement paste in the concrete cube. The test was also used to access the aggregate shape and surface texture. The details of test procedure are as shown in Figure 3.32. The workstation of the stereo microscope can be referred to Figure 3.33.



Step 1: Red colour hair dye is mixed with distilled water, then stirred. The GAA is left for 24 hours to soak in the coloured water.



Step 2: Then, GAA in the SSD condition is prepared before cast into cubic mortar samples. After 3, 7, and 28 days, the samples were cut in the middle using a concrete grinder.



Step 3: The samples that were cut is observed under the stereo microscope.

Figure 3.32 The Procedures for Colour Propagation Test Using Stereo Microscope



Figure 3.33 The Workstation for Stereo Microscope Used for Observing Morphological Structure of Aggregates and Water Movement from Aggregates to Cement Paste

3.13 Data Collection and Analysis

The data acquired from the compressive strength, UPV, density, flexural strength and modified compressive strength test was then analysed statistically with Statistical Package for the Social Sciences (SPSS). Statistical analysis using independent samples t-test and two-way ANOVA was adopted to assess five factors under study that influencing the compressive strength, UPV, density value, flexural strength and modified compressive strength of the resulted concrete specimens. It is noted that independent samples t-test and two-way ANOVA are method to compare means between groups on a variable. The method is particularly useful to determine whether there is a statistically significant difference between the means of two or more distinct populations. The key distinction lies in the number of groups being analysed. An independent samples t-test is specifically designed to compare means between exactly two independent groups. In contrast, a two-way ANOVA is employed to compare means across three or more independent groups and the interaction.

In this study, the independent samples t-test was used to evaluate the significant difference in the mean of the various variables namely SSD comparing AD, 50% comparing 100%, GAA comparing granite and water curing comparing air curing. While two-way ANOVA was used to evaluate the significant different in the mean of various variables namely;

- (a) One (1) day demoulding, three (3) days demoulding, seven (7) days demoulding SSD comparing one (1) day demoulding, three (3) days demoulding, seven (7) days demoulding AD.
- (b) one (1) day demoulding, three (3) days demoulding, seven (7) days demoulding WC comparing one (1) day demoulding, three (3) days demoulding, seven (7) days demoulding AC.
- (c) One (1) demoulding, three (3) days demoulding, seven (7) days demoulding GAA comparing one (1) demoulding, three (3) days demoulding, seven (7) days demoulding granite.

The statistic results gained were used to conclude whether there are differences in the mean of the different variables as mentioned. The p -value (in term of probability, between 0 and 1 which known as α) is computed based on the compressive strength,

UPV and density value, flexural strength and modified compressive strength obtained with respect to the variables. The level of significance (α) is used to determine whether there is significant difference among the compressive strength, UPV and density value, flexural strength and modified compressive strength with respect to the variables. On that matter, if the p -value is less than or equal to α , it depicts that there is a significant difference on the compressive strength, UPV and density value, flexural strength and modified compressive strength. Otherwise, if the p -value is greater than α , it infers that there is no significant difference on the compressive strength, UPV and density value, flexural strength and modified compressive strength. Therefore, in the present study, compressive strength, UPV and density, flexural strength and modified compressive strength data was analysed using IBM SPSS statistic Version 29 procedure based on 5% (0.05) confident interval. The statistical analysis in corresponding to the compressive strength, UPV and density, flexural strength, modified compressive strength and the effects of related variables in this study are hypothesised as follows:

- $P > \alpha (0.05)$ = There is no difference on the compressive strength, UPV and density, flexural strength and modified compressive strength of concrete for using SSD or AD aggregate, GAA or granite, 50% replacement and full replacement of GAA, water curing or air curing, and effect of demoulding time.
- $P < \alpha (0.05)$ = There is difference on the compressive strength, UPV and density, flexural strength and modified compressive strength of concrete for using SSD or AD aggregate, GAA or granite, 50% replacement and full replacement of GAA, water curing or air curing, and effect of demoulding time.

CHAPTER 4

CHARACTERISATION OF MATERIALS AND INITIAL PERFORMANCE OF CONCRETE CONTAINING GREEN ARTIFICIAL AGGREGATE (GAA)

4.1 Introduction

This chapter presents the characteristics of green artificial aggregate (GAA) properties as a self-curing agent in concrete related to the initial performance of normal-strength concrete in terms of its mechanical properties containing 50% and 100% of GAA cured in water (WC) and air (AC). The physical characteristics of GAA, namely the density/specific gravity, water absorption and desorption, and texture of aggregate are presented. The mechanical property, in term of its Aggregate Crushing Value (ACV) is presented. Furthermore, the microscopic of GAA captured using Stereo Microscope and Mercury Intrusion Porosimetry (MIP) also discussed. All results obtained from GAA are compared with those obtained using granite aggregate. The compressive strength data for both batches, the one contained 50% and 100% GAA are presented. Subsequently, the influence of GAA towards concrete properties with curing and without proper curing process are discussed.

4.2 Characteristics of Coarse Aggregates

In this study, the GAA was used to replace either 50% or 100% of granite in the concrete mix. Prior to that, the physical characteristics of granite and GAA were tested in terms of specific gravity, water absorption, and water desorption. Meanwhile, the mechanical property of the granite and GAA was tested in terms of ACV. The physical and mechanical properties for both coarse aggregates, GAA and granite is shown in Table 4.1. The results are explained in the following sub-sections.

4.2.1 Specific Gravity

The specific gravity of granite and GAA is shown in Table 4.1. The recorded specific gravity of granite and GAA are 2.65 and 1.92, respectively. The specific gravity for GAA is lower than specific gravity of granite. The 28% difference in specific gravity between GAA and granite is attributed to the presence of voids and air spaces within the GAA. According to Przychodzień and Katzer (2021) and Demirboğa and Kan (2013), the density of lightweight aggregates is generally below 2000 kg/m³, and this was supported by Durga *et al.* (2018) and Chai *et al.* (2017). Therefore, GAA is classified as lightweight aggregate.

Table 4.1
Physical and Mechanical Properties of Coarse Aggregate Used in the Present Study

Properties	Granite	GAA	Standard for testing
Physical properties			
Specific gravity	2.65	1.92	ASTM C127, 2015
Water absorption (%)	0.32	10.6	ASTM C127, 2015
Shape & surface texture	Angular & smooth	Spherical & rough	-
Mechanical properties			
Aggregate crushing value (ACV) (%)	17.6	24.35	BS 812-110, 1990
Aggregate crushing resistance (100 – ACV) (%)	82.4	75.65	

4.2.2 Water Absorption

Water absorption for granite and GAA are tabulated in Table 4.1 as shown in Section 4.2.1. The recorded water absorption for granite and GAA are 0.32 % and 10.6 %, respectively. It shows the water absorption in GAA is more than thirty (30) times higher than those of granite due to the pores inside the GAA. In contrast, granite shows almost no water absorption. Water absorption is an important property when considering the use of aggregates in concrete mixes, particularly in the context of self-curing concrete (Ahmed *et al.*, 2021; Grabiec *et al.*, 2020). The high-water absorption of GAA makes it a more suitable and potential aggregate for self-curing concrete. The porous nature of GAA allows it to absorb and store water during the mixing and casting

of the concrete. Over time, as the concrete dries, the stored water can be gradually released from the GAA aggregates, helping to maintain the necessary moisture levels within the concrete for continued hydration and curing. Figure 4.1 depicts the coloured pigment surrounding the GAA as absorbed water. The average depth of water absorbed by GAA was 1.29 mm after 24 hours of immersion in pigmented water.

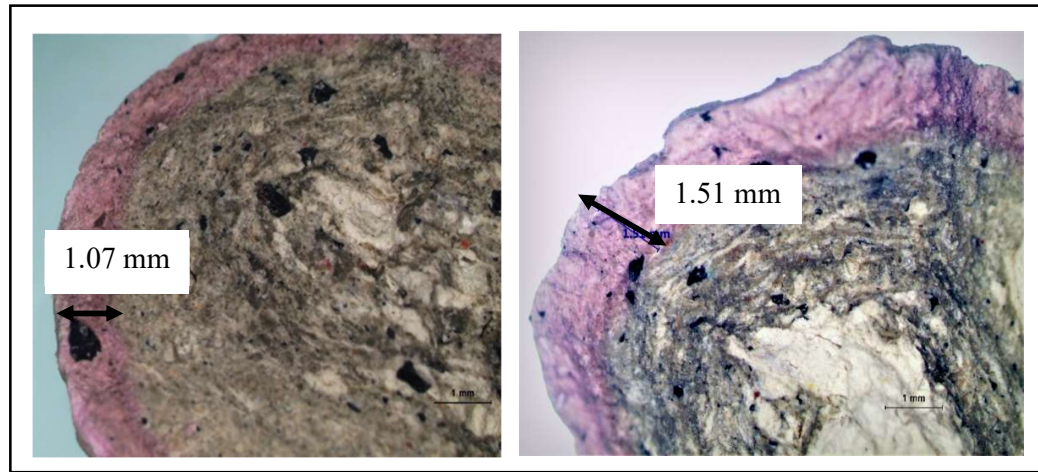


Figure 4.1 Water Absorption of GAA after 24 Hours Soaked in Pigmented Water

4.2.3 Aggregate Crushing Value (ACV)

Table 4.1 in Section 4.2.1 shows the results of ACV of granite and GAA. The recorded ACV for GAA and granite were 24.35% and 17.6%, respectively. The percentage of ACV for GAA is still considered as good related to quality assessment scale indicating comparable strength to granite and suitable to be used in concrete mix (BS EN 12620, 2002). In addition, it also means that the GAA produces a higher percentage of debris particles than granite if the same compressive load is applied. This might be because of inherent porosity in GAA, which weakens the aggregate structure and makes it more prone to deformation and fragmentation under compressive loading condition. Therefore, the aggregate crushing resistance of granite and GAA are 82.4%, and 75.65% respectively. It infers that granite possesses higher resistant towards crushing load. ACV is related on the strength properties of aggregates itself (Hossain *et al.*, 2012; Iffat *et al.*, 2017; Zhutovsky & Kovler, 2017; Ma *et al.*, 2019). Previous researchers found that the strength of concrete reduced as the replacement of lightweight aggregate increased which the latter associates with low strength (Grabiec

et al., 2020; Rasheed & Abdulrasool, 2020; Costa *et al.*, 2012; Raoufi *et al.*, 2011). According to BS EN 12620 (2002), aggregate with a crushing value below 25% is suited for heavy-duty floors, while value beyond 30% is more appropriate for concrete wearing surfaces. Aggregate with a crushing value exceeding 45% can be utilised for various concrete purpose.

4.2.4 Water Desorption

Since granite almost does not absorb water, the desorption test for granite is not performed. The desorption test results for specimen of concrete containing GAA after soaking in pigmented water at 14 days is shown in Figure 4.2. The measurement of water desorption through distance from the outer surface of LWA to the cement paste has been established by previous researchers as an effective method by which internal curing effectiveness in concrete can be evaluated (Akçay & Tasdemir, 2010; Lura, 2003). The estimated average distance of water movement from pre-wetted GAA to cement paste in the concrete specimen was 0.77 mm. The results showed that the absorbed water moved at an average distance of 0.77 mm from the pre-wetted GAA into the cement paste. This distance was compared to the total absorption distance capacity of the pre-wetted GAA, which was measured at average distance of 1.29 mm. The ratio between these distances ($0.77 \text{ mm} / 1.29 \text{ mm}$) indicates that approximately 61% of the absorbed water was released from the pre-wetted GAA into the surrounding cement paste matrix. This water release ratio suggests that pre-wetted GAA effectively functions as an internal water reservoir, contributing to the internal curing process. The release of approximately 61% of its stored water demonstrates the capability of aggregate to provide supplementary water to the surrounding cement paste during the hydration process, potentially benefiting the microstructural development of concrete and reducing the risk of self-desiccation. Figure 4.3 shows a desorption behaviour of GAA exposed at different Relative Humidity (RH). At 97% RH, the GAA released 52% of its absorbed water. The curve becomes steeper almost plateau and steeper again, indicating rapid in water release rates as RH reduces. The absorption for 24 hours was selected as it is frequently used in practice by previous researchers to saturate LWAs for internal curing (Aghaee & Khayat, 2023; Xu *et al.*, 2021). According to ASTM C1761 (2017), LWA is acceptable for internal curing if absorbed water is released readily. This occurs when internal relative humidity (RH) of the concrete

reduces owing to self-desiccation. The water release rate of the aggregates are affected by RH and types of aggregates (D. Zou et al., 2018). Based on the results from Figures 4.2 and 4.3, it is indicated that GAA is a potential to be used as an internal curing agent in concrete due to its capability to release absorbed water.

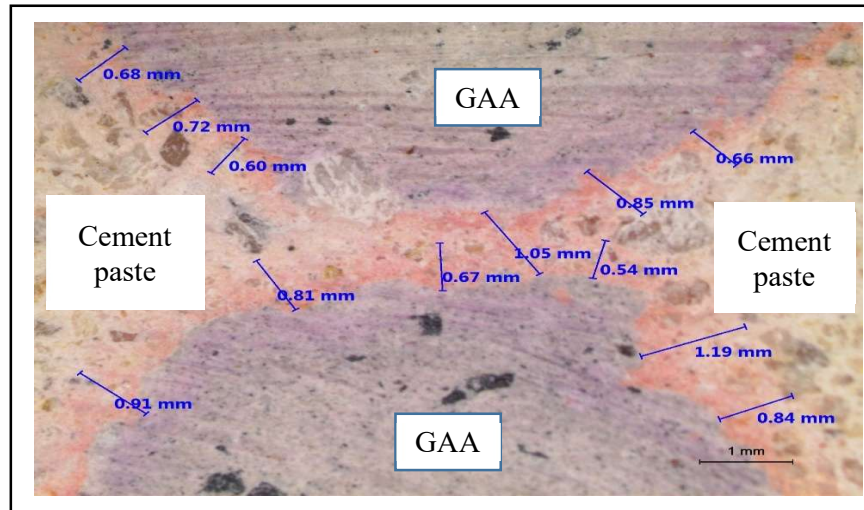


Figure 4.2 The Water Movement in the Concrete Specimen Containing GAA Shows From Pre-Wetted GAA to Cement Paste

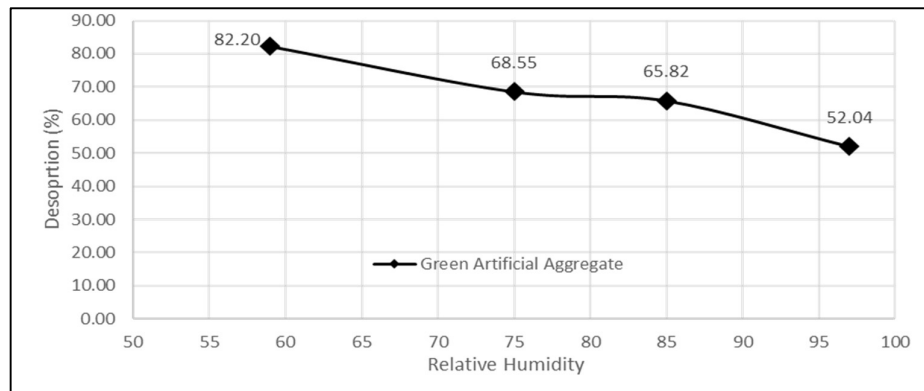


Figure 4.3 Water Desorption Properties of Pre-Wetted GAA at Different RH

The water migration from GAA to the concrete paste is based on the law of fluid flow and the system's law of capillary attraction (Nguyen & Le, 2018), whereby the radius of pores in cement paste is smaller than the pores in GAA. Capillary suction pressure generated by capillary pores in concrete is greater than the capillary suction pressure in GAA pores, causing of water movement from GAA to the concrete capillary pores for the curing process during the self-desiccation of concrete (Zhutovsky *et al.*,

2011, Bandara *et al.*, 2019). Therefore, the diagram of the movement of water from pre-wetted GAA to the cement paste is illustrated in Figure 4.4. It can be said that GAA studied presently are able to be used as self-curing agent in concrete.

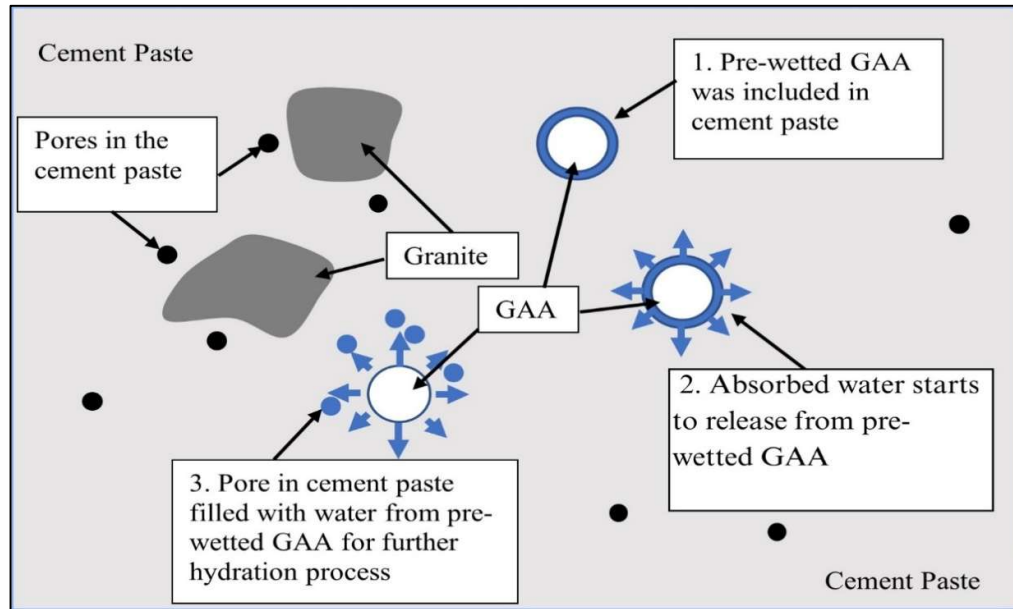


Figure 4.4 The Model Illustrating the Movement of Water from Pre-Wetted GAA to Cement Paste

4.3 Morphology and Microstructure of Aggregates

The morphology and microstructure of the GAA was investigated through Stereo Microscope and MIP test. The results are reported and discussed in the following sub-sections.

4.3.1 Stereo Microscope

Stereo Microscope was used to examine the morphological structure of GAA and granite. Figure 4.5 shows the stereo microscope image of GAA and granite used in concrete. The GAA consists of spherical shape and rough surface texture compared to that granite which is irregular shape, and the texture is smooth. Spherical aggregates improve the workability of fresh concrete, while a rough surface contact area allows a better adherence to cement paste and increases the splitting tensile strength of the

concrete (Douglas & Garboczi, 2007; Matias *et al.*, 2013; Mehta & Monteiro, 2014; Balapour *et al.*, 2020).

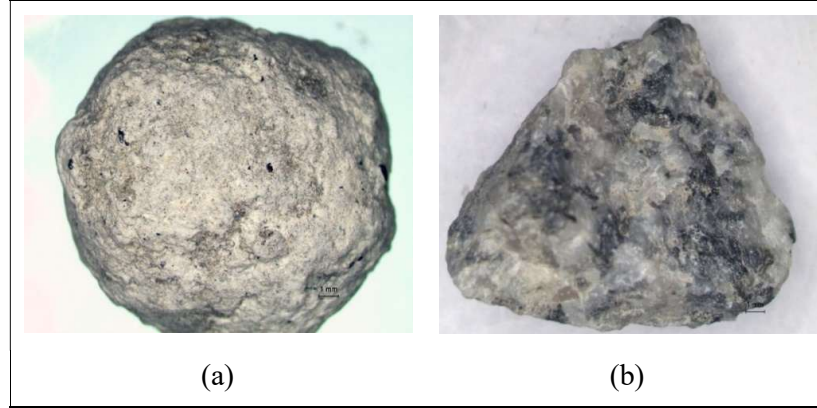


Figure 4.5 Image of (a) GAA and (b) Granite (Magnification 0.67x~4.5x)

4.3.2 Mercury Intrusion Porosimetry (MIP)

Previous researchers reported that when the pores of the self-curing agents are very small whereby less than 100 nm, the internal curing effect does not occur due to the difficulty in releasing the stored water into the paste caused by the phenomenon of capillary suction inside the pores (J.H. Kim *et al.*, 2018). Figure 4.6 depicts the pore size distribution of GAA as determined by MIP. The pores of GAA were in the range of 100 to 600 nm size with multiple continuous peaks, with 52% pores being greater than or equal to 100 nm. It was observed that the larger the pore diameter, the higher the peak pore volume, indicating that GAA can act as an internal reservoir for water. These pores can store the amount of water and gradually release it into the cement paste to promote the continued hydration process. According to Gao *et al.* (2021), the pore size of granite showed multiple discontinuous peaks, indicating that the granite was a dense rock with poor pore connectivity as shown in Figure 4.7.

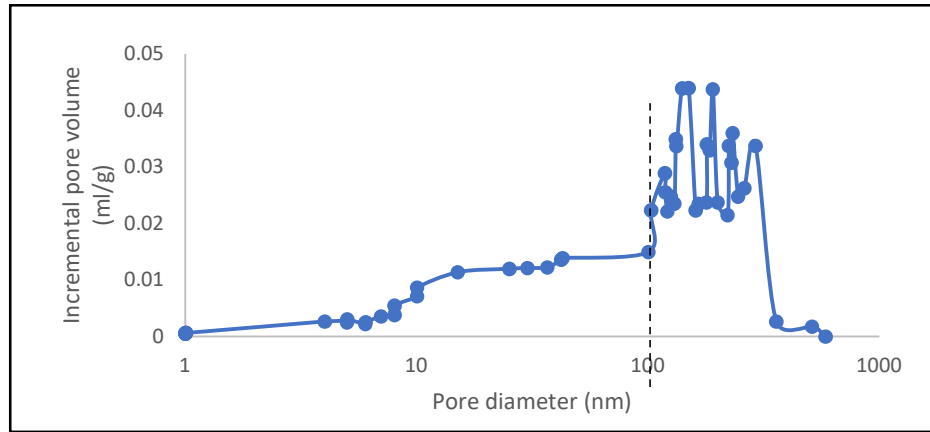


Figure 4.6 Pore Size Distribution of GAA

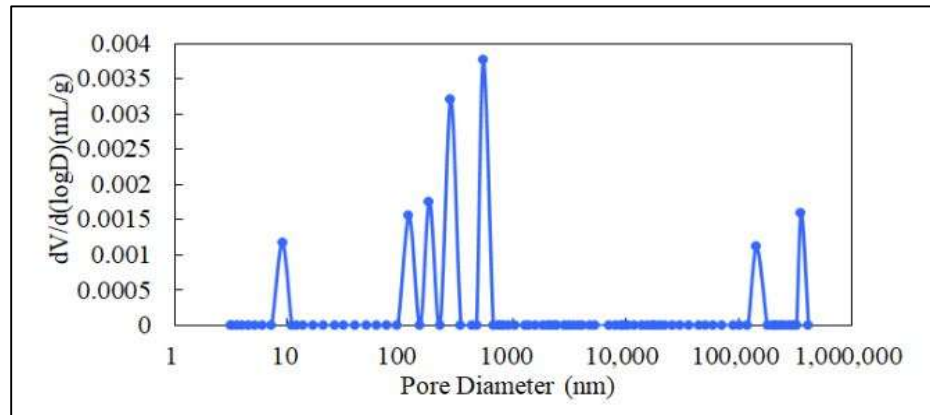


Figure 4.7 Pore Size Distribution of Granite

Source: (Gao *et al.*, 2021)

4.4 Workability of Concrete With and Without GAA

The percentage of GAA replacement used in this study was 50% and 100% of the granite content, while the use of 100% granite in concrete was used as a reference. Thus, the mix design deals with different percentage of aggregate replacement specimen. The aggregates used were divided into two (2) conditions where the first condition is saturated-surface-dry (SSD) after soaking in the water for 24 hours, and the second condition is air-dry (AD) which are designated as SSD GAA and AD GAA, respectively. Then, the concrete specimens containing the two (2) conditions of aggregates were cured in water curing and air curing. The effect of incorporating SSD and AD GAA in concrete mix towards to slump values with constant water-cement ratio is presented in Figure 4.8. It exhibits a decrease in slump values as the proportion of

AD GAA increases in the mixes. The slump of fresh concrete decreased by 26% when 50% of the granite was replaced with AD GAA and further reduced to 40% when 100% of the granite was replaced with AD GAA. The reduction in slump can be attributed to the water absorption capacity of AD GAA. This finding was also supported by Tang *et al.* (2017), who reported that additional water is needed during the mixing if LWA is used to produce fresh concrete with good workability. Conversely, it was found that slump increases as the proportion of SSD GAA increases in the mixes. The slump of fresh concrete increases by about 2% to 5% when 50% of the granite is replaced with SSD GAA and further rises by about 6% to 7% when 100% of the granite is replaced by SSD GAA. This is because of the moisture that contains near to the surface of GAA and their round shape improved the workability of the concrete that made of such aggregate.

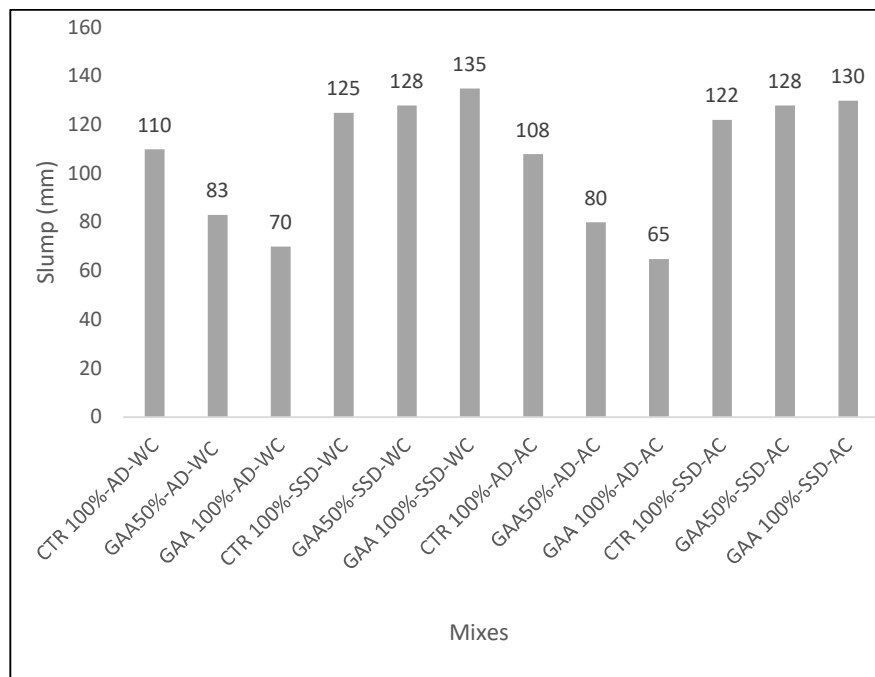


Figure 4.8 Slump (in mm) of Fresh Concrete Containing 50% and 100% GAA Which Prior to That are in SSD and AD Conditions

4.5 Compressive Strength of Concrete With and Without GAA

The compressive strength of concrete is one of the most important properties in evaluating the performance and quality of concrete. The compressive strength and percentage of increase in concrete strength from 3 days, to 7 days and 28 days of concrete specimens made of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA), control concrete (CTR) cured in water curing conditions are summarised in Table 4.2. As can be seen in Table 4.2, it is revealed that the compressive strength decreased at all ages as the proportion of GAA increased. The compressive strength of control concrete, CTR 100%-AD-WC, was the highest at all ages compared to the rest of the series specimens. However, at early age, the ratio of the concrete specimens made of AD GAA and SSD GAA from 3 days to 7 days were, 1.34 and 1.32 times higher, compared to concrete containing AD granite as control. This suggests that the use of GAA contributes to improved early-age strength development. The compressive strength of concrete specimens made of AD GAA are higher than concrete specimens made of SSD GAA, at an early age, may be attributed to the AD GAA in concrete mix absorbing the water in cement paste, causing the decrease in water-cement ratio and later on water stored in AD GAA gradually releasing water during the hydration process. At later age, the ratio of the concrete specimens made of SSD GAA and concrete specimens made of 50% SSD GAA from 7 days to 28 days were 2.77 and 1.81 times higher compared to concrete containing AD granite as control. The observed results may be due to the water that was absorbed and stored within the SSD GAA functions as an internal reservoir, progressively releasing water during the hydration process. The prolonged availability of water ensures continued hydration of cement particles, particularly beneficial for later-age strength development. Concrete containing SSD GAA and AD GAA cured in water is achieving the targeted design concrete strength, which is a minimum of 30 MPa for the 28-day strength, even though there is a full replacement of granite with GAA. It shows and proves that GAA is effectively acting as an agent for self-curing.

Table 4.2

The Compressive Strength and Percentage of Increase for Concrete Specimens at 3 Days, 7 Days, and 28 Days of Age Cured in Water

Types	Compressive Strength (MPa)			Percentage of increase concrete strength from 3 days to 7 days (%)	Percentage of increase concrete strength from 7 days to 28 days (%)	Ratio of increase concrete strength from 3 days to 7 days	Ratio of increase concrete strength from 7 days to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	32.44	38.55	42.69	18.81	10.74	1.00	1.00
GAA 50%-AD-WC	28.15	33.54	38.42	19.13	14.56	1.02	1.36
GAA 100%-AD-WC	24.45	30.64	36.52	25.30	19.21	1.34	1.79
CTR 100%-SSD-WC	32.28	38.11	42.28	18.09	10.93	0.96	1.02
GAA 50%-SSD-WC	27.41	32.70	39.06	19.28	19.45	1.02	1.81
GAA 100%-SSD-WC	23.32	29.13	37.80	24.91	29.77	1.32	2.77

The compressive strength and percentage of increase in concrete strength from 3 days, to 7 days and 28 days of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA) and control concrete (CTR) cured air are summarised in Table 4.3. As can be seen in Table 4.3, it is shown that the compressive strength decreased at all ages as the proportion of GAA increased. The compressive strength of control concrete, CTR 100%-AD-AC, was the highest at all ages compared to all other specimens. However, at early age, the ratio of the concrete specimens made of AD GAA and SSD GAA from 3 days to 7 days were, 1.43 and 1.59 times higher, compared to concrete containing AD granite as control. The compressive strength for concrete specimens made of SSD GAA are higher than concrete specimens made of AD GAA, at an early age. This can be attributed to the enhanced internal curing effect, where the saturated-surface dry (SSD) aggregates provide a steady supply of water for continued hydration. At later age, the ratio of the concrete specimens made of SSD GAA and concrete specimens made of 50% SSD GAA from 7 days to 28 days were 2.59 and 2.05 times higher compared to concrete containing AD granite as control. This enhanced strength development can be attributed to internal curing mechanism of GAA, whereby water stored within porous structure of aggregate is gradually released to sustain hydration processes. The SSD conditioning method proved particularly advantageous, creating an optimal internal moisture reservoir that facilitated prolonged cement hydration. Hence, it is feasible to substitute complete granite with GAA in concrete, rendering it suitable for both domestic and commercial construction. It also indicates that GAA is effectively acting

as curing agent for self-curing in air condition. As the concrete cures in air, the cement paste begins to lose moisture due to evaporation and internal consumption during hydration reactions. This creates a humidity gradient between the cement paste and the water-filled pores of the GAA. In response to this gradient, water slowly migrates from the GAA into the surrounding cement paste.

Table 4.3

The Compressive Strength and Percentage of Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Air

Types	Compressive Strength (MPa)			Percentage of increase concrete strength from 3 days to 7 days (%)	Percentage of increase concrete strength from 7 days to 28 days (%)	Ratio of increase concrete strength from 3 days to 7 days	Ratio of increase concrete strength from 7 days to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-AC	26.71	30.83	34.67	15.45	12.45	1.00	1.00
GAA 50%-AD-AC	22.38	26.32	30.24	17.60	14.91	1.14	1.20
GAA 100%-AD-AC	18.10	22.10	27.73	22.09	25.46	1.43	2.05
CTR 100%-SSD-AC	25.20	29.70	34.13	17.84	14.92	1.15	1.20
GAA 50%-SSD-AC	21.39	26.10	31.34	22.01	20.09	1.42	1.61
GAA 100%-SSD-AC	17.61	21.92	28.99	24.49	32.22	1.59	2.59

Table 4.4 shows the compressive strength and ratio of percentage of increase on concrete strength from 3 days, to 7 days and 28 days for air-dried GAA (AD GAA), surface-dried GAA (SSD GAA) and control concrete (CTR) cured in water and air. The compressive strength of control concrete cured in water, CTR 100%-AD-WC, was the highest at all ages in comparison with other series of concrete specimens. However, at early age, the ratio of the concrete specimens made of AD GAA and SSD GAA cured in air were 1.17 and 1.30 times higher compared to control concrete containing AD granite cured in water. Same result was observed at later age, whereby the ratio of the concrete specimens made of SSD GAA and concrete specimens made of AD GAA cured in air were 3 and 2.37 times higher compared to concrete containing AD granite cured in water, respectively. While concrete specimens cured in water achieved higher compressive strength than those cured in air. The ratio percentage increase in compressive strength over time is actually greater for those of air-cured specimens compared to water-cured specimens as shown in Figure 4.9. This phenomenon can be attributed to the self-curing mechanism, wherein the internal moisture retention and

gradual release of water from GAA as curing agents facilitate continued hydration despite the absence of external water supply. The enhanced percentage strength gained in air-cured specimens suggests that the self-curing process effectively compensates for the limited external moisture availability by maintaining a favourable internal RH, conducive to sustain cement hydration. While SSD GAA concrete generally shows higher ratios in the later curing period (7-28 days), AD GAA concrete demonstrated more consistent strength development across both time intervals. This suggests that pre-saturated aggregates may have a delayed but more pronounced self-curing effect, possibly due to their higher initial moisture content providing sustained hydration benefits over longer periods. Despite the GAA concrete containing SSD aggregate and AD aggregate not achieving the minimum targeted design strength of 30 MPa at 28 days under air curing conditions, these mixes still demonstrate viable for lower strength element purpose. As established by Barakat *et al.* (2025), normal strength concrete with compressive strengths ranging from 25 MPa to 55 MPa finds widespread use across various structural applications. This compressive strength range validates the complete substitution of granite with GAA in concrete as a feasible option for both domestic and commercial construction purposes. The effectiveness of GAA as a self-curing agent under air-cured conditions is evidenced by its internal moisture regulation mechanism. When concrete cures in air, moisture loss occurs in the cement paste through evaporation and hydration processes, establishing a humidity gradient between the cement paste and the water-filled pores within the GAA. This gradient facilitates the gradual migration of water from the GAA to the surrounding cement paste. By utilising AD GAA rather than SSD GAA in concrete, it eliminates pre-wetting steps while delivering sufficient 28-day compressive strength (27.73 MPa) for structural application. While the highest compressive strength at all ages was achieved by control concrete, the feasibility of 100% GAA replacement as a self-curing agent rather than the achievement of optimal strength is prioritised in this research. The 50% replacement serves as a comparative benchmark through which transition characteristics can be evaluated. Practically, on-site proportioning of two different aggregate types is eliminated by 100% replacement, whereby batching errors are reduced and quality control is improved. Furthermore, sustainability is maximised by complete replacement through the utilisation of waste materials and the complete elimination of natural aggregate extraction. The adoption of GAA in construction practice presents economic advantages, particularly in resource-constrained environments. The elimination of

continuous water curing requirements translates to reduced water consumption, decreased labour allocation for curing operations, simplified construction scheduling and reduced project costs. These benefits are particularly pronounced in infrastructure development projects in arid regions, where water scarcity necessitates careful resource management and where traditional curing methods may be economically prohibitive.

Table 4.4

The Compressive Strength and Ratio of Percentage Increased for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air

Types	Compressive Strength (MPa)			Percentage of increase concrete strength from 3 to 7 days (%)	Percentage of increase concrete strength from 7 to 28 days (%)	Ratio of % increased concrete strength from 3 to 7 days	Ratio of % increased concrete strength from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	32.44	38.55	42.69	18.81	10.74	1.00	1.00
GAA 50%-AD-WC	28.15	33.54	38.42	19.13	14.56	1.02	1.36
GAA 100%-AD-WC	24.45	30.64	36.52	25.30	19.21	1.34	1.79
CTR 100%-SSD-WC	32.28	38.11	42.28	18.09	10.93	0.96	1.02
GAA 50%-SSD-WC	27.41	32.70	39.06	19.28	19.45	1.02	1.81
GAA 100%-SSD-WC	23.32	29.13	37.80	24.91	29.77	1.32	2.77
CTR 100%-AD-AC	26.71	30.83	34.67	15.45	12.45	0.82	1.16
GAA 50%-AD-AC	22.38	26.32	30.24	17.60	14.91	0.94	1.39
GAA 100%-AD-AC	18.10	22.10	27.73	22.09	25.46	1.17	2.37
CTR 100%-SSD-AC	25.20	29.70	34.13	17.84	14.92	0.95	1.39
GAA 50%-SSD-AC	21.39	26.10	31.34	22.01	20.09	1.17	1.87
GAA 100%-SSD-AC	17.61	21.92	28.99	24.49	32.22	1.30	3.00

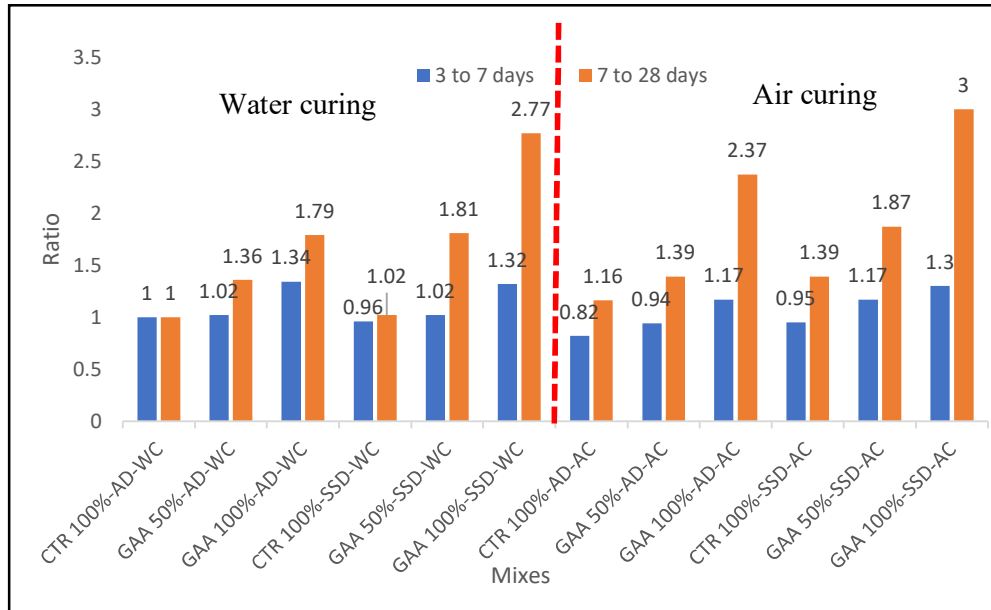


Figure 4.9 Ratio of Percentage Increment of Compressive Strength From 3 to 7 Days and 7 to 28 Days Cured in Water and Air

The mode of failure pattern for control concrete, concrete containing 100% AD and SSD GAA cured in water is shown in Figure 4.10. Most failure sections of all concrete specimens at 28 days exhibited failure on aggregate, indicating that cement matrix strength exceeded aggregate strength. This occurred because specimens were properly water-cured, ensuring complete cement hydration, which is crucial for strength development as noted by other researchers. (Butler, 2012; Siregar, 2020). Besides, it is assumed that the absorbed water from GAA is released for self-curing in hydrating cement pastes apart from the complete hydration process due to cured in water. The mode of failure pattern for control concrete, concrete containing 100% AD and SSD GAA cured in air is shown in Figure 4.11. Figure 4.11 shows that the failure section of the specimens was consists of two parts: (1) failure through paste and (2) failure on aggregate. Aggregate failure refers to physical fracture of GAA particles within the concrete matrix. It was observed that GAA particles were fractured into two or more pieces along their weakest planes, with the aggregate typically being bisected longitudinally. This trans-aggregate fracture behaviour is typical of porous aggregates with lower mechanical strength than conventional granite (Bogas & Gomes, 2013). Control concrete, refer to Figure 4.10 (a) and 4.11(a) recorded failure through cement matrix estimated about 50% and similarly, failure on aggregate 50%. Concrete containing AD GAA, refer to Figure 4.10 (b) and 4.11 (b) was also recorded failure

through cement matrix was about 30% and failure on aggregate 70%. Concrete cube made of SSD GAA, refer to Figure 4.10 (c) and 4.11 (c) recorded failure through cement matrix about 40% and failure on aggregate about 60%. The failure pattern percentage distribution was determined by assessing the proportion of each failure type across the entire failure plane by visual quantification method (Siregar, 2020). The observed outcomes can be ascribed to the internal reservoir function of the water absorbed and retained within the GAA, which progressively discharges water throughout the hydration process caused strength development increase (Butler, 2012; Siregar, 2020). In addition, the intrinsic porosity in GAA weakens the aggregate structure, increasing its susceptibility to deformation and fragmentation when subjected to compressive pressure.

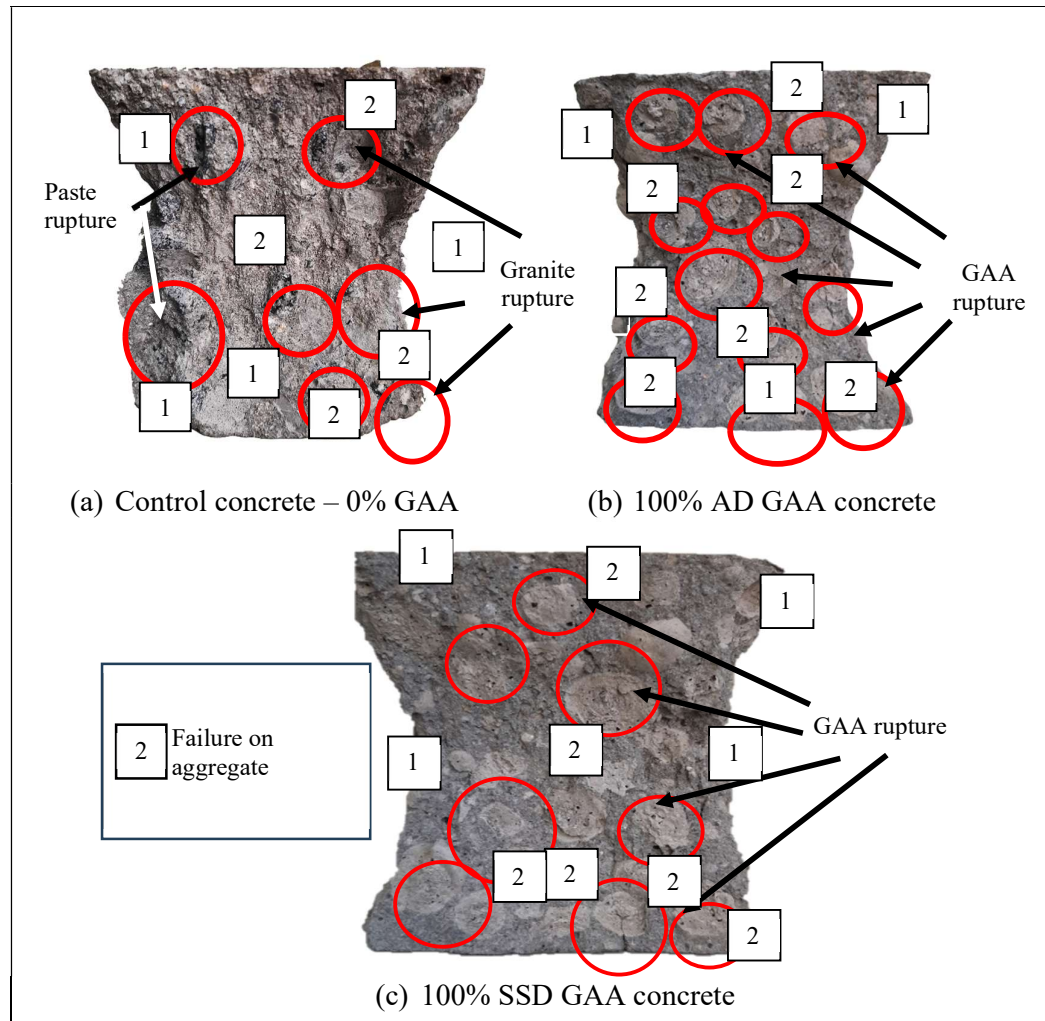


Figure 4.10 Failure Pattern of Concrete Cube Made of Granite, AD and SSD GAA Cured in Water After Compression Test at Age of 28 Days

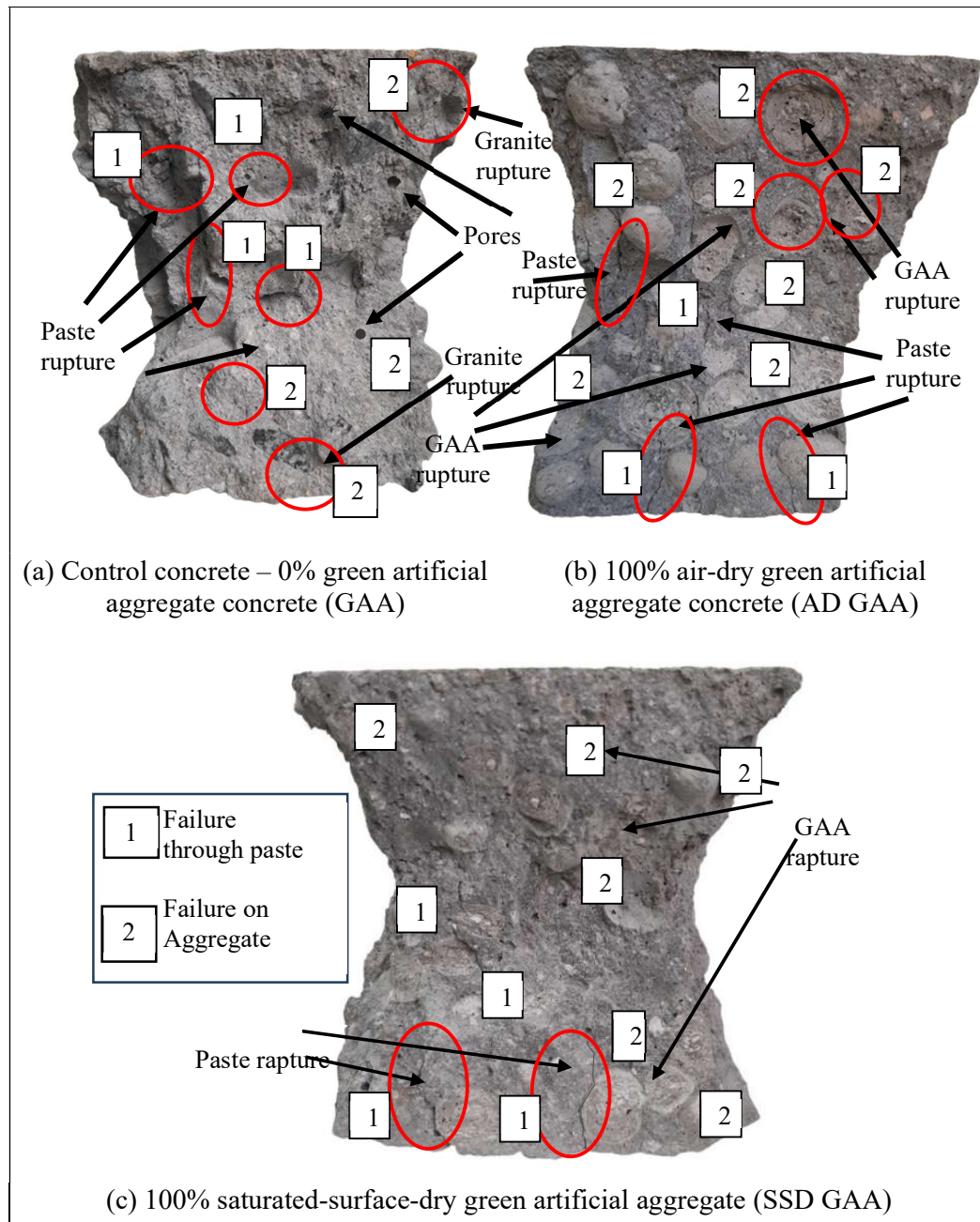


Figure 4.11 Failure Pattern of Concrete Made of Granite, AD and SSD GAA Cured in Air After Compression Test at Age of 28 Days

4.6 Ultrasonic Pulse Velocity (UPV) of Concrete With and Without GAA

The UPV results and percentage of increase in UPV for control concrete and GAA concrete specimens from at age 3 days to 7 days and 28 days of concrete containing AD GAA, SSD GAA and control concrete (CTR) cured in water are summarised in Table 4.5. As can be seen in Table 4.5, it is shown that the UPV decreases as the proportion of GAA increases. This was because of the presence of air voids in the GAA, whereas pulse waves took longer time to be transmitted through air voids in a material. Moreover, it might be that the GAA was in round shape which gave up lower propagation speeds than specimens containing irregular shape of natural aggregate (Hannachi & Guetteche, 2012; Ndagi *et al.*, 2019). The control concrete mixture (CTR 100%-AD-WC) had the highest ultrasonic pulse velocity (UPV) at all testing ages compared to all other concrete specimens. However, during early curing, the UPV increase ratio from 3 days to 7 days was 1.74 times higher for concrete made with 100% air-dried GAA and 1.18 times higher for concrete made with 100% saturated surface-dry GAA, when compared to concrete containing air-dried granite. This suggests that the use of GAA contributes to improve early-age strength development indicating a denser and more homogenous concrete. The results for the concrete specimens made of 100% AD GAA are higher than those made of 100% SSD GAA at an early age may be attributed to the AD GAA in the concrete mix absorbing the water in cement paste, resulting in a decrease in the water-cement ratio. Subsequently, the water stored in AD GAA gradually releases water during the hydration process. At later age, the ratio of the UPV for those concrete specimens made of 100% SSD GAA and concrete specimens made of 100% AD GAA from the UPV measured at 7 days to 28 days were 1.49 and 1.44 times higher compared to concrete containing AD granite, respectively. The reported results could be attributed to the water that is absorbed and stored within the SSD aggregates. The GAA acts as an internal reservoir, gradually releasing water throughout the hydration process. The prolonged availability of water supports the continual hydration of cement particles, which is especially important for later-age strength development.

Table 4.5

The UPV and Percentage of Increase Measured at 3 Days to 7 Days and 28 Days of Concrete Specimens Containing AD GAA, SSD GAA and Control Concrete (CTR) Cured in Water

Types	UPV (km/s)			Percentage of increase UPV from 3 to 7 days (%)	Percentage of increase UPV from 7 to 28 days (%)	Ratio of increase UPV from 3 to 7 days	Ratio of increase UPV from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	4.21	4.29	4.58	1.91	6.29	1.00	1.00
GAA 50%-AD-WC	4.06	4.14	4.51	2.02	8.15	1.06	1.30
GAA 100%-AD-WC	3.78	3.91	4.30	3.32	9.07	1.74	1.44
CTR 100%-SSD-WC	4.16	4.21	4.57	1.39	7.71	0.73	1.22
GAA 50%-SSD-WC	4.04	4.13	4.46	2.01	7.48	1.06	1.19
GAA 100%-SSD-WC	3.85	3.94	4.35	2.26	9.35	1.18	1.49

The UPV and percentage increase measured at 3 days, to 7 days and 28 days of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA) and control concrete (CTR) cured in air are summarised in Table 4.6. As can be seen in Table 4.6, it is shown that as the proportion of GAA in the concrete reached 100%, a comparable trend of decreased in UPV was observed at all ages. The UPV of control concrete, CTR 100%-AD-AC, was the highest at all ages compared to all specimen concrete. However, at early age, the ratio of the concrete specimens made of 100% AD GAA and 100% SSD GAA from 3 days to 7 days were, 1.5 and 1.2 times higher, compared to concrete containing AD granite, respectively. The results for concrete specimens made of 100% AD GAA are higher at an early age than concrete specimens made of 100% SSD GAA, can be attributed to a dual mechanism: firstly, the initial absorption of water from the cement paste by AD GAA, which effectively reduces the water-cement ratio. Secondly, the subsequent gradual release of this absorbed water during the hydration process. This phenomenon, akin to internal curing, facilitates continued cement hydration, thereby promoting enhanced early-age strength development in the AD GAA concrete specimens. At later ages of UPV, the concrete specimens made with 100% SSD GAA showed a UPV increase ratio 2.23 times higher from 7 days to 28 days, while concrete specimens made with 100% AD GAA showed a UPV increase ratio 1.5 times higher during the same period, both compared to concrete containing AD granite. The results that have been observed may be ascribed to the water that was absorbed and stored within SSD GAA which serves as an internal reservoir that gradually was released during the hydration process. The prolonged availability of water ensures continued

hydration of cement particles, particularly beneficial for later-age on the UPV development. According to Neville (2011), a pulse velocity greater than 4.5 km/s generally exhibits concrete with excellent quality. Therefore, in this study, most of the UPV value readings range from 3.5 km/s to 4.5 km/s indicated that the concrete specimens are considered as good quality. This finding was particularly important for sustainable construction applications, as it demonstrated the viability of GAA as a complete replacement for conventional aggregates without compromising fundamental concrete quality metrics.

Table 4.6

The UPV and Percentage of Increase from 3 Days to 7 Days and 28 Days of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Air

Types	UPV (km/s)			Percentage of increase UPV from 3 to 7 days (%)	Percentage of increase UPV from 7 to 28 days (%)	Ratio of increase UPV from 3 to 7 days	Ratio of increase UPV from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-AC	3.78	3.92	4.06	3.54	3.44	1.0	1.00
GAA 50%-AD-AC	3.59	3.73	3.86	3.83	3.37	1.1	0.98
GAA 100%-AD-AC	3.51	3.71	3.91	5.43	5.17	1.5	1.50
CTR 100%-SSD-AC	3.74	3.85	3.96	2.91	2.67	0.8	0.78
GAA 50%-SSD-AC	3.63	3.76	3.92	3.56	4.05	1.0	1.18
GAA 100%-SSD-AC	3.54	3.69	4.00	4.16	7.68	1.2	2.23

Table 4.7 shows the UPV and ratio of percentage increased in UPV from 3 days, to 7 days and 28 days of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA) and control concrete (CTR) cured in water and air. The experimental investigation revealed that the control concrete cured in water (CTR 100%-AD-WC) showed the highest overall UPV values. Nevertheless, a noteworthy observation emerged during the early-age of UPV development, where concrete specimens incorporating complete replacement with AD GAA and SSD GAA under air-curing conditions demonstrated remarkably UPV development ratio of 2.85 and 2.18 times higher, respectively, compared to the water-cured control specimens containing AD granite. This efficient early internal water supply triggered accelerated hydration reactions, resulting in quick early-age densification and higher UPV development ratios compared to traditionally water-cured specimens. This pattern continued into the later age ratio of percentage UPV development, where the percentage UPV development ratios of air-cured

specimens containing both fully SSD GAA and fully AD GAA maintained comparable values to the water-cured control concrete as shown in Figure 4.12. SSD GAA showed a higher UPV development ratio (1.22) compared to AD GAA (0.54) cured in air. This significant difference indicated that surface-dried GAA retained its internal moisture reserves more effectively for later-age hydration, while air-dried GAA might have depleted its internal moisture more rapidly during the early accelerated hydration phase. This comparison highlighted how aggregate moisture condition significantly influenced self-curing effectiveness, with SSD GAA proving more reliable for sustained internal curing while AD GAA excelled primarily in accelerated early-age development. Although water-cured specimens generally achieved higher UPV values, the comparable percentage ratio of UPV development in air-cured specimens suggests effective internal moisture regulation through the self-curing mechanism. This phenomenon can be attributed to the porous nature of GAA, which acts as an internal water reservoir, facilitating continued hydration by gradually releasing moisture to the surrounding cement matrix even without external water curing.

Table 4.7
The UPV and Ratio of Percentage Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air

Types	UPV (km/s)			Percentage of increase UPV from 3 to 7 days (%)	Percentage of increase UPV from 7 to 28 days (%)	Ratio of increase UPV from 3 to 7 days	Ratio of increase UPV from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	4.21	4.29	4.58	1.91	6.29	1.00	1.00
GAA 50%-AD-WC	4.06	4.14	4.51	2.02	8.15	1.06	1.30
GAA 100%-AD-WC	3.78	3.91	4.30	3.32	9.07	1.74	1.44
CTR 100%-SSD-WC	4.16	4.21	4.57	1.39	7.71	0.73	1.22
GAA 50%-SSD-WC	4.04	4.13	4.46	2.01	7.48	1.06	1.19
GAA 100%-SSD-WC	3.85	3.94	4.35	2.26	9.35	1.18	1.49
CTR 100%-AD-AC	3.78	3.92	4.06	3.54	3.44	1.86	0.55
GAA 50%-AD-AC	3.59	3.73	3.86	3.83	3.37	2.00	0.54
GAA 100%-AD-AC	3.51	3.71	3.91	5.43	5.17	2.85	0.82
CTR 100%-SSD-AC	3.74	3.85	3.96	2.91	2.67	1.52	0.42
GAA 50%-SSD-AC	3.63	3.76	3.92	3.56	4.05	1.86	0.64
GAA 100%-SSD-AC	3.54	3.69	4.00	4.16	7.68	2.18	1.22

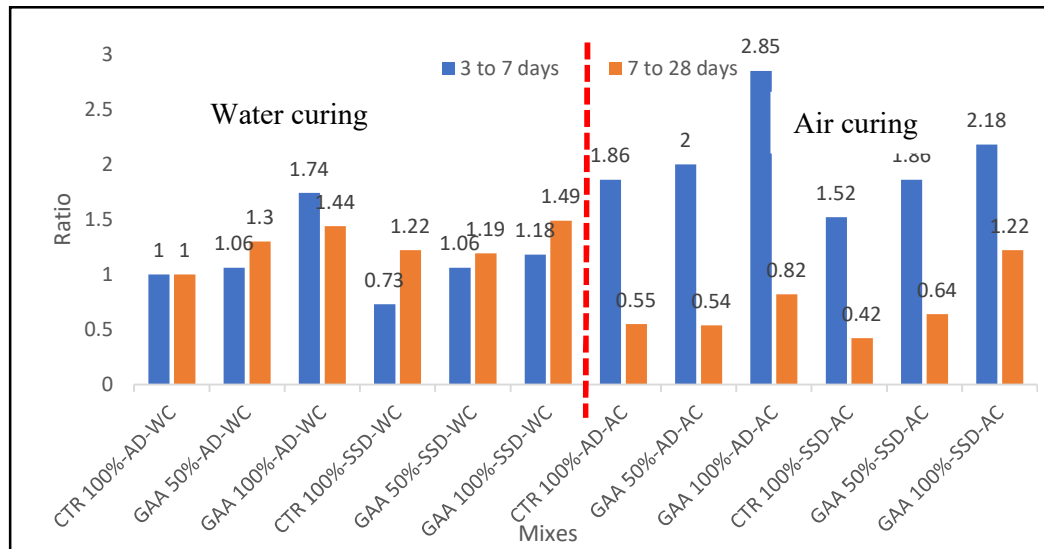


Figure 4.12 Ratio of Percentage Increment of UPV From 3 to 7 Days and 7 To 28 Days Cured in Water and Air

4.7 Density

The density of concrete containing GAA was determined by dividing the average weight value of three (3) specimens by their volume after being surface dried. The dry density values of the specimen cured in water are depicted in Table 4.8. It is noticed that, there is a decrease in density of concrete with the increase in GAA content as compared to control concrete. This is due to the lower density of GAA itself thus, when using it in large quantities it reduces the density of concrete. As a result, the concrete produced is lighter than the one formed using lower amount of GAA as granite substitution. Concrete specimens made with 100% AD GAA and 100% SSD GAA exhibited early density development (3-7 days) that was 3.22 and 2.57 times higher than concrete containing AD granite. This suggests that GAA contributes to improved early-age strength development, whereby water stored in GAA is gradually released to further the hydration process, resulting in denser and more homogenous concrete. The density

of concrete specimens made of 100% AD GAA are higher than those made of 100% SSD GAA at an early age may be attributed to the AD GAA in the concrete mix absorbing the water in cement paste, resulting in a decrease in the water-cement ratio and later on water stored in AD GAA gradually releasing water during the hydration process as reported Tang (2017). At later age, the ratio of the concrete specimens made of 100% SSD GAA and concrete specimens made of 100% AD GAA from 7 days to 28 days were 3.10 and 1.91 times higher compared to concrete containing AD granite,

respectively. It may be attributed to the water that was absorbed and stored within SSD GAA serves as an internal reservoir that progressively will release the water during the hydration process. This is particularly crucial for the development of later-age strength, as the continuous hydration of cement particles is facilitated by the extended availability of water.

Table 4.8

The Density and Percentage of Increase from 3 Days to 7 Days and 28 Days of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Water

Types	Density (kg/m ³)			Percentage of increase density from 3 to 7 days (%)	Percentage of increase density from 7 to 28 days (%)	Ratio of increase density from 3 to 7 days	Ratio of increase density from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	2292	2345	2394	2.27	2.05	1.00	1.00
GAA 50%-AD-WC	2197	2256	2340	2.62	3.60	1.15	1.76
GAA 100%-AD-WC	2102	2172	2260	3.22	3.91	1.42	1.91
CTR 100%-SSD-WC	2270	2310	2410	1.73	4.15	0.76	2.03
GAA 50%-SSD-WC	2197	2223	2331	1.20	4.63	0.53	2.26
GAA 100%-SSD-WC	2087	2142	2287	2.57	6.35	1.13	3.10

Table 4.9 summarises the density and percentage density increase of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA), and control concrete (CTR) specimens cured in air at 3, 7, and 28 days. As can be seen in Table 4.9, it is shown that as the proportion of GAA in the concrete reached 100%, a comparable trend of decreased in density was observed at all ages. The control concrete (CTR 100%-AD-AC) maintained the highest density at all ages compared to other specimens. However, between days 3 and 7, concrete made with 100% SSD GAA and 100% AD GAA showed density increase ratios 6 and 3.3 times higher than concrete with AD granite. The results that have been observed may be attributed to the water that absorbed and stored within SSD GAA serves as an internal reservoir that gradually releases water during the hydration process. The prolonged availability of water ensures continued hydration of cement particles, particularly beneficial for later-age density development. At later age density development, the ratio of the concrete specimens made of 100% SSD GAA and concrete specimens made of 100% AD GAA from 7 days to 28 days were 2.48 and 1.43 times higher compared to concrete containing AD granite, respectively. The observed results suggest that water absorbed and stored within SSD

GAA functions as an internal reservoir, facilitating a gradual release of moisture throughout the hydration process. This stored water contributed to ongoing hydration mechanisms, resulting in C-S-H gel formation that filled the concrete matrix pore structure. Progressive densification through extended hydration increased solid volume fraction and bulk density over time, consistent with previous research (Tang, 2017; Ma *et al.*, 2019; Sun *et al.*, 2022). While internal curing facilitated continued hydration and cement paste densification, GAA aggregates' lightweight nature ensured overall concrete density remained within acceptable lightweight parameters. Thus, it is encouraged that the designer uses lightweight aggregate to reduce the dead load of the building without a reduction in strength.

Table 4.9

The Density and Percentage of Increased from 3 Days to 7 Days and 28 Days Of Concrete Containing AD GAA, SSD GAA, and Control Concrete (CTR) Cured in Air

Types	Density (kg/m ³)			Percentage of increase density from 3 to 7 days (%)	Percentage of increase density from 7 to 28 days (%)	Ratio of increase density from 3 to 7 days	Ratio of increase density from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-AC	2173	2200	2272	1.21	3.18	1.0	1.00
GAA 50%-AD-AC	2014	2072	2141	2.78	3.24	2.3	1.02
GAA 100%-AD-AC	1802	1877	1966	3.98	4.54	3.3	1.43
CTR 100%-SSD-AC	2120	2186	2262	3.00	3.38	2.5	1.06
GAA 50%-SSD-AC	2033	2100	2207	3.17	4.83	2.6	1.52
GAA 100%-SSD-AC	1708	1842	2000	7.29	7.90	6.0	2.48

Table 4.10 shows the density and ratio of percentage increase in density from 3 days, to 7 days and 28 days of air-dried GAA (AD GAA), surface-dried GAA (SSD GAA) and control concrete (CTR) cured in water and air. The density values measured at 3, 7, and 28 days demonstrate that control concrete subjected to water curing (CTR 100%-AD-WC) consistently achieved the highest absolute density values throughout the testing period, reaching 2394 kg/m³ at 28 days. However, when examining the ratio of percentage increase in density, a different pattern emerges. During the early-age period (3 to 7 days), concrete specimens containing full replacement of AD GAA and SSD GAA under air-curing conditions exhibited significantly higher development rate of density 1.33 and 3.20 times higher respectively compared to the water-cured control specimens with granite aggregate. This trend continued in the later-age period (7 to 28

days), where specimens with full replacement of SSD GAA and AD GAA maintained superior density development rates of 3.85 and 2.22 times higher than the control specimens as shown in Figure 4.13. This enhanced rate of density development in GAA specimens can be attributed to the effective self-curing mechanism, where the porous structure of GAA serves as an internal water reservoir within the concrete matrix. As the cement paste loses moisture during hydration, a humidity gradient develops between the paste and the water-filled pores of GAA. This gradient triggers the gradual release of stored water from GAA into the surrounding cement paste. This self-curing capability explained why GAA specimens, especially those with SSD preparation, demonstrated enhanced density development during both early and later age periods compared to conventional concrete. The advantage became more pronounced in air-curing conditions and at later ages when external moisture was limited. Analysis of the density measurements reveals that specimens with higher GAA content consistently exhibited lower initial density values. This substantial density reduction directly correlates with the primary benefits of lightweight concrete in construction practice, including reduced structural dead load, decreased foundation requirements, and enhanced seismic performance.

Table 4.10
The Density and Ratio of Percentage Increase for Concrete Specimens at Age 3 Days, 7 Days, and 28 Days Cured in Water and Air

Types	Density (kg/m ³)			Percentage of increase density from 3 to 7 days (%)	Percentage of increase density from 7 to 28 days (%)	Ratio of increase density from 3 to 7 days	Ratio of increase density from 7 to 28 days
	3 days	7 days	28 days				
CTR 100%-AD-WC	2292	2345	2394	2.27	2.05	1.00	1.00
GAA 50%-AD-WC	2197	2256	2340	2.62	3.60	1.15	1.76
GAA 100%-AD-WC	2102	2172	2260	3.22	3.91	1.42	1.91
CTR 100%-SSD-WC	2270	2310	2410	1.73	4.15	0.76	2.03
GAA 50%-SSD-WC	2197	2223	2331	1.20	4.63	0.53	2.26
GAA 100%-SSD-WC	2087	2142	2287	2.57	6.35	1.13	3.10
CTR 100%-AD-AC	2173	2200	2272	1.21	3.18	0.53	1.56
GAA 50%-AD-AC	2014	2072	2141	2.78	3.24	1.22	1.58
GAA 100%-AD-AC	1820	1877	1966	3.02	4.54	1.33	2.22
CTR 100%-SSD-AC	2120	2186	2262	3.00	3.38	1.32	1.65
GAA 50%-SSD-AC	2007	2100	2207	4.44	4.83	1.95	2.36
GAA 100%-SSD-AC	1708	1842	2000	7.29	7.90	3.20	3.85

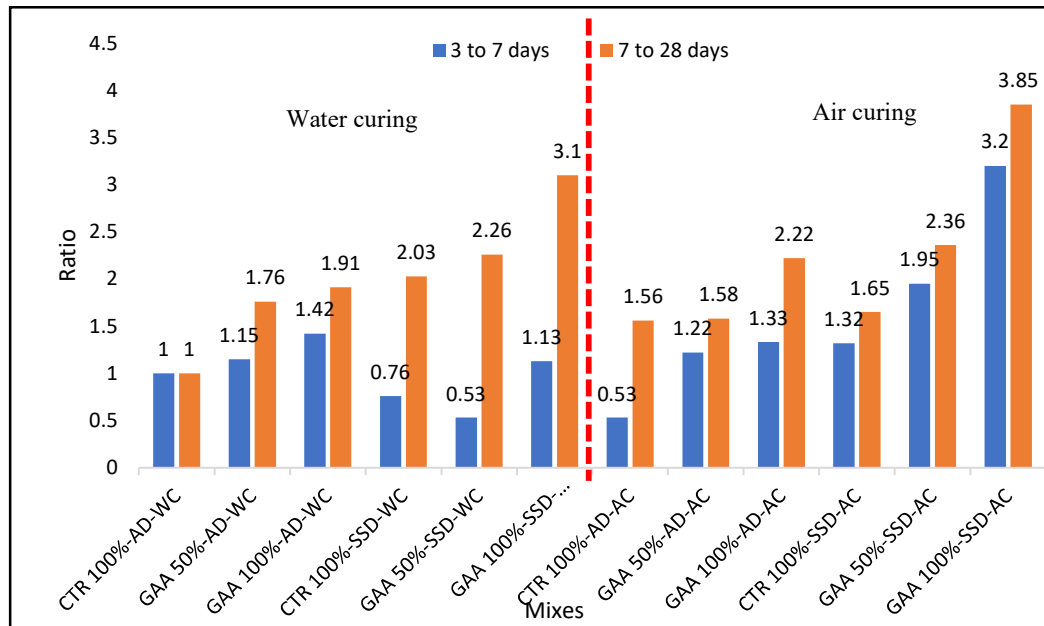


Figure 4.13 Ratio of Percentage Increment of Density From 3 to 7 Days And 7 To 28 Days Cured in Water and Air

4.8 Summary of Statistical Analysis for Concrete Properties

Statistical analysis was performed using Independent Samples T-Test to evaluate the significance of differences between various concrete mix designs and curing conditions. The analysis focused on three (3) key parameters: compressive strength, ultrasonic pulse velocity (UPV), and density. For each parameter, comparisons were made between air-dried (AD) and saturated surface-dry (SSD) conditions, different replacement levels of GAA (50% and 100%), between GAA and granite concrete and between those cured in water and those in air curing. A significance level of 0.05 (95% confidence interval) was used as the threshold for determining statistical significance. A p-value greater than 0.05 indicates no significant difference between compared groups, while a p-value less than 0.05 indicates a statistically significant difference. Table 4.11 presents a summary of these statistical analyses, highlighting the patterns observed across different parameters and curing conditions.

Table 4.11
Summary of Statistical Analysis for Concrete Properties

Parameter	Comparison Type	Water Curing	Air Curing	Interpretation
Compressive Strength	AD vs SSD	Not significant ($p > 0.898$)	Not significant ($p > 0.935$)	The control and GAA concrete specimens under AD and SSD conditions perform similarly.
	50% vs 100% GAA	Not significant ($p > 0.771$)	Not significant ($p > 0.939$)	Both replacement levels are equally effective. Thus, it is suggested that the used of GAA 100% AD on construction site can simplify the concrete mixing process, as it eliminates the need for pre-soaking aggregates, which can lead to time and labour savings.
	GAA vs Granite	Significant ($p < 0.035$)	Significant ($p < 0.017$)	Due to GAA's higher porosity compared to granite. Nevertheless, the strength development of concrete containing GAA at all ages is greater than that concrete containing granite. Thus, the replacement of granite with GAA in self-cured concrete is suggested due to achieving in-design concrete strength, which is minimum of 30 MPa for the 28-day strength.
	WC vs AC	Significant ($p < 0.025$)		While water-cured specimens achieved higher strength values, the air-cured specimens showed significantly higher in percentage rates of strength development over time. This result explained by the self-curing mechanism of GAA, where internal moisture is gradually released to support continued hydration even without external water.
UPV	AD vs SSD	Not significant ($p > 0.898$)	Not significant ($p > 0.977$)	Wave transmission comparable in both conditions.
	50% vs 100% GAA	Not significant ($p > 0.956$)	Not significant ($p > 0.488$)	Replacement level does not affect wave transmission even though GAA contains the pores. It shows that the stored water in GAA probably assists in the continual hydration of cement particles and filling up the pores in concrete containing GAA.
	GAA vs Granite	Significant ($p < 0.035$)	Significant ($p < 0.034$)	Due to GAA's porosity affecting wave transmission. Nevertheless, the UPV development of concrete

Parameter	Comparison Type	Water Curing	Air Curing	Interpretation
Density				containing GAA at all ages is greater than that of concrete containing granite, indicating that the concrete made of GAA denser than those made of granite
	WC vs AC	Significant ($p < 0.031$)		While water-cured specimens achieved higher UPV values, the air-cured specimens showed comparable in percentage rates of UPV development over time. It confirmed that GAA's porous nature effectively functions as an internal water reservoir, enabling comparable UPV development ratios in later ages despite the absence of external water curing.
	AD vs SSD	Not significant ($p > 0.808$)	Not significant ($p > 0.935$)	Similar density regardless of initial condition.
	50% vs 100% GAA	Not significant ($p > 0.971$)	Not significant ($p > 0.476$)	Replacement level does not significantly affect density. it is recommended that the concrete mixing process be simplified by the use of GAA 100% AD on construction sites in comparison to SSD GAA and granite.
	GAA vs Granite	Significant ($p < 0.006$)	Significant ($p < 0.003$)	Significant differences in density between GAA and granite concrete under both water curing and air curing due to GAA's inherent lower density. Nevertheless, the density development of concrete containing GAA is greater than that of concrete containing granite at all ages, indicating that the concrete becomes denser.
	WC vs AC	Significant ($p < 0.005$)		While water-cured specimens achieved higher density values, the air-cured specimens showed significantly higher in percentage rates of density development over time. GAA's porous structure effectively maintains internal moisture conditions that support continued density development

4.9 Finalisation of Mix Design for Self-Cured Concrete

After observation and findings from the preliminary performance of concrete, 100% GAA replacement were chosen as mix design for self-cured concrete specimens. This is due to the compressive strength produced that is comparable with normal strength concrete (control that made of granite). Therefore, the mix proportion for control and self-cured concrete, the one containing 100% GAA replacing granite for further fresh and hardened properties examination is as shown in Table 4.12. The fresh and hardened properties of control and self-cured concrete were then tested, including density, UPV, ISAT, compressive strength, flexural strength, modified compressive strength, expansion, and dry shrinkage. The results will be presented and discussed in Chapter 5.

Table 4.12
Mix Design for Control and Self-Cured Concrete

Mix	Cement (kg/m ³)	Water (kg/m ³)	Fine Aggregate (kg/m ³)	Coarse Aggregate	
				Granite	GAA
Control (CTR)	472	250	928	700	0
100%GAA (Self-cured concrete)	472	250	928	0	514 (by volume)

4.10 Summary

This chapter focuses on the properties of GAA as a granite replacement and internal curing agent, besides a preliminary performance of concrete containing a proportion of SSD and AD GAA. In the first stage of the study, the properties of GAA as an internal curing agent were obtained. The result of the first phase showed that the GAA can act as an internal curing agent in the concrete due to its ability to absorb and release retained water from the GAA to the matrix within the concrete mixes. In the second stage of the study, 50% and 100% SSD and AD GAA were used to replace granite in concrete mixes, which were cured in water and air curing conditions. In both curing conditions, the results indicated that the early-age strength development of concrete containing GAA was enhanced, despite the fact that compressive strength

generally decreased as the GAA content increased. The internal curing effects of surface-saturated dry (SSD) GAA were notably effective in enhancing the development of later-age strength. In water-cured conditions, both SSD GAA and air-dried (AD) concrete attained the desired 28-day strength of 30 MPa, despite the complete replacement of granite. While air-cured GAA concrete did not achieve this objective, it still falls within the range of 20-50 MPa, which is suitable for a variety of structural use.

The statistical analysis conducted did not reveal any significant differences between those contained AD or SSD aggregates, 50% or 100% granite/GAA concrete. However, it did reveal significant differences between granite and GAA concrete, which may be attributed to the higher porosity of GAA. The research indicated that GAA is a viable alternative to granite in the production of concrete, providing benefits in the areas of internal curing and strength development, particularly in situations where water curing may not be practicable. By eliminating the necessity for pre-soaking aggregates, the utilisation of AD GAA could facilitate concrete mixing processes, potentially resulting in time and labour savings in construction.

UPV decreased with increasing GAA content due to air voids and GAA's rounded shape. However, GAA concrete showed improved early-age UPV development in both water and air curing conditions, with air-dried (AD) GAA initially outperforming surface-saturated dry (SSD) GAA. At later ages, SSD GAA concrete exhibited higher UPV development ratios compared to control concrete. Statistical analysis revealed no significant differences between AD/SSD aggregates and 50%/100% granite/GAA concrete in both curing conditions, but showed significant differences between granite and GAA concrete due to GAA's higher porosity. Despite this, GAA concrete demonstrated greater UPV development over time, indicating denser concrete formation. UPV readings mostly ranged from 3.5 to 4.5 km/s, signifying good quality concrete suitable for various applications. The study suggests GAA, particularly AD GAA, as a viable alternative to granite in concrete production, offering advantages in hydration and internal curing, while potentially simplifying the mixing process by eliminating pre-soaking.

The density decreased as the proportion of GAA increased, due to GAA's lower density compared to granite. However, GAA concrete exhibited improved early-age density development in both curing conditions. In water curing, air-dried (AD) GAA initially outperformed surface-saturated dry (SSD) GAA, while in air curing, SSD GAA showed higher early density development. At later ages, SSD GAA concrete

demonstrated higher density development ratios compared to control concrete in both curing conditions. This was attributed to the internal curing effect of water stored in GAA, which gradually released during hydration, promoting denser concrete formation.

Statistical analysis revealed no significant differences between AD/SSD aggregates and 50%/100% granite/GAA concrete in both curing conditions. However, significant differences were observed between granite and GAA concrete due to GAA's higher porosity, resulting in lighter concrete. Despite this, GAA concrete showed greater density development over time compared to granite concrete. The study suggests that GAA, particularly AD GAA, can be a viable alternative to granite in concrete production, offering advantages in continuous hydration and internal curing. It also has the potential to simplify the mixing process by eliminating the need for pre-soaking aggregates, leading to time and labour savings while maintaining concrete strength. The use of GAA as a lightweight aggregate is recommended to reduce building dead load without compromising strength.

CHAPTER 5

MECHANICAL PROPERTIES OF SELF-CURED SPECIMENS CONTAINING GREEN ARTIFICIAL AGGREGATE (GAA)

5.1 Introduction

This chapter demonstrates the performance of normal-strength concrete containing full replacement of AD and SSD GAA as an internal water reservoir and demoulding time effects. In the present study, the specimens tested were cured under six (6) types of curing conditions to assess the influence of aggregate conditions on the de-moulding times in self-cured concrete namely; curing in water after 24 hours de-moulding (1D-WC), curing in a lab environment after 24 hours de-moulding (1D-AC), curing in water after three (3) days demoulding (3D-WC), curing in a lab environment after three (3) days de-moulding (3D-AC), curing in water after seven (7) days demoulding (7D-WC), and curing in a lab environment after seven (7) days demoulding (7D-AC). Self-cured concrete properties were evaluated in terms of compressive strength, ultrasonic-pulse velocity, density, flexural strength, modified compressive strength, shrinkage, expansion and initial surface absorption of concrete grade of 30. There are 288 cubes of concrete and 24 prisms were prepared and tested at this stage. In this chapter, the results were analysed based on four (4) variables. Firstly, the effect of using saturated surface-dried (SSD) aggregate compared to air-dried (AD) aggregate in the mix towards the mechanical properties of self-cured concrete specimens. Secondly, the effect of using GAA compared to granite aggregate towards the mechanical properties of self-cured concrete specimens. Thirdly, the effect of water curing compared to air curing on the mechanical properties, and fourthly, the influence of different demoulding times (1 day, 3 days, and 7 days) on the mechanical properties' development. The mechanical properties with respect to these four (4) variables were then analysed statistically with Statistical Package for the Social Sciences (SPSS) by using Independent Samples T-Test and univariate analysis of variance (ANOVA) method. The statistical analysis was adopted to investigate the significant difference in the means of these variables towards mechanical properties development. The following

sections explain the influence of GAA as an internal water reservoir to the mechanical properties of concrete subjected to water curing and air curing.

5.2 Compressive Strength of Self-cured Concrete

The compressive strength and ratio of increase from 3 days to 7 days, 7 days to 28 days and 28 days to 56 days cured in different water and air curing conditions are summarised in Table 5.1. As can be seen in Table 5.1, the compressive strength of the concrete specimens decreased at all ages as the de-moulding times increased and followed by water curing. While the compressive strength of concrete specimens increased at all ages as the de-moulding times increased followed by air curing. The ratio of compressive strength concrete at 28 days cured in water shows a decreasing trend with later demoulding. The compressive strength of control concrete containing air-dry (AD) granite, cured in water curing conditions (CTR -1D-AD-WC) was highest at all ages compared to others series of concrete specimens. The not applicable (NA) values consistently appear in the percentage of increased concrete strength from 3 days to 7 days column for all specimens with 7D (7-day demoulding). This occurs because these specimens were still in the mould at 3 days, making it impossible to measure their strength at that time point. For GAA-SSD-WC, the ratios were 1.00 for 1D demoulding, 0.94 for 3D demoulding, and 0.88 for 7D demoulding. Similarly, GAA-AD-WC specimens showed ratios of 1.00, 0.95, and 0.90 for 1D, 3D, and 7D demoulding respectively. This demonstrates that earlier demoulding in water curing conditions benefited the strength development of GAA concrete, likely due to better access to external moisture for the porous aggregates from an early age. While, CTR-SSD-WC specimens exhibited ratios of 1.00, 0.93, and 0.86 for 1D, 3D, and 7D demoulding respectively. CTR-AD-WC showed a similar trend with ratios of 1.00, 0.93, and 0.85. The declining pattern with delayed demoulding suggests that early exposure to water curing is crucial for strength development in conventional granite concrete.

Interestingly, concrete containing GAA showed improved performance with delayed demoulding under air curing condition. GAA-SSD-AC specimens achieved ratios of 1.00, 1.08, and 1.15 for 1D, 3D, and 7D demoulding respectively. GAA-AD-AC followed a similar trend with ratios of 1.00, 1.07, and 1.13. This suggests that extended formwork protection in air curing conditions helps preserve internal moisture within the porous aggregates, enhancing the self-curing mechanism.

CTR-SSD-AC showed ratios of 1.00, 1.03, and 1.09 for 1D, 3D, and 7D demoulding, while CTR-AD-AC exhibited ratios of 1.00, 1.02, and 1.07. The slight improvement with delayed demoulding indicates that extended formwork protection benefits even conventional concrete under air curing conditions. While control concrete relied heavily on external water availability and suffered from moisture shock when transitioned to air curing, GAA concrete demonstrated superior adaptability through its self-curing capacity. The findings demonstrated that the impact of demoulding time showed opposite trends between water and air curing conditions. At 28 days of curing in air, self-cured specimens GAA-7D-AD-AC and GAA-7D-SSD-AC successfully attained the minimum design strength requirement of 30 MPa. In contrast, self-cured specimens, GAA-1D-AD-AC, GAA-3D-AD-AC, GAA-1D-SSD-AC, and GAA-3D-SSD-AC, failed to reach this threshold despite identical air-curing conditions. However, according to Alhamad *et al.* (2022), normal-strength concrete with a compressive strength ranging from 20 MPa to 50 MPa or 55 MPa can be used in different structural concrete applications. This suggests that even the specimens demoulded at earlier intervals, while falling short of 30 MPa, may still possess adequate strength for certain structural implementations within the construction industry.

Early demoulding (1D) proves beneficial in water curing, while delayed demoulding (7D) shows advantages in air curing for both GAA and granite concrete. Concrete containing GAA showed higher sensitivity to demoulding time compared to control concrete, particularly under air curing. This can be attributed to the porous of aggregates role in internal moisture retention and distribution. The self-curing mechanism in GAA concrete appears more effective with delayed demoulding under air curing, suggesting that extended formwork protection helps establish optimal internal moisture conditions for strength development. The demoulding time effects are more pronounced in water curing compared to air curing for both types of concrete, indicating that early access to external water has a significant impact on long-term strength development. The contractors and construction managers enable to make informed decisions based on their specific project conditions. For time-sensitive projects with adequate curing facilities, conventional granite concrete with one-day demoulding and proper water curing offers an efficient solution. In contrast, projects with limited curing supervision might benefit from porous aggregate concrete with extended demoulding periods, even under air curing conditions. This approach helps maintain concrete quality despite reduced maintenance requirements.

Table 5.1

The Compressive Strength and Ratio of Increase Concrete Strength from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Different Water and Air Curing Conditions

Types	Compressive Strength (MPa)				Ratio of increase concrete strength from 3 to 7 days	Ratio of increase concrete strength from 7 to 28 days	Ratio of increase concrete strength from 28 to 56 days	Ratio of compressive strength at 28 days respect to 1 day demoulding
	3 days	7 days	28 days	56 days				
CTR-1D-AD-WC	28.52	37.56	42.34	42.92	1.00	1.00	1.00	1.00
CTR-3D-AD-WC	26.47	34.65	39.17	40.02	0.98	1.02	1.58	0.93
CTR-7D-AD-WC	NA	31.81	36.13	36.58	NA	1.07	0.92	0.85
GAA-1D-AD-WC	20.06	30.60	37.20	38.63	1.66	1.69	2.82	1.00
GAA-3D-AD-WC	19.58	29.47	35.28	36.36	1.59	1.55	2.23	0.95
GAA-7D-AD-WC	NA	27.94	33.32	34.00	NA	1.51	1.49	0.90
CTR-1D-SSD-WC	27.07	36.42	41.87	42.86	1.09	1.17	1.74	1.00
CTR-3D-SSD-WC	25.48	33.98	39.00	39.93	1.05	1.16	1.74	0.93
CTR-7D-SSD-WC	NA	31.39	36.03	37.00	NA	1.16	1.97	0.86
GAA-1D-SSD-WC	19.07	29.86	38.61	39.85	1.79	2.30	2.36	1.00
GAA-3D-SSD-WC	18.68	28.40	36.21	37.36	1.64	2.16	2.33	0.94
GAA-7D-SSD-WC	NA	26.86	34.05	35.03	NA	2.10	2.10	0.88
CTR -1D-AD-AC	22.53	25.91	31.60	31.88	0.47	1.72	0.65	1.00
CTR-3D-AD-AC	24.29	26.97	32.09	32.73	0.35	1.49	1.45	1.02
CTR-7D-AD-AC	NA	28.50	33.94	34.28	NA	1.50	0.75	1.07
GAA-1D-AD-AC	14.72	20.04	26.95	27.92	1.14	2.71	2.63	1.00
GAA-3D-AD-AC	16.00	21.07	28.83	29.93	1.00	2.89	2.79	1.07
GAA-7D-AD-AC	NA	22.08	30.34	31.99	NA	2.94	3.97	1.13
CTR-1D-SSD-AC	21.86	23.50	30.06	30.88	0.24	2.19	1.99	1.00
CTR-3D-SSD-AC	23.36	25.95	31.11	31.60	0.35	1.56	1.17	1.03
CTR-7D-SSD-AC	NA	27.04	32.91	33.29	NA	1.70	0.85	1.09
GAA-1D-SSD-AC	13.53	19.05	27.57	28.01	1.29	3.51	1.15	1.00
GAA-3D-SSD-AC	14.87	20.23	29.74	30.38	1.14	3.69	1.57	1.08
GAA-7D-SSD-AC	NA	21.09	31.82	32.99	NA	4.00	2.70	1.15

However, the data revealed an interesting pattern in strength development ratio between self-cured concrete and control specimens. When examining the ratio of increase for concrete strength during the critical curing periods from 7 to 28 days and from 28 to 56 days, GAA concrete exhibited dramatically enhanced performance. Specifically, the specimens demoulded at different times (1-day, 3-day, and 7-day demoulding) containing GAA demonstrated strength increase ratios approximately 2 to 3 times greater than control concrete when cured in water conditions. This performance differential becomes even more pronounced in air curing, where self-cured concrete achieved strength increase ratios 3 to 4 times higher than control specimens. Figure 5.1 visually confirms this significant performance advantage, highlighting the exceptional capability of self-cured concrete to continue developing strength at advanced curing ages regardless of initial demoulding time, with this effect being particularly magnified under air curing conditions. The significantly higher strength increase ratios in self-cured concrete can be explained through the self-curing properties of GAA. Unlike conventional granite, GAA contains a network of internal voids that absorbed and retained water during mixing and early curing stages. This creates an internal reservoir system distributed throughout the concrete matrix. Besides, the GAA-1D-AD-AC, GAA-3D-AD-AC, and GAA-7D-AD-AC demonstrated markedly increased compressive strength ratios from 7 to 28 days (2.71, 2.89, and 2.94, respectively) compared to their CTR-1D-AD-WC, CTR-3D-AD-WC, and CTR-7D-AD-WC counterparts (1.0, 1.02, and 1.07, respectively). Figure 5.1 also showed that GAA concrete performed better than control concrete no matter when the formwork was removed - whether after 1 day, 3 days, or 7 days. The porous structure of GAA particles, established during the pre-saturation or mixing stage, continuously supplies moisture to the surrounding cement paste throughout the hydration process, independent of formwork presence. At 1-day demoulding, while premature moisture loss is suffered by control concrete, adequate internal humidity is maintained in GAA concrete as the stored water in GAA particles is gradually migrated to the cement paste in response to the humidity gradient created by ongoing hydration. At 3-day and 7-day demoulding, the self-curing advantage persists because internal moisture reserves continue to be released by GAA, whereby hydration is sustained even in the absence of external water supply. This consistent improvement demonstrated that the self-curing properties of GAA concrete worked reliably under different construction timing conditions. This pronounced enhancement in ratio values for the GAA specimens approximately 2.7 to

2.9 times higher than CTR specimens, indicated that GAA-based mixes could offer a promising alternative to conventional curing methods. Such self-curing mechanisms are particularly valuable in challenging environmental conditions, remote construction sites, or in structures where traditional water curing was impractical.

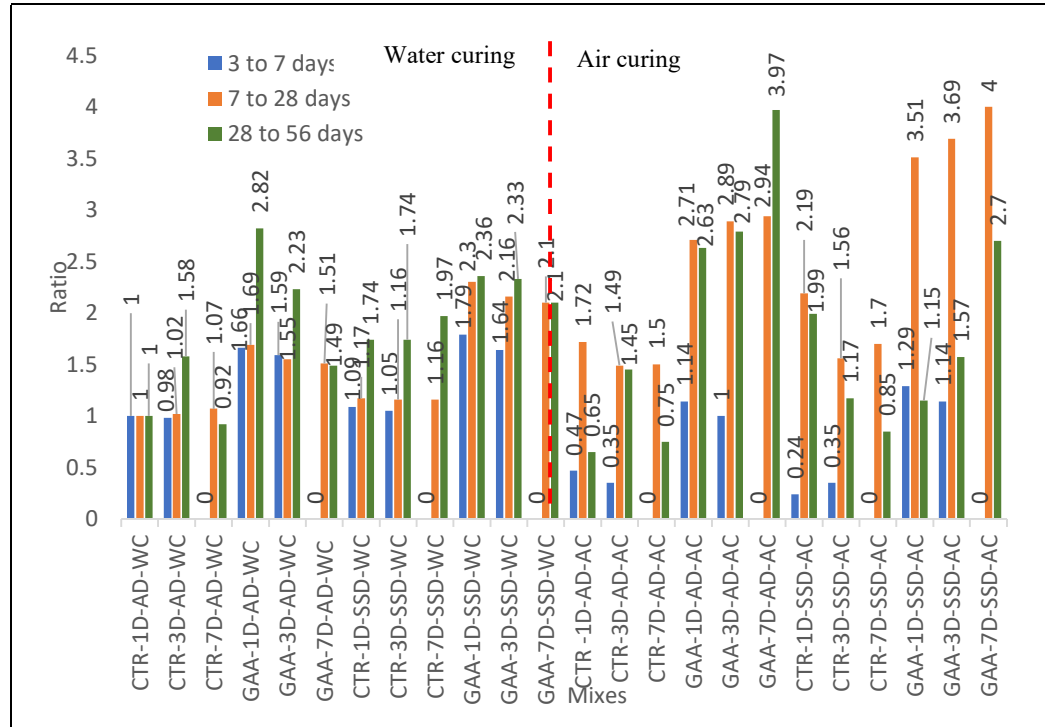


Figure 5.1 Ratio of Increased Concrete Strength from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing at Different Time Demoulding

5.3 Ultra-Pulse Velocity (UPV) of Self-cured Concrete

The UPV and ratio of increase for UPV from 3 days to 7 days, 7 days to 28 days and 28 days to 56 days cured in different water and air curing conditions are summarised in Table 5.2. As depicted in Table 5.2, the UPV value decreased at all ages as the demoulding times increased. The UPV of control concrete containing air-dry (AD) granite, cured in water curing conditions (CTR -1D-AD-WC) was highest at all ages compared to other series of concrete specimens. In water curing conditions, the ratio UPV of concrete containing GAA at 28 days revealed small difference across demoulding times. GAA-1D-AD-WC achieved a ratio of 1.00, while GAA-3D-AD-WC showed 0.97, and GAA-7D-AD-WC reached 0.96. For the SSD condition, GAA-1D-SSD-WC maintains 1.00, GAA-3D-SSD-WC showed 0.98, and GAA-7D-SSD-WC

achieved 0.95. This decreasing trend suggests that early exposure to water curing allows the porous aggregates to quickly absorb and store water, initiating an effective self-curing process and development of concrete density and uniformity in water curing conditions. The self-curing mechanism becomes even more evident when examining GAA concrete under air curing conditions. The ratio of increase for UPV from 7 days to 28 days under air curing revealed that these ratios are consistently higher for SSD specimens (GAA-1D-SSD-WC: 2.37, GAA-3D-SSD-WC: 1.99, GAA-7D-SSD-WC: 1.42) compared to AD specimens (GAA-1D-AD-WC: 1.61, GAA-3D-AD-WC: 1.60, GAA-7D-AD-WC: 1.56). This indicated that pre-saturated GAA facilitate more efficient hydration during intermediate curing stages, likely due to their superior internal moisture distribution capabilities. Interestingly, the trend reversed, showing improved UPV ratios with delayed demoulding. The ratios increased from 1.00 at one-day (1-D) demoulding to 1.03 at three days and further to 1.05 at seven days (7-D). This improvement can be attributed to the enhanced moisture retention within the formwork, allowing the porous aggregates more time to establish their internal water reservoirs. Under air curing, granite concrete showed only slight improvements with delayed demoulding, with ratios moving from 1.00 to 1.02 to 1.04, demonstrating less effective internal moisture distribution compared to GAA concrete. A finding emerges regarding the relationship between curing conditions and demoulding times. While early demoulding proved beneficial in water curing environments, delayed demoulding becomes advantageous in air curing conditions, especially for GAA concrete. The ratio of increased UPV from 7 days to 28 days under air curing revealed another critical finding. For GAA-SSD-AC specimens, these ratios (GAA-1D-SSD-AC: 3.61, GAA-3D-SSD-AC: 3.57, GAA-7D-SSD-AC: 3.95) substantially exceeded those of their AD counterparts (GAA-1D-AD-AC: 1.74, GAA-3D-AD-AC: 2.07, GAA-7D-AD-AC: 2.00). This pronounced difference confirmed that pre-saturated porous aggregates provided exceptional self-curing capabilities in moisture-limited environments, with this effect further enhanced by extended formwork protection. According to Neville (2011), a pulse velocity greater than 4.5 km/s generally exhibits concrete with excellent quality. Therefore, in this study, most of the UPV value readings range from 3.5 km/s to 4.5 km/s at 28 days indicated that the concrete specimens are in good quality. Generally, it is suitable for wide variety of common structural and non-structural applications in construction.

Table 5.2

The UPV and ratio of increase in UPV from 3 days to 7 days, 7 days to 28 days and 28 days to 56 days cured in water and air curing

Types	UPV (km/s)				Ratio of increase in UPV from 3 days to 7 days	Ratio of increase in UPV from 7 days to 28 days	Ratio of increase in UPV from 28 days to 56 days	Ratio of UPV at 28 days respect to 1 day demoulding
	3 days	7 days	28 days	56 days				
CTR-1D-AD-WC	4.27	4.40	4.53	4.62	1.00	1.00	1.00	1.00
CTR-3D-AD-WC	4.14	4.25	4.40	4.47	0.87	1.17	0.73	0.97
CTR-7D-AD-WC	NA	4.23	4.36	4.40	NA	1.07	0.42	0.96
GAA-1D-AD-WC	3.75	3.93	4.12	4.28	1.66	1.61	1.81	1.00
GAA-3D-AD-WC	3.66	3.83	4.01	4.12	1.54	1.60	1.31	0.97
GAA-7D-AD-WC	NA	3.77	3.94	4.04	NA	1.56	1.14	0.96
CTR-1D-SSD-WC	4.26	4.35	4.52	4.57	0.74	1.29	0.55	1.00
CTR-3D-SSD-WC	4.21	4.27	4.43	4.45	0.44	1.25	0.24	0.98
CTR-7D-SSD-WC	NA	4.28	4.39	4.40	NA	0.86	0.09	0.97
GAA-1D-SSD-WC	3.67	3.89	4.17	4.31	2.03	2.37	1.63	1.00
GAA-3D-SSD-WC	3.60	3.82	4.04	4.14	1.99	1.99	1.17	0.97
GAA-7D-SSD-WC	NA	3.78	3.95	4.06	NA	1.42	1.36	0.95
CTR -1D-AD-AC	3.81	3.92	4.08	4.17	1.00	0.75	1.04	1.00
CTR-3D-AD-AC	3.82	3.97	4.16	4.29	1.35	1.59	1.46	1.02
CTR-7D-AD-AC	NA	4.08	4.24	4.33	NA	1.32	1.02	1.04
GAA-1D-AD-AC	3.38	3.55	3.74	3.83	1.63	1.74	1.17	1.00
GAA-3D-AD-AC	3.43	3.63	3.86	3.95	1.91	2.07	1.21	1.03
GAA-7D-AD-AC	NA	3.70	3.92	4.07	NA	2.00	1.81	1.05
CTR-1D-SSD-AC	3.78	3.94	4.10	4.19	1.40	1.35	1.01	1.00
CTR-3D-SSD-AC	3.80	3.95	4.19	4.31	1.33	2.01	1.39	1.02
CTR-7D-SSD-AC	NA	3.96	4.20	4.32	NA	1.96	1.46	1.02
GAA-1D-SSD-AC	3.30	3.45	3.83	3.91	1.54	3.61	1.08	1.00
GAA-3D-SSD-AC	3.40	3.57	3.96	4.06	1.71	3.57	1.22	1.03
GAA-7D-SSD-AC	NA	3.60	4.02	4.16	NA	3.95	1.64	1.05

The UPV values of control specimens (CTR) are generally higher than those of GAA-incorporated specimens at all testing ages. However, the ratio of increase in UPV provides valuable insights into the self-curing mechanism. The specimens demoulded at different times (1-day, 3-day, and 7-day demoulding) containing GAA demonstrated UPV increase ratios approximately 2 times greater than those of control concrete when cured in water. This performance differential becomes even more pronounced in air curing, where self-cured concrete achieved UPV increase 2 to 4 times higher than those of control specimens. Figure 5.2 visually confirms this significant performance advantage, highlighting the exceptional capability of self-cured concrete to continue developing strength at advanced curing ages regardless of initial demoulding time, with this effect being particularly magnified under air curing conditions. The significantly higher UPV increased ratios in self-cured concrete can be explained through the self-curing properties of GAA. Unlike conventional granite, GAA contains a network of internal voids that absorbed and retained water during mixing and early curing stages. This creates an internal reservoir system distributed throughout the concrete matrix.

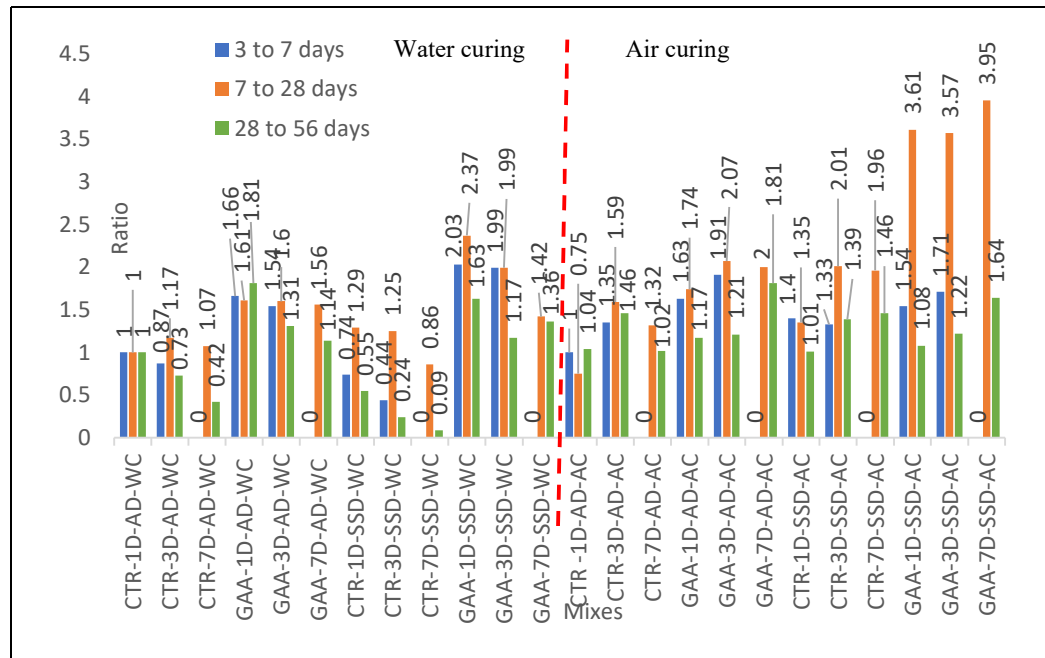


Figure 5.2 Ratio of Increase in UPV for Control and GAA Concrete Specimens from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing at Different Time Demoulding

5.4 Density of Hardened Self- Cured Concrete

The density of GAA and granite was 1820 kg/m^3 and 2650 kg/m^3 , respectively. Therefore, the density of self-cured concrete was expected to be lower than that of the control concrete since self-cured concrete replaced 100% of granite with GAA. The density and ratio of increase in density from 3 days to 7 days, 7 days to 28 days and 28 days to 56 days cured in different water and air curing conditions are summarised in Table 5.3. As depicted in Table 5.3, the density value increased at all ages as the demoulding times increased. The density of control concrete containing air-dry (AD) granite, cured in water curing conditions (CTR -1D-AD-WC) was highest at all ages compared to all other series of specimen. Under water curing conditions, granite concrete (CTR) exhibits a clear pattern in density development. For CTR-AD-WC, the density ratio at 28 days shows 1.00 for one-day demoulding (1D), decreasing to 0.98 for three-day demoulding (3D), and further reducing to 0.95 for seven-day demoulding (7D). Similarly, for CTR-SSD-WC, the ratios follow a comparable trend, showing 1.00, 0.97, and 0.92 for one- (1D), three-(3D), and seven-day (7D) demoulding respectively. GAA concrete under water curing demonstrated different behaviour due to its porous aggregate structure. For GAA-AD-WC, the density ratios at 28 days are 0.91, 0.88, and 0.85 for one-, three-, and seven-day demoulding respectively. The GAA-SSD-WC specimens showed slightly better performance with ratios of 0.94, 0.90, and 0.88. The lower overall density ratios compared to granite concrete reflect the inherent porosity of the aggregates, but the declining trend with delayed demoulding remains consistent. GAA concrete under air curing reveals interesting insights about the self-curing mechanism. GAA-AD-AC specimens show progressive improvement in density ratios, reaching 1.00, 1.05, and 1.06 for one-, three-, and seven-day demoulding. The GAA-SSD-AC specimens demonstrated even better performance with ratios of 1.00, 1.06, and 1.13. The extended formwork time enhances porous aggregates' self-curing effectiveness. Delayed demoulding benefits both concrete types under air curing, with GAA concrete showing greater improvement. This highlights moisture retention importance when external water is limited. Aggregate condition impacts GAA concrete more significantly, where pre-saturated aggregates improved density development. Extended formwork protection enables better utilisation of internal moisture from porous aggregates, maximising the self-curing mechanism.

Table 5.3

The density and ratio of increase in density for control and GAA concrete specimens from 3 to 7 days, 7 days to 28 days and 28 days to 56 days cured in water and air curing

Types	Density (kg/m ³)				Ratio of increase in density from 3 to 7 days	Ratio of increase in density from 7 to 28 days	Ratio of increase in density from 28 to 56 days	Ratio of density, 28 days respect to 1 day demoulding
	3 days	7 days	28 days	56 days				
CTR-1D-AD-WC	2266	2334	2392	2440	1.00	1.00	1.00	1.00
CTR-3D-AD-WC	2227	2285	2351	2387	0.87	1.16	0.76	0.98
CTR-7D-AD-WC	NA	2209	2274	2293	NA	1.16	0.44	0.95
GAA-1D-AD-WC	1980	2078	2168	2250	2.03	1.73	1.88	1.00
GAA-3D-AD-WC	1925	2014	2106	2185	1.99	1.83	1.87	0.97
GAA-7D-AD-WC	NA	1938	2029	2097	NA	1.87	1.69	0.94
CTR-1D-SSD-WC	2265	2315	2383	2410	0.74	1.16	0.58	1.00
CTR-3D-SSD-WC	2236	2266	2332	2367	0.44	1.16	1.30	0.98
CTR-7D-SSD-WC	NA	2157	2213	2217	NA	1.03	0.09	0.93
GAA-1D-SSD-WC	1946	2065	2243	2310	1.66	3.45	1.50	1.00
GAA-3D-SSD-WC	1920	2035	2157	2232	1.54	2.40	1.72	0.96
GAA-7D-SSD-WC	NA	1927	2095	2175	NA	3.48	1.91	0.93
CTR-1D-AD-AC	2060	2121	2185	2232	1.0	1.20	1.08	1.00
CTR-3D-AD-AC	2042	2125	2213	2258	1.4	1.67	1.02	1.01
CTR-7D-AD-AC	NA	2146	2259	2307	NA	2.12	1.06	1.03
GAA-1D-AD-AC	1644	1724	1814	1880	1.6	2.09	1.82	1.00
GAA-3D-AD-AC	1690	1787	1898	1965	1.9	2.49	1.76	1.05
GAA-7D-AD-AC	NA	1821	1931	2003	NA	2.40	1.88	1.06
CTR-1D-SSD-AC	1930	2011	2093	2137	1.4	1.62	1.06	1.00
CTR-3D-SSD-AC	1904	1980	2099	2160	1.3	2.41	1.45	1.00
CTR-7D-SSD-AC	NA	2052	2173	2218	NA	2.36	1.02	1.04
GAA-1D-SSD-AC	1591	1665	1845	1905	1.5	4.33	1.62	1.00
GAA-3D-SSD-AC	1682	1768	1957	2027	1.7	4.28	1.77	1.06
GAA-7D-SSD-AC	NA	1866	2087	2158	NA	4.74	1.71	1.13

In water curing conditions, GAA-1D, 3D, and 7D specimens showed moderate density increase ratios because external water is abundantly available. The self-curing mechanism from the porous aggregates becomes somewhat redundant when specimens are continuously exposed to external moisture. This explains why the density ratios for water-cured GAA samples are relatively modest, the primary hydration mechanism relies on the external water rather than the internal reservoirs. In air curing conditions, the significantly higher density increased ratios for air-cured GAA specimens (particularly GAA-1D and GAA-7D during the 7-28 day period) demonstrated the effectiveness of the self-curing mechanism. Without external water, moisture stored in porous aggregates becomes the primary hydration source, enabling continued reactions, densification and strength development despite lack of external curing water (Figure 5.3). The relationship between porous aggregates and self-curing explains why air-cured GAA specimens can achieve comparable or even superior density development compared to their water-cured counterparts. The internal water reservoirs in GAA provide a more efficient, localised source of moisture for hydration reactions, promoting better microstructure development particularly in environments where external water is limited.

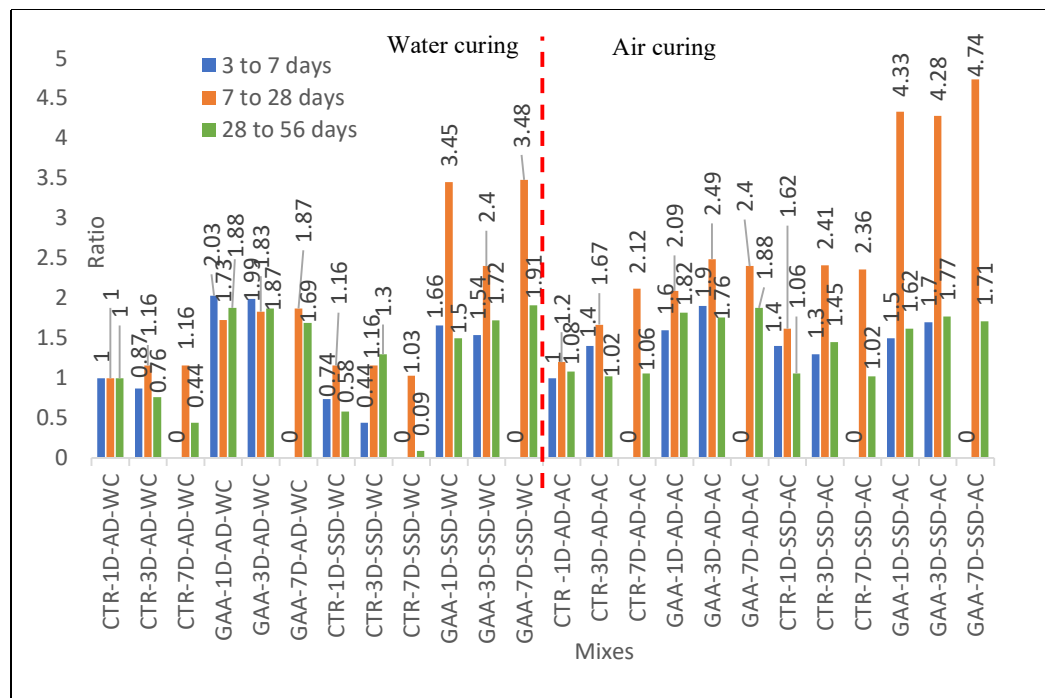


Figure 5.3 Ratio of Increase in Density from 3 to 7 Days, 7 to 28 Days and 28 to 56 Days Cured in Water and Air Curing Conditions at Different Time Demoulding

5.5 Flexural Strength

Flexural test was carried out at age of 28 days. Flexural strength of control concrete and self-cured concrete (concrete containing GAA) at 28 days cured in water and air as presented in Table 5.4. From the table, the flexural strength ranges from 3.85 MPa to 4.97 MPa for those specimens cured in water and 3.18 MPa to 3.75 MPa for those of air cured. Under water curing conditions, control concrete consistently demonstrated higher flexural strength ratios compared to those of self-cured concrete. The highest flexural strength was recorded for control concrete with AD aggregate specimens cured in water (CTR -1D-AD-WC). The flexural strength at 28 days shows that (CTR-1D-AD-WC) achieved the highest flexural strength ratio of 1.00, which serves as our reference point for comparison while GAA concrete (GAA-1D-AD-WC) showed a lower ratio of 0.77. This significant difference can be attributed to the inherent properties of porous aggregates in GAA concrete, by which potentially weaker zones are created within the concrete matrix. This could be related to the strength of the aggregate itself as suggested by previous results (Góra & Piasta, 2020; Ma *et al.*, 2019), whereby lower mechanical strength and susceptibility to trans-aggregate fracture under tensile stress are resulted from GAA possessing more pores compared to granite. The difference between AD and SSD conditions of control concrete is minimal, with ratios of 1.00 and 0.98 respectively, suggesting that initial aggregate moisture has little impact on strength development. However, for self-cured, the one containing SSD aggregates improved the flexural strength recording ratio from 0.77 (AD) to 0.81 (SSD), indicating that pre-saturated porous aggregates contribute to better internal curing and strength development.

Under air curing conditions, both concrete types showed reduced flexural strength ratios compared to those of water curing. Control concrete (CTR-1D-AD-AC) achieved a ratio of 0.75, while GAA concrete (GAA-1D-AD-AC) reached 0.64 with respect to that of air cured. The impact of aggregate moisture condition becomes more pronounced, particularly for self-cured concrete. While control concrete maintained the same ratio (0.75) for both AD and SSD conditions, self-cured concrete showed improvement from 0.64 (AD) to 0.69 (SSD) when using pre-saturated GAA. This enhancement in GAA concrete under air curing demonstrated the effectiveness of the self-curing mechanism provided by saturated porous aggregates. The curing condition has a substantial impact on flexural strength development. Water-cured specimens

consistently achieved higher flexural strength ratios compared to those of air-cured specimens for both concrete types. The most significant finding is that strength reduction under air curing conditions is helped to be minimised by the self-curing mechanism in self-cured concrete, particularly with SSD aggregates. While conventional granite concrete showed a 25% reduction in flexural strength ratio when moving from water to air curing, GAA concrete with SSD aggregates showed a smaller proportional reduction, demonstrating the effectiveness of internal curing provided by the pre-saturated porous aggregates. This leads to a denser microstructure and stronger cement paste, which contributes to higher flexural strength. As per previous research, flexural strength typically falls within 10–20% of the compressive strength, depending on variables such as coarse aggregates type, size, and volume (Lee & Lee, 2016; Marín-Urbe & Navarro-Gaete, 2021). Indeed, with fully replacement of GAA with granite in the concrete, the flexural strength remained within the acceptable range. Therefore, replacement with GAA in concrete as self-curing agent is the preferred choice.

Table 5.4
Flexural Strength of Control Concrete and GAA Concrete at 28 Days Cured in Water and Air

Types of concrete	Curing	Flexural strength (MPa)	Ratio flexural strength at 28 days with respect to CTR-1D- AD-WC
CTR-1D- AD-WC	Water	4.97	1.00
CTR-1D- SSD-WC	Water	4.85	0.98
GAA-1D-AD-WC	Water	3.85	0.77
GAA-1D- SSD-WC	Water	4.04	0.81
CTR-1D- AD-AC	Air	3.75	0.75
CTR-1D- SSD-AC	Air	3.71	0.75
GAA-1D- AD-AC	Air	3.18	0.64
GAA-1D- SSD-AC	Air	3.43	0.69

5.6 Modified Compressive Strength

The modified compression test was conducted by testing the compressive strength of the broken prism parts after completing the flexural test at 28 days. Table 5.5 presents the modified compressive strength of control and a concrete containing GAA at 28 days cured in water and air. The value of modified compressive strength tested on the broken prism parts at 28 days was found to be less than the compressive strength of cube specimens at the same age. The reduction values of modified compressive strength due to specimens were suffered of damage because of the flexural strength test. Table 5.5 shows that the results range from 39.38 MPa to 23.18 MPa. The highest modified compressive strength was recorded for control concrete with AD aggregate specimens cured in water (CTR -1D-AD-WC) and this specimen become the reference for ratio calculation. Significant performance differences were identified when comparing concrete containing GAA with control concrete under water curing conditions. The control concrete with air-dried granite (CTR-1D-AD-WC) achieved the highest ratio of 1.00, serving as the reference point. In contrast, concrete containing GAA with air-dried aggregates (GAA-1D-AD-WC) showed a lower ratio of 0.86. This difference could be related to the inherent properties of porous aggregates, which typically had lower strength compared to dense granite aggregates (Góra & Piasta, 2020; Ma *et al.*, 2019). The influence of aggregate moisture condition (SSD vs AD) revealed interesting patterns. Under water curing, control concrete showed minimal sensitivity to aggregate moisture state, with ratios of 1.00 for AD and 0.99 for SSD conditions. However, self-cured concrete demonstrated more sensitive to aggregate moisture condition, with the ratio improving from 0.86 (AD) to 0.89 (SSD). This improvement suggested that pre-saturated porous aggregates contributed to better internal curing and strength development through the self-curing mechanism.

The impact of curing conditions (water vs air) indicated substantial difference in performance. When subjected to air curing, both concrete types exhibited large losses in strength ratio. Control concrete with air-dried aggregates exhibited a decrease from 1.00 (water curing) to 0.71 (air curing) representing 29% reduction. Similarly, the ratio for granite concrete using SSD aggregates reduced from 0.99 to 0.67, a 32% decrease with respect to the water-cured reference specimen (CTR-1D-AD-WC). Self-cured concrete had a similar trend under air curing but with several noticeable changes. The

ratio for self-cured concrete with air-dried aggregates reduced from 0.86 (water curing) to 0.59 (air curing), whereas the SSD condition exhibited a reduction from 0.89 to 0.61 from water to air curing. Although the absolute values were lower, the percentage drop in strength for self-cured concrete (about 31-32%) was similar to that reported in control concrete. These findings revealed several important insights about concrete behaviour. While self-cured concrete generally achieved lower absolute strength compared to control concrete, the use of SSD aggregates consistently improved its performance under both curing conditions. The persistent improvement shown by SSD aggregates in self-cured concrete, even under air curing, validated the effectiveness of the self-curing mechanism provided by pre-saturated porous aggregates.

Table 5.5
Modified Compressive for Prism Control and GAA (Self-Cured) Specimens at 28 Days Cured in Water and Air

Types of concrete	Curing	Compressive strength (MPa)	Ratio of compressive strength at 28 days with respect to CTR-1D- AD-WC
CTR-1D- AD-WC	Water	39.38	1.00
CTR-1D- SSD-WC	Water	38.94	0.99
GAA-1D- AD-WC	Water	33.85	0.86
GAA-1D- SSD-WC	Water	35.14	0.89
CTR-1D- AD-AC	Air	28.12	0.71
CTR-1D- SSD- AC	Air	26.55	0.67
GAA-1D- AD- AC	Air	23.18	0.59
GAA-1D- SSD- AC	Air	23.99	0.61

5.7 Summary of Statistical Analysis for Self-cured Properties

Statistical analysis was performed using Independent Samples T-Test to evaluate the significant difference in the mean of the various variables namely SSD comparing AD, GAA comparing granite and water curing in reference with those of air curing on flexural strength and modified compressive strength for self-cured concrete. Two-way ANOVA was selected to analyse the effect of demoulding time on concrete compressive strength, UPV and density because it allows for the simultaneous examination of two independent variables and their interaction. A significance level of 0.05 (95% confidence interval) was used as the threshold for determining statistical

significance. A p-value greater than 0.05 indicates no significant difference between compared groups, while a p-value less than 0.05 indicates a statistically significant difference. Table 5.6 presents a summary of these statistical analyses, highlighting the patterns observed across different parameters and curing conditions

Table 5.6
The Summary of Statistical Analysis for Experimental Variables Tested on GAA Concrete (Self-Cured)

Parameter	Comparison	p-value	Significance	Interpretation
Compressive Strength	AD vs SSD	0.870	Not significant	The results showed no significant difference between these two conditions, suggesting that the self-curing mechanism is effectively compensating for these initial moisture differences. Construction teams can use aggregates in either AD or SSD condition without compromising compressive strength performance.
	CTR vs GAA	0.038	Significant	GAA has higher porosity than granite, but its compressive strength development at all ages is greater than those made of granite. However, GAA concrete developed greater strength than those of granite. This result suggests that GAA's porosity actually benefits by providing internal water reservoir.
	WC vs AC	0.004	Significant	The significant difference between WC and AC specimens confirmed the fundamental importance of water availability for cement hydration.
	Demoulding time and aggregate condition (SSD vs. AD)	0.995	Not significant	This indicated that the effect of demoulding time on strength is consistent whether using SSD or AD aggregates. The demoulding time effect appears to be independent of the initial moisture condition of the aggregates. This independence from demoulding timing gives construction teams tremendous flexibility to accelerate project schedules without risking strength development. Practically, contractors could potentially remove formwork earlier than with conventional concrete, freeing up formwork for reuse and accelerating construction cycles without compromising structural integrity.

Parameter	Comparison	p-value	Significance	Interpretation
UPV	Demoulding time and aggregate type (CTR vs. GAA)	0.820	Not significant	Effect of demoulding time on compressive strength appears to be consistent regardless of whether CTR or GAA aggregate was used. Both aggregate types showed similar patterns of strength development across different demoulding times. The self-curing mechanism appears to provide continuous internal moisture for cement hydration, creating a protective "moisture envelope" around cement particles that persists even after formwork removal. Unlike conventional concrete, which may suffer from premature moisture loss if demoulded too early, self-curing concrete maintains its internal water supply.
	Demoulding time and curing condition (WC vs. AC)	0.351	Not significant	This suggests that the demoulding time effect on strength follows a similar pattern for both WC and AC specimens. While curing condition itself had a significant effect on strength ($p = 0.004$), with WC specimens generally showing higher strength, the relationship between demoulding time and strength was not significantly altered by the curing method.
	AD vs SSD	0.988	Not significant	None of the factors significantly affected UPV measurements, suggesting that self-curing concrete's internal structure and wave propagation properties are consistent across aggregate conditions, types, and curing methods. This uniformity in UPV values suggested that self-curing concrete has identical internal integrity regardless of these variables, which aids construction quality control.
	CTR vs GAA	0.144	Not significant	
	WC vs AC	0.327	Not significant	
	Demoulding time and aggregate condition (SSD vs. AD)	0.995	Not significant	This finding suggested that the self-cured concrete properties measured by UPV are not affected by demoulding time in the same manner regardless of the initial moisture state of the aggregates.
	Demoulding time and aggregate type (CTR vs. GAA)	0.496	Not significant	This means that the effect of demoulding time does not significantly change the UPV reading depending on the type of aggregate used.

Parameter	Comparison	p-value	Significance	Interpretation
Density	Demoulding time and curing condition (WC vs. AC)	0.692	Not significant	It indicated that the relationship between demoulding time and UPV measurements remained consistent whether specimens are water-cured or air-cured. This suggested that the curing environment does not substantially modify how demoulding timing affects the internal structural properties of concrete as measured by UPV.
	AD vs SSD	0.899	Not significant	Similar density regardless of initial condition.
	CTR vs GAA	0.042	Significant	The higher density in CTR compared to GAA is expected given granite's naturally higher specific gravity.
	WC vs AC	0.130	Not significant	Self-curing concrete contained mechanisms to retain water internally, meaning that whether additional water is supplied externally (WC) or not (AC), the concrete maintains similar moisture content and thus similar density.
	Demoulding time and aggregate condition (SSD vs. AD)	0.999	Not significant	This finding suggested that the effect of demoulding time on density is consistent regardless of whether saturated surface dry (SSD) or air-dried (AD) aggregates are used in the concrete mix.
	Demoulding time and aggregate type (CTR vs. GAA)	0.283	Not significant	This means that the impact of demoulding time on concrete density does not significantly differ between different aggregate types (CTR vs. GAA). In practical terms, this suggested that regardless of whether CTR or GAA aggregates are used, the effect of demoulding time on density follows a similar pattern
	Demoulding time and curing condition (WC vs. AC)	0.320	Not significant	This means that the effect of demoulding time on concrete density does not significantly change when switching between water curing and air curing methods.
Flexural Strength	AD vs SSD	0.772	Not significant	The similar performance between AD and SSD specimens indicated that the flexural strength development in this critical zone is not compromised by starting with AD aggregates. Construction teams can use aggregates in either AD or SSD conditions without compromising flexural performance.

Parameter	Comparison	p-value	Significance	Interpretation
Modified Compressive Strength	CTR vs GAA	0.013	Significant	CTR specimens showed substantially higher flexural strength than GAA specimens. This suggested that the GAA might adversely affect the flexural properties of concrete.
	WC vs AC	0.027	Significant	These findings strongly suggested that water curing creates more favourable conditions for strength development material, likely by promoting better hydration processes or other strengthening mechanisms.
	AD vs SSD	0.911	Not significant	The similar performance between AD and SSD specimens indicated that the compressive strength development in this critical zone is not compromised by starting with AD aggregates. Construction teams can use aggregates in either AD or SSD conditions without compromising strength performance.
	CTR vs GAA	0.021	Significant	CTR specimens showing higher modified compressive strength than GAA specimens, indicating the GAA may reduce this property.
	WC vs AC	0.001	Significant	The significant difference between WC and AC specimens confirmed the fundamental importance of water availability for cement hydration.

5.8 Expansion and Shrinkage

Figure 5.4 shows the shrinkage and expansion of control concrete (CTR-1D-AD-WC, CTR-1D-SSD-WC, CTR-1D-AD-AC, and CTR-1D-SSD-AC) and the concrete containing GAA (GAA-1D-AD-WC, GAA-1D-SSD-WC, GAA-1D-AD-AC and GAA-1D-SSD-AC) cured in water and air. It is indicated that shrinkage and expansion were drastically increased at an early age and started to be constant after seven (7) days for all series of concrete specimens. These results suggested that at early age, cement hydration occurs at its fastest rate. This process consumed water and generated heat, leading to significant volume changes. The rate of cement hydration significantly decreased after seven days, leading to more stable volume conditions (Silva et al., 2021). Control concrete specimens exhibited the highest both shrinkage

and expansion at all ages compared to those concrete containing GAA. This may be explained by concrete containing GAA act as internal water reservoirs, gradually releasing moisture to the cement paste. This mechanism helps maintain a more stable internal relative humidity (RH), reducing both extreme shrinkage in drying conditions and excessive expansion in wet conditions (Zhutovsky & Kovler, 2012). The voids within concrete containing GAA were already filled with water, while control concrete had empty air voids within concrete. As a result, the water entry into control concrete was greater than that into concrete containing GAA, resulting in greater expansion of control concrete specimens. At age of 3 days, the expansion strain of concrete GAA-1D-AD-WC, and GAA-1D-SSD-WC were 56×10^{-6} and 72×10^{-6} respectively. It showed that the expansion strain of concrete GAA-1D-AD-WC reduced by 28% compared to that of concrete GAA-1D-SSD-WC. These results suggested that porous aggregates initially have more capacity to absorb water from the surrounding cement paste and external curing environment. This absorption can temporarily counteract some of the expansion forces, resulting in less overall expansion (Xu *et al.*, 2022). However, at 28 days the expansion strain of concrete GAA-1D-AD-WC, and GAA-1D-SSD-WC were 167×10^{-6} and 121×10^{-6} respectively. Compared to the concrete GAA-1D-AD-WC, the expansion strain of concrete GAA-1D-SSD-WC reduced by 38% at 28 days. These results suggested that the SSD aggregates in concrete GAA-1D-SSD-WC provide a more stable internal curing environment, leading to more controlled long-term expansion.

It can be seen from Figure 5.4 that the shrinkage of the control group reached 295×10^{-6} for CTR-1D-AD-AC and 318×10^{-6} for CTR-1D-SSD-AC in the first 72 hours, which is 66% and 68%, respectively, of the 28-day shrinkage value. This means that the shrinkage of concrete mainly occurred in the first 72 hours after casting. Compared to the control concrete CTR-1D-AD-AC and CTR-1D-SSD-AC, the shrinkage of self-cured concrete GAA-1D-AD-AC and GAA-1D-SSD-AC can be reduced by 35% and 51% respectively at 28 days. These results suggested that the water stored in the GAA is important to support the continuous hydration when free water inside concrete is insufficient, and the shrinkage of concrete would take place due to the rapid drop in the internal humidity. Moreover, the state of conventional aggregate prior entering the mix does not affect the autogenous shrinkage. Compared to the concrete mixes GAA-1D-AD-AC, the shrinkage strains of GAA-1D-SSD-AC can be reduced by 22% at 28 days. These results suggest that the saturated surface-dried (SSD) porous

aggregates provide immediate internal curing. It released water to the surrounding cement paste, maintaining a higher internal RH and reducing early-age shrinkage and continue to release water gradually, mitigating long-term shrinkage.

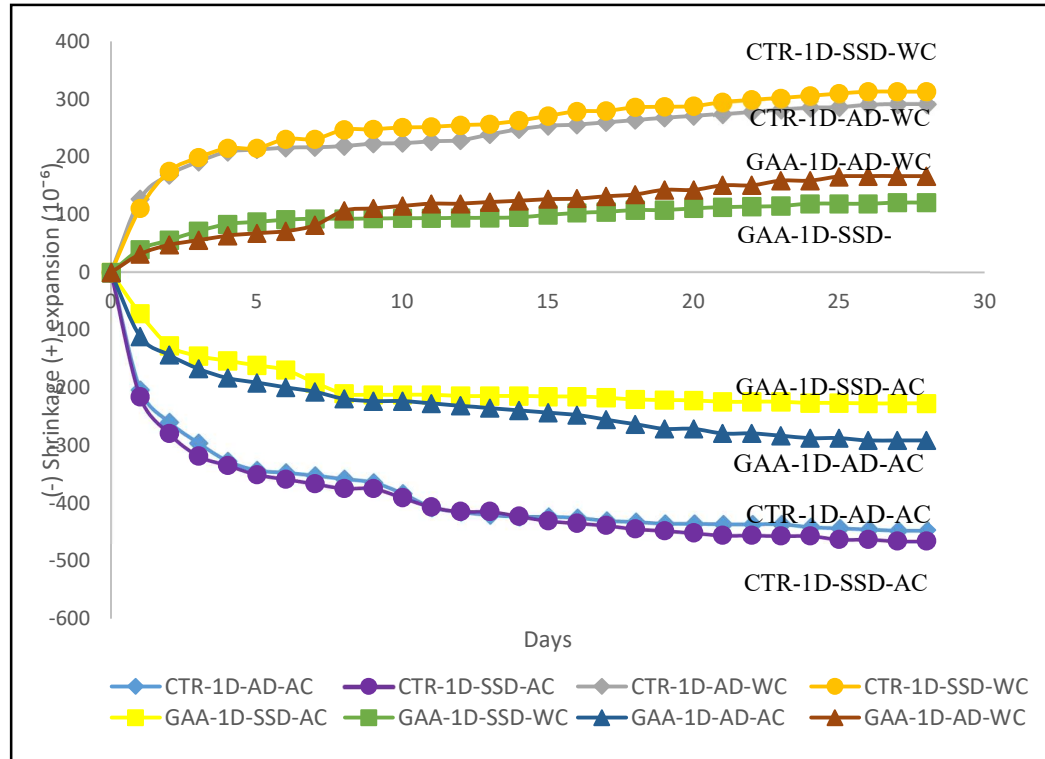


Figure 5.4 Expansion and Shrinkage Values of Self-Cured (GAA) and Control Concrete Up to 28 Days

5.9 Initial Surface Absorption (ISAT)

The test process is based on the rate of water diffusion across the surface of the concrete specimen. The main objective was to denote the presence of a pore within the concrete. Additionally, the initial surface absorption test (ISAT) establishes the surface of concrete permeability to provide better resistance to water absorption and reducing the risk of corrosion of reinforcements. Figure 5.5 shows the results of the ISAT of all concrete mixes obtained at 28 days. As expected, the ISAT value of concrete under water curing was significantly lower than those of concrete under dry air curing in this study. The graph demonstrates the rate of absorption of control concrete was lower than that of concrete containing of GAA in water curing. It is believed to be due to the inherent porosity of GAA, while beneficial for internal curing, can create pathways for initial water ingress at the concrete surface, particularly in early-age testing. Rodríguez-

Torres & Torres-Castellanos (2019) reported similar observations in their experiments. While the ISAT results at 28 days may indicate a higher absorption for concrete with GAA, this does not inherently imply inferior long-term durability. The continued internal curing process can lead to further hydration and pore refinement over time, potentially resulting in improved long-term performance and durability compared to conventional concrete. The absorption at 10 minutes (min) was higher than 60 min because the absorption capacity of concrete depends on effective porosity. At 60 min, the pores of concrete are mostly likely filled with water. However, it demonstrated the rate of absorption of concrete containing GAA was lower than that control concrete cured in air curing. GAA concrete provided a steady supply of water for cement hydration, leading to a more refined pore structure and potentially lower surface absorption rates whereas control concrete may suffer from insufficient hydration (Yang *et al.*, 2022). The rate of absorption of concrete containing SSD GAA was lower compared to concrete containing AD GAA. This could be related to the concrete containing SSD GAA, being pre-saturated, provide a more consistent and readily available source of internal moisture for cement hydration compared to their AD counterparts. Concrete containing AD GAA may initially absorb some of the mixing water, potentially reducing the water available for early-stage hydration. While they still contribute to self-curing, their effectiveness may be slightly delayed compared to concrete containing SSD GAA.

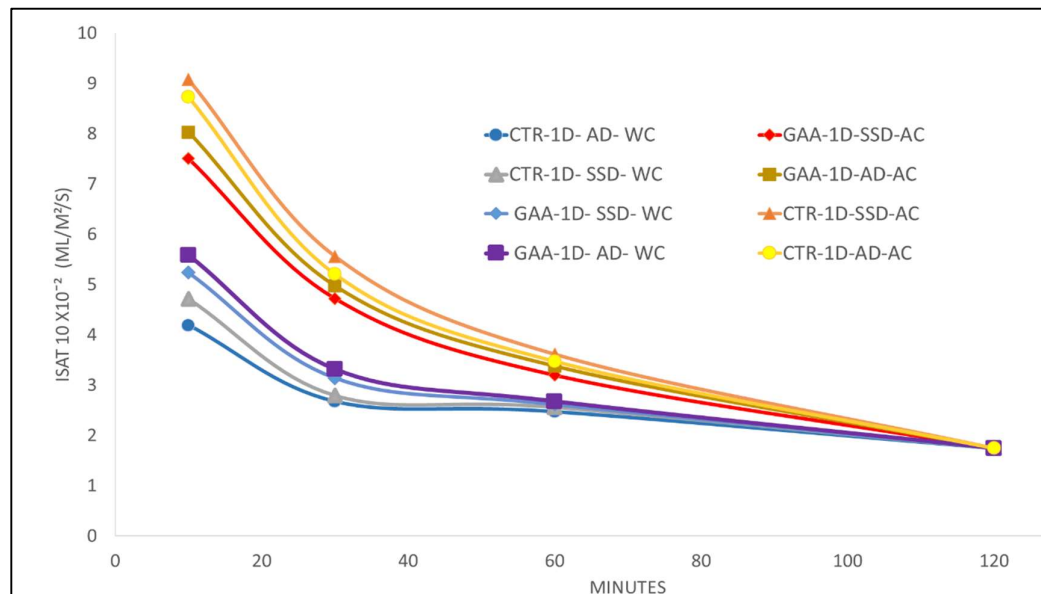


Figure 5.5 ISAT for All Series of Control and GAA Concrete Specimens at 28 Days

5.10 Summary

The properties of normal-strength concrete internally cured by GAA and control concrete were studied experimentally, including compressive strength, ultrasonic-pulse velocity, density, flexural strength, modified compressive strength, shrinkage, expansion and initial surface absorption test. Based on the experimental results, the following conclusions can be drawn as follows:

- i) At 28 days, SSD GAA concrete showed slightly higher compressive strength than AD GAA concrete under both curing conditions, though all variants achieved comparable strengths to granite control concrete. AD GAA application offers practical construction advantages by eliminating pre-soaking requirements, reducing time and labor while maintaining normal-strength performance through internal curing effects. Statistical analysis confirmed that demoulding time (1-, 3-, or 7-day periods) did not significantly impact compressive strength. This enables early formwork removal compared to conventional concrete, accelerating construction cycles, improving formwork reuse, and enhancing construction scheduling and resource management while preserving structural integrity.
- ii) At 28 days, SSD GAA concrete exhibited slightly higher UPV than AD GAA concrete under both curing conditions, while control concrete achieved the highest values. However, UPV readings for AD GAA, SSD GAA, and granite concrete were comparable, ranging from 3.5-4.5 km/s, indicating good quality concrete suitable for various structural and non-structural construction applications.
- iii) At 28 days, the density of concrete incorporating SSD GAA cured in water and air showed slightly higher compared to those made of AD GAA, while control concrete had the highest density. However, the density of concrete containing AD GAA, SSD GAA and granite is comparable.
- iv) At 28 days, SSD GAA concrete exhibited slightly higher flexural strength than AD GAA under both curing conditions, while control concrete achieved the highest strength. However, AD GAA, SSD GAA, and granite concrete showed comparable flexural strengths. AD GAA use at construction sites optimises mixing by eliminating pre-soaking requirements, saving time and labour while

maintaining normal-strength concrete flexural performance through effective aggregate integration.

- v) Replacing granite with GAA significantly reduces concrete shrinkage, particularly during the critical first 72 hours. Self-cured GAA concrete (GAA-1D-AD-AC and GAA-1D-SSD-AC) reduced shrinkage by 35% and 51% respectively compared to control concrete. Additionally, GAA-1D-SSD-WC showed 38% less expansion strain than GAA-1D-AD-WC, demonstrating GAA's effectiveness in controlling dimensional changes in concrete.
- vi) Control concrete showed lower absorption than GAA concrete under water curing due to GAA's inherent porosity. However, under air-curing, self-cured concrete achieved lower surface absorption through steady internal water supply, creating refined pore structure. SSD GAA concrete outperformed AD GAA concrete due to pre-saturated aggregates providing consistent internal moisture for enhanced hydration and improved pore structure development.

CHAPTER 6

MICROSTRUCTURE, CHEMICAL COMPOSITION AND POROSITY OF SELF-CURED CONCRETE

6.1 Introduction

This chapter presents the microstructural properties of control concrete and self-cured concrete specimens. Scanning Electron Microscopy (SEM) coupled with Energy Dispersive X-Ray Analysis (EDX) was employed to visualise and analyse the concrete at microscopic levels, providing insights into the morphological features and elemental composition of the hydration products. The SEM imaging revealed concrete microstructure details, including the interfacial transition zone (ITZ), clarifying how hydration mechanisms were influenced by curing and without curing processes. Simultaneously, EDX analysis complemented these observations by identifying the elemental composition of specific regions in the concrete samples, which facilitated the characterisation of chemical phases and their distribution throughout the matrix. To further enhance the analytical depth, X-ray Powder Diffraction (XRD) analysis identified and quantified crystalline phases in concrete samples, revealing phase transformations during hydration and showing how GAA as a self-curing agent influences mineralogical development. This crystallographic investigation provided data regarding the formation, consumption, and evolution of mineral phases such as calcium hydroxide ($\text{Ca}(\text{OH})_2$) and calcium silicate hydrate (C-S-H) at different curing ages and under varying curing conditions. Additionally, Mercury Intrusion Porosimetry (MIP) testing was performed to quantify critical parameters of the pore network structure, including pore size distribution, total porosity, threshold pore diameter, and pore connectivity, which significantly impact the durability and performance characteristics of concrete. Pore analysis revealed self-curing efficacy in modifying microstructure and reducing permeability compared to conventional curing methods. The results were interpreted by providing suitable discussion based on the existing theories. The microstructure and mineralogical development of normal-strength concrete containing GAA as a curing agent in comparison to conventional concrete are

presented. The effect of curing and without curing process towards the microstructure of concrete due to self-curing actions are assessed.

6.2 Scanning Electron Microscope (SEM)

The SEM was used in conjunction with an energy dispersion X-ray spectroscopy (EDX) instrument to determine the chemical composition of a specific point or area and ITZ in the micrograph image. The examination was conducted to observe the internal features of concrete containing GAA compared to the control concrete. The ITZ of concrete samples was analysed to observe the distribution of atomic ratios in aggregates and hydrated phases of ITZ. The ITZ of concrete adopted at 7 and 28 days of air curing and water curing are shown in Figure 6.1 and Figure 6.2, respectively. From Figures 6.1 and 6.2, it was noted that the boundary between the cement matrix and the GAA is not distinct at 28 days of age, indicating that the GAA bonds tightly and continuously with the cement matrix. The well-bonded interfacial zone is a characteristic of concrete containing GAA that contributes to its increased strength development. Additionally, both control and concrete containing GAA display numerous microcracks between the cement paste and aggregate in the ITZ area at early ages, as illustrated in Figures 6.1 and 6.2. The appearance of microcracks could be observed at the core portion of the concrete which indicates the improper presence of C-S-H gel products. These microcracks will lead to the formation of the weak zone. The ITZ zone between aggregate and cement matrix is visible at an early age.

Furthermore, the microcracks in the ITZ area of control concrete are mainly bigger than those microcracks in the ITZ area of concrete containing GAA. This is because granite with a dense structure has difficulty absorbing free water inside the cement matrix, resulting in the formation of a layer of water around the aggregate particles (Wall Effect). Thus, causing an increase on the water-cement ratio in its surrounding cement paste and leading to microcracks in the ITZ area (Tang, 2017). Contrary, the rough surface texture and pore structure of the GAA allow water to be absorbed easily, lowering the water-cement ratio in the surrounding cement paste and resulting in a denser matrix, which facilitates the spreading of microcracks in the rear of the dense matrix (Tang, 2017). There was enhanced integration of the GAA with the cement matrix composed of calcium-silicate -hydrate (C-S-H). The concrete containing GAA exhibited improvement in mechanical behaviour, as evidenced by the lower strength ratio that indicates the increment in strength.

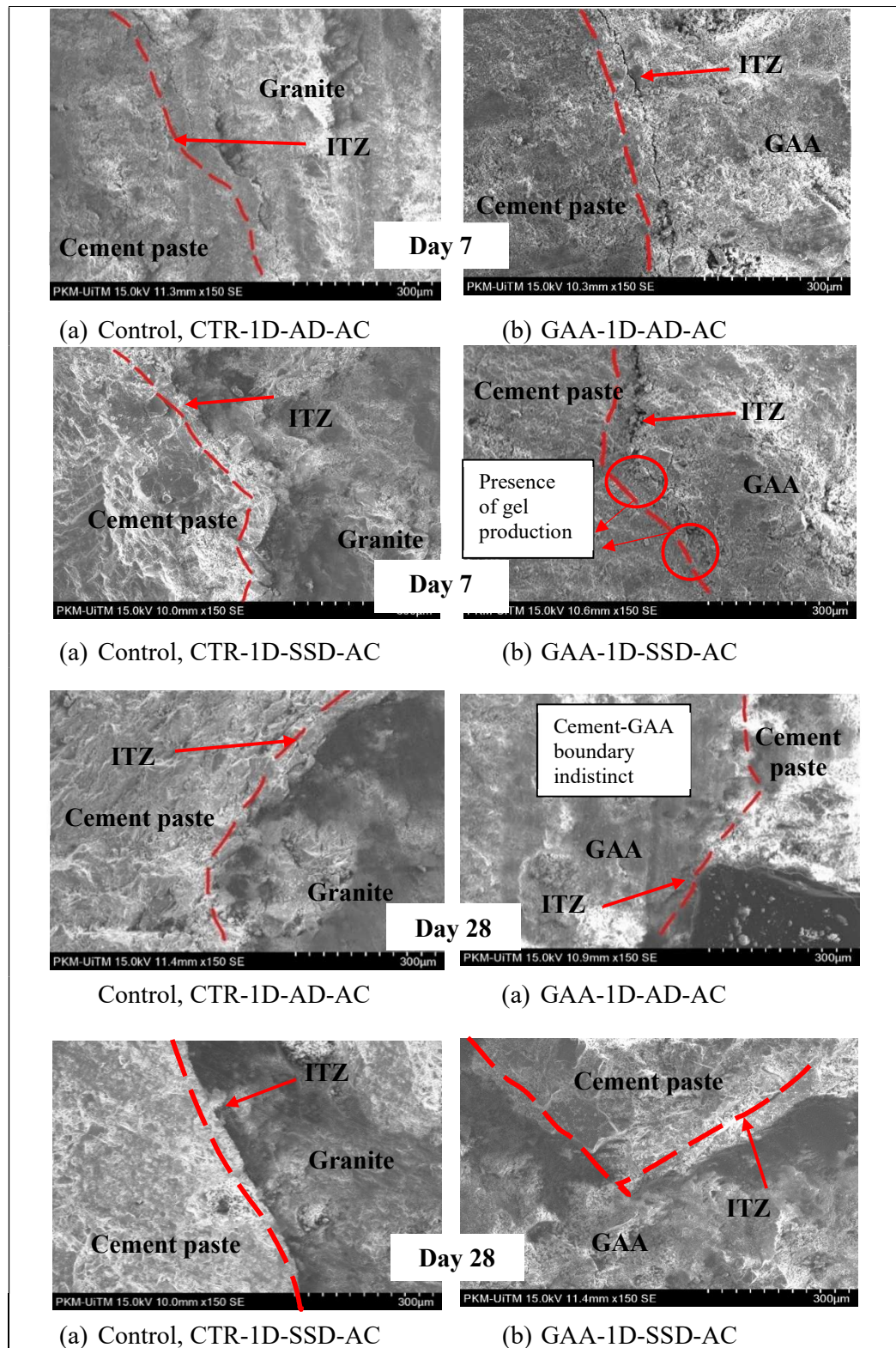


Figure 6.1 Scanning Electron Micrograph of (a) Control Concrete (b) Concrete Containing GAA at Low Magnification of 150x at the Age of 7, and 28 Days, Cured in Air

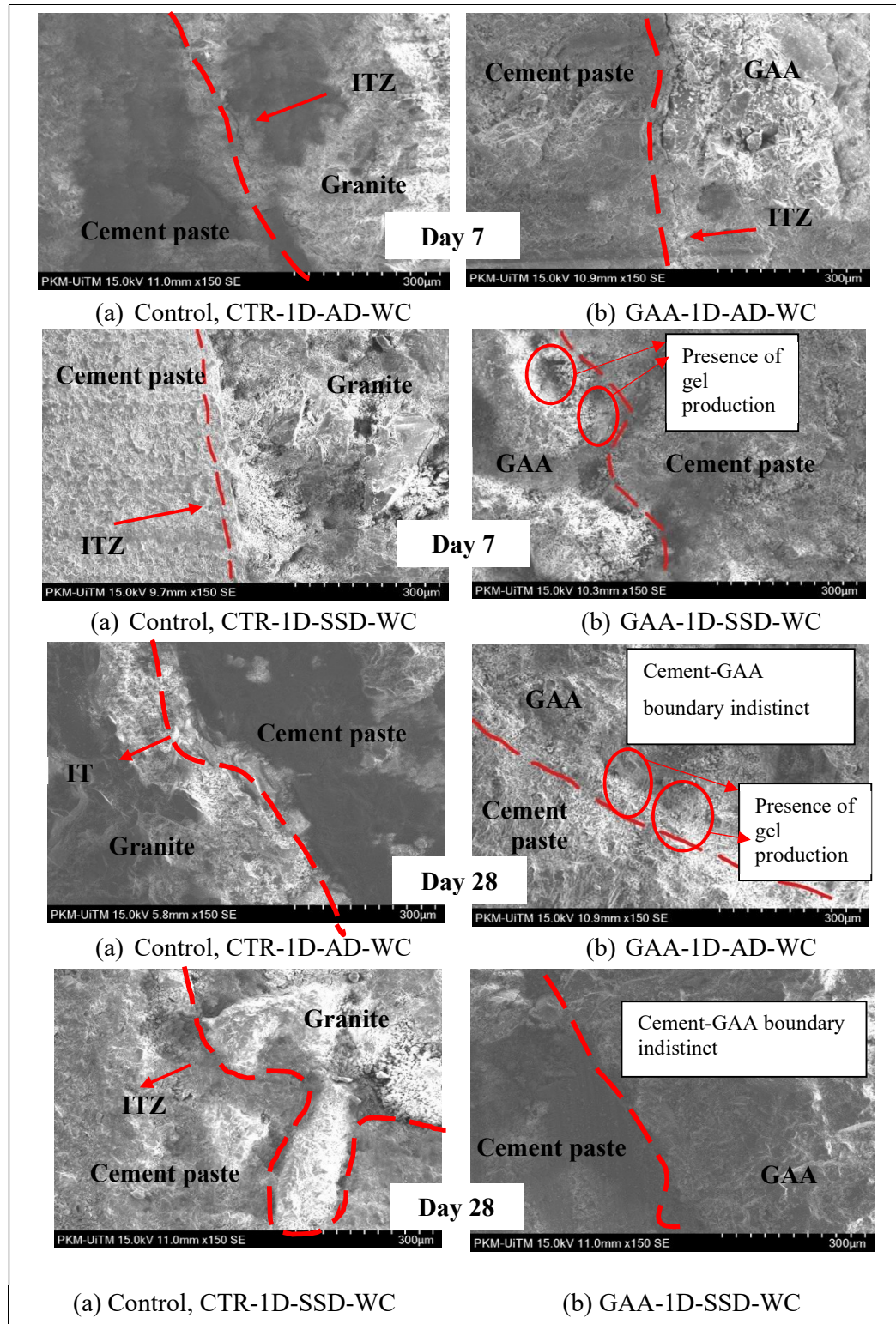


Figure 6.2 Scanning Electron Micrograph of (a) Control Concrete (b) Concrete Containing GAA at Low Magnification of 150x at the Age of 7, and 28 Days, Cured in Water

6.3 Energy-Dispersive X-Ray (EDX)

The complete hydration of both control concrete and concrete containing GAA was formed at the age of 28 days. Figure 6.3 illustrates the EDX results of the control concrete (CTR-1D-AD-AC) and concrete which containing AD GAA (GAA-1D-AD-AC) and SSD GAA (GAA-1D-SSD-AC) at 1 day cured in air curing conditions. The CTR-1D-AD-AC specimen can be seen in needle-shaped surface as shown in Figure 6.3 (a) compared to concrete containing AD GAA (GAA-1D-AD-AC) and SSD GAA (GAA-1D-SSD-AC) which was flat smooth surface that produce more denser concrete as depicted in Figures 6.3 (b) and 6.3 (c). It can be said that part of free water in concrete mixes was absorbed by the AD GAA, which then released it to reach the unhydrated cementitious material in concrete and turn it into internal curing water to assist the continuous hydration in the later curing period as reported by other research works (Chen et al., 2019). The high concentration of calcium (Ca) composition of about 46.7% by weight was detected in GAA-1D-SSD-AC in comparison with that of control concrete which recorded only 19.6%. While the concentration of calcium (Ca) composition detected in GAA-1D-AD-AC is 40.9%. The high concentration of calcium (Ca) composition shows the hydration product was formed due to high ratio recorded for Ca/Si of 3.33 for GAA-1D-SSD-AC while ratio of Ca/Si in control, CTR-1D-AD-AC concrete sample was 0.52. While GAA-1D-SSD-AC recorded Ca/Si with proportion of 2.76. EDX results were used to calculate the Ca/Si ratio based on the relative proportion of atomic percentage recorded in Ca and Si (Escalante-Garcia & Sharp, 2004). This result confirmed that self-curing in concrete containing saturated surface-dried GAA occurred during the air-curing conditions and produced more C-S-H compared to the control concrete. However, concrete containing AD GAA also produced more C-S-H compared to control concrete and the result of EDX is comparable with SSD GAA. In air-curing conditions, the self-curing effect is especially advantageous when there is a limited or non-existent external water supply. The moisture retained within the GAA particles creates localised high-humidity micro zones around unhydrated cement particles, allowing hydration to continue long after it would normally cease in conventional concrete. This extended hydration period facilitates more complete cement reaction, reduced porosity, and improved mechanical properties.

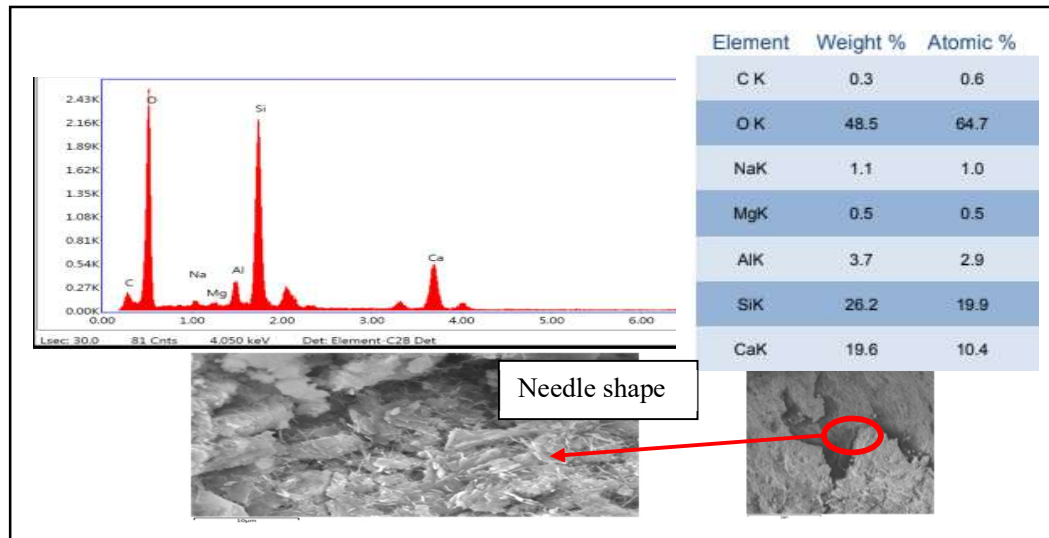


Figure 6.3(a) EDX Spectra and Maps of Control Concrete (CTR-1D-AD-AC) at 28 Days of Age, Cured in Air

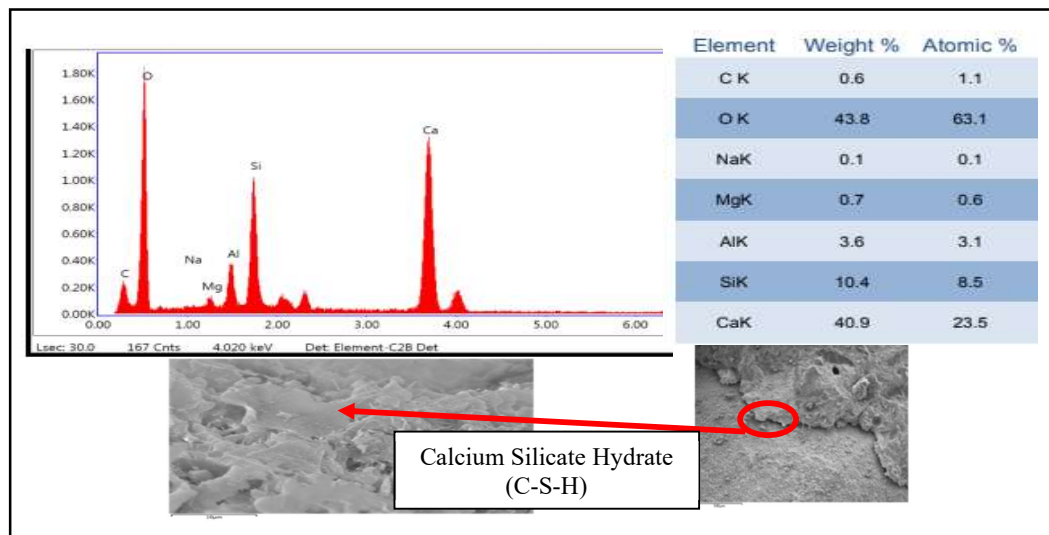


Figure 6.3(b) EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-AD-AC) at 28 Days of Age, Cured in Air

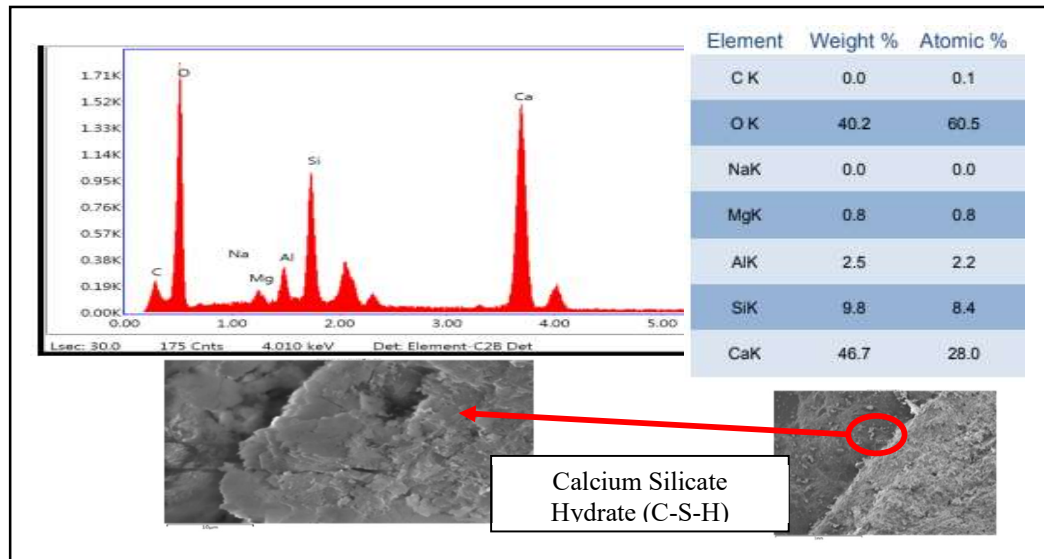


Figure 6.3(c) EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-SSD-AC) at 28 Days of Age, Cured in Air

Figure 6.4 illustrates the EDX results of the control concrete (CTR-1D-AD-WC) and concrete containing AD GAA (GAA-1D-AD-WC) and SSD GAA (GAA-1D-SSD-WC) at 1 day cured in water curing conditions. Most of the specimens shows flat smooth surface at the major area in internal structure that indicated denser morphology of fully hydrated cement matrix. This is most likely because sufficient water was available to maximise the extent of cement hydration. The concrete containing SSD GAA showed a slightly higher Ca/Si ratio of 3.33 compared to AD GAA concrete at 3.10, with both performing significantly better than the control concrete's ratio of 1.84. The higher Ca/Si ratio in GAA concrete results from the porous aggregates functioning as internal water reservoirs that ensure continuous moisture availability throughout the hydration process. This sustained water supply enables more complete hydration of calcium-rich cement compounds, leading to greater formation of calcium-based hydration products like $\text{Ca}(\text{OH})_2$ and C-S-H. Similarly, the calcium content analysis revealed that SSD GAA concrete achieved 46.7% by weight, while AD GAA concrete reached 42.7% by weight, both surpassing the control concrete's that recorded 37.9%. This enhanced performance of calcium-based hydration products that attributed to the water-retaining capability of SSD GAA, which acts as an internal water reservoir for continuous cement hydration. The presence of readily available water in SSD GAA promotes better dissolution of cement compounds and formation of calcium-based hydration products, resulting in a higher calcium content. The marginally better performance of SSD GAA

over AD GAA (difference of 0.32 in Ca/Si ratio and 4% in calcium content) suggests that pre-saturating the aggregates provides additional water for hydration process, though both conditioning methods demonstrate effective self-curing capabilities through their internal water retention and release mechanisms that promote better cement hydration and calcium-based product formation. The comparison between water-cured and air-cured GAA samples is particularly interesting. The SSD GAA samples exhibit nearly comparable Ca/Si ratios (3.33) and calcium content (46.7%) irrespective of external curing conditions. This notable constancy suggests that the internal water reservoirs within pre-saturated GAA can sustain appropriate hydration conditions despite limited or missing external water supply. The self-curing method involves successfully establishing an internal microenvironment that replicates optimal water-curing conditions. The pore structure of GAA likely creates an ideal capillary pressure condition that promotes gradual water release at rates that match the cement's hydration demands.

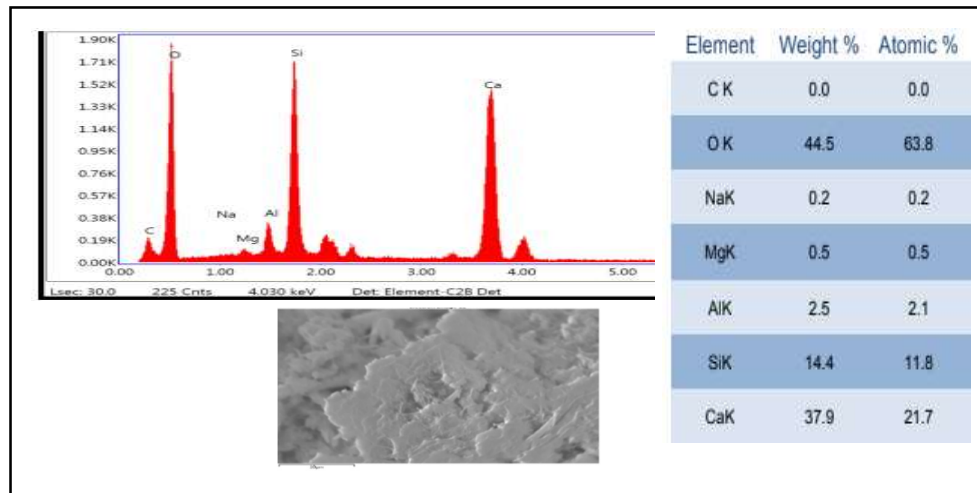


Figure 6.4(a) EDX Spectra and Maps of Control Concrete (CTR-1D-AD-WC) at 28 Days, Cured in Water-Curing Condition

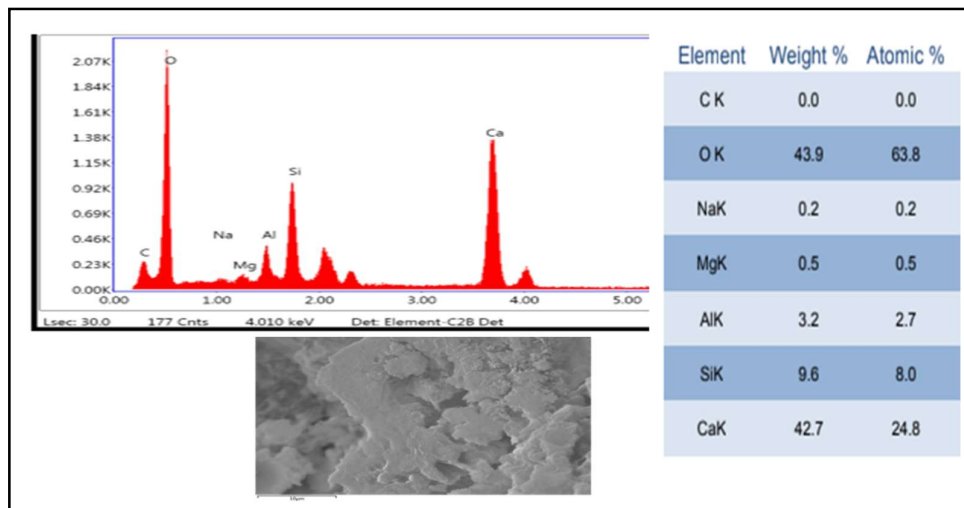


Figure 6.4(b) EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-AD-WC) at 28 days, Cured in Water-Curing Condition

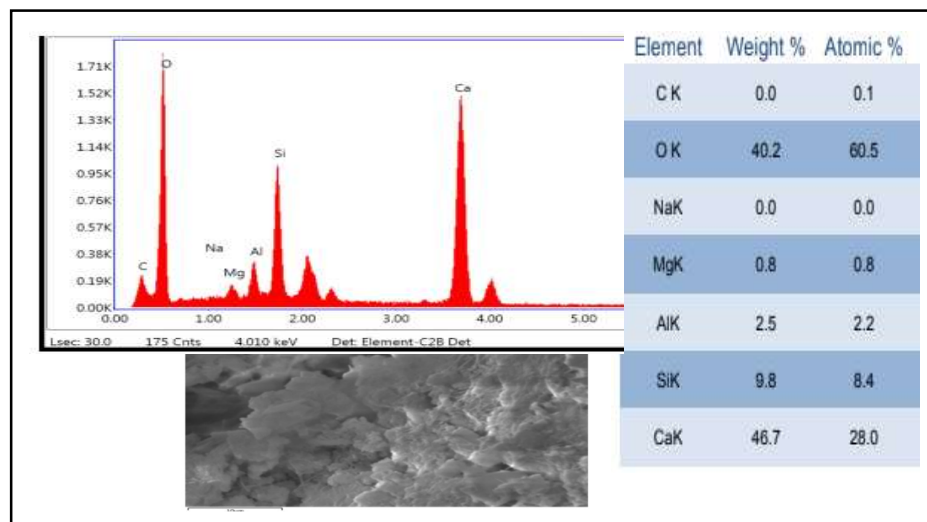


Figure 6.4(c) EDX Spectra and Maps of Self-Cured Concrete (GAA-1D-SSD-WC) at 28 Days, Cured in Water-Curing Condition

6.4 X-Ray Diffraction (XRD)

The mineral analysis of control concrete and concrete containing GAA was monitored using X-ray diffraction (XRD) at the curing age of 7, and 28 by tracing the main cement hydration products of portlandite ($\text{Ca}(\text{OH})_2$), and calcium silicate hydrate (C-S-H). Table 6.1 shows the compound and index names as recognised by the X-Pert Pro software with files of standard mineral from International Center for Diffraction Data database (JCPDS-ICDD). The reason for selecting these two (2) compounds was their contribution to cement strength and cement hydration (Stepkowska *et al.*, 2003).

Table 6.1

Compound and Index Name of Chemical and Mineral Composition in Concrete Recognised by X-pert Pro Software

Compound name	Portlandite	Calcium Silicate Hydrate
Chemical formula	$\text{Ca}(\text{OH})_2$	CSH
Index name	Calcium hydroxide	Calcium Silicate Hydrate

The intensity changes from the diffractometer were plotted at diffraction peaks against the scattering angle (2θ) of control concrete and concrete containing GAA cured in air curing at the ages of 7 days and 28 days. The intensity peaks for 7 and 28 days are illustrated in Figure 6.5, and Figure 6.6 respectively. The formation of hydration product shown in Figure 6.5 shows an early age profile of XRD for control concrete and concrete containing GAA cured in air curing condition. The major peak of calcium hydroxide ($\text{Ca}(\text{OH})_2$) are dominant due to the self-curing effect, and minor peaks of calcium silicate hydrate (C-S-H) were also identified in the intensity peaks. These two (2) hydrations products were formed with higher intensity in concrete containing GAA. For both control and concrete containing GAA specimens, the $\text{Ca}(\text{OH})_2$ compound reached its maximum intensity at $2\theta = 17^\circ$. The additional peak of $\text{Ca}(\text{OH})_2$ in concrete containing GAA was also observed at $2\theta = 34^\circ$, $2\theta = 36^\circ$, and $2\theta = 50^\circ$ more than control concrete. In this present study, the additional formation of calcium silicate hydrate (C-S-H) at the age of 7 days was recorded in concrete containing GAA at $2\theta = 20^\circ$, $2\theta = 39^\circ$, and $2\theta = 55^\circ$ at higher intensity than control concrete. The peak intensity of GAA-1D-SSD-AC specimen was observed higher than that of GAA-1D-AD-AC specimen, probably because of the presence of internal water reservoir in GAA that provide extra water for the hydration process, hence improved self-cured concrete

properties. The formation of C-S-H contributes the strength of concrete and the formation of $\text{Ca}(\text{OH})_2$ at early hydration process.

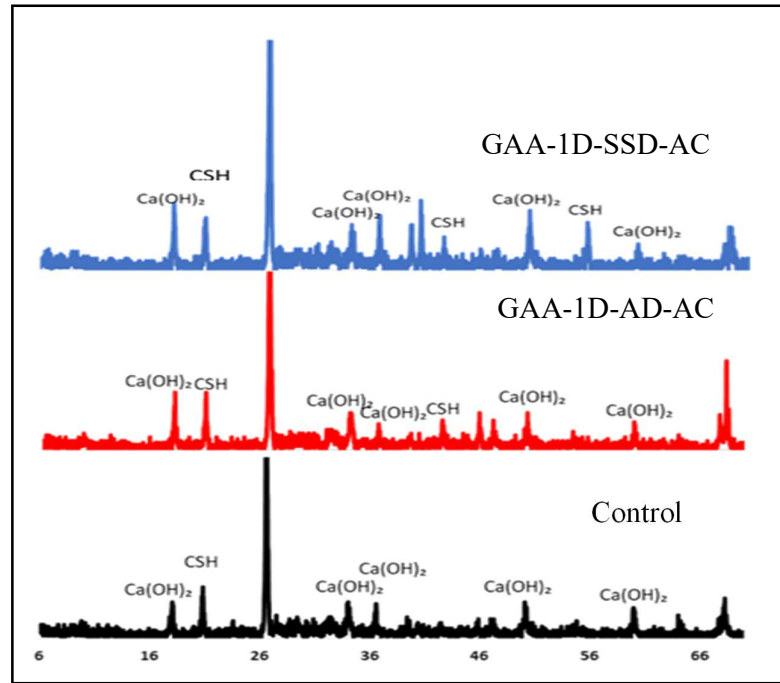


Figure 6.5 X-Ray Diffraction (XRD) Spectra of Control Concrete and Self-Cured Concrete at 7 Days Cured in Air

Diffractogram at 28 days of the sample as shown in Figure 6.6 illustrates the variation of peaks of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in self-cured concrete was found at $2\theta = 17^\circ$ and 50° which is more than control concrete. Analysis of XRD on self-cured concrete shows more formation of C-S-H compared to control concrete. The peak of C-S-H was observed at $2\theta = 20^\circ$, and 55° with the higher intensity recorded in self-cured concrete than control concrete. C-S-H formation depends on both adequate calcium availability (from dissolved cement compounds) and sustained moisture presence that allows for continued silicate hydration. The porous GAA structure creates a network of microscopic water reservoirs that sustain the moisture in the concrete then gradually release its water during the cement hydration process.

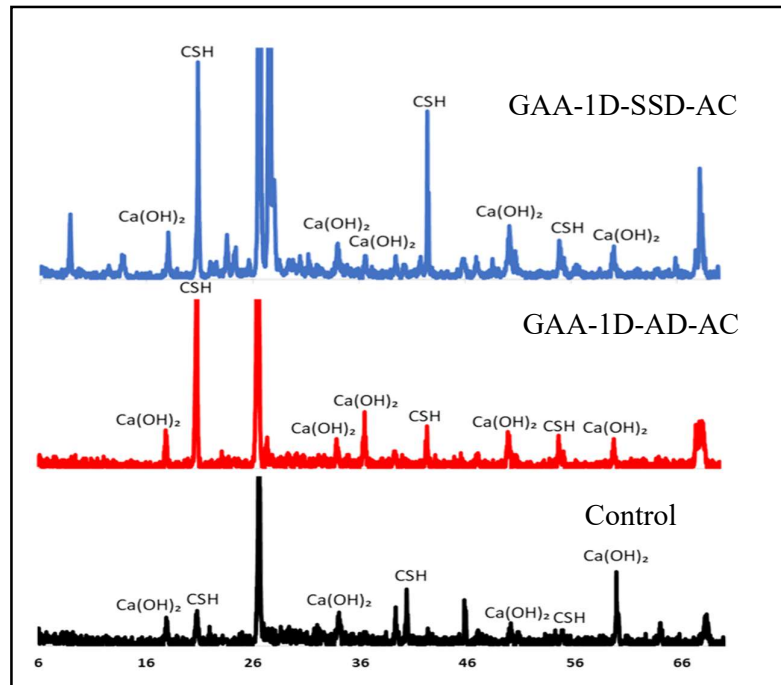


Figure 6.6 X-Ray (XRD) Diffractogram of Control Concrete and Self-Cured Concrete at 28 Days Cured in Air

Similar trend was also found in XRD diffractogram of control concrete and self-cured concrete specimens cured in water curing at the ages of 7 and 28 days as shown in Figure 6.7 and 6.8 respectively. It can be observed from Figure 6.7 that the major peak of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in self-cured concrete appeared at $2\theta = 17^\circ, 34^\circ, 36^\circ, 50^\circ$, and 60° more than control concrete with intensity of 44%, 13%, 74%, 98%, and 15% for SSD GAA and 33%, 4%, 2%, 29%, and 98% for AD GAA. The higher of calcium hydroxide ($\text{Ca}(\text{OH})_2$) considered as a good indicator of the evaluation of hydration reactions. At the age of 7 days, the increased calcium silicate hydrate (C-S-H) production was observed in self-cured concrete at $2\theta = 21^\circ, 39^\circ$, and 55° with a higher intensity than in control concrete. The XRD patterns of control and self-cured concrete at 28 days cured in water curing condition is presented in Figure 6.8. The variation peaks of calcium hydroxide ($\text{Ca}(\text{OH})_2$) in self-cured concrete appeared at $2\theta = 17^\circ, 34^\circ, 36^\circ, 50^\circ$, and 60° more than control concrete with intensity of 43%, 10%, 2%, 1%, and 84% for AD GAA while 50%, 5%, 59%, 29%, and 98% for SSD GAA. The formation of calcium silicate hydrate (C-S-H) peak was observed higher intensity than in control concrete. It can be observed that specimens cured in water curing, the calcium hydroxide ($\text{Ca}(\text{OH})_2$) intensity increased, showing a higher degree of hydration. In contrast, specimens cured in air curing conditions, there is a reduction in

calcium hydroxide ($\text{Ca}(\text{OH})_2$) intensity. As demonstrated in Figure 6.5 and 6.7, the presence of portlandite results in the formation of calcium hydroxide ($\text{Ca}(\text{OH})_2$) during early hydration as a result of the reaction between calcium oxide (CaO) and water (H_2O). Similar pattern of calcium hydroxide ($\text{Ca}(\text{OH})_2$) diffraction peak was also recorded at the same position of $2\theta = 17^\circ$, 34° , and 50° by Liu *et al.* (2014) and Tang (2017). The evolution of portlandite formation over time is demonstrated by the temporal comparison of the 7-day and 28-day patterns. As hydration reactions slow down and external moisture becomes scarcer, portlandite formation in traditional concrete frequently slows down. However, the continued portlandite synthesis in GAA-modified concrete is ensured by the sustained internal water supply, which explains the 28-day diffractograms' consistent intensity advantage.

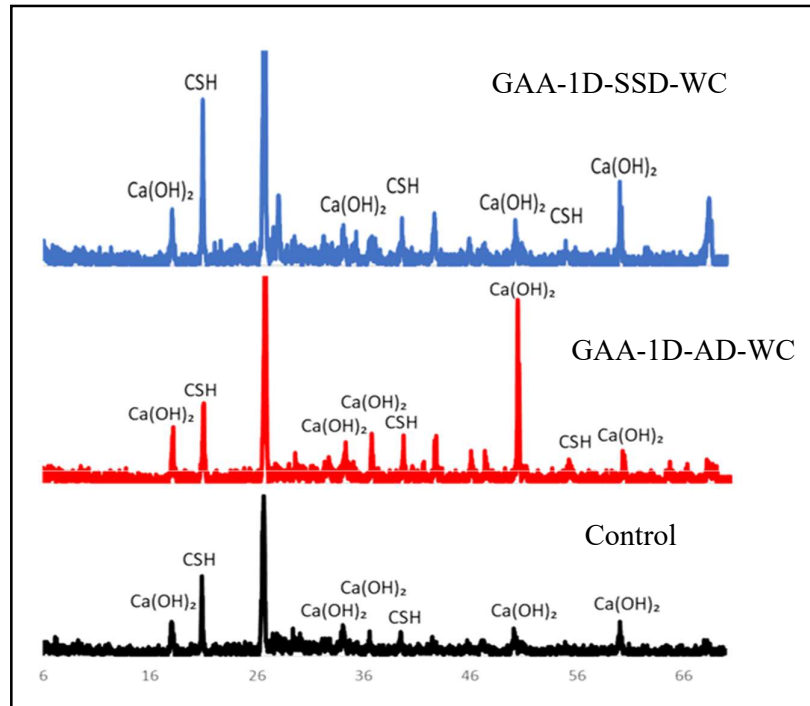


Figure 6.7 X-Ray Diffraction (XRD) of Control Concrete and Self-Cured Concrete at 7 Days Cured in Water

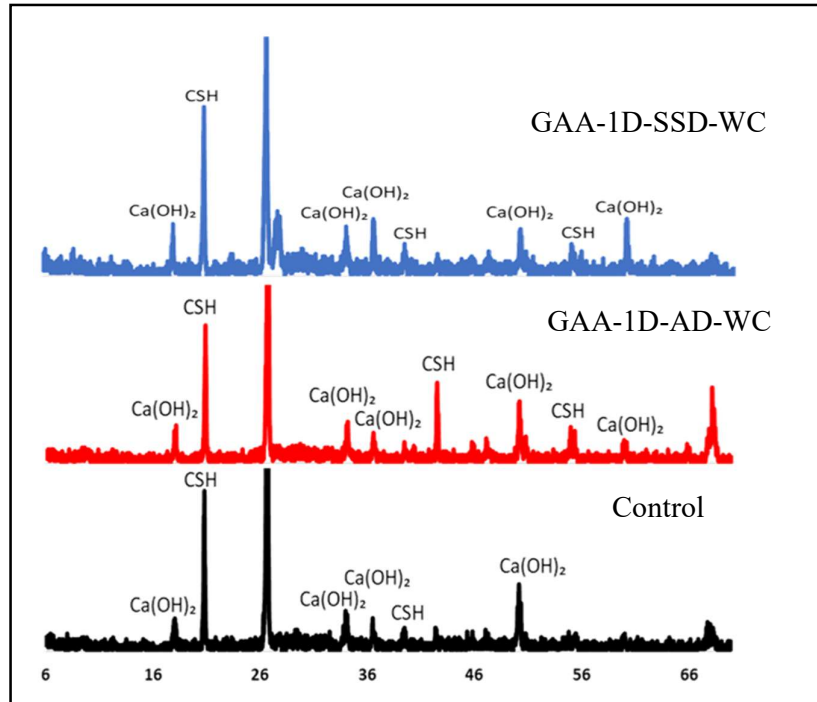


Figure 6.8 X-Ray Diffraction (XRD) of Control Concrete and Self-Cured Concrete at 28 Days Cured in Water Curing Condition

6.5 Mercury Intrusion Porosimetry (MIP)

The pore structure analysis was carried out at the age of 28 days using MIP (AutoPore IV 9500) to investigate the pore structure inside the concrete. The crushed samples were obtained around the aggregates. Table 6.2 displays the porosity and average pore diameter samples determined by the MIP test at the age of 28 days. The percentage of porosity and average pore diameter of the samples were found to be in similar pattern with those samples cured in water curing but were lower than samples cured in air curing conditions. This indicated that the samples cured in water curing conditions were denser due to proper curing. However, the porosity of samples containing SSD GAA and AD GAA is lower by 18% and 9% in corresponding to the conventional samples cured in air curing, which simulates improper curing conditions. Meanwhile, the percentage of porosity samples containing AD GAA is 3.5% higher than samples containing SSD GAA cured in air curing conditions. This showed the water stored in SSD GAA may have acted as an internal reservoir that contributes water internally for the hydration process. While, the AD GAA absorbed a certain amount of water, decreasing the water cement ratio in the ITZ area. The water that was absorbed

produced hydrates that gradually fill the pores in the ITZ (Gonzalez-Corominas *et al.*, 2016).

Table 6.2
The Total Porosity (%) and Average Pore Diameter (μm) for Self-Cured and Control Concrete Samples Taken at the Age of 28 Days

Mixtures Designature	Air-cured conditions				Water-cured conditions			
	CTRL-28D-AD-AC	CTRL-28D-SSD-AC	GAA-28D-SSD-AC	GAA-28D-AD-AC	CTRL-28D-AD-WC	CTRL-28D-SSD-WC	GAA-28D-SSD-WC	GAA-28D-AD-WC
Total porosity (%)	21.03	22.6	18.52	19.2	17.43	17.39	16.36	17.11
Average Pore diameter (μm)	0.09	0.11	0.08	0.082	0.06	0.06	0.054	0.055

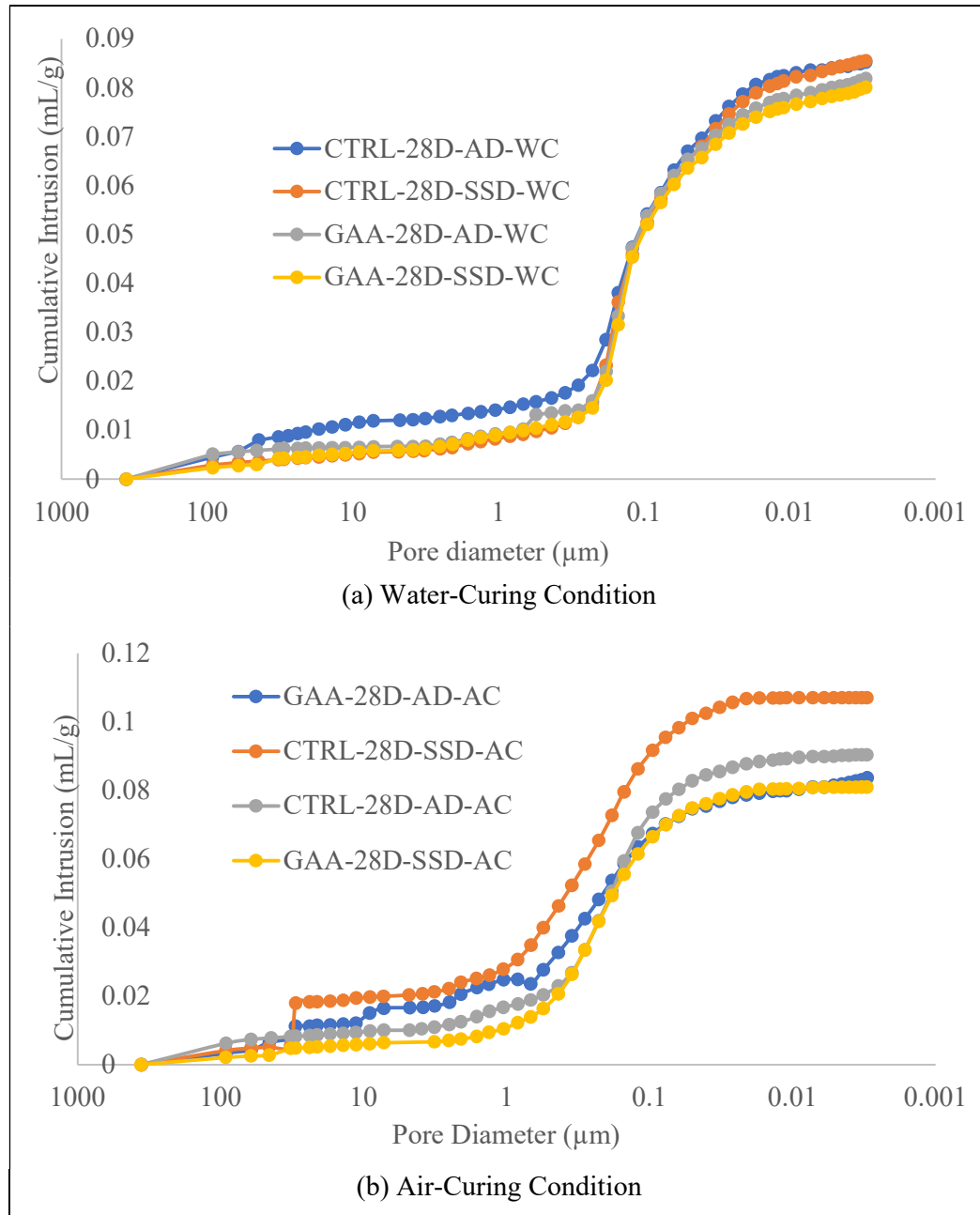


Figure 6.9 Pore Size Cumulative Distribution Of A) Water-Cured And B) Air-Cured GAA And Control Concrete At Age Of 28 Days

Figure 6.9 exhibits the cumulative mercury intrusion volume at 28 days employing both curing methods. The pore size distributions of all the samples followed the same pattern, with three (3) unique zones on each curve: one with a gradual rise in pore volume of up to 0.55 μm; the second within the pore size range between 0.55 μm and 0.01 μm with a significant increase in pore volume; and the final range is between 0.01 and 0.001 μm with a slight inclination. Most of the intrusion volume in the first

range is attributable to macro-pores, macro-cracks, and mercury filling the rough outer surface of the crushed sample (Gonzalez-Corominas *et al.*, 2016; Valcuende *et al.*, 2012). The majority of the intrusion in the second range is due to capillary pores, while the final is caused by the gel pores (Gonzalez-Corominas *et al.*, 2016).

Generally, for both curing methods, concrete samples containing GAA had lower average pore diameters than those of conventional concrete samples at the age of 28 days. The average pore diameters of concrete samples containing SSD GAA were 27% lower than control concrete cured in air curing conditions. A similar situation to the average pore diameters of concrete having AD GAA was 9% lower than control concrete cured in air curing conditions. Meanwhile, the percentage of average pore diameters samples containing AD GAA is 2% higher than samples containing SSD GAA cured in air curing, which is simulating an improper curing condition. It shows a slight difference in the percentage of average pore diameters between samples containing SSD GAA and AD GAA cured in air curing. Water-cured concrete containing either SSD or AD GAA exhibited average pore diameters that were 10% smaller than those of the control concrete under the same curing conditions. Among the GAA samples, those containing AD GAA had marginally larger pores, with average diameters approximately 2% greater than samples with SSD GAA. Similarly, under air-curing conditions, the difference in average pore diameters between SSD GAA and AD GAA samples was minimal. This indicates that concrete containing GAA shows a finer pore structure and lower pore volumes to those of control concrete for both cured in air and water curing condition. The finer pore structures could be explained by an improvement of ITZ and internally cured concrete by GAA as internal reservoir.

6.6 Summary

Based on the experimental results, the following conclusions can be drawn as follows:

- i. EDX analysis showed significantly higher calcium (Ca) content in GAA concrete compared to control concrete cured in water and air, with GAA-1D-SSD-AC showing 46.7% calcium by weight versus 37.9% in the control, cured in water. While GAA-1D-SSD-AC exhibited a calcium content of 46.7% by weight versus only 19.6% in the control, cured in air. The difference between

control and self-cured concrete (4.8-8.8% higher calcium content) cured in water and (21.3-27.1% higher calcium content) cured in air indicates that GAA's internal curing mechanism enhances hydration in both curing conditions.

- ii XRD analysis at 28 days showed increased in $\text{Ca}(\text{OH})_2$ peaks ($2\theta = 17^\circ, 50^\circ$) and C-S-H peaks ($2\theta = 20^\circ, 55^\circ$) in self-cured concrete compared to those control concrete in air curing, proving GAA's internal moisture supported hydration without external water. In water cured, GAA concrete still maintained higher $\text{Ca}(\text{OH})_2$ peak intensities at $2\theta = 17^\circ, 34^\circ, 36^\circ, 50^\circ$, and 60° compared to control concrete.
- iii Self-cured concrete showed significant reduction in capillary pores ($0.01\text{-}0.55\ \mu\text{m}$) compared to control concrete in both curing regimes, but the effect was more pronounced in air-cured conditions where self-cured concrete exhibited a 27% reduction in average pore diameter versus control. SSD GAA concrete consistently outperformed AD GAA concrete in both curing environments, but with a more significant advantage in air-cured condition. The pore refinement in self-cured concrete, particularly in the critical capillary range, explains the improved durability and reduced permeability in the self-cured concrete.

CHAPTER 7

CONCLUSION DAN RECOMMENDATION

7.1 Introduction

The aim of this study is to assess GAA as a self-curing agent in concrete by characterising its properties, evaluating its impact on strength and durability compared to conventional concrete under proper and improper curing conditions. Furthermore, the microstructural and mineralogical developments were examined, and the concrete's microstructural changes resulting from self-curing mechanism in GAA were verified. The experimental investigation encompassed multiple variables including effect of air-dried (AD) and saturated surface dried (SSD) prior to casting, effects of GAA and granite, effects of curing condition and demoulding times (1D, 3D and 7D). These variables were examined to determine the effects on physical, mechanical properties of concrete and microstructural characteristics. The benefits resulting from this study will provide technical information for the construction industry regarding effectiveness, implementation methods, and performance benefits of using GAA as an innovative self-curing agent in concrete. It offers an alternative to traditional water-intensive curing practices while potentially improving strength, durability, and microstructural properties in control and self-cured concrete. Besides ensuring effective waste utilisation to reduce negative environment impacts. The conclusions were drawn based on research objectives (RO) as listed in Chapter 1 and as follows:

- RO1: To characterise the physical, mechanical and microstructure properties of GAA as a self-curing agent in concrete.
- RO2: To evaluate strength and durability performance of normal-strength concrete containing GAA as a curing agent in comparison with conventional concrete with curing and without curing process.
- RO3: To examine the microstructure and mineralogical development of normal-strength concrete containing GAA as a curing agent in comparison with those made of conventional concrete with curing and without curing process.

RO4: To confirm and verify the change in microstructure and mineralogical of concrete mixes due to self-curing actions.

7.2 Conclusions

From the experimental programme, the following conclusions are drawn:

- 1) GAA can act as an internal curing agent in the concrete due to its ability to absorb and release retained water from the GAA to the concrete mixes.
- 2) In water-cured condition, both SSD GAA and air-dried (AD) concrete attained the desired 28-day strength of 30 MPa, despite the complete replacement of granite. Meanwhile, air-cured concrete did not achieve this targeted strength, however, it still fell within the range of 20-30 MPa, which is suitable for a variety of structural use. The statistical analysis conducted did not reveal any significant differences between those made of AD or SSD aggregates. However, it did reveal significant differences between granite and GAA concrete due to GAA has higher porosity than granite. Thus, it suggests that the application of AD GAA on the construction site can streamline the concrete mixing process by eliminating the necessity for pre-soaking aggregates.
- 3) Control concrete achieves the highest overall strength when water-cured with early demoulding, with CTR-1D-AD-WC performing best at all ages compared to other specimens. Self-cured concrete, however, shows superior performance under air curing with delayed demoulding, demonstrating effective self-curing capabilities. This indicates that self-cured concrete exhibits higher sensitivity to demoulding time than conventional concrete, particularly under air curing condition.
- 4) The statistical analysis showed that demoulding time does not significantly affect compressive strength. This suggests that concrete containing granite and GAA has similar compressive strength after 1-, 3-, or 7-days demoulding time prior to curing. By removing formwork earlier than those with control concrete, contractors could potentially accelerate construction cycles and free up formwork for reuse, all while maintaining structural integrity. This could help with construction scheduling and resource management.
- 5) Control concrete exhibited superior performance in compressive strength at all

ages cured in water and air. The increased in compressive strength of control concrete compared to those made of GAA may be due to GAA has higher porosity than granite. However, compressive strength development of concrete containing GAA showed higher than those made of granite at all ages cured in water and air. The statistical analysis revealed that the aggregate type and curing conditions showed significantly affect in compressive strength. Nevertheless, compressive strength of concrete containing GAA ranging from 20 MPa to 50 MPa, which may still possess adequate strength for certain structural concrete application. This result suggests that the application of GAA concrete within the construction industry can be considered to replace the conventional concrete.

- 6) At 28 days, the UPV of concrete incorporating SSD GAA cured in water and air showed slightly higher UPV compared to AD GAA, while control concrete had the highest UPV. However, the UPV of concrete containing AD GAA, SSD GAA and granite is comparable. In this study, most of the UPV value readings range from 3.5 km/s to 4.5 km/s indicated that the concrete specimens are in good quality. Generally, it is suitable for wide variety of common structural and non-structural applications in construction. The statistical analysis also showed that there is no significant difference in aggregate conditions, types, and curing methods.
- 7) At 28 days, the density of concrete incorporating SSD GAA, cured in water and air, exhibited slightly higher density compared to AD GAA, whereas control concrete demonstrated the highest density. Nevertheless, the density of concrete containing AD GAA, SSD GAA, and granite remains comparable. The statistical analysis showed that there is no significant difference in aggregate conditions, curing methods and demoulding time except the aggregate type which may be attributed to the higher porosity of GAA. Consequently, it is advisable for the designer to utilise GAA to diminish the dead load of the structure without compromising strength.
- 8) At 28 days, the flexural strength of concrete with SSD GAA cured in water and air was slightly higher than AD GAA, whereas control concrete had the maximum flexural strength, suggesting GAA may adversely affect the flexural strength properties of concrete. However, statistical analysis showed that the flexural strength of concrete containing AD GAA and SSD GAA, is

comparable and there is no significant difference in demoulding time. Thus, the use of AD GAA on the building site can optimise the concrete mixing process by eliminating the requirement for pre-soaking aggregates, saving time and effort while maintaining the flexural strength performance of normal-strength concrete.

- 9) Concrete shrinkage can be decreased by substituting GAA for granite. Especially in the first 72 hours when the shrinkage is most significant, GAA can effectively reduce the shrinkage of concrete. The shrinkage of self-cured concrete GAA-1D-AD-AC and GAA-1D-SSD-AC can be decreased by 35% and 51%, respectively, in comparison to the control concrete CTR-1D-AD-AC and CTR-1D-SSD-AC. The expansion strain of concrete GAA-1D-SSD-WC can be 38% lower than that of concrete GAA-1D-AD-WC.
- 10) The absorption rate of water-cured concrete containing GAA was higher than that of control concrete, which had a lower rate. The decreased rate of absorption in water curing of concrete containing GAA compared to control concrete is related to the natural porosity of GAA. Self-cured concrete left to cure in air has a more refined pore structure and have lower surface absorption rates due to the constant water supply for cement hydration. SSD GAA-containing concrete absorbed slower than AD GAA-containing concrete. Due to its pre-saturation, SSD GAA-containing concrete may have a more stable and accessible internal moisture supply for cement hydration than those of AD concrete.
- 11) The SEM morphology and EDX analysis revealed substantially elevated calcium (Ca) concentrations in GAA concrete specimens relative to control concrete under both water and air curing regimes. Specifically, GAA-1D-SSD-AC specimens demonstrated calcium content of 46.7% by weight compared to 37.9% in water-cured control specimens. Under air curing conditions, GAA-1D-SSD-AC exhibited calcium content of 46.7% by weight in contrast to merely 19.6% observed in air-cured control specimens. The differential calcium content between control and self-curing concrete formulations, ranging from 4.8-8.8% higher under water curing conditions and 21.3-27.1% higher under air curing conditions, provides evidence that the internal curing mechanism inherent in GAA concrete promotes enhanced hydration processes across both curing environments.

- 12) X-ray diffraction (XRD) analysis conducted at 28 days revealed enhanced intensities of calcium hydroxide $[\text{Ca}(\text{OH})_2]$ peaks at diffraction angles of $2\theta = 17^\circ$ and 50° , along with increased calcium silicate hydrate (C-S-H) peak intensities at $2\theta = 20^\circ$ and 55° in self-curing concrete specimens compared to control concrete under air curing conditions. These findings demonstrate that the internal moisture retention mechanism of GAA concrete effectively facilitates hydration processes in the absence of external water supply. Under water curing conditions, GAA concrete specimens continued to exhibit superior calcium hydroxide peak intensities at diffraction angles of $2\theta = 17^\circ, 34^\circ, 36^\circ, 50^\circ$, and 60° relative to control concrete formulations, indicating sustained enhancement of hydration products even when external moisture is readily available.
- 13) Self-cured concrete exhibited capillary pore reduction about 27% compared to control specimens, particularly under air-cured conditions. Self-cured concrete with containing SSD GAA demonstrated superior pore refinement than those self-cured concrete containing AD GAA contributes in enhancing durability and reducing permeability.

The study recommends using air-dried (AD) rather than saturated-surface dried (SSD) GAA as a self-curing agent in concrete, as no significant performance differences were observed between these conditions. The finding that demoulding time does not significantly affect compressive strength suggests that formwork can be removed earlier than with conventional concrete, enhancing project efficiency without compromising structural integrity. However, GAA concrete (self-cured concrete) demonstrated superior compressive strength with delayed demoulding under air-curing conditions, making it particularly valuable for structures where traditional water curing is impractical.

7.3 Future Recommendations

For future study, the following subjects are recommended as follows:

1. There is no study on life-cycle cost analysis of GAA self-curing concrete in present study. Therefore, for future study, comprehensive life-cycle cost analysis and environmental assessment should be conducted to evaluate the economic viability and environmental benefits of GAA self-curing concrete compared to conventional curing methods. This integrated approach should quantify both the direct cost savings from reduced curing requirements and the indirect environmental benefits, including potential carbon credit opportunities, thereby providing a holistic understanding of the long-term economic and sustainability advantages of GAA self-curing concrete systems.
2. The present study utilized GAA with unknown thermal treatment parameters, creating variability in pozzolanic activity and porosity that affects self-curing reliability. Future research should establish controlled sintering temperatures and durations to optimize GAA properties, ensuring consistent performance for construction site implementation and enabling development of quality control specifications necessary for commercial adoption of GAA self-curing concrete systems.
3. Further research on freeze-thaw resistance, chloride penetration, and carbonation resistance is crucial as GAA's enhanced porosity enabling self-curing may increase vulnerability to environmental degradation. These durability concerns directly impact construction project viability, maintenance costs, and material selection decisions. Future studies must establish performance thresholds under aggressive conditions to enable confident field implementation across diverse environmental exposures.

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APPENDICES

APPENDIX 1

Example of SPSS

T-Test

[DataSet1]

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Strength	AD	9	33.9333	5.71648	1.90549
	SSD	9	33.5656	6.22145	2.07382

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Strength	Equal variances assumed	.153	.701	.131	16
	Equal variances not assumed			.131	15.887

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Strength	Equal variances assumed	.449	.898	.36778	2.81631
	Equal variances not assumed	.449	.898	.36778	2.81631

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
Compressive strength	100	12	34.0175	6.38264	1.84251
	50	6	33.2133	4.91893	2.00814

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Compressive strength	Equal variances assumed	1.014	.329	.270	
	Equal variances not assumed			.295	

Independent Samples Test

		t-test for Equality of Means		
		df	Significance	
			One-Sided p	Two-Sided p
Compressive strength	Equal variances assumed	16	.395	.791
	Equal variances not assumed	12.829	.386	.773

Independent Samples Test

		t-test for Equality of Means		
		Mean Difference	Std. Error Difference	95% Confidence Interval of the Difference
Compressive strength	Equal variances assumed	.80417	2.98197	-5.51733
	Equal variances not assumed	.80417	2.72534	-5.09155

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
Compressive strength	CTR	6	37.7250	4.55648	1.86017
	GAA	12	31.7617	5.44086	1.57064

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means
		F	Sig.	t
Compressive strength	Equal variances assumed	.635	.437	2.302
	Equal variances not assumed			2.449

Independent Samples Test

		t-test for Equality of Means		
		df	Significance	
			One-Sided p	Two-Sided p
Compressive strength	Equal variances assumed	16	.018	.035
	Equal variances not assumed	11.917	.015	.031

Independent Samples Test

Group Statistics

	Condition	N	Mean	Std. Deviation	Std. Error Mean
Strength	AD	9	26.5644	5.09818	1.69939
	SSD	9	26.2644	5.30982	1.76994

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Strength	Equal variances assumed	.079	.783	.122	16
	Equal variances not assumed			.122	15.974

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Strength	Equal variances assumed	.452	.904	.30000	2.45370
	Equal variances not assumed	.452	.904	.30000	2.45370

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
Compressive strength	100	12	26.4742	5.66747	1.63606
	50	6	26.2950	4.01098	1.63748

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means
		F	Sig.	t
Compressive strength	Equal variances assumed	1.224	.285	.069
	Equal variances not assumed			.077

Independent Samples Test

		t-test for Equality of Means		
		df	Significance One-Sided p	Two-Sided p
Compressive strength	Equal variances assumed	16	.473	.946
	Equal variances not assumed	13.741	.470	.939

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
Compressive strength	CTR	6	30.2067	3.82760	1.56261
	GAA	12	24.5183	4.58465	1.32348

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means
		F	Sig.	t
Compressive strength	Equal variances assumed	.861	.367	2.608
	Equal variances not assumed			2.778

Independent Samples Test

		t-test for Equality of Means		
		df	Significance One-Sided p	Two-Sided p
Compressive strength	Equal variances assumed	16	.010	.019
	Equal variances not assumed	11.951	.008	.017

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
UPV	100	12	4.2158	.29072	.08392
	50	6	4.2233	.20695	.08449

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
UPV	Equal variances assumed	.690	.418	-.056	16
	Equal variances not assumed			-.063	13.681

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
UPV	Equal variances assumed	.478	.956	-.00750	.13369
	Equal variances not assumed	.475	.951	-.00750	.11908

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
UPV	CTR	6	4.3367	.18928	.07727
	GAA	12	4.1225	.23902	.06900

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
UPV	Equal variances assumed	.342	.567	1.907	16
	Equal variances not assumed			2.067	12.531

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
UPV	Equal variances assumed	.037	.075	.21417	.11233
	Equal variances not assumed	.030	.060	.21417	.10359

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	type	N	Mean	Std. Deviation	Std. Error Mean
UPV	AD	9	3.7856	.17227	.05742
	SSD	9	3.7878	.15611	.05204

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
UPV	Equal variances assumed	.025	.877	-.029	16
	Equal variances not assumed			-.029	15.847

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
UPV	Equal variances assumed	.489	.977	-.00222	.07749
	Equal variances not assumed	.489	.977	-.00222	.07749

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
UPV	100	12	3.8058	.17521	.05058
	50	6	3.7483	.12766	.05212

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
UPV	Equal variances assumed	1.203	.289	.710	16
	Equal variances not assumed			.792	13.436

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
UPV	Equal variances assumed	.244	.488	.05750	.08093
	Equal variances not assumed	.221	.442	.05750	.07262

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
UPV	CTR	6	3.8850	.11895	.04856
	GAA	12	3.7417	.16214	.04680

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
UPV	Equal variances assumed	.902	.356	1.911	16
	Equal variances not assumed			2.125	13.362

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
UPV	Equal variances assumed	.037	.074	.14333	.07499
	Equal variances not assumed	.026	.053	.14333	.06745

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	type	N	Mean	Std. Deviation	Std. Error Mean
Density	AD	9	2262.00	93.047	31.016
	SSD	9	2250.78	99.559	33.186

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	.074	.789	.247	16
	Equal variances not assumed			.247	15.927

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.404	.808	11.222	45.424
	Equal variances not assumed	.404	.808	11.222	45.424

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
Density	100	12	2255.83	108.168	31.225
	50	6	2257.33	64.376	26.281

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	1.820	.196	-.031	16
	Equal variances not assumed			-.037	15.259

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.488	.976	-1.500	48.319
	Equal variances not assumed	.486	.971	-1.500	40.813

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
Density	CTR	6	2336.83	56.365	23.011
	GAA	12	2216.17	82.571	23.836

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	1.086	.313	3.202	16
	Equal variances not assumed			3.642	14.105

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.003	.006	120.667	37.683
	Equal variances not assumed	.001	.003	120.667	33.131

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	type	N	Mean	Std. Deviation	Std. Error Mean
Density	AD	9	2057.44	156.111	52.037
	SSD	9	2050.89	179.756	59.919

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	.064	.803	.083	16
	Equal variances not assumed			.083	15.692

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.468	.935	6.556	79.361
	Equal variances not assumed	.468	.935	6.556	79.361

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Conditions	N	Mean	Std. Deviation	Std. Error Mean
Density	100	12	2034.00	193.860	55.963
	50	6	2094.50	71.579	29.222

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	10.072	.006	-.730	16
	Equal variances not assumed			-.958	15.312

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.238	.476	-60.500	82.823
	Equal variances not assumed	.176	.353	-60.500	63.133

Independent Samples Test

T-Test

[DataSet1]

Group Statistics

	Type	N	Mean	Std. Deviation	Std. Error Mean
Density	CTR	6	2202.17	57.140	23.327
	GAA	12	1980.17	147.770	42.658

Independent Samples Test

		Levene's Test for Equality of Variances		t-test for Equality of Means	
		F	Sig.	t	df
Density	Equal variances assumed	4.473	.050	3.507	16
	Equal variances not assumed			4.566	15.511

Independent Samples Test

		t-test for Equality of Means			
		Significance		Mean Difference	Std. Error Difference
		One-Sided p	Two-Sided p		
Density	Equal variances assumed	.001	.003	222.000	63.310
	Equal variances not assumed	<.001	<.001	222.000	48.619

Independent Samples Test

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