

Faculty of Engineering

Performance-based Durability Specifications of Fly Ash Concrete for Chloride-induced Environment

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Performance-based Durability Specifications of Fly Ash Concrete for Chloride-induced Environment

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A thesis submitted

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DECLARATION

I declare that the work in this thesis was carried out in accordance with the regulations of Universiti Malaysia Sarawak. Except where due acknowledgements have been made, the work is that of the author alone. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.



……

Signature

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ABSTRACT

Existing standard concrete practices under implementation of Standard Specifications for Building Works (SSBW) promptly altered from prescriptive specifications to Performance-based Durability Specifications (PBDS) as advocated by Eurocode 2. This study was carried out to overcome the chloride-induced attack problem on reinforced concrete (RC) structures settled under XS3 class exposure by utilising fly ash waste, producing non-destructive test (NDT) models and developing PBDS indicators model. The Taguchi Approach was used in this study with a combination of survey questionnaires, field investigation, experimental works and Statistical Product and Service Solutions (SPSS) modelling. The experimental work includes compressive strength (Cu), water absorption (WA), void of permeable voids (VPV) and ultrasonic pulse velocity (UPV) tests. Which, tested on tree different grades of ready-mix concretes, as well as concrete blended with Class-F fly ash with a 10% percentage increment up to 60%. Experimental work revealed that the Class-F fly ash was optimised at 30%. NDT models as represented by equation correlations of Cu1 = 31.699UPV1 – 84.641, Cu2 = 30.998UPV2 – 79.275 and Cu3 = 36.438UPV3 – 100.337. Developed PBDS indicators model equation was WA = 0.843VPV – 0.078UPV + 0.104. Meanwhile, "EXCELLENT" concrete quality rating bounded to Quality Rating Durability Compliance (QRDC) indicator values for UPV, VPV, WA and Cu should be more than 4.5 km/s, less than 10%, less than 7% and at least 55 MPa, respectively. The outcome indicators were found provide a flexible interface for client, designer or decision maker to make an accurate decision based on concrete performance, environmental sustainability and public user's safety.

Keywords: Chloride-induced, fly ash, NDT models, performance-based

Spesifikasi Ketahanan Konkrit Berasaskan Prestasi Disebabkan oleh Klorida Persekitaran

ABSTRAK

Amalan konkrit standard sedia ada di bawah pelaksanaan Spesifikasi Standard untuk Kerja Bangunan (SSBW) adalah perlu diubah daripada spesifikasi preskriptif kepada Spesifikasi Ketahanan Berasaskan Prestasi (PBDS) seperti yang dianjurkan oleh Eurocode 2. Kajian ini dijalankan untuk mengatasi masalah serangan akibat klorida pada tetulang struktur konkrit (RC) di bawah pendedahan kelas XS3 dengan menggunakan sisa abu terbang, menghasilkan model ujian tidak merosakkan (NDT) dan membangunkan model penunjuk PBDS. Kajian dilaksanakan dengan menggabungkan pendekatan Taguchi bersama soal selidik tinjauan, penyiasatan lapangan, kerja amali makmal dan pemodelan Penyelesaian Produk dan Perkhidmatan Statistik (SPSS). Kerja amali makmal termasuk kekuatan mampatan (Cu), penyerapan air (WA), lompang telap kosong (VPV) dan ujian halaju nadi ultrasonik (UPV). Diuji pada tiga gred konkrit berbeza siap campur yang diadun dengan abu terbang Kelas-F dengan peratusan penggantian sebanyak 10% hingga 60%. Kerja amali makmal mendedahkan bahawa abu terbang telah dioptimumkan pada 30%. Model NDT seperti yang diwakili oleh korelasi persamaan Cu1 = 31.699UPV1 – 84.641, Cu2 = 30.998UPV2 – 79.275 and Cu3 = 36.438UPV3 – 100.337. Persamaan model penunjuk PBDS ialah WA = 0.843VPV – 0.078UPV + 0.104. Sementara itu, penarafan kualiti konkrit "CEMERLANG" mengikut nilai penunjuk Pematuhan Ketahanan Penarafan Kualiti (QRDC) untuk UPV, VPV, WA dan Cu hendaklah masing-masing lebih daripada 4.5 km/s, kurang daripada 10%, kurang daripada 7% dan sekurang-kurangnya 55 MPa. Hasil kajian mendapati penunjuk penarafan kualiti konkrit yang dibangunkan adalah mudah diguna pakai oleh pelanggan, pereka bentuk atau pembuat keputusan untuk membuat keputusan

yang tepat berdasarkan prestasi konkrit, kelestarian alam sekitar dan keselamatan pengguna awam.

Kata kunci: *Kakisan-klorida, abu terbang, model NDT, berasaskan prestasi*

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LIST OF ABBREVIATIONS

AASHTO	American Association of State Highway and Transportation Officials
ABNT	Brazilian National Standards Organization
ACI	American Concrete Institute
AECB	Atomic Energy Control Board
ANOVA	Analysis of Variance
AS	Australian Standard
ASTM	American Society for Testing and Materials
AVPV	Apparent Volume of Permeable Voids
BDS	Bulgarian Institute for Standardization
BS	British Standards
BSI	British Standards Institution
CCAA	Cement Concrete & Aggregates Australia
CCANZ	Cement & Concrete Association of New Zealand
CEN	Committee of European Norms
CFG	Carbon Fibre Sheets/Glass
CFS	Conceptual Framework Study
CIA	Concrete Institute of Australia
CNS	Colloida Nano Silica
COST	National Standard UPV Test Method (Russia)
COVENIN	National Standard UPV Test Method (Venezuela)
CP	Concrete of Practice
CSN	National Standard UPV Test Method (Czech Republic)

Cu	Compressive Strength
CV1	Controllable Variable 1
CV2	Controllable Variable 2
CV3	Controllable Variable 3
DBKU	Dewan Bandaraya Kuching Utara
DID	Department of Irrigation and Drainage Sarawak
DIS	National Standard UPV Test Method (International)
DOE	Design of Experiments
DS	National Standard UPV Test Method (Denmark)
DSM	Department of Statistic Malaysia
EN	European Standard
EU	European Union
FA	Fly Ash
GB/T	China Voluntary National Standard
HAC	High Alumina Cement
HAT	Highest Astronomical Tide
HSC	High Strength Concrete
HyFRC	Hybrid Fibre Reinforced Concrete
ICS and ICF	The Irish Concrete Society and The Irish Concrete Federation
IEM	The Institution of Engineers Malaysia
IS	Code of Standard / Designation (India)
ISN	Ideal Steps NDT
ISO	International Organization for Standardization
ISOiDIS	National Standard UPV Test Method (Germany)
ITDC	In-place Testing or Drilled Cores

JKR	Jabatan Kerja Raya
JSCE	Japan Society of Civil Engineers
JUS U.M.	National Standard UPV Test Method (Yugoslavia)
LAT	Lowest astronomical tide
MaCP	Macro Capillary Pore
MAVCOM	Malaysian Aviation Commission
MeCP	Meso Capillary Pore
MeGP	Meso Gel Pores
MI	National Standard UPV Test Method (Hungary)
MiCP	Micro Capillary Pore
MiGP	Micro Gel Pores
MITI	Ministry of International Trade and Industry
MLR	Multiple Linear Regression
MP	Macropores
MS EN	Malaysia's Standard Publications According to Government Agencies
NA	National Annex
NBN	National Standard UPV Test Method (Belgium)
NCCI	Non-Contradictory Complementary Information
NDP	National Determined Parameters
NDT	Non-destructive Testing
NOM	National Standard UPV Test Method (Mexico)
NRMC	Non-ready-Mixed Concrete
NSW	New South Wales
NT BUILD	National Standard UPV Test Method (Scandinavia)

NZS	New Zealand Standard
OA	Orthogonal Arrays
OPC	Ordinary Portland Cement
PBDS	Performance-based Durability Specifications
PD	Published Document
PN-B	National Standard UPV Test Method (Poland)
QA/QC	Quality Assurance / Quality Control
QRDC	Quality Rating Durability Compliance
RC	Reinforced Concrete
RCPT	Rapid Chloride Permeability Test
RILEM	International Union of Laboratories and Experts in Construction Materials, Systems and Structures
RMC	Ready-mixed Concrete
RMCREF	Ready Mixed Concrete Research & Education Foundation
RMS	Roads & Maritime Services
S/N	Signal-to-noise
SCM	Supplementary Cementitious Materials
SDG	Sustainable Development Goal
SFDT	State of Florida Department of Transportation
SLR	Single Linear Regression
SPPS	Statistical Product and Service Solutions
SS	National Standard UPV Test Method (Sweden)
SSBW	Standard Specifications for Building Works
SSM	Suruhanjaya Syarikat Malaysia
SSRW	Standard Specifications for Road Works

TGL	National Standard UPV Test Method (German Democratic Republic)
UCV	Uncontrollable Environmental
UFGS	Unified Facilities Guide Specifications
UNE	National Standard UPV Test Method (Spain)
UPV	Ultrasonic Pulse Velocity
VPV	Volume of Permeable Voids
W/C	Water–cement Ratio
WA	Water Absorption
WR	Water Reducer
XS	Chloride-induced Corrosion by Sea Water

CHAPTER 1

INTRODUCTION

1.1 Study Background

The durability of a construction material is defined by its ability to withstand environmental deterioration without having to incur unforeseen high cost for maintenance or repair. Durability of reinforced concrete (RC) structures in hostile marine environment, typically lies from tidal to splash and spray zones progressively with time is a great of concern for practicing engineers worldwide due to penetration of chloride-induced corrosion. Chloride ions penetration through concrete cover is a regionally complex phenomenon that can be effectively addressed by using local Supplementary Cementitious Materials (SCM). Presently, several developed countries have been developing their own performance-based specifications adapting to local conditions for the purpose of extending service life of marine structures. This covers a range of performing durability test methods widely known as non-destructive tests, ranging from the expensive to the cheapest ones that offer the quickest and reliable results.

1.2 Prescriptive Specification Versus Performance-based Durability Specifications

"Prescriptive" in nature simply means controlling target mean strength over required characteristic strength by specifying the material proportion such as maximum water cement ratio and minimum cement content based on class exposure through Concrete Design Mixed submission during Pre-qualification testing. Currently, this method is widely known as Prescriptive specification or sometimes pronounced as Prescribed concrete, deemed-to-satisfy approach, Conventional-method, Method-based, or Recipe-based. Meanwhile, in performance-based specifications or namely as Performance-based Durability Specifications

(PBDS) thereafter, the concrete performance must be examined by a series of concrete experiments throughout the construction phases or at end concrete products. Major advantages of PBDS over Prescriptive specification are summarized as follows;

i. Designers can focus on client's expectation by utilizing advantages of local unique material as blended cements suit local condition for high durable concrete and promote environmental sustainability.

ii. End concrete products that meet client's satisfaction offer more value for money due to lower maintenance costs and greater cash flow management.

iii. Enhanced safety builds up public users' trust often via long-term testing procedures using sophisticated testing tools to monitor service life performance of RC structures.

With the performance advantages listed above, several developed countries have fully moved forward from Prescriptive specification to PBDS to ensure more durability, more value for money, enhanced environmental sustainability, enhanced safety and most importantly the end-result concrete products are measurable or monitorable by sophisticated testing tools. Table 1.1 shows the list of national specific concrete durability standards or designations developed by various countries.

In addition, Asian countries such as Japan (JSCE, 2010a) and India (IS, 2007) as well as CEN members (BSI, 2013) have incorporated durability specifications in their concrete standard practices. Unfortunately, Southeast Asian countries have continued fully or partially adopted ACI, EN, AS or NZS concrete standard codes in their concrete works without taking in-depth consideration of local unique materials, geography and environmental effects on national concrete products. Meanwhile, Malaysia has not

developed any standard concrete durability specifications and currently still rely on Eurocode 2 as explained in Section 1.4.

Table 1.1: List of National Concrete Durability Standards or Designations

Country	**Code of Standard / Designation**	**Title Description**
USA	ACI 201.2R-08 (ACI, 2008)	Guide to Durable Concrete
Australia	Z7/07 (CIA, 2015)	Performance Tests to Assess Concrete Durability
New Zealand	NZS 3109 (CCANZ, 2010)	Guide to Concrete Construction
China	GB/T 50476:2019 (GB, 2019)	Standard for Design of Concrete Structure Durability

1.3 Standard Practices in Marine Structures

In conjunction with the transition of standard concrete specifications elaborated in Section 1.2 above, some developed countries have produced more specific guidelines for marine structure protection. These guidelines, have been developed to combat chloride attack based on local SCMs with the assistances of QA/QC monitoring tools system. Table 1.2 shows the list of specific design guidelines for marine structures implemented by USA and Australia.

Table 1.2: List of Specific Design Guidelines for Marine Structures

Country	**Publisher (Year Implemented)**	**Title Description**
USA	Naval Facilities Engineering Systems Command (UFGS, 2010)	Unified Facilities Guide Specifications Marine Concrete
Australia	Standards of Australia (AS, 2005)	Guidelines for The Design of Maritime Structures
	Cement Concrete & Aggregates Australia (CCAA, 2009)	Chloride Resistance of Concrete
	Roads & Maritime Services (RMS, 2012a)	Guide to QA Specification B80 Concrete Work for Bridges

Before acceptance of limitations recommended values in these guidelines, various test techniques have been performed to measure chloride penetration due to capillary absorption or other transport mechanisms. Among these tests, Water Absorption (WA) and Volume of Permeable Voids (VPV) were proven effective to be utilized as parameters to approximately predict SCM's overall corrosive substance penetration by water (Phaedonos, 2000; RMCREF, 2006; Phaedonos, 2007). Furthermore, several studies strongly recommended VPV as a great durability indicator for testing due to its high-level precession and cost-effectiveness compared to other chloride tests (Phaedonos, 2007; Phaedonos, 2012; Zhang & Zong, 2014; CIA, 2015).

Fly Ash Contribution to Marine Structures

The development of corrosion-resistant concrete focusing on blended cements between Portland cement and SCMs has started since 1990s and fly ash still remains as the largest SCM's contribution due to huge quantities of by-products of coal combustion worldwide. Initially, several specifications integrated fly ash as blended cements up to 30% by mass of cement and were tested on large marine infrastructures for determination of optimised performance.

As a result, it is widely known that fly ash provides many excellent effects including minimizing capacity pore size immobilization and often results in decrease of water penetration to promote long term protection against chloride-induced attack (RMCREF, 2011; Kocatepe and Osmangazi, 2012; Islam et al., 2018). In addition, several national concrete guidelines report that fly ash blended cements have shown good performance in seawater conditions (ACI, 2005; NZS, 2006; CCAA, 2009; CCANZ, 2010; UFGS, 2010; RMS, 2012a). Due to great effects contributed by fly ash on the marine structures in combating chloride attack, a few national specifications or guidelines have integrated local fly ash at different percentages partially as cement replacement as summarized in Table 1.3 (ACI, 2005; NZS, 2006; CCAA, 2009; UFGS, 2010; RMS, 2012a; BSI, 2016).

Table 1.3: Summary of National Specifications or Guidelines Integrating Fly Ash to Combat Chloride-induced Attack on Marine Structures

Country	**Code of Standard / Designation**	**Fly Ash Percentage Application for Marine Structures**
CEN	BS 8500-2:2015+A1:2016	21 - 55% for all XS's exposure classes.
USA	UFGS-03 31 29: 2010	Varies percentages based on total chemical (SiO_2, Al_2O_3 and Fe_2O_3) as follows; i. More than 65% = 30 – 40% ii. More than 70% = 25 – 40% iii. More than 80% = 20 – 40% iv. More than 90% = 15 – 40%
	ACI 318-08	Limiting to 25%
Australia	Specification Guide NB80:2012	20 - 40%
	Chloride Resistance of Concrete:2009	Optimize at 30%

As for Malaysia, concrete standard specifications that were generally used mostly referred to Standard Specifications for Building Works (SSBW) and Standard Specifications for Road Works (SSRW) (SSRW, 1988; SSBW, 2005; SSRW, 2008; SSBW, 2014; SSBW, 2020). Throughout development of standard specifications, fly ash Class-C and Class-F were first introduced in 2014 before being superseded by the latest standard in 2020. Present standard declares only fly ash Class-F allows for blended cements to combat chloride attack with ranging proportion of 21% to 55% for all XS's exposure classes exactly as recommended by BS 8500-2:2015+A1:2016 (BSI, 2016). Unfortunately, this standard

strictly stipulated to does not adopt requirements and performance materials to hot climate countries as statement below;

"The requirements in this part of BS 8500 are given for defined materials with an established or accepted adequate performance in the conditions found in the United Kingdom. These requirements might not be appropriate for use in exposure conditions different from the United Kingdom, particularly in **hot climates**".

Finally, it is clearly shown from PBDS implementation among the pioneer countries discussed above, varied geographical conditions were proven to cause different levels of deterioration and reflect different optimised dosage of fly ash for cement replacement. Therefore, it is crucial to develop our own fly ash optimisation value and PBDS suited to local conditions to make concrete more durable and also make the environment more sustainable.

1.4 Problem Statement

Most cities and towns in Sarawak are located along the coastal land, river side or near to river estuary. Main cities or towns such as Bintulu, Miri, Sematan and Mukah are laid within 1-3 km from seashore. Furthermore, Sarawak is well known for having the longest and largest tributaries and rivers in Malaysia. Therefore, most of the main cities and towns including Kuching, Sibu, Sri Aman, Sarikei, Limbang, Lawas, and Kapit were developed nearby river side. Geographically, all main cities and towns are in the chloride-induced corrosion prone areas as shown in Figure 1.1 (MAVCOM, 2022).



Figure 1.1: Development of Cities and Towns Along the Coastal Areas of Sarawak

In order to bring development along the coastal and remote areas, infrastructure facilities especially marine structures have been constructed rapidly. According to Department of Statistic Malaysia (DSM), the total number of bridges and wharfs maintained by Jabatan Kerja Raya (JKR) has slightly increased from 1180 in 2013 to 1437 in 2018 (DSM, 2014; DSM, 2019). Currently, a huge number of bridges and culverts construction are still in progress under Coastal Road Network and Second Trunk Road Programmes. Presently, Batang Lupar bridge with an estimated cost of RM 849 million has already begun its construction phase and will become the longest river-crossing bridge in Malaysia after its completion on 6th January 2025 (MalayMail, 2021). Besides, Department of Irrigation and Drainage (DID) Sarawak reported a total of nine drainage schemes in Samarahan have been

fully constructed to resolve flood issues due to peatland and king tide effects. Meanwhile, other districts such as Sibu, Mukah, Bintulu, Miri and Limbang still require a number of flood mitigation structures to be constructed under flood mitigation projects as Sarawak possess the largest area of peatlands in Malaysia.

Most of these infrastructures were constructed nearby the sea or river crossing and are exposed to chloride-induced attack resulting from seawater. Without proper mitigation, these structures will be a burden on the economy either to federal or state governments as reported by JKR Sarawak, DID Sarawak and Dewan Bandaraya Kuching Utara (DBKU). Total costs of rehabilitation or maintenance due to chloride-induced attack continue to rise year after year, with a few marine structures requiring replacement with new bridges or wharfs before their service life expires (JKR, 2019; DID, 2019). Currently there is a total of nine marine structures which require urgent repairs as reported by various authorities and agencies located in Kuching and Samarahan districts. Visits to marine structures in service affected by chloride-induced corrosion is shown in Figure 1.2.



Figure 1.2: Marine Structures Affected by Chloride-induced Attack in Kuching and Samarahan Areas

Besides, the standard concrete practice still remains as prescriptive specifications by specifying design parameters such as compression strength, water cement ratio, cement content, nominal cover, and service life span to combat chloride-induced attack on RC marine structures as stated in Tables D1, D2, D9, and D10 (SSBW, 2020).

Practically, Malaysia has depended entirely on Eurocode 2 while fully adopting National Annex (NA) and Non-Contradictory Complementary Information (NCCI) with minor adjustments since April 2019 (Mysol, 2022). Item no. E in NA as a guideline indicative of strength classes for durability does not apply in Malaysia, which still adopts BS 8500-1:2002 (BSI, 2002a). Unfortunately, clearly shown from this BS is prescriptive specification and it does not provide clear indicating treatment against chloride-induced attack. Presently and more crucial, Malaysia Standard still fails to produce its own NA and NCCI suited to local condition and utilises SCMs (particularly fly ash waste) as advocated by Eurocode 2. Table D1 in SSBW 2020, only provides indication usage of fly ash ranges from 21% to 55% to combat chloride attack. Currently, the fly ash utilisation as blended cements in Malaysia does not exist or is not familiar due to unclear guidelines from fly ash standard itself as there is no real study conducted on identifying the significant effectiveness of local fly ash on local ready-mixed concrete. Meanwhile, according to The Star Newspapers dated 23rd November 2014, Sarawak holds nearly 70% of Malaysia's coal reserves with the largest coal deposits in Merit Pila being used for coal-fired power stations in Sejingkat, Mukah and Balingian (Thestar, 2014).

Environmentally, climatological records from 2013 to 2017 show that the relative humidity in Sarawak is very high and remain almost constant throughout the year with annual means of 83.0%, 86.1%, 83.0%, 83.5% and 85.6% for Bintulu, Kuching, Miri, Sibu

and Sri Aman respectively (DSM, 2019). High relative humidity of more than 75% under hot climate conditions expedite chloride exhibition in RC structures (Mahran, 2013).

Based on the crucial factors namely geographical, environmental issues and prescriptive specifications above, it is time to determine the most valuable treatment for chloride-induced corrosion problems locally by using survey questionnaires before the most cost-effective SCM used to improve local concrete supply. Followed by the development of effective sophisticated testing tools used for regular inspection during the service lifespan of RC structures. Thus, it is crucial to produce NDT correlations and formulate PBDS indicators model suited to local condition as advocated by Eurocode 2 to promote a healthy environment, enhance public safety and offer more value for investments.

1.5 Objectives of the Study

The objectives of the study are as follows;

1) To determine the perceptions of construction industry players on chloride-induced corrosion RC structures in Sarawak.

2) To optimise of ready-mixed concrete partially replaced of cement with Class-F fly ash.

3) To correlate performance Non-destructive Testing (NDT) guidelines between compressive strength (Cu) and ultrasonic pulse velocity (UPV).

4) To formulate Performance-based Durability Specifications (PBDS) indicators model based on water absorption (WA), volume of permeable voids (VPV) and ultrasonic pulse velocity (UPV) tests.

1.6 Hypothesis of the Study

Chloride-induced attack on RC marine structures can be treated comprehensively by strictly entertained the most crucial control factors (variables) that affect the local real problem scenario as advocated by Eurocode 2. Subsequently, utilising local fly ash at optimum performance combined with mitigation action through performance-based durability specification (PBDS) assessments implemented using NDT and PBDS indicator monitoring systems throughout the construction phases and service life span.

1.7 Significance of the Study

The primary research significance is to develop PBDS indicators model by integrating local fly ash waste with the famous ready-mixed grade concretes supplied in Sarawak. The finalised percentage optimisation of Class-F fly ash accommodated in SSBW and SSRW for concrete works will make RC structures in marine environment more resistant to chloride-induced attack. In addition, usage of fly ash waste as cement replacement indirectly promotes Sustainable Development Goal (SDG) No. 12 and No. 13 by substantially reducing waste generation and integrating policy climate change measures respectively (SDG, 2015). Meanwhile, formulating PBDS indicators model based on NDT with low-cost implementation at high level precession is useful for structure sustainable health monitoring as well as promoting SDG No. 9. The PBDS indicators model accompanied by Quality Rating Durability Compliance (QRDC) indicators monitoring is expected to provide a very flexible interface to local authorities, designers and owners in order for them to make an accurate decision based on the best concrete performance and financial capacity. Finally, practicing an initial medical check-up throughout the construction phases with the use of developed a PBDS indicators model adapted to local conditions provides greater value for money and guarantees the safety of public users.

1.8 Scope of Works

Taguchi Approach was used in this study with a combination of survey questionnaires, detailed field investigation, experimental works and Statistical Product and Service Solutions (SPSS) modelling to meet the specific objectives. Survey questionnaires about perceptions of chloride-induced corrosion for RC structures in Sarawak were distributed, collected, and analysed to determine most significant control variables for objectives 2, 3 and 4. Based on the results from survey questionnaires, three famous grade of concretes was blended with local Class-F fly ash waste ranging from 20% to 60% by mass of cement. Followed by experimental works based on established worldwide absorption standard test determined from detailed field investigation suit to local condition. The experimental work includes compressive strength (Cu), water absorption (WA), void of permeable voids (VPV) and ultrasonic pulse velocity (UPV) tests. Cu, UPV and WA test results were analysed to determine the optimal concrete enhancement of local ready-mixed concrete partially replaced with local Class-F fly ash before suggestion made into Table D1 in SSBW 2020. Cu and UPV test results were analysed by using Microsoft Excel and SPPS software prior to NDT modelling and development of Ideal Steps NDT (ISN) Guidelines. ANOVA analyses were used to develop models of correlation between Cu and UPV for selected grade concretes before improvement made on Figure D1 in SSBW 2020 for the QA/QC monitoring purpose throughout lifespan of RC structure. All variable test results were analysed by using SPPS software prior to PBDS modelling and development of QRDC indicators. Analysis of Variance (ANOVA) were used to formulate a PBDS indicators model and followed by generating QRDC indicator monitoring variables according to Taguchi's approach.

1.9 Chapter Summary

The works presented in this thesis are divided into eight chapters, which include an introduction, literature review, research methodology, reports on objectives 1, 2, 3 and 4; and conclusion & recommendations, as detailed below;

- Chapter 1: Introduction. Detailed explanations of the study background, concrete work specifications, utilisation of fly ash in marine structures, and a concise depiction of the problem statement were presented. The study's objectives were emphasised, along with the stated hypothesis and the study's significance. Additionally, the scope of work was outlined, and a summary of the chapters was provided.

- Chapter 2: Literature Review. The relevant literature concerning chloride-induced corrosion in RC marine structures, local fly ash characteristics, standard concrete practices, PBDS, indicators of concrete durability and Taguchi's approach was comprehensively reviewed.

- Chapter 3: The conceptual framework of the study, data sources, sampling of questionnaires, execution of field investigation, utilization of ready-mixed concrete, characterisation of materials, preparation of specimens, implementation of standard test methods, execution of Taguchi’s approach and statistical analysis of data were all detailed.

- Chapter 4: Report of objective 1. The survey questionnaire results concerning the perceptions of construction industry stakeholders regarding chloride-induced corrosion in reinforced concrete structures in Sarawak were presented. The

identification of the underlying causes of the issue, critical variables and potential cost-effective local treatments was undertaken.

- Chapter 5: Report objective 2. The process of optimising fly ash content was carried out through experimentation on famous local ready-mixed concrete grades. The evaluation encompassed the analysis of results obtained from tests measuring compressive strength (Cu), ultrasonic pulse velocity (UPV) and water absorption (WA) for concrete specimens containing varying replacement levels of fly ash, ranging from 20% to 60% by mass of cement. The optimal concrete enhancement was achieved by partially substituting Class-F fly ash in the cement composition of local ready-mixed concrete.

- Chapter 6: Report objective 3. The examination of mechanical and durability test outcomes was conducted. Subsequently, non-destructive testing (NDT) models were developed to establish a correlation between compressive strength (Cu) and ultrasonic pulse velocity (UPV) for specific concrete grades using ANOVA analyses. In addition, a set of guidelines termed "Ideal Steps NDT (ISN) Guidelines" was established in the form of ideal scenarios suit to existing Concrete Testing Flow Chart.

- Chapter 7: Report objective 4. Pre-emptively analyse the results of all variable tests. Formulate a model for PBDS by employing ANOVA analyses. Subsequently, develop QRDC indicators that are specifically designed for the purpose of monitoring Quality Assurance and Quality Control (QA/QC) in terms of concrete durability.

- Chapter 8: Conclusion and Recommendations. Key findings derived from the study summarised, along with the provision of recommendations aimed at enhancing the existing concrete standard specifications and facilitating future research in the interconnected domains of constructing a comprehensive PBDS indicators model.

CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Chloride-induced corrosion on reinforced concrete (RC) marine structures includes chloride mechanism, transport mechanism and factors affecting chloride resistance were explained detail in Section 2.2 to overcome chloride-induced attack problem through fly ash concrete optimisation as described detail in Section 2.3. Followed by a widely review of national and international standard test methods that suit to the local real scenario problem as detailed out in Sections 2.4 and 2.5 respectively. Finally, an explanation of Taguchi's approach and research gaps were discovered in Sections 2.6 and 2.7 respectively. Summary of literature review as shown in Table 2.1.

Table 2.1: List of Chapter Sections

Section	Description of Section
1	Overview
2	Chloride-induced corrosion on reinforced concrete marine structures
3	Fly ash Concrete Optimisation
4	Sarawak's standard concrete practices
5	Performance-based durability specifications approach
6	Concrete durability indicator test methods
7	Optimization of concrete durability properties using Taguchi's approach
8	Summary of research gaps

2.2 Chloride-induced Corrosion on Reinforced Concrete Marine Structures

To provide excellent corrosion protection for embedded rebar, chloride-induced attack is a factor to be considered when developing guidelines for RC marine structures. Particularly, a chloride ion penetrating concrete cover is the main factor governing localised disruption of the protective passive film of the rebar. The penetration of chloride ions through concrete covers is a complicated phenomenon that requires further local investigation and treatment based on factors that lead to rapid increases in chloride-induced corrosion ingress on RC structures. It has been successfully proven among the countries with concentrated developments along the seaside, i.e. Australia, New Zealand, and South Africa that local considerations including making use of local fly ash, have produced great protection (CIA, 2015; CCANZ, 2010).

2.2.1 Mechanism of Chloride-induced Corrosion

The conversion of iron into rust is an electrochemical process that occurs naturally and is widely recognised as the main mechanism of RC structural deterioration over time (Ming et al., 2022). Physically, the concrete cover serves as the first line of defence for embedded rebar before the chloride ions damage the passivating film. In such a case, a passivating film that is just 2 to 3 nm thick is produced on the steel surface due to the high alkalinity of $Ca(OH)_2$ on the concrete pore solution (Revie and Uhlig, 2008). With the presence of sufficient chloride ions to surpass corrosion threshold value and the electrolyte in an acidic state, the passivating film may expeditiously break down to trigger localised corrosion of the underlying rebar.

The chloride-induced corrosion process is described by the reactions shown in Equations 2.1 through 2.6 (Bentur et al., 1997). Under a damaged passivating film state, the

electrochemical processes take place on the surface of rebar. Since the anode region is in an almost pure anodic state, iron dissolution may take place and introduce an oxidation process as represented in Equation 2.1.

$$Fe \rightarrow Fe^{2+} + 2e^{-}$$ Equation 2.1

Where;
Fe = Iron, Fe^{2+}= Ferrous ion and $2e^{-}$ = electron

In the presence of oxygen and water, electrons from the anode's oxidation process are released through the electrolyte and consumed by the cathode at the same rate. De-oxygenation occurs if oxygen diffusion into the macro-cell is slower than its depletion through the reduction process. As a result, the reduction reaction shown in Equation 2.2 occurs in the cathode area to produce hydroxide.

$$H_2O + \frac{1}{2}O_2 + 2e^{-} \rightarrow 2OH^{-}$$ Equation 2.2

Where;
H_2O = water, O_2 = Oxygen and OH^{-} = hydroxide.

The dissolution of iron ions in the anode region is equivalent progressively to the reaction in the cathode region. As a result, Equations 2.3 to 2.5 simplify the overall reactions of hydroxide and chloride ions to form $Fe(OH)_2$ via depolarization and hydrolyse processes.

$$2OH^{-} + Fe^{2+} \rightarrow Fe(OH)_2$$ Equation 2.3

Where;
$Fe(OH)_2$ is the corrosion product.

$$2Cl^- + Fe^{2+} \rightarrow FeCl_2$$ Equation 2.4

Where;

$FeCl_2$ $2Cl^-$= chloride ions and
= iron (II) chloride

$$FeCl_2 + H_2O \rightarrow Fe(OH)_2 + HCl$$ Equation 2.5

Where;

HCl is the hydrogen chloride

During rusting process in the atmosphere, there is an opportunity for drying and the corrosion product $Fe(OH)_2$ will be dehydrated in the presence of sufficient oxygen and water (CDO, 2010). As a result, a secondary reaction takes place to form rust product (Fe_2O_3) through an oxidation process as shown in Equation 2.6.

$$2Fe(OH)_2 + \frac{1}{2}O_2 + H_2O \rightarrow 2Fe(OH)_3 \rightarrow Fe_2O_3 \cdot 3H_2O$$ Equation 2.6

Where;

Fe_2O_3 $Fe(OH)_3$= iron (III) oxide-hydroxide and
= rust product

Rust products take up approximately six times the volume of the affected original rebar (Obla et al., 2005), thereby exerting an internal pressure on the affected areas leading to the concrete defects. Such, concrete defects provide more access to the atmosphere for further chronic corrosion. In most catastrophic circumstances, concrete pieces serving as the first line of defence against embedded rebar may crack and spall before causing significant damage to RC structures. The electrochemical mechanism of chloride-induced corrosion on the RC structure is depicted schematically in Figure 2.1 below.

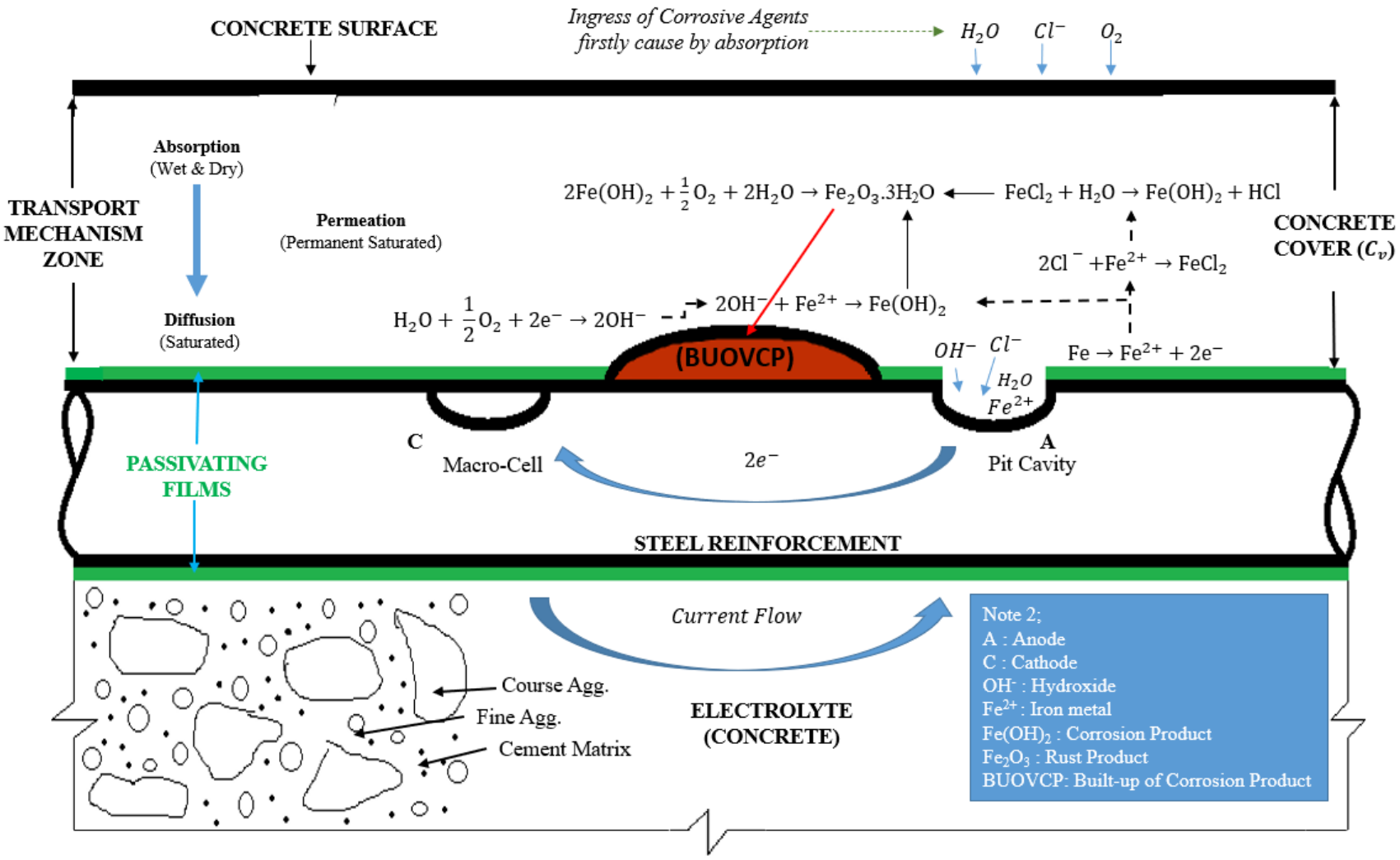


Figure 2.1: Electrochemical Mechanism of Chloride Induced Corrosion on RC Structures

2.2.2 Chloride Ions Transport Mechanism

The transport of corrosive agents through the concrete cover as shown in Figure 2.1 has an adverse effect on the long-term durability of RC marine structures. Transport mechanisms depend on the boundary conditions as well as on the moisture state and its distribution in the electrolyte element. Different environment exposures will employ different modes of transportation to convey corrosive agents toward passive film. Primary chloride transport mechanisms for various chloride exposures include diffusion, permeation, Wick's action and capillary absorption as summarised in Table 2.2 (CCAA, 2009). Meanwhile, according to various studies, the modes of transport of chloride ions into concrete are primarily divided into diffusion, permeation, and absorption (Rose, 1965; CCAA, 2009; Castro et al., 2011).

Table 2.2: Summary of Various Chloride Exposures Identical to Transport Mechanisms

Exposure	Transport Mechanism
Submerged	Permeation, diffusion and possibly Wick's action.
Tidal	Capillary absorption and diffusion.
Splash and spray	Capillary absorption and diffusion.
Coastal	Capillary absorption

Note: Definition for class exposures described in Section 2.2.3(A)

In addition, the main transport mechanisms for conveying corrosive agents within concrete are dependent solely on the transport properties that can take place (i.e., concentration gradient, action of pressure or moisture movement effects) as summarised in Table 2.3 below (Beushausen and Fernandez Luco, 2016).

Table 2.3: Summary of Transport Mechanisms Categories

Transport Mechanism	**Cause of Action**
Absorption	Movement of fluid or moisture due to the capillary forces created inside the capillary pores
Diffusion	Movement of fluid due to a concentration gradient
Permeation	Movement of fluid due to the hydrostatic pressure gradient

Among the transport mechanisms stated in Table 2.2, diffusion and capillary absorption are the significant mobility of chloride ions on RC structures which lie from tidal to splash and spray zones. These two transport mechanisms strongly depend on the concrete porosity due to the number of interconnected capillary pores in microstructures. Meanwhile, capillary absorption is regarded as a much more efficient and dominant transport mechanism than diffusion since the chloride ions are carried with moving water rather than being diffused in static water (Angst et al., 2010). Besides, only a few chloride ions ingress is caused by permeation for submerged RC structures (CCAA, 2009).

It is necessary to understand the individual transport mechanisms and the dominant transport mechanism in order to determine the proper PBDS (test methods) for monitoring and eliminating chloride attack on RC marine structures (McCurrich, 1987). The following sections explain details of primary transport mechanisms namely diffusion, permeation and absorption. Meanwhile, durability test methods related to chloride ingress based on individual transport mechanisms will be discussed in detail in Section 2.5.

A. Diffusion

Diffusion is the mass mobility of free molecules or ions in the pore solution from regions of higher concentration to regions of lower concentration, i.e., marine structures exposed in tidal and fully submerged zones (SFDT, 2007). It is highly dependent on the interconnected capillary pores and only occurs under a saturated concrete state (SFDT, 2007; ACI, 2008; CCAA, 2009). Meanwhile, for the tidal zone, the chloride ions' penetration takes place by diffusion instead of absorption in the deeper region (CCAA, 2009). Nevertheless, considering ion diffusion is a very slow transport mechanism, the test procedure is lengthier in time and requires an expert to conduct or interpret the test results (Phaedonos, 2012; CIA, 2015). In fact, RC marine structures most severely affected by chloride attack is in splash and spray zones. This mechanism is dominated by absorption due to cyclic wetting and drying as explained in detail in Section 2.2.2(C).

In porous concrete, the diffusion coefficient may be described as the mobilisation of a given substance under different concentrations and is indicated as D. For transient or non-steady-state diffusion conditions, i.e. when the concentration gradient changes with time, the flux can be described by Fick's second law of diffusion, also known as the mass balance equation as shown in Equation 2.7 (Stanish et al., 2001; CCAA, 2009).

$$\frac{\partial C}{\partial t} = D\frac{\partial^2 C}{\partial^2 x} \qquad \text{Equation 2.7}$$

Where;
D = chloride diffusion coefficient and C = chloride concentration

B. Permeation

Permeation of chloride ions will only occur under fully submerged exposure conditions with the presence of the hydrostatic pressure gradient, which is characterised by water and air permeability. Such, small hydraulic pressure heads can support the chloride ions' ingress by permeation into narrow pores spaces at great depths below the concrete surface (Boddy et al., 1999). However, the pressure heads to be exerted on RC marine structures are rare (Stanish et al., 2001) and obviously no significant chloride attack prevails in most cases for concrete structures in service under fully submerged exposure conditions (CCAA, 2009).

In saturated concrete, a coefficient of permeability under a steady-state flow is obtained when a constant flow rate is established. It is expressed as the volume of water per unit area of surface per unit time, flowing through concrete under a constant pressure head and at a constant temperature. Water flow in the pores due to hydraulic pressure can be described by D'Arcy's law as shown in Equation 2.8 (CCAA, 2009).

$$Q = \frac{\mathrm{Kw}\,\Delta\mathrm{PA}}{\mathrm{l}} \qquad \text{Equation 2.8}$$

Where;
Q is the water flow (m^3/s)
Kw is the coefficient of water permeability (m/s)
ΔP is the pressure difference (m) across the sample
A is the surface area of sample (m^2)
l is the thickness of sample (m)

C. Absorption

Capillary absorption is the transport of liquids by surface tension action within capillaries due to wetting and drying cycles that occur in the shallow region of the concrete surface built in the tidal, splash or spray zones. Capillary absorption is primarily influenced by interconnected capillary pores as a result of ingredient material performance and on-site work execution effects (CCAA, 2009). During cyclic wetting and drying, capillary water uptake occurs in the wetting stage, while the drying periods allow the capillaries to be at least partly empty to enhance capillary suction in the next wetting cycle (Long et al., 2001). In this case, the amount of liquid absorbed on the concrete surface as well as the amount of liquid transported at any distance from the concrete surface is a function of time. Thus, non-saturated concrete in contact with corrosive agents' solution will be drawn chloride ions cumulatively into the concrete cover by capillary suction much faster than by diffusion alone (Stanish et al., 2001; CCAA, 2009; CIA, 2015).

Particularly, under dry conditions the principal mechanism is molecular absorption to the sides of the pores as shown in Figure 2.2a. Once the pore walls have reached their absorption limits as illustrated by Figure 2.2b, the water vapour will diffuse across the pore. Under moist conditions, the restrictions to the pore inlet and outlet become blocked with water and further water movement must involve a transfer across this film as indicated by Figure 2.2c. Subsequently, at much higher moisture levels water is transported by liquid flow through the pore continuously as represented by Figure 2.2d to 2.2f. Figure 2.2 shows the movement of water and ions within concrete pores (McCurrich, 1987).

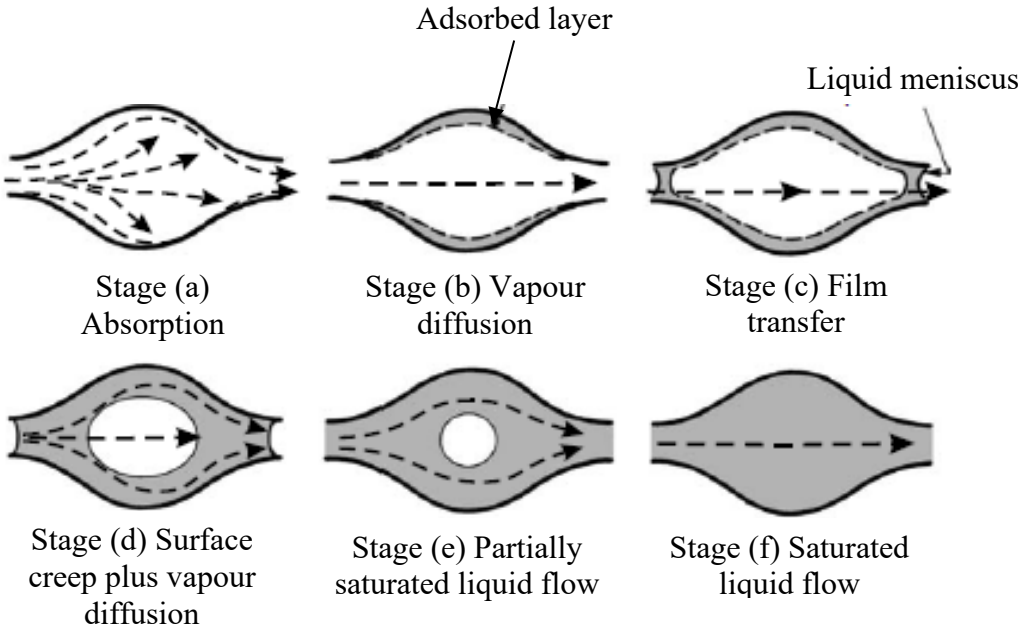


Figure 2.2: Movement of Water Level and Ions within Concrete Pores

D. Relationship Between Absorption, Diffusion and Permeability

Absorption test results are often referred to as the "volume of permeable voids (VPV)" or the "apparent volume of permeable voids (AVPV)". VPV is the apparent volume of void space of a hardened concrete specimen which is emptied during specified oven drying and filled with water during the subsequent immersion and boiling, expressed as a percentage (CCAA, 2009). Meanwhile, absorption is commonly known as the mass of absorbed water as a percentage of the dry mass of a hardened concrete specimen (CIA, 2015). The relationship between absorption (WA) and the absorption after boiling (VPV) is found to be highly correlated with a correlation coefficient of 99% as shown in Figure 2.3 (Sherman et al., 1996).

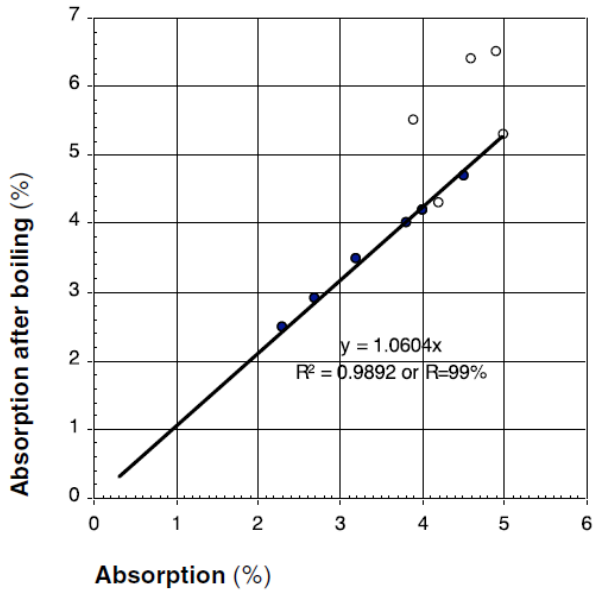


Figure 2.3: Effect of Boiling on Absorption

Furthermore, a study that examined the relationship between the VPV test and a short-term 90-day salt ponding test conducted on hardening concrete specimens was shown to have a great correlate with a recorded correlation coefficient of 99% as shown in Figure 2.4. Both tests were conducted based on standard testing of ASTM C642 and AASHTO T259, respectively. Besides, studies on the relationship between water absorption and chloride attack based on chloride ions diffusion coefficient also found an excellent correlation coefficient of about 91% as shown in Figure 2.5. In addition, the high correlation coefficients of 90% indicated that there was a significant linear correlation between permeability and water absorption (Zhang & Zong, 2014).

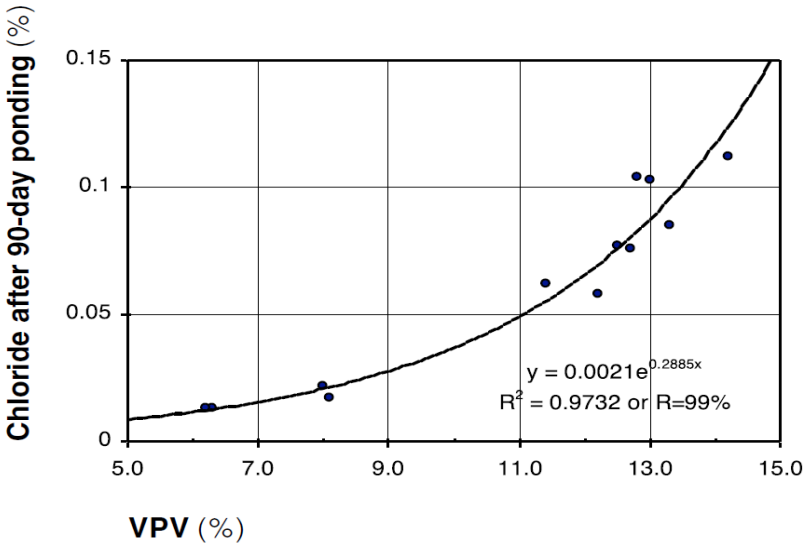


Figure 2.4: The Effect of Water Absorption on Chloride Resistance as Measured by the Salt Ponding Test

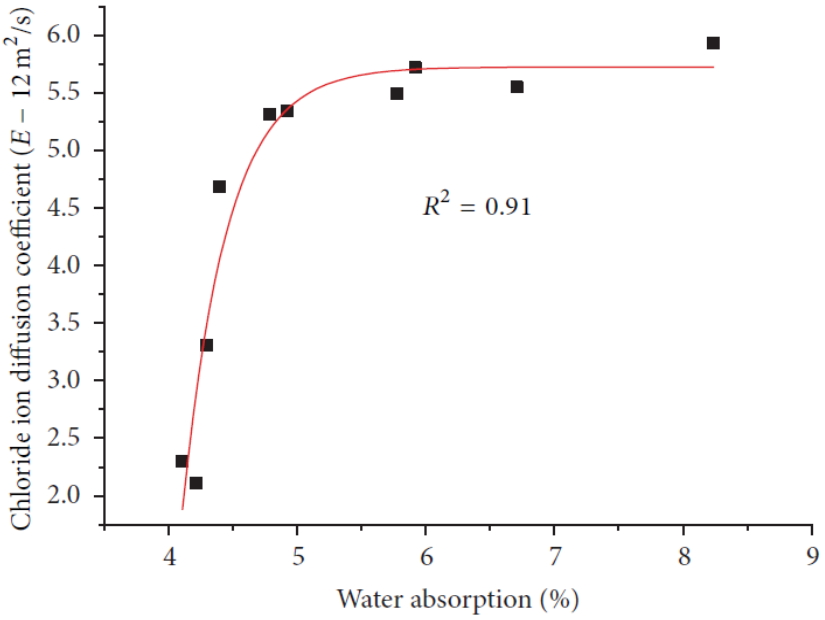


Figure 2.5: Influence of Water Absorption on Chloride Resistance based on Chloride Ions Diffusion Coefficient Test

In addition, the VPV test method has a very satisfactory correlation coefficient with the longer-term chloride diffusion resistance compared to other durability test methods ranging from 86% to 99% (Phaedonos, 2012). Furthermore, Table 2.4 summarises the performance comparisons between absorption and diffusion transport mechanisms revealed in Sections 2.2.2(A), 2.2.2(C), and 2.2.2(D).

Table 2.4: Performance Comparison of Absorption and Diffusion Transport Mechanisms

Performance criteria	**Diffusion**	**Absorption**
Zone exposures (RC structure defect)	Lies from fully submerged to tidal zones (low to moderate defect)	Lies from tidal to splash and spray zones (severe defect)
Dominancy of transport mechanism	Not dominant and occur after absorption	Dominant
Region transportation in concrete cover	Deeper region under concrete surface	Shallower region under concrete surface
Corrosive agent's penetration duration	Very slow	Faster

Based on the great advantages of absorption against diffusion stated in Table 2.4 and the valuable correlations between VPV and diffusion tests shown above, the absorption test as well as the VPV test were clearly identified as two of the most reliable measurements. As such, they can be used to evaluate concrete durability performance for RC marine structures without requiring expensive laboratories and/or specialised interpreters.

2.2.3 Factors Affecting Chloride Resistance

Physically, the integrity of the concrete cover always plays the main role as the first line of defense to resist chloride ions penetration within a shallow region state. Chemically, the passivating film formed during the passivation process in electrolyte under alkalinity conditions acts as the last line of defense for the embedded rebar in the deeper region state before it is damaged by chloride ions. Thus, regardless of the method of construction, the immunity of RC structures to chloride ions penetration is primarily controlled by environmental exposure and the concrete properties themselves as explained in detail in the following sections.

A. Factors Relating to Environment Exposures

Severe chloride ions' penetration into the concrete was influenced by dominant transport mechanisms under severely corrosive environmental exposure. In most cases, severely corrosive environments occurred in splash and spray zones due to the availability of capillary absorption combined with the high relative humidity, hot climate, and strong wind factors.

For instance, it was reported in 1959 and 1965 that at Los Angeles Harbour in California component structures in splash and spray zones were severely damaged by chloride attack (RMCREF, 2006). Meanwhile, it was revealed that in Iluka Wharf in Northern South Wales, tidal or splash zone was the most severely affected followed by the fully submerged and atmospheric zones. Similarly, in Japan, standard specifications for concrete structures stated that RC marine structures located in tidal or splash zones would be the most severely affected by chloride attack (JSCE, 2010b). Other severely corrosive

environmental factors affecting RC marine structures are reported by various standards in studies as summarised as below:

1. Relative humidity higher than 75% was expeditious in chloride exhibition in RC structures (Mahran, 2013).

2. Hot weather area, create the optimal circumstances for chloride-induced exhibit in RC structures (Wang et al., 2019).

3. Chloride ions' concentration is higher in warm sea water compared to cold sea water region (ACI, 2008).

4. Chloride ions' concentration is especially higher in shallow coastal areas with high evaporation rates and heavy wave action (Mackechnie, 2001; ACI, 2008).

According to EN 206, the corrosive exposure environments are assigned to Classes 3, 4, and 6 (BSI, 2002a). Therefore, the most significant contribution to chloride-induced corrosion is devoted to class 4 and denoted as XS. Under this class, class designations of XS1, XS2 and XS3 represent exposure conditions exposed to airborne salt but not in direct contact with sea water, permanently submerged; and tidal, splash and spray zones, respectively. In addition, the typical diagram of corrosive exposure environments due to chloride-induced corrosion according to EN 206 is shown in Figure 2.6 (ICS and ICF, 2004).

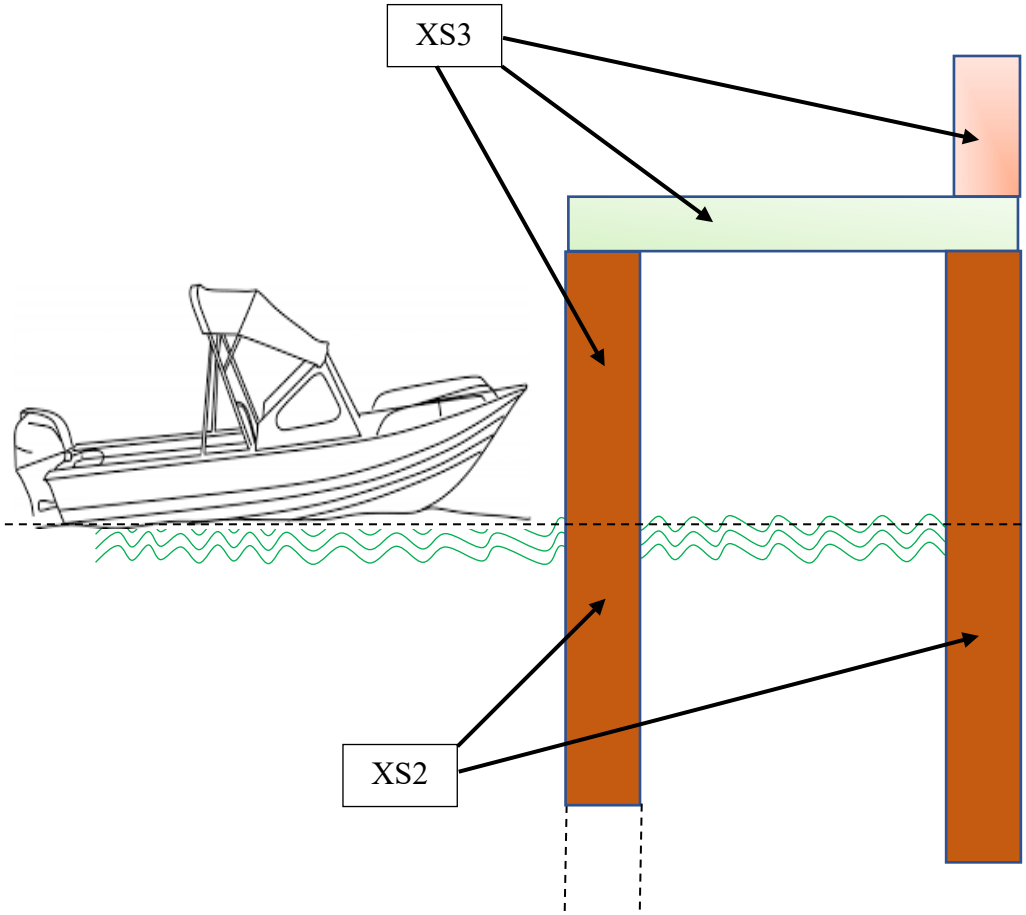


Figure 2.6: Typical Diagram of Corrosive Exposure Environments Caused by Sea Water Chloride

Due to the crucial attacking factors explained above, various national specific concrete durability standards or designations are developed to treat chloride-induced attack based on severe corrosive exposure environments as shown in Table 2.5.

Table 2.5: Comparison of National Severity Corrosive Exposure Environment

Severity	GB/T 50476:2019 (GB, 2019)		IS 456:2000 (Kulkarni, 2009)	
	CD	Environment Description	CD	Environment Description
Mild	III-D	Atmospheric area, air area above 15m from the average water level and outdoor land environment within 100m off the coast line of Highest Astronomical Tide (HAT)	Cr3	Exposed to airborne salts, but not in direct contact with sea water
	III-E	III-D + Tidal zone and splash zone, not at hot area		
Moderate	III-C	Permanently submerged	x	-
Severe	III-F	Tidal zone and splash zone, at hot area	Cr4	Tidal, splash and spray zones of sea water

Note: CD=Class Designation, x=Not Stated

Table 2.5 Continued

Severity	EN 206: 2013 (BSI, 2013)		ACI 318: 2005 (ACI, 2005)		AS 3600: 2018 (AS, 2018)		NZS 3101: 2006 (NZS, 2006)	
	CD	Environment Description	CD	Environment Description	CD	Environment Description	CD	Environment Description
Mild	XS1	Exposed to airborne salt but not in direct contact with seawater	x	-	B1	Climatic zone and near coastal (1 km to 50 km)	B1	Coastal perimeter
							B2	Coastal frontage i. Downwind – Between 30m and 500m inland of the HAT ii. Other wind direction – from the HAT to 100m inland
Moderate	XS2	Permanently submerged	x	-	B2	Permanently submerged	B2	Permanently submerged
Severe	XS3	Tidal, splash and spray zones	C2	Exposed to moisture and an external source of chlorides	C1	Spray zone	C	Tidal/splash/spray i. Offshore and up to 30m inland of the HAT ii. Offshore and up to the HAT
					C2	Tidal / splash zone		

Note: CD=Class Designation, x=Not Stated

Based on various national standards summarised in Table 2.5 and crucial attacking factors explained above, it is clearly shown that different geographic and climate conditions were major contributors to the different dosage treatments against chloride-induced attack. Therefore, in order to provide maximum protection to RC marine structures, it is crucial to develop durability indicators based on local conditions and the most severe effects, which focus on splash and spray zones treatment.

B. Factors Relating to Concrete Properties

The chloride-induced corrosion ingress in concrete is greatly influenced by the porosity of the concrete and is denoted by interconnectivity of the different sizes of pore distribution. The mobility of chloride ions in the pore structure system is increased as the number of interconnected capillary pores in the concrete cover increase. In concrete, the largest pores may be more than one million times larger than the smallest ones. According to the Powers-Brownyard model, pore structures are primarily classified as gel, capillary and macro pores with ascending size arrangement'.

Gel pores are categorised into micro gel pores (MiGP) and meso gel pores (MeGP) with sizes of less than 1 nm and ranging from 1 to 30 nm respectively (Brameshuber, 2008). Meanwhile, pores ranging in size from a few nanometres to several micrometres are generally considered as capillary pores. Capillary pores are categorised into micro capillary pore (MiCP), meso capillary pore (MeCP) and macro capillary pore (MaCP) with sizes ranging from 30 nm to 1 μm, 1 to 30 μm and 30 μm to 1 mm respectively. Macro pores (MP) in concrete are due to entrained air voids and entrapped air voids and can have diameters of up to several millimetres (Angst et al., 2011a).

Among these pores, the capillary pore has the most significant mobility of ions if they are interconnected, with sizes varying from 0.1 to 100 μm (Brameshuber, 2008). However, large pores such as air voids or gaps of several hundreds of micrometres in size remain saturated under submerged conditions and plainly do not fill up throughout wetting and drying cycles due to the absence of capillary forces. Thus, embedded rebar interface is considered harmless defect since it is essentially air-filled (Angst et al., 2011b). Meanwhile, gel pores with sizes less than 3 nm are not detrimental to concrete durability (Angst et al., 2019).

As a result, the compilation of information including indicators for a variety of sizes of pores in concrete, fly ash particles, Ordinary Portland Cement (OPC) particles and JKR's standard sieve sizes discussed above is shown in Figure 2.7. Based on the discussion above, it is clearly pronounced that durability is heavily influenced by concrete porosity in terms of pore size, pore distribution and interconnectivity of pore structure system. By using blended cement in ready-mixed concrete mixtures, linked capillary pores may be treated to have a denser microstructure. Particularly for long-term effects, fly ash chemical reactions refine the pore structure and make concrete more impervious to chloride-induced corrosion ingress.

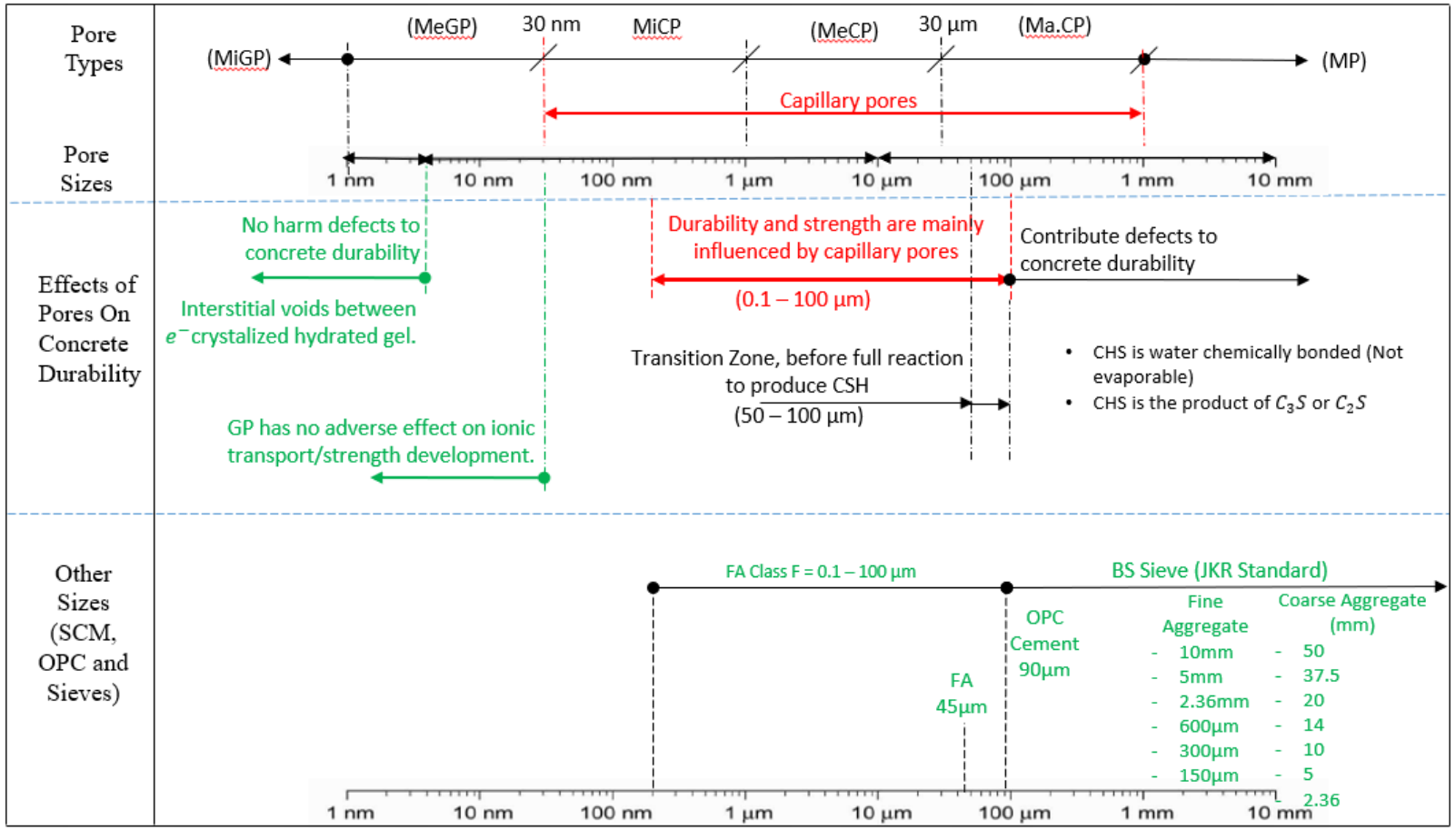


Figure 2.7: Pore Sizes in Concrete

2.3 Fly Ash Concrete Optimisation

Fly ash is a by-product that is obtained from the combustion of pulverised coal in power plants and is most widely used locally as Supplementary Cementitious Materials (SCM) in concrete mixtures because it is available in large quantities as a waste material. The use of fly ash in concrete as blended cement by mass of cement replacement method or volumetric ratio may enhance the quality of the environment and give technical advantages to the concrete products. Fly ash is available in two classes as defined by MS EN 450:2014, ASTM C 618:2019 and IS 3812:2003, which are named as Class-C and Class-F. The quality of fly ash can vary a lot, depending on the type and properties of the coal used, the combustion mechanism and processes of collection in the power plants. There is fly ash available locally in Sarawak that is classified as Class-F and it is being dumped at the landfill area in increasing amounts without being used commercially. The following sections describe in more detail the application, availability and contribution of fly ash to concrete durability, specifically to combat chloride-induced attack for RC structures in marine environment.

2.3.1 Fly Ash Concrete applications

Around the world, there is a lot of fly ash waste being produced by electric generation power plants each year. The increase in ash waste that is not used for valuable products is causing many environmental issues and more importantly may generate serious environmental pollution for future generation (Das et al., 2022). Therefore, turning this notorious waste product into useful construction material is urgently being researched by researchers worldwide (CCANZ, 2010; Ngo and Huynh, 2020). Furthermore, the employment of fly ash as blended cement results in significant cost-effective concrete production (Saraswathy et al., 2003; Chakraborty and Banerjee, 2016) and offers conducive

healthy environment due to CO_2 elimination by reducing the consumption of OPC (RMCREF, 2011; Kiran, 2014; Islam et al., 2018).

In addition, fly ash as blended cement was reported by several studies to enhance the service lifespan of RC marine structures due to excellent results in improving mechanical and durability concrete properties (Bouzoubaa et al., 2000, Saraswathy et al., 2003). Technically, the main applications of utilising fly ash in concrete works under the mass of cement replacement method reported by several studies are summarised as follows;

1. Enhanced compressive strength at a later age (Harison et al., 2013; Chakraborty and Banerjee, 2016; Mallisa and Turuallo, 2017)

2. Improved durability due to high resistance against environmental deterioration from easily penetrating concrete cover (Malhotra, 1990; Marthong, 2012; Islam et al., 2018)

3. Reduced shrinkage caused by high heat of hydration in massive structures construction (Studocu, n.d.)

4. Improved workability at a lower w/c ratio (Khatib and Siddique, 2007)

Based on the applications listed above, the most beneficial fly ash application is durability enhancement due to suitable chemical composition and finer particle sizes compared to OPC (Khale and Chaudhary, 2007; Mehta and Siddique, 2016). This application has been officially utilised by national specifications or guidelines to combat chloride-induced attack since in the year 2008 as stated in Table 1.3. In fact, along with the increasing demands in the area of durability placed on structural concrete came the increased use of SCM, particularly the use of fly ash for RC marine structures (CCANZ, 2010; Yao et al.,

2022). Further explanations of the effects of fly ash on the strength and durability of concrete are available in Sections 2.3.3 and 2.3.4 respectively.

2.3.2 Fly Ash Availability in Sarawak

According to The Star Newspaper dated 23rd November 2014, Sarawak holds nearly 70% of Malaysia's coal reserves with the largest coal deposits in Merit Pila. Merit Pila's coal is classified as anthracite (bituminous), which is the most useful for power generation as a result of the lowest impurities and the highest content of carbon and energy (Chen, 1993). At the moment, there are three coal-fired power stations which are located in Sejingkat, Mukah, and Balingian with an energy production of 210, 270 and 600 MW respectively (Thestar, 2014). In fact, Sejingkat power plant requires almost 2000 tonnes of coal annually, which is equivalent to 200 tonnes of fly ash production. Furthermore, fly ash is collected at three different particle fineness size categories ranging from very fine to harsh (Angkui, 2005). For the purpose of production, the fly ash being used is from the finest category. Then, the fly ash is packed into a paper bag weighing 35 kg selling at RM 9.50 each. Fly ash from Sejingkat power plant has been classified as Class-F fly ash based on the total mass combination of Silicon dioxide (SiO_2), Aluminium oxide (Al_2O_3) and Iron oxide (Fe_2O_3) of more than 70%. Table 2.6 shows the chemical composition of Sejingkat's fly ash, which meets national standards requirements. According to these chemical compositions data provided by supplier, Sejingkat's fly ash is qualified for use in concrete mixtures.

Table 2.6: Chemical Composition of Sejingkat's Class-F Fly Ash Comparable to National Standards Requirements

Chemical properties	**Sejingkat's Fly ash**	**EN 450**	**ASTM C-618**	**IS 3812**
Silicon dioxide (SiO_2) + Aluminium oxide (Al_2O_3) + Iron oxide (Fe_2O_3)	87.2	≥70%		
Silicon dioxide (SiO_2)	58.8	≥ 35	-	≥ 35
Aluminium oxide (Al_2O_3)	21.0	-	-	-
Iron oxide (Fe_2O_3)	7.4	-	-	-
Calcium oxide, (CaO)	4.6	≤ 10	≤ 5 to ≤ 10	≤ 10
Magnesium oxide (MgO)	2.7	≤ 4	-	≤ 5
Sulphur trioxide (SO_3)	0.2	≤ 3	≤ 5	≤ 3
Loss on Ignition	0.5	< 5	< 6	< 5

Note: All units are in %

Besides, according to Statistics Yearbook Sarawak Year 2018, there is no record ceiling price for fly ash due to reasons stated in Section 2.4.3. In contrast to OPC, the highest reported price was RM 22.84 for 50 kg (DSM, 2019). Previously, based on the Market Review of Building Materials in the Construction Industry under Competition Act 2010 published in 2017, ceiling price for OPC per bag slightly increased from RM16.50 in 2013 to RM21.30 in 2017. Based on prices provided by these statistics and the current price of fly ash, it is clear that local fly ash is about 41% more cost-effective compared to OPC as shown in Table 2.7.

Table 2.7: Comparison Prices between Fly Ash and OPC

Chemical properties	Sejingkat's Fly ash (RM)	OPC (RM)
Price per bag	9.5	22.84
Weight per bag	35	50
Price per kg	**0.27**	**0.46**

2.3.3 Effects of Fly Ash on Concrete Strength

The compressive strength of concrete containing fly ash widely differs from that of concrete with no-fly ash depending on the amount of fly ash addition (Hwang et al., 2004). The addition of fly ash to concrete mixtures alters the rate of hydration and the subsequent development of mechanical strength. In most research, it is shown that concrete with fly ash additions has a higher mechanical strength than others, even though it needs more time to reach the final strength (Li & Zhang, 2019).

When cement, water, and aggregates are mixed together, the void between the particle ingredients is initially filled with water to form macro and capillary pores. At the first stage, tricalcium silicate (C_3S) as major chemical component of OPC hydrate to form silicate hydrates (C-S-H) and calcium hydroxide ($Ca(OH)_2$) as shown in Equations 2.9. As such, these C-S-H products are responsible for filling more macro capillary pores. Once a sufficient amount of $Ca(OH)_2$ develops in the first stage, the second production of C-S-H through pozzolanic reaction takes place as shown in Equation 2.10 and leads to pores refinement by reducing the development of micro-cracks in the transition zones. Second products of the pozzolanic reaction react chemically more easily and fill the macro capillary pore due to the typical particle size of fly ash being under 20 μm and only 10 to 30% are larger than 45 μm (Lee et al., 1999; Khatib & Siddique, 2007; Bernal et al., 2016; Mármol

et al., 2016). Meanwhile, the transition zone pore sizes ranges from 50 to 100 μm which is significantly larger than fly ash particle sizes as shown in Figure 2.7. Throughout continuous moist curing, the pozzolanic reaction products continue to fill the meso capillary pores and cause a denser concrete structure and gain more resistance to compression forces.

$$C_3S + H \longrightarrow C\text{-}S\text{-}H + Ca(OH)_2 \qquad \text{Equation 2.9}$$

$$Ca(OH)_2 + S \longrightarrow C\text{-}S\text{-}H \qquad \text{Equation 2.10}$$

2.3.4 Effect of Fly Ash on Concrete Durability

For long-term durability effects, the resistance of concrete cover to chloride-induced corrosion ingress is mainly influenced by interconnected capillary pores due to ingredient materials properties and on-site concrete work execution as discussed in Section 2.2.2(C). Particularly, the use of fly ash as blended cement in an aggressive environment is strongly influenced by the decomposition state of the cement paste, which is due to internal chemical reactions occurring in the paste already hardened. Precisely, the volume of interconnected capillary reduces effectively due to sufficient amorphous silica reacting chemically with the available maximum amount of $Ca(OH)_2$ and increases remarkably with time (Longarini et al., 2014). Furthermore, the large specific surface area provided by the finer particle size of fly ash with sizes ranging from 0.1 to 100 μm aids in filling capillary pores. As such, these size ranges are assigned to zones where capillary pores have the greatest influence on durability and strength as shown in Figure 2.7. Furthermore, the older the concrete, the greater the amount of hydration that has occurred, thus greatly reducing the interconnected capillary due to C-S-H development through water chemically bound reaction (Zeng et al., 2012; Nguyen et al., 2019). This is especially true for concrete that contains slower-reacting

SCM such as fly ash, which takes longer to hydrate (Naik, 2003; Kocatepe and Osmangazi, 2012; Chakraborty and Banerjee, 2016). Many studies have shown that concrete with fly ash additions outperforms no-fly ash concrete in terms of durability at the maximum pozzolanic chemical reaction level. The determination of maximum pozzolanic chemical reaction is mostly conducted by an optimisation-based lab test through mass of cement replacement method.

2.3.5 Fly Ash Concrete Optimisation

In order to combat chloride-induced attacks, national specifications or guidelines have been proposed for the usage of fly ash ranging from 15% to 40%, as per the explanation earlier in Section 1.1.3 and stated in Table 1.3. However, the optimum amount of fly ash is a function of a wide range of parameters and has to be determined on a case-by-case basis (Torrent & Luco, 2007). These are mainly influenced by factors affecting chloride-induced resistance as discussed in detail in Section 2.2.3 and properties of the fly ash according to standard specifications as detailed in this section. At the same time, variations in percentage usage for fly ash optimisation are also strictly governed by the composition and proportions of all the materials in the concrete mixtures. In addition, by carefully selecting mixed proportions through the mass of cement replacement method with the assistance of sophisticated durability test methods, it has become possible to produce RC marine structures with high resistance to chloride-induced attack. Since 2008, fly ash concrete optimisation for chloride-induced resistance has been proven to be workable when concurrently conducted with the application of durability tests. Several studies using this method to combat chloride-induced attack by adding Class-F of fly ash to concrete mixtures are summarised in Table 2.8.

Table 2.8: Worldwide Optimised Fly Ash (Class-F) Studies to Combat Chloride-induced Attack

Study Description	Fly Ash Origin	Optimum usage
Study on Unit weight, UPV, Modulus of dynamic elasticity, Schmidt hardness, Splitting-tensile strength, compressive strength, accelerated corrosion and RCPT (ASTM C 1202) tests of fly ash concrete (15%, 30% and 45% cement replacement) by using constant w/c ratio mixes (Boga and Topcu, 2012).	Seyitömer power plant in Turkey	15%
Study on chloride diffusion coefficient test of fly ash concrete (20% and 30% cement replacement) by using 32, 40, 50 and 60 grade concretes (Angst et al., 2011b).	Australian fly ash	30%
Study on compressive strength and chloride-ion penetration (ASTM C 1202) tests of fly ash concrete made from various sources (Monco used 40% and others 50% cement replacements) by using constant w/c ratio mixes (Bouzoubaa et al., 2000). • Chloride-ion penetration with descending arrangement (Point Tupper, Monco, Belews Creek, Genesee, Forestburg and Coal Creek)	Power plants in USA and Canada	Tested on 40% and 50%
Study on compressive strength and water absorption tests of fly ash concrete (5%, 10%, 15% and 20% cement replacement) by using prescribed mixes (Mehta et al., 2017).	Rajiv Gandhi power plant in Northern India	20%
Study on density, compressive strength, de-icing salt scaling resistance, chloride-ion penetration (ASTM C 1202) tests of fly ash concrete pavement (35%, 53% and 67% cement replacement) by using prescribed mixes (Naik, 2003)	Wisconsin power plant in USA	35%

Table 2.8 Continued

Study on compressive strength, Splitting-tensile strength, chloride migration (NT-BUILD 492), carbonation-phenolphthalein, accelerated frost–thaw tests of fly ash concrete (10%, 40% and 60% cement replacement) by using constant w/c ratio mixes (Baert et al., 2008).	Rodenhuize Power plant in Belgium	40%
Study on compressive strength, chloride-ion penetration (ASTM C 1202) and pore-size distribution tests of fly ash concrete (25% and 58% cement replacement) by using prescribed mixes (Ramezanianpour and Malhorta, 1995)	Fly ash Eastern Canada	25%
Study on compressive strength, UPV, carbonation depth and chloride Contents tests of fly ash concrete (10%, 20% and 30% cement replacement) by using prescribed mixes (Islam et al., 2018)	Barapukuria power plant in Bangladesh	20%

According to Table 2.8, it is clearly shown that the fly ash concrete optimisation varies depending on the fly ash origins. In addition, presently there is no study being conducted using local fly ash tested on various grades given by a local ready-mixed concrete supplier. In fact, the development of blended cements with SCM including fly ash is a large area for research and innovation in the field of cement sciences (Angst et al., 2011a). Thus, in order to utilise local fly ash at optimal performance, it is very crucial to incorporate PBDS in concrete design mixtures prior to actual construction on-site. In addition, for more effective and efficient ways of fly ash concrete optimization application on local ready-mixed concrete plants, Taguchi's approach is the best performer for reliable results. PBDS and Taguchi's approach are explained in detail in Sections 2.5 and 2.7 respectively.

2.4 Sarawak's Standard Concrete Practices

The construction of RC structures in Malaysia, specifically in Sarawak was initially implemented according to BS codes as it was a former British colony. Presently, Malaysia has transitioned to the Structural Eurocodes due to a total of 50 documents or parts of structural BS being withdrawn on 31st March 2010 and there being no further updates or improvements planned. In order to successfully implement Eurocodes in Malaysia, a lot of efforts have to be undertaken by all industry players, including government agencies, local councils, legislators, researchers, developers, consulting engineers, contractors, suppliers, and laboratory testers, to completely update Malaysian Standards based on the latest Eurocodes. In addition, structural Eurocodes will be implemented along with other relevant codes, i.e., standard test methods, material specifications, and standard works execution. Thus, publication of all these standards necessitates a significant number of tasks and will take several years. Government agencies responsible for publishing all of these standards are summarised in Table 2.9 (Mysol, 2022). Meanwhile, the current scenario of Malaysia's EN standards transition and Malaysian Standards publications are explained in detail in the following sections.

Table 2.9: List of Malaysia's Standard Publications by Government Agencies

Standard Description	Government Agencies
MS EN design codes	Department of Standards Malaysia, Ministry of International Trade and Industry (MITI) or SIRIM Berhad
Standard test methods	
Material specifications	
Standard works execution	Public Works Department of Malaysia (JKR)

2.4.1 EN Standards

Generally, Eurocodes are designed to pursue two main component design stages as summarised in Table 2.10 (Mysol, 2022).

Table 2.10: Eurocodes According to Component Design Stages

Eurocode	**Code Description**	**Design stages**
EN 1990 (EC0)	Basis of Structural Design	Loading analysis
EN 1991 (EC1)	Action on Structures	
EN 1992 (EC2)	Design of Concrete Structures	Design and detailing
EN 1993 (EC3)	Design of Steel Structures	
EN 1994 (EC4)	Design of Composite Steel and Concrete Structures	
EN 1995 (EC5)	Design of Timber Structures	
EN 1996 (EC6)	Design of Masonry Structures	
EN 1997 (EC7)	Geotechnical Design	
EN 1998 (EC8)	Design of Structures for Earthquake Resistance	
EN 1999 (EC9)	Design of Aluminium Structures	

In addition, Eurocodes are also intended for use with National Annex (NA) and Non-Contradictory Complementary Information (NCCI) documents in the form of National Determined Parameters (NDP) and Published Document (PD) respectively. Table 2.11 provides a detailed description of both documents (Robert, 2010; Tu, 2010).

Table 2.11: National Annex and Non-Contradictory Complementary Information Description

Documents	Description
National Annex (NA)	Complimentary documents (58 Parts) are required to be produced separately by each country to suit the local practices/conditions. These include the alternative values, country specific data (NDPs=Nationally Determined Parameters; i.e. geographical, climatic, ways of life etc.) and alternative procedures. It may also include a judgement on the use of informative annexes as well as references to NCCI.
Non-Contradictory Complementary Information (NCCI)	Supplementary documents are created by national committees or other organisations to assist in the implementation of the Eurocode, but they are not always required for compliance with the Eurocodes and do not contradict them. It includes background material or other guidance. NCCI is in the form of a PD.

According to the description in Table 2.11, the only way to successfully implement Eurocode 2 is to make use of NA and NCCI documents based on the local practices/conditions of a specific country (Tu, 2010; Chiang et al., 2014).

2.4.2 Malaysia's EN Standard Transition

The idea of studying options to replace BS with Eurocodes came up in 2002 after BSI announced that Eurocodes would be fully implemented in the UK on 31st March 2010 with a five-year review by the CEN/TC250 committee (Robert, 2010; Chiang, 2015). Since 2004, the Department of Standards Malaysia (DSM) has been progressively collaborating with The Institution of Engineers Malaysia (IEM) and other industry players to adopt Eurocodes as the basis for design standards with permission to use the prefix of MS EN199x

(Chiang et al., 2014). In 2006, Ministry of International Trade and Industry (MITI) gave approval to IEM to organise a Technical Committee on design standards through its C&S Technical Division. Finally, Malaysia has fully adopted Eurocodes as design standards since 2010 (Chiang, 2014; Chiang, 2015). After sixteen years of hard work, the Department of Standards Malaysia has published 7 out of 10 Parts, 12 out of 36 topics, and 9 out of 58 NAs for the local construction industry as summarised in Table 2.12 (Mysol, 2022). In particular, 2 out of 3 topics and 2 out of 4 NAs of MS EN standards for the EC2 are available for sale online on the website of the Department of Standard Malaysia.

Table 2.12: Current MS EN Standards Published by SIRIM Berhad

Eurocode	Code Name
EN 1990	MS EN 1990:2010; Eurocode - basis of structural design
	MS EN 1990:2010 (NA); Malaysia national annex to Eurocode - basis of structural design
EN 1991	MS EN 1991-1-1:2010; Eurocode 1: Actions on structures - part 1-1: general actions - densities, self-weight, imposed loads for buildings
	MS EN 1991-1-1:2010 (NA); Malaysia national annex to Eurocode 1: actions on structures - part 1-1: general actions - densities, self-weight, imposed loads for buildings
	MS EN 1991-1-4:2017; Eurocode 1: Actions on structures - Part 1-4: General actions - Wind actions

Table 2.12 Continued

EN 1992	MS EN 1992-1-1:2010; Eurocode 2: design of concrete structures - part 1-1: general rules and rules for buildings
	MS EN 1992-1-1:2010 (NA); Malaysia national annex to Eurocode 2: design of concrete structures - Part 1-1: general rules and rules for buildings
	MS EN 1992-3:2021; Eurocode 2: Design of concrete structures - Part 3: Liquid retaining and containment structures
	MS EN 1992-3: 2021 (NA); Malaysia National Annex to Eurocode 2: Design of concrete structures - Part 3: Liquid retaining and containment structures
EN 1993	MS EN 1993-1-1:2010; Eurocode 3: design of steel structures - part 1-1: general rules and rules for building
	MS EN 1993-1-1:2010 (NA); Malaysia national annex to Eurocode 3: design of steel structures - part 1-1: general rules and rules for buildings
	MS EN 1993-1-3:2019 (Note Double on SIRIM); Eurocode 3 - design of steel structures - part 1-3: general rules - supplementary rules for cold-formed members and sheeting
	MS EN 1993-5:2017; Eurocode 3: Design of steel structures - Part 5: Piling
	MS EN 1993-5:2017 (NA:2018); Malaysia National Annex to MS EN 1993-5:2017, Eurocode 3: Design of steel structures - Part 5: Piling
	MS EN 1993-1-8:2017; Eurocode 3: Design of steel structures - Part 1-8: Design of joints
EN 1997	MS EN 1997-1:2012; Eurocode 7: Geotechnical design - Part 1: General rules
	MS EN 1997-1:2012 (NA); Malaysia National Annex to Eurocode 7: Geotechnical designs - Part 1: General rules
	MS EN 1997-2:2015; Eurocode 7: Geotechnical design - Part 2: Ground investigation and testing
	MS EN 1997-2:2016 (NA); Malaysia National Annex to Eurocode 7: Geotechnical design - Part 2: Ground investigation and testing

EN 1998	MS EN 1998-1:2015; Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings
	MS EN 1998-1:2015 (NA:2017); Malaysia National Annex to Eurocode 8: Design of structures for earthquake resistance - Part 1: General rules, seismic actions and rules for buildings

On the implementation of EC2, Malaysia has entirely adopted this standard as well as essentially fully employing all of UK's NDP. In fact, this NA is not really adapted to the local conditions and contradicts Eurocode's recommendations as explained in Chapter 1 (Tu, 2010; MS, 2010a; MS, 2010b; BSI, 2016). More crucially, NA for item no. E as a guideline for indicative strength classes for durability is not considered as a still adapts BS 8500-1:2002 for concrete quality guidance (BSI, 2002b; MS, 2010a; BSI, 2016). Unfortunately, the guidelines stated in Tables A6, A7, A10, A11, A12, and A13 from this standard are clearly prescriptive deemed-to-satisfy approaches and challengeable (Ching, 2004; RMCREF, 2006; RMS, 2012a).

2.4.3 JKR Standards

In conjunction with Eurocodes implementation, Malaysia through JKR has been continuously updating several existing standard specifications for concrete works execution to accommodate MS EN design codes, standard test methods, and material specifications. Figure 2.8 illustrates the relationship between JKR's concrete works standard specifications and MS EN standard codes. Standard test methods and material specifications are explained in detail in Section 2.4.4.

Practically, Standard specifications for concrete works execution refer to Standard Specifications for Building Works (SSBW) and Standard Specifications for Road Works (SSRW). JKR Malaysia has prepared SSBW 2020 to replace the first revision, which was published in 2014 after being compiled in 2005 (SSBW, 2005; SSBW, 2014; SSBW, 2020). Meanwhile, the current SSRW was issued in 2008 after being first compiled in 1998 (SSRW, 1988; SSRW, 2008). However, the contents of the concrete works section for this standard are similar to the content of SSBW 2005. More crucial, SSBW 2020 in the concrete works section is still based on prescriptive specification with little improvements on selecting concrete desires based on class exposure to reflect compressive strength class, maximum w/c ratio, minimum cement content and concrete cover (BSI, 2002b; SSBW, 2020). Furthermore, the quality of concrete is solely determined by workability and compressive strength tests performed on freshly prepared specimens as shown in Figure 2.9 (SSBW, 2020). Based on this concrete testing flow chart, it is clearly shown again that present concrete works standards specifications are massively prescriptive deemed-to-satisfy approach by assuming that the workmanship in preparing the test specimen is be the same as the as-built structure (Ching, 2004).

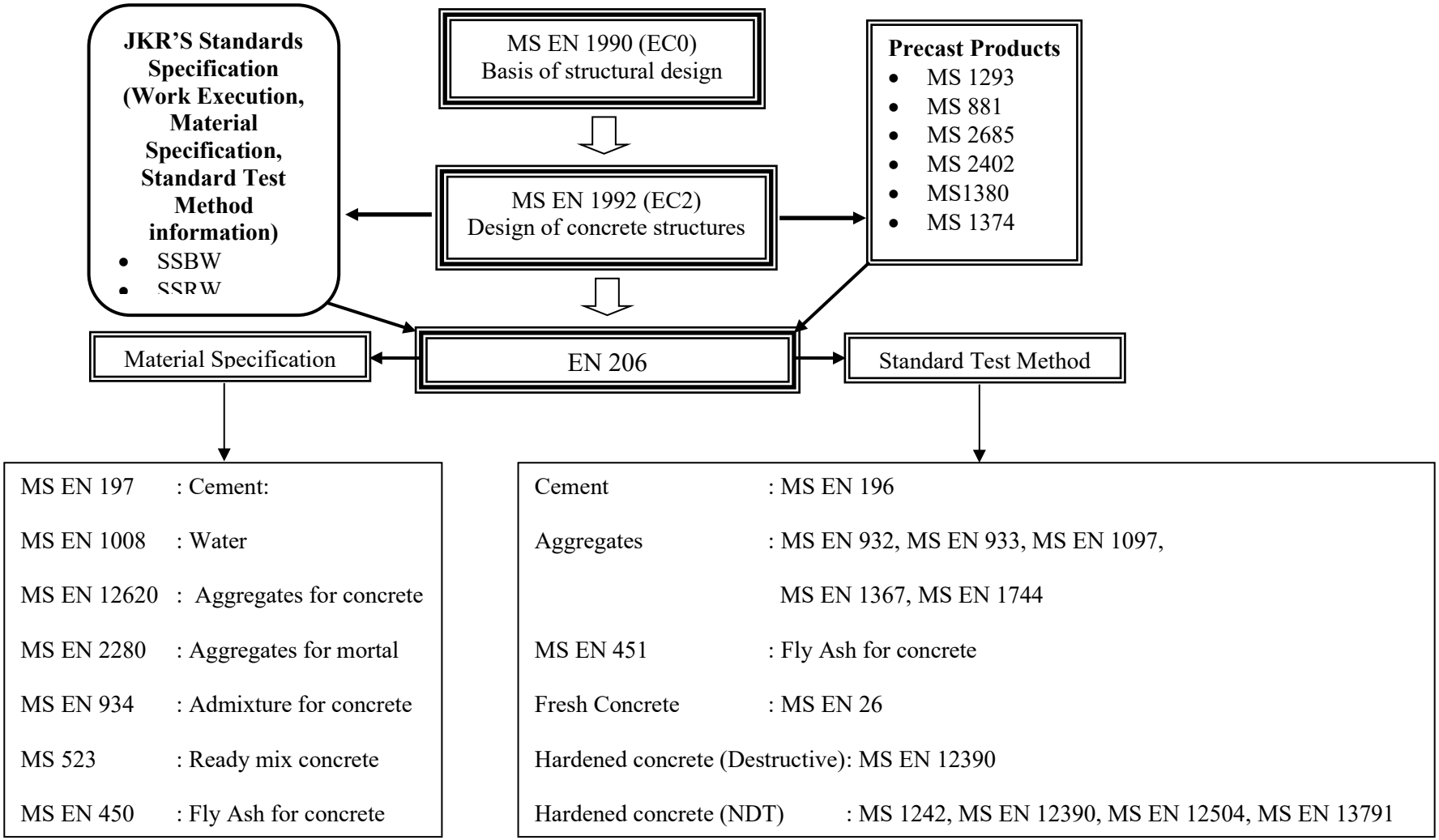


Figure 2.8: Relationship between JKR's Concrete Works Standard Specifications and MS EN Standard Codes

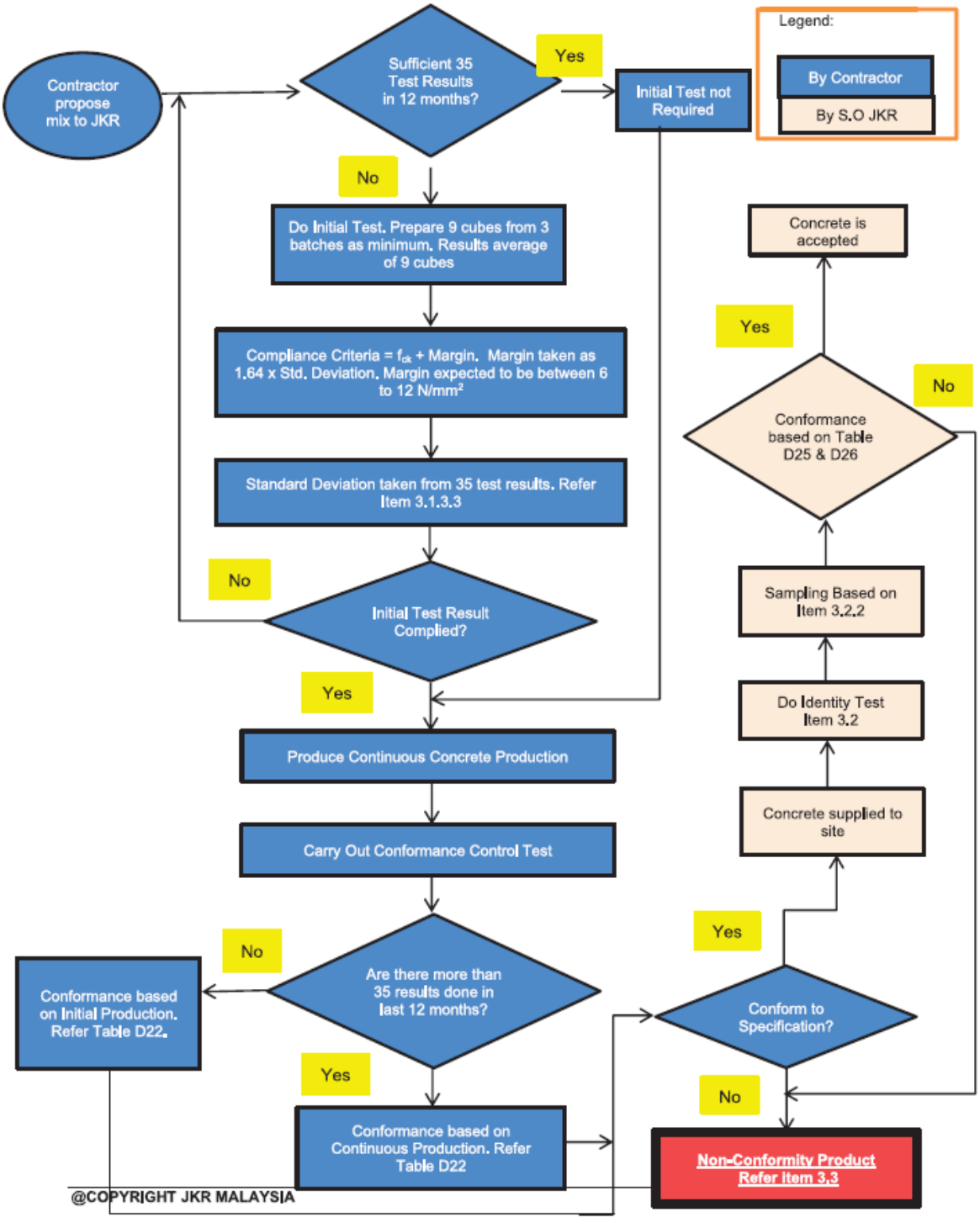


Figure 2.9: Concrete Testing Flow Chart

Throughout development of JKRs standard specifications, fly ash was first introduced in 2014 as one of the allowable supplement cementitious cement for construction industry with the allowable proportion of 6%-35%. Nevertheless, the present standard for the proportion of fly ash recommended in SSBW 2020 is up to 55% as shown in Figure 2.10 was similar as stated in Table A6 of BS 8500-1:2002 (BSI, 2016).

Broad Designation[b]	Composition	Comprises cement and combination types (see Table D2)
CEM I	Portland cement	CEM I
CEM I-SR 0 CEM I-SR 3	Sulphate-resisting Portland cement	CEM I-SR 0 CEM I-SR 3
IIA	Portland cement with 6 % to 20 % fly ash, ground granulated blastfurnace slag, limestone, or 6 % to 10 % silica fume[c]	CEM II/A-L, CIIA-L, CEM II/A-LL, , CIIA-LL, CEM II/A-S, CIIA-S, CEM II/A-V, CIIA-V, CEM II/A-D
IIB-S	Portland cement with 21 % to 35 % ground granulated blastfurnace slag	CEM II/B-S, CIIB-S
IIB-V	Portland cement with 21 % to 35 % fly ash	CEM II/B-V, CIIB-V
IIB+SR	Portland cement with 25 % to 35 % fly ash	CEM II/B-V + SR, CIIB-V + SR
IIIA[d]	Portland cement with 36 % to 65 % ground granulated blastfurnace slag	CEM III/A, CIIIA
IIIA + SR	Portland cement with 36 % to 65 % ground granulated blastfurnace slag with additional requirements that enhance sulphate resistance	CEM III/A + SR[e], CIIIA + SR[e]
IIIB[f]	Portland cement with 66 % to 80 % ground granulated blastfurnace slag	CEM III/B, CIIIB
IIIB+ SR	Portland cement with 66 % to 80 % ground granulated blastfurnace slag with additional requirements that enhance sulphate resistance	CEM III/B + SR[e], CIIIB + SR[e]
IVB-V[g]	Portland cement with 36 % to 55 % fly ash	CEM IV/B-V, CIVB-V

Figure 2.10: JKR's Table D1 of Cement and Combination Types

Unfortunately, usage of fly ash as blended cement in the construction industry is still not seen due to unclear local guidelines and the lack of study to determine the significant effectiveness of local fly ash tested on local ready-mixed concrete. The usage and local availability of fly ash are explained in detail in Sections 2.3.1 and 2.3.2 respectively.

2.4.4 SIRIM Standards

In order to fulfil the standard test methods and material specifications stated in Figure 2.8, Department of Standard Malaysia has published 24 documents of material specifications or guidelines and 58 documents of standard test methods, including revision for both standard categories as summarised in Table 2.13 (Mysol, 2022).

Table 2.13: Total Available Material Specifications and Standard Test Methods Published by SIRIM Berhad

Item	Material specification / guidelines	Standard test methods
Cement	7	11
Aggregate	3	27
Water	1	-
Admixture	6	-
Fresh concrete	4	8
Hardened concrete	-	8
NDT on hardened concrete	3	4
TOTAL	**24**	**58**

The only accessible durability tests for hardened concrete in the publication of standard test methods were the density test and the depth penetration of water under pressure

test. However, these two tests are rarely used by the construction industry due to their lack of reliability and testing does not reflect the actual problem. In particular, in the case of the water pressure penetration test, the apparatus is too expensive.

On NDT techniques, UPV and rebound hammer have already been available online since 2013. Unfortunately, none of these tests is explicitly included in the present concrete works standard specifications for execution. The list of available standard test methods for hardened concrete and NDT techniques on the website of the Malaysia Standard Online are summarised in Table 2.14 and Table 2.15 respectively (Mysol, 2022). Meanwhile, material specifications publications for fly ash have been available since 2014 as listed in Table 2.16 (Mysol, 2022).

Table 2.14: Standard Test Methods for Hardened Concrete

MS EN Standard	Standard description
MS EN 12390-1:2012	Testing Hardened Concrete - Part 1: Shape, Dimensions and Other Requirements for Specimens and Moulds (2nd rev.)
MS EN 12390-2:2012	Testing HC - Part 2: Making and Curing Specimens for Strength Tests (2nd rev.)
MS EN 12390-3:2012	Testing Hardened Concrete - Part 3: Compressive Strength of Test Specimens (2nd rev.)
MS EN 12390-4:2012	Testing HC - Part 4: Compressive Strength - Specification for Testing Machines (2nd rev.)
MS EN 12390-5:2012	Testing Hardened Concrete - Part 5: Flexural Strength of Test Specimens (2nd rev.)

MS EN 12390-6:2012	Testing Hardened Concrete - Part 6: Tensile Splitting Strength of Test Specimens (2nd rev.)
MS EN 12390-7:2012	Testing Hardened Concrete - Part 7: Density of Hardened Concrete (2nd rev.)
MS EN 12390-8:2012	Testing HC - Part 8: Depth of Penetration of Water Under Pressure (2nd rev.)

Table 2.15: Standard Test Methods for NDT Techniques

MS EN Standard	Standard description
MS EN 12504-1:2013	Testing Concrete in Structures - Part 1: Cored Specimens – Taking, Examining and Testing in Compression (2nd rev.)
MS EN 12504-2:2013	Testing Concrete in Structures - Part 2: Non-Destructive Testing - Determination of Rebound Number (2nd rev.)
MS EN 12504-3:2013	Testing Concrete in Structures - Part 3: Determination of Pull-Out Force (2nd rev.)
MS EN 12504-4:2013	Testing Concrete in Structures - Part 4: Determination of Ultrasonic Pulse Velocity (2nd rev.)

Table 2.16: Material Specification for Fly Ash

MS EN Standard	Standard description
MS EN 450-1:2014	Fly Ash for Concrete – Part 1: Definition, Specification and Conformity Criteria (First Revision)
MS EN 450-2:2014	Fly Ash for Concrete – Part 2: Conformity Evaluation (First Revision)

2.5 Performance-based Durability Specifications Approach

The durability of RC marine structures is critical for controlling its target service life before incurring unanticipated high repair costs due to corrosion ingress. Thus, rather than relying solely on the prescriptive rules as identified in Sections 2.4.2 and 2.4.3, the Performance-based Durability Specifications (PBDS) of a concrete product should be determined using the most relevant durability parameters. Thus, the concrete performance examination conducted in the laboratory should be monitored on-site by a series of concrete experiments throughout the construction phases or at end concrete products. This PBDS approach has been agreed upon among the developed countries as to the quality of the as-built RC marine structures can be evaluated on-site and actions can be taken in the event of non-conformity. Nowadays, there are numerous standardised durability test methods that offer the quickest results and Quality Rating Durability Compliance (QRDC) available in the construction industry. The following sections discussed in detail the principle, types, and international development of PBDS.

2.5.1 Principles of PBDS

Eurocodes, among the most advanced codes of practise for participating PBDS in the world are designed to be used with NA and NCCI documents as PD (Chiang, 2014; Robert, 2010; Chiang, 2015). Such, documents are the most important that each country is required to produce separately for effective and efficient Eurocodes implementation as detailed in Table 2.11. Since the development of Eurocodes 2 in 1992, several countries including the European Union (EU), the United States, Australia, New Zealand and other countries have rushed to adopt PBDS based on regional conditions as detailed in Section 2.5.3.

According to the principle of equivalent performance-based durability concept, the equivalent performance durability indicators must be shown from the comparison with a reference concrete mixture (Beushausen & Fernandez Luco, 2016). Thus, the actual concrete mixtures must be monitored on a regular basis and comply with more restrictive durability indicators than those specified in the standard for each exposure class, i.e., minimum compressive strength, minimum cement content, and maximum water-cement ratio. Figure 2.10 shows an example of implementation of equivalent performance-based durability concept to concrete microstructures by using porosity measurement as a durability indicator, which has the greatest impact on carbonation depth penetration (Younsi et al., 2011).

Besides, NDT techniques may be useful in monitoring QA/QC of concrete delivered to the construction site. As such, sample methodology for quality monitoring of cement-based materials at an early stage was developed by combining NDT techniques, including UPV test and capillary pressure measurement as durability indicators, and has shown good potential to become a promising quality control methodology. Figure 2.11 shows an experimental setup for early age monitoring of cement-based products (Barluenga, 2018).

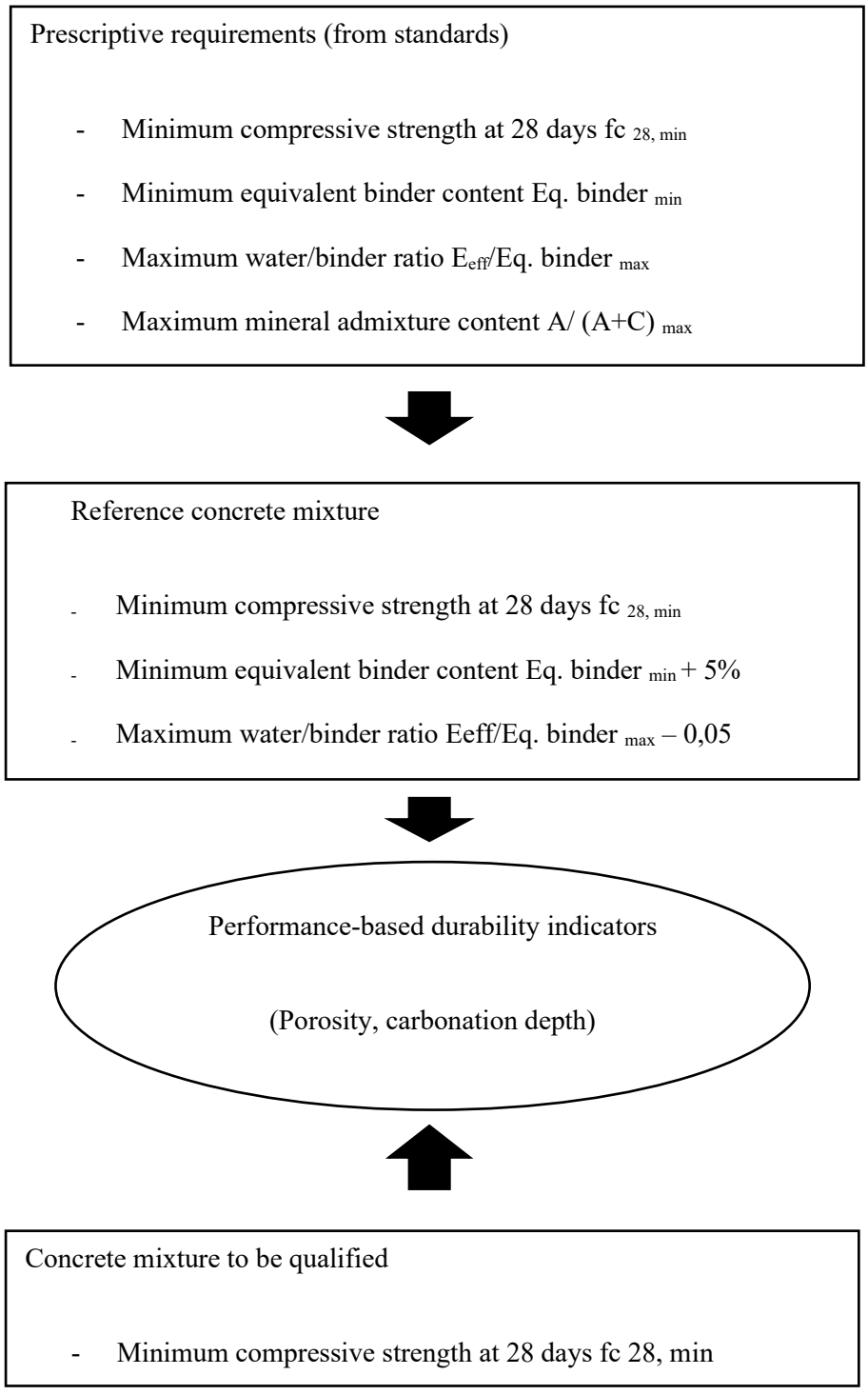
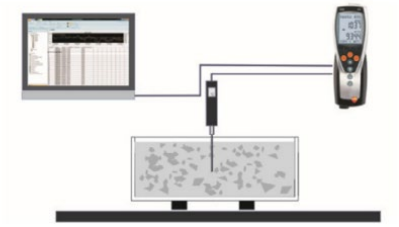
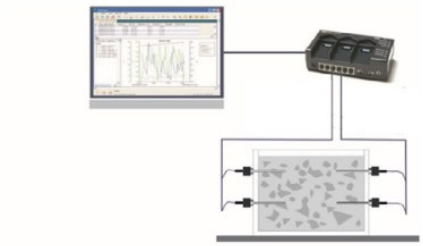


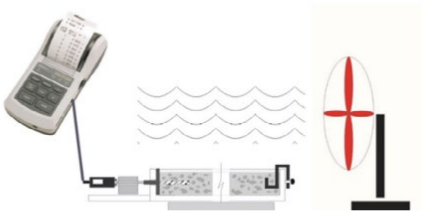
Figure 2.11: Application Principle of Equivalent Performance-based Durability Concept In-case Concrete Exposed to Carbonation



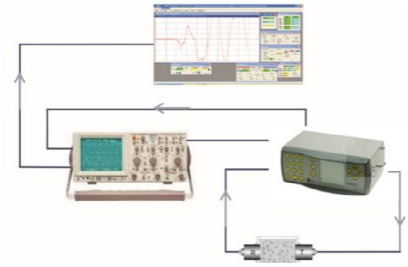
Temperature



Capillary Pressure



Evaporation Rate and Free Shrinkage



P- and S- waves Ultrasonic Pulse Velocity

Figure 2.12: Experimental Setup for Early Age Monitoring of Cement-based Materials

2.5.2 Types of Performance Testing in PBDS

Concrete test methods for PBDS evaluation conducted throughout the construction project phases can be classified into three types namely as (i) pre-qualification testing, (ii) quality control testing and (iii) in-place testing (Beushausen and Fernandez Luco, 2016). In standard concrete work construction local practice, these types of testing are represented as pre-casting, casting and post-casting. Thus, the amended PBDS based on types of performance adapted to Sarawak's standard concrete practices according to Section 2.4 is described briefly in Table 2.17.

Table 2.17: Types of Performance Testing Used in PBDS

Types	Descriptions
Pre-qualification testing (Pre-casting)	Conducted during pre-casting or prior to the start of any concrete work on site and subjected to client's approval as per the concrete works specification criteria. Pre-qualification of concrete mix design, it is compulsory to meet agreed-upon specifications, including compliance with the QRDC indicators. Concrete performance properties testing ranges from fresh to hardened states.
Quality control testing (Casting-QA/QC)	Conducted during casting by obtaining samples directly at site construction, either at the truck cute, or more comprehensively on cast in-place. Compulsory for sampling test results to meet the QRDC indicators stipulated in the approved pre-qualification document. Concrete performance properties testing covers fresh concrete to hardened concrete states.
In-place testing (Post-casting)	Applied NDT techniques on hardened concrete during the defect liability period and/or during the service period are compulsory to surpass or equivalent to desired QRDC indicators.

Available concrete performance properties of interest considered as performance criteria throughout the project phases are listed in Table 2.18 (Hover et al., 2008). Meanwhile, the standardised test methods used to measure these performance criteria are influenced by numerous factors, as detailed in Section 2.5.3. Finally, instructions in assessing selected performance criteria and durability indicators should be clear, achievable, measurable and enforceable (RMCREF, 2006).

Table 2.18: Concrete Performance Properties of Interest

Fresh Concrete	Transition	Hardened Concrete
• Slump • Plastic viscosity • Response to vibrator • Pumpability • Finish ability • Segregation • Bleeding • Air content • Stability of air bubbles • Uniformity of mixing • Consistency of properties • Temperature	• Rate of slump loss • Time to initial set • Time to final set • Rate of strength gain (compression) • Rate of strength gain (tension) • Rate of stiffness gain • Time to frost resistance • Tolerable rate of evaporation • Plastic shrinkage • Temperature	• Strength • Fracture toughness • Elastic properties • Shrinkage • Creep • Porosity • Pore size distribution • Permeability • Chloride resistance • Air void system • Abrasion resistance • Sulphate resistance • Acid resistance • Thermal volume change • Heat capacity • Thermal conductivity • Electrical conductivity • Density • Radiation absorption • Colour • Texture • Cost

2.5.3 International PBDS by Absorption Tests

In order to eliminate chloride-induced attack on RC marine structures with the implementation of PBDS approach, it is necessary to study durability indicators based on the dominant transport mechanism as explained in Section 2.2. Furthermore, worldwide

reviews for concrete standard test documents relevant to absorption transport mechanisms are limited to European Union (EU) countries, the United States of America, Australia, New Zealand, China, Japan, and India. As such, the selection was based on pioneer PBDS, as well as climate and geographic similarities to the Malaysian condition. As a result, common absorption standardised test methods practised in these countries are summarised in Table 2.19. (RMCREF, 2006; Bungey et al., 2006; Kulkarni, 2009; Phaedonos, 2012; CIA, 2015; Beushausen and Fernandez, 2016; Kwon, 2017). Besides, criteria considerations in selecting the most valuable concrete durability indicators focus on standardised test, precession, PBDS testing fulfilment (Pre-qualification and In-place testing or Drilled cores (ITDC), Quality Rating Durability Compliance (QRDC), test duration, practicality, cost-effectiveness and test applicability to the local concrete standard specifications are summarised in Tables 2.20 and 2.21 (AS, 1999; NZS, 2006; ASTM, 2006; NSW, 2012).

According to Tables 2.20 and 2.21, the most valuable standard test durability indicators conforming to the assessed criteria considerations are WA and VPV. These test methods have been used extensively in Australia, New Zealand, Canada and USA. AS 1012.21, an Australian adaptation of ASTM C642, divides cylinders or cores into four equal slices so that several results are obtained from one test specimen (ASTM, 2006; CCAA, 2009). Thus, the extensive experience gained by Australia using the durability indicators approach can be utilised beneficially. In addition, the climatic conditions for the northern part of Australia is similar to that of Malaysia with its tropical rainforest climate.

Meanwhile, China, Japan and India are not included in the Table summary as performance durability indicator test methodologies used were not absorption transport mechanism-based. (IS, 2007; JSCE, 2010a; JSCE, 2010b; GB, 2015; IS, 2019).

Table 2.19: Common Absorption Tests

Test Type	Standard / Test Name
Water absorption	• ASTM C642, Standard Test Method for Density, Absorption, and Voids in Hardened Concrete • AS 1012.21: Methods of testing concrete Determination of water absorption and apparent volume of permeable voids in hardened concrete • BS 1881: Part 122, Method for determination of water absorption • RILEM CPC11.2, Absorption of water by capillarity • BS 1881: Part 208, Initial surface absorption test (ISAT) • RILEM 25-PEM Test II.4, ISAT water absorption tube • BS 1881: Part 124, Methods for analysis of hardened concrete - Determination of capillary porosity
Sorptivity	• ASTM C1585, Standard Test Method for Measurement of Rate of Absorption of Water by Hydraulic-Cement Concretes • Autoclam Sorptivity test • Taywood Sorptivity Test • RMS T362 Sorptivity test

Table 2.20: Water Absorption (WA) Tests

Test Name	Country	Test Type	Standardised	Precession (%)	Pre-qualification	ITDC	QRDC	Maximum test duration (days)	Practicality	Cost-effective	Comments
RILEM CPC11.3	Portugal	Capillary Suction	Y	NS	NS	Y	Y	3-4	II	2	The test is not commonly used and is not cost-effective.
BS 1881: Part 208 / ISAT	Croatia	Initial Capillary Absorption	Y	NS	NS	NCU	Y	hours	III	2	Fairly difficult to practice as results can be difficult to interpret since the test is very sensitive to existing concrete moisture and surface conditions.
	Northern Ireland / Sweden	Capillary Suction									

Notes:

1. Check marks: (Y) = Available, (X) = Not Available, (NS) = Not Stated, (D) = Sample Test to Damage, (NCU) = Not Commonly Used
2. Cost-effective: (1) = Acceptable, (2) = Poor, (3) = Not acceptable
3. Practicality: (I) = Easy, (II) = Fairly Easy, (III) = Fairly Difficult, (IV) = Difficult

Table 2.20 Continued

AS 1012.21 / ASTM C642	New Zealand	WA & VPV	Y	2-6	Y	Y	Y	2	I	1	AS 1012.21 is essentially an Australian adaptation of ASTM C642, with minor procedural changes. Both test methods fulfil almost all criteria considerations.
	Australia	VPV									
	USA / Canada	WA & VPV					NS	4			
BS 1881: Part 122	Australia / EN	WA	Y	5.0 - 5.5	NS	Y	NS	28-32	I	1	QRDC is not provided and sample conditioning is critical as it does not suit JKR's qualification testing age specimen of earlier 7-day compressive strength test required for formwork removal purposes.
RILEM 25-PEM	Portugal	Open Porosity	X	NS	NS	Y	NS	hours	I	1	Test not standardised or not commonly used and QRDC not provided.
BS 1881: Part 124	EN	Capillary porosity	Y	NS	NS	Y	NS	2-3	III	2	Fairly difficult to practise due to the prescribed solvent being difficult to obtain as well as extra precautions on conducting laboratory and QRDC not being provided.

Notes: (Refer Table starter)

Table 2.21: Sorptivity Tests

Test Name	Country	Standardised	Precession (%)	Pre-qualification	ITDC	QRDC	Maximum test duration (days)	Practicality	Cost-effective	Comments
ASTM C1585 Sorptivity	USA / Canada / Australia / New Zealand	Y	6.0	Y	Y	Y	28-56	II	1	Sample conditioning is critical due to specimen ageing and does not suit JKR's qualification testing age test of earlier 7-day compressive strength test as required for formwork removal purposes.
Sorptivity test	Croatia	NS	X	X	Y	Y	7-8	I	2	Test not commonly used, pre-qualification not available and not cost-effective.
Taywood Sorptivity Test	New Zealand	X	5.2 - 16.8	NS	Y (D)	X	2-3	I	2	Test not standardised or not commonly used, QRDC not available and not cost-effective.
RMS T362 Sorptivity test	Australia	NS	X	NS	X	NS	36	II	2	Test not commonly used, in-place testing not available, test duration does not suit JKR's requirements and not cost-effective.

Notes: (Refer Table 2.20)

Furthermore, as compared to other durability test techniques, VPV has a substantially higher correlation coefficient to longer-term chloride diffusion resistance (365-day) as shown in Table 2.22 (Phaedonos, 2012). VPV demonstrates 86% correlation, making this test method potentially the best overall assessment method for durability performance (Phaedonos, 2012). In addition, due to the test's capacity to roughly forecast the cementitious material's overall water penetration, international studies strongly accept VPV as a fantastic durability indicator test (Chougan et al., 2020; Chougan, 2022). A detailed explanation of this test method is provided in Section 2.6.2.

Table 2.22: Correlation to Longer-term Chloride Diffusion Resistance

	AS 1012.21 / ASTM 642 (VPV)	**ASTM C1585 (Sorptivity)**	**ASTM C1202 (RCPT)**	**ASTM C1556 (De.)**
Correlation coefficient	86%	76%	76%	74%

2.5.4 International PBDS by NDT Techniques

A worldwide review was conducted on similar documents assessed in Section 2.5.3 to determine reliable NDT techniques based on mechanical or acoustic test methods and the valuable absorption tests determined in Sections 2.5.2 and 2.5.3 above. As a result, the findings on NDT techniques utilisation around the world are summarised in Table 2.23 (Khan, 2002; NIST, 2013; CIA, 2015; Beushausen & Fernandez Luco, 2016). Some criteria considerations are not provided in the table summary due to similar findings for both test methods.

Based on Table 2.23, rebound hammer is merely a measure of surface hardness, hence the results may not be indicative of bulk, unformed, or degraded surfaces. Meanwhile, UPV is widely recognised as excellent for determining the quality and uniformity of concrete with the availability of QRDC (Khan, 2002). Besides, WA and VPV tests are promising methodologies that fit NDT method's criteria. (Torrent & Luco, 2007). This test method can be carried out using the drilling core method yielding the quickest results without causing significant structural damage. Further explanations of UPV, WA, and VPV as NDT technique methods adopted for this study are available in Section 2.6.

Table 2.23: NDT Techniques

Test Name	Standardised	Pre-qualification	ITDC	QRDC	Practicality	Cost-effective	Comments
UPV	Y	NS	Y	Y	II	2	Commonly used for concrete homogeneity determination as well as QA/QC performance.
Rebound hammer	Y	NS	Y	NS	I	1	Commonly used as an indicator of concrete surface hardness. However, the accuracy of estimating concrete compressive strength is ± 25 % (Malhotra and Carino, 2003)

Notes: (Refer Table 2.20)

2.6 Concrete Durability Indicator Test Methods

Concrete durability indicator test methods are among the most essential satisfaction indicators that should be monitored on hardened concrete to ensure greater value for money, satisfy client's quality desires and guarantee the safety of public users. To provide long-lasting concrete, the precise demands on concrete in its intended application must be carefully considered. Its conformance to limiting values according to specification requirements is continuously tested using sophisticated standard tool testing throughout the construction phases. Using non-destructive tests or extracting cores from the body of the structure for diagnosis of concrete is an efficient and versatile monitoring technique which can be effectively applied in any field conditions (Malhotra & Carino, 2003; Hobbs & Tchoketch, 2007). Thus, based on the credibility test methods mentioned in Section 2.5, a detailed explanation of NDT, namely UPV, WA and VPV, is given in the following sections.

2.6.1 Ultrasonic Pulse Velocity (UPV)

The earliest reports of measuring the velocity of mechanically generated pulses in concrete occurred in the United States in the mid-1940s, based mostly on the material's elastic properties. Due to its significant potential value approach, it resulted in the development of repetitive mechanical pulse equipment in France, which was followed by testing development in Canada and the United Kingdom using electro-acoustic transducers. This test method has evolved into the present modern ultrasonic method, which employs pulses in the frequency range of 20–150 kHz that are created and recorded by electronic circuits (Khan, 2002; Bungey et al., 2006). Currently, UPV is extensively used around the world since it has a high correlation with other mechanical properties and is excellent for determining the uniformity or quality of concrete (Lawson et al., 2011). Furthermore, it is commercially manufactured, robust, lightweight equipment that is suited for both on-site and

laboratory usage, resulting in simplicity and cost-effectiveness (Terzić et al., 2010; McLaskey et al., 2010). Great performance offered by UPV test method has resulted in substantial UPV testing adoption across national standard makers since 1972 as stated in Table 2.24 (Castro & Carino, 1998).

Table 2.24: List of National Standard UPV Test Method

Country	Designation	Year
RILEM	NDT 1	1972
Romania	C-26-72	1972
Poland	PN-B-06261	1974
Belgium	NBN 15-229	1976
Bulgaria	BDS 15013-80	1980
Venezuela	COVENIN 1681-80	1980
Czech Republic	CSN 731371	1981
Yugoslavia	JUS U.M1.042	1982
DDR (German Democratic Republic)	TGL 33437102	1983
Brazil	ABNT 18:04.08.001	1983
Germany	DRAFT. SAME AS ISOiDIS 8047	1983
International	ISO/DIS 8047	1983
Sweden	SS 137240	1983
USA	ASMTM C 597	1983
Denmark	DS 423.33	1984
Scandinavia	NT BUILD 213	1984

Table 2.24 Continued

Mexico	NOM-C-275-1 986	1986
Spain	UNE 83-308-86	1986
Russia	COST 17624	1987
Hungary	MI 07-3318	1994
United Kingdom	BS 12504-4: PART 4	2004

A. Fundamental Principle of UPV Test

The pulse velocity measurement specified in all national standards in Table 2.24 above is based on the same principle (Komlos, 1996; Khan, 2002; Bungey et al., 2006; NIST, 2013; MS, 2013; CIA, 2015). As such, a pulse of longitudinal vibrations is generated by an electro-acoustical transmitting transducer with the assistance of an electrical pulse generator that is held in direct contact with the surface of the concrete under test. The pulse generated is transmitted into the concrete from the transmitting transducer (T) using a liquid coupling material. It undergoes multiple reflections on the boundaries of the different material phases, resulting in a complex system of stress waves within the concrete. The first waves, known as longitudinal waves that reach the receiving transducer (R) at a distance L from the transmitting transducer are converted into an electrical signal. The transit time T is measured electronically by the time measuring circuit with the assistance of an amplifier, and then sent to the Time Display Unit. The schematic diagram of the UPV test apparatus is shown in Figure 2.12 (ASTM, 2009).

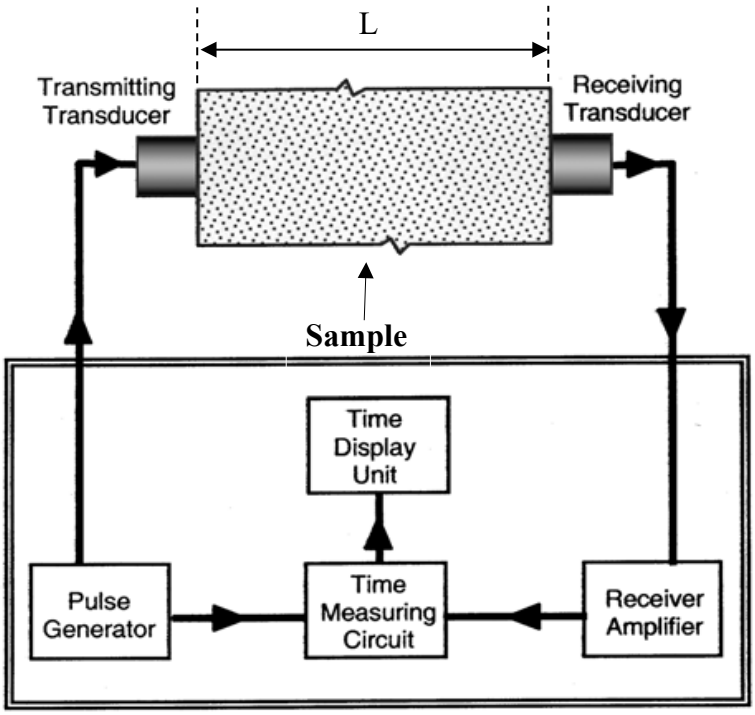


Figure 2.13: Schematic Diagram of UPV Test Apparatus

Most of the standards describe three possible arrangements for measuring pulse velocity as shown in Table 2.25 (MS, 2013). Among the measurement arrangements, the direct approach provides the greatest sensitivity and is therefore superior to the other arrangements (Khan, 2002; Malhotra & Carino, 2003). Direct transmission is defined as the propagation of ultrasonic stress waves along a straight-line path between the opposite surfaces of a specimen (Komlos, 1996). However, in the field of measurement, access to opposite surfaces of a component may not be readily available and tests may need to be conducted using indirect transmission. Indirect transmission is defined as the propagation of ultrasonic stress waves between points that are located on the same surface of the material (Kaouther, 2014). The pulse velocity measurement arrangements are given by Equation 2.11.

Table 2.25: Types of UPV Test Method Measurement Arrangements

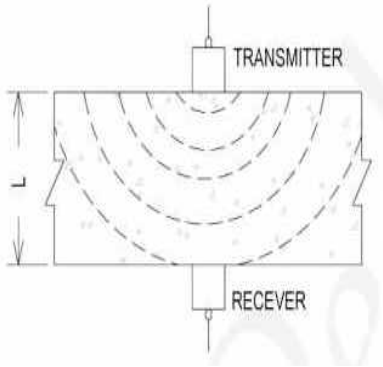
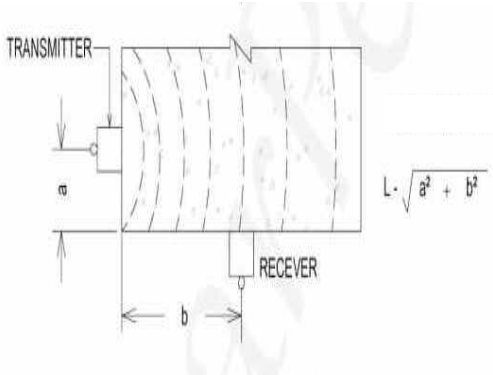
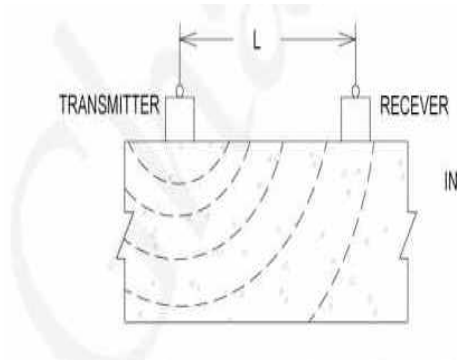
Description	Method (Diagram)	Remarks
Two transducers are placed in such a way that one is placed at one end and the other at the other end throughout the member.	Direct Method 	• Mostly applied on columns, beams, walls, or slabs of concrete structural members and cubes, cylinders, or prisms for laboratory specimens. • Most satisfactory accuracy of ± 1 %.
Two transducers are placed 90º each other at different surface of concrete.	Semi-Direct Method 	• Typically applied to the corners of concrete structural members • Some satisfactory accuracy of 1% to 2%.

Table 2.25 Continued

Two transducers are placed on the surface of concrete, and the receiver receives the pulse coming from the concrete molecules.	Indirect Method 	• Mostly applied on slabs of concrete structural members. • Some satisfactory accuracy of 1 to 2%.

$$V = \frac{L}{T}$$ Equation 2.11

Where

V is the longitudinal pulse velocity

L is the path length

T is the time taken by the pulse to traverse that length.

B. Applications and Limitations of UPV Test

In the last few decades, the application of UPV in civil engineering work has become a subject of interest in various countries due to the fact that UPV does not affect the appearance or performance of the analysed structures. Table 2.26 summarises the most valuable UPV applications for physical properties, workmanship and prediction or correlation assessments employed by researchers for concrete studies. Such, workmanship criteria are devoted to the quality of any discontinuity in cross section such as cracks, voids, imperfections or defects.

Table 2.26: Most Valuable UPV Applications Adopted by Researchers

Measurement criteria	Concrete Properties / parameter	Researchers
Concrete Physical Properties	Measurement of concrete homogeneity or uniformity	Arundas, 2016; Beushausen and Fernandez Luco, 2016
	Measurement of the compacity or density	Lorenzi et al., 2007; Panzera et al., 2011; Vidyarthi, 2014
	Measurement of layer thickness	Bungey et al., 2006
Workmanship	Diagnosis of defects, deterioration or heterogeneous regions includes cracking and honeycomb	Lorenzi et al., 2007; Kar, 2013; CIA, 2015
	Diagnosis, prognosis or quality control of concrete conditions	Saraswathy et al., 2003; Panzera et al., 2011; Ramana, 2016
Prediction / correlation	Strength estimation or correlation	CIA, 2015; Arooj and Yadav, 2017; Frappa et al., 2022
	Dynamic elastic modulus estimation	Kar, 2013; NIST, 2013
	Static elastic modulus estimation	Khan, 2002

Besides, the limitations of UPV measurement in concrete and required extra precaution actions during measurement are listed as follows;

1. Require experienced operator due to reading being relatively small only ranges from 3.5 to 4.8 km/s.

2. Proper surface preparation is required.

C. Factors Affecting UPV Test

Despite the fact that ultrasonic testing is a useful method that helps engineers determine the properties of concrete and for quality control monitoring purposes, the results can be influenced by several factors. Major factors affecting the reading of UPV test result are listed as follows;

1. Concrete properties affected by the density associated with the concrete ingredients.
2. Concrete environment exposure.
3. Presence of metal in concrete.
4. Presence of crack, void or honeycomb in concrete.

Pulse velocity increases due to concrete density improvement as the pozzolanic reaction progresses. In comparison to OPC, fly ash is more effective at reducing chloride-induced attack because of its long-term capacity to fill the meso capillary pores in concrete pore structures. In addition, pulse velocity is highly affected by concrete aggregate content and increases with the increase of aggregate content at similar concrete strength (Berriman et al., 2005). In such, crushed limestone has the highest pulse velocity followed by crushed granite, while rounded gravel has the lowest pulse velocity due to the higher void in concrete (Trtnik, 2009). Meanwhile, as density decreases, pulse velocity decreases with increasing water-cement ratio (Lorenzi et al., 2007). Figure 2.13 shows the effects of water-cement ratio on UPV results (Ye et al., 2004).

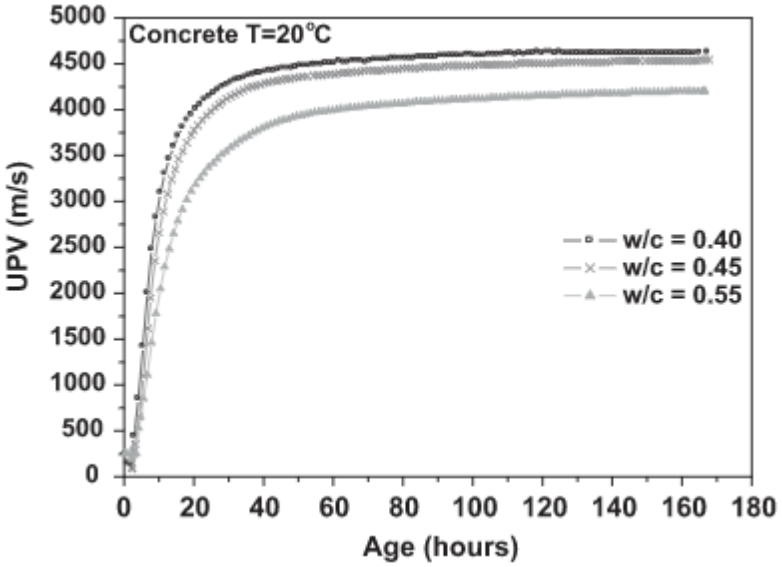


Figure 2.14: Effects of Water-cement Ratio on UPV Results

The moisture content of concrete can have a small but significant influence on pulse velocity (Khan, 2002). As such, the pulse velocity is decreased with an increase in moisture content contributed by a higher water-cement ratio (Panzera et al., 2011). Besides, pulse velocity is not affected by temperatures ranging from 10 to 30 °C. However, a correction should be made for temperatures outside this range as stated in Table 2.27 (Khan, 2002). Furthermore, the pulse velocity (time taken to travel) is lower for dry material than for wet material because cavities are filled with air in the dry state.

Besides, UPV test results affected by the presence of metal should be disqualified and repeated with the assistance of cover metre test apparatus. Meanwhile, UPV test results affected by the presence of cracks, voids or honeycomb in concrete are only useful for diagnosis, prognosis or quality control of concrete assessments.

Table 2.27: The Effect of Temperature on Pulse Transmission

Temperature (°C)	Correction to the Measured UPV (%)	
	Air-dried Concrete	Water-saturated Concrete
60	+5	+4
40	+2	+1.7
20	0	0
0	-0.5	-1
-4	-1.5	-7.5

D. Compliance Control Values Specification of UPV Test

Previous sections explicitly covered the UPV test method as a principle for evaluating quality related to density, homogeneity and uniformity associated with void state in the concrete. As such, voids have a significant effect on pulse velocity and indicate that concrete is more resistant to the deleterious substances of an aggressive environment (Estévez et. Al., 2020). Thus, the quality of concrete given by BS1881:1986 ranges from excellent to doubtful as a function of UPV as shown in Table 2.28 (BSI, 1986; Vidyarthi, 2014). Meanwhile, several studies agreed to downgrade quality scales for medium into doubtful or questionable and doubtful to poor, followed by very poor (Jones and Facaoanu, 1969; Costa and Marques, 2018; Estévez et al., 2020). In addition, the lower limit for good quality concrete varies from 4.1 to 4.7 km/s (Jones & Facaoanu, 1969).

Table 2.28: Concrete Quality as Determined by Several Standards and Research as a Function of UPV

BS1881:1986		**Researchers**	
UPV (km/s)	**Concrete Quality (QC)**	**Jones and Facaoanu, 1969; Costa and Marques, 2018**	
		UPV (km/s)	**Concrete Quality (QC)**
Above 4.5	Excellent	Above 4.5	Excellent
3.5 – 4.5	Good	3.5 – 4.5	Good
3 – 3.5	Medium	3 – 3.5	Doubtful / Questionable
Below 3	Doubtful	2-3	Poor
		Below 2	Very Poor

2.6.2 Absorption

Capillary absorption is clearly found to be a dominant transportation mode in providing access to chloride ions penetrating RC marine structures as explained in Sections 2.2.2 and 2.2.2(D). As a result, WA and VPV have emerged as critical test methods to consider in durability concrete monitoring indicators. The following sections explain the details of WA and VPV tests.

A. Fundamental Principle of WA Test

Water absorption is a measure of the amount of water that penetrates into a concrete surface-dried sample when immersed in the water for not less than 48 hours, and until two successive values of mass at intervals of 24 hours show an increase in mass of less than 0.5% of the larger value (ASTM, 2006). Equation 2.12 presents the calculation of the water

absorption as a fraction of the total mass of water absorbed by a surface-dried sample over the mass of an oven-dried sample in air and indicates it as a percentage (%).

$$\text{Water absorption} = (\frac{M_s - M_d}{M_d})100 \quad \text{Equation 2.12}$$

M_dWhere;

M_s= mass of the surface-dried sample (g) and
= mass of oven-dried sample (g)

B. Compliance Control Values Specifications of WA Test

There is no published precision data for WA test, and narrow performance classes can be set only with known precision data. However, there is an excellent relationship between WA and VPV of up to 99% as explained in Section 2.2.2 (D). In addition, WA has a great influence on VPV due to both tests being affected by the pore structures of the concrete microstructure. Thus, compliance quality control by this test can be compared based on the recommended VPV values in Section 2.6.2 (D).

C. Fundamental Principle of VPV Test

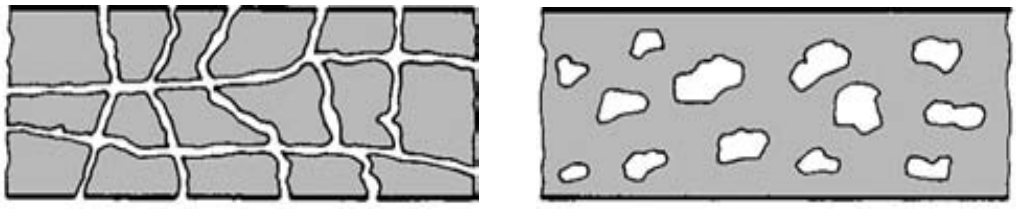
Porosity or void fraction is a measure of the void spaces governed by pores in a material and is a fraction of the volume of voids over the total volume as denoted by Equation 2.13 below.

$$\emptyset = \frac{Vv}{VT} \quad \text{Equation 2.13}$$

Where

V_V = void volume and V_T = total volume

Porous concrete is often permeable and vice versa. Permeable conditions are represented by Figure 2.15a as voids are jointed via interconnected capillary pores. While impermeable states occur due to pores not connected to each other and prevent water along with chloride ions from penetrating into deeper regions of concrete cover as shown in Figure 2.15b (McCurrich, 1987).



a: Permeable State b: Impermeable State

Figure 2.15: Porosity States

D. Compliance Control Values Specifications of VPV Test

In order to avoid chloride-induced attack on RC marine structures, several standards have been set at the maximum permissible value for VPV. The Cement & Concrete Association of New Zealand recommends a maximum permissible value for VPV in watertight concrete to be 13%. Meanwhile, VicRoads Australia's recommends VPV value should not be more than 12% (Phaedonos, 2008; CCAA, 2009). In addition, quality rating of VPV values depend on the specimen preparation condition and method of compaction as shown in Table 2.29 (CCAA, 2009).

Table 2.29: Quality Classification for Concrete Durability based on VPV Values

Durability Classification Indicator	Vibrated Cylinders (VPV %)	Rodded Cylinders (VPV %)	Cores (VPV %)
Excellent	<11	<12	<14
Good	11-13	12-14	14-16
Normal	13-14	14-15	16-17
Marginal	14-16	15-17	17-19
Bad	>16	>17	>19

E. Factors Affecting WA and VPV Tests

The performance of capillary absorption is mainly influenced by the interconnectivity of the different sizes of pore distribution as explained in detail in previous Section 2.2.2(C). Reduction of interconnected capillary pores has been attributed to the lower total porosity of concrete, which gives lower absorption (Hilsdorf & Kropp, 1995). Meanwhile, research on the impact of cement binder on concrete water absorption indicates that absorption is influenced by the water-cement ratio and the amount of paste in the matrix. In which, decreasing the water-cement ratio makes the concrete denser as it makes it less porous, resulting in lower absorption (Kolias & Georgiou 2005). Furthermore, the porosity of concrete is largely influenced by free water content. Therefore, increasing the water-cement ratio amplifies the cement paste and makes it less porous, making the concrete more durable (AECB, 1986).

Besides, moist-cured samples show lower absorption rates compared to air-cured concrete samples (Kelham, 1988). Furthermore, WA test is influenced by the duration of curing. Thus, water absorption decreases steadily with an early cure duration of up to 7 days

before remaining slightly constant as the curing period approaches 28 days (Dhir et al., 1987). Moreover, a study of SCM's influence on WA test finds that curing for more than 3 days reduces absorption rates for concrete made with fly ash, with only a small effect recorded for OPC (Kelham, 1988).

2.7 Optimization of Concrete Durability Properties using Taguchi's Approach

Recently, the use of the Taguchi approach in conjunction with analysis of variance (ANOVA) in concrete technology has become increasingly popular. This approach offers effective and appropriate designs in determining optimised concrete products performance and a reliable quality monitoring system with minimal test specimens under Design of Experiments (DOE). A limited study has shown that this technique works well on optimising SCM concrete mixtures. Besides, it shows appropriate potential for integrating with PBDS applications and concrete specification development. The following sections explain about the philosophy, applications and DOE by Taguchi's approach.

2.7.1 Taguchi's Philosophy

The complete technology and approaches that handle quality concerns in Taguchi's philosophy are based on three main principles as summarised in Table 2.30 (Roy, 2010).

Table 2.30: Taguchi's Philosophy Principles

No.	Description
1	Quality should be designed into the product and not inspected into it.
2	The greatest way to minimise variation from a target is that products should be developed to be as resistant to uncontrollable environmental factors as possible.
3	The cost of quality should be measured as a function of deviation from the standard, and the losses should be measured systemically.

Suit to the Taguchi's philosophy principles and adopted to local concrete construction industry, the best strategy to improve concrete quality is to design and build-in preventative actions from the very beginning of design stage to the service lifespan period. Followed by PBDS indicators development was carried out based on the most dominant transport mechanism environment to trigger the most suitable and established durability test methods. Meanwhile, fly ash optimisation and NDT periodic assessment should be incorporated throughout the project as QA/QC monitoring system purpose for long-term cost-effective performances. Merging Taguchi's approach in PBDS before desired concrete specifications can be implemented to assure value for money for clients, extend service lifespan and most importantly, cause safety guarantee to public users as per the famous adage "prevention is better than cure".

2.7.2 Taguchi's Approach Application

Initially, optimise performance and make a robust design with the use of DOE, which was introduced by R.A. Fisher in England for agricultural work in the 1920's (Fisher, 1951). Furthermore, Dr. Genechi Taguchi carried out significant research on DOE techniques at the Electronic Control Laboratory (Japan) in the late 1940's. In the early 1980's, a standardised version of DOE was established and was known as Taguchi's approach or Taguchi's Method. Simultaneously, this method was introduced in the USA for manufacturing processes by focusing on optimising performance and making robust design through the use of the statistical technique. Since the revised book of "A Primer on the Taguchi Method" was released in 2010 (Roy, 2010), it has become one of the most effective quality-building tools assessment utilised by engineers worldwide in all sorts of industrial operations including in SCM concrete optimisation.

Currently, concrete technology is adopting Taguchi's approach for the robust design with minimal test specimens. Since 2011, a limited study has been undertaken throughout the world employing Taguchi's approach with ANOVA analysis to determine the optimal fly ash mixture and most important durability indicators as described in Table 2.31.

Table 2.31: List of Fly Ash Concrete Studies using Taguchi's Approach with ANOVA Analysis (2011-2022)

Year	Description
2022	Taguchi's approach with ANOVA analysis was used to determine the optimum design of fly ash light weight concrete. Reported that pre-soaked with 14% of water, 80:20 proportion of Coarse, finer fly ash and 30 second compaction vibration provides optimum results (Dhemla et al., 2022).
2019	Taguchi's approach was used to determine the impact of temperature on residual properties of self-compacting based hybrid fibre reinforced concrete (HyFRC) with fly ash and colloidal nano silica. Reported that all the mixes of HyFRC passed the self-compacting properties specifications requirements up to a temperature of 600 °C; sustainable residual strengths were available in HyFRC with fly ash and Colloida Nano Silica (CNS) (Mahapatra & Barai, 2019).
2018	Taguchi's approach with ANOVA analysis has used to determine optimize durability properties of concrete containing fly ash. Reported that the optimal mix design with fly ash improved concrete quality (Uysal et al., 2017).
2017	Taguchi's approach with ANOVA analysis was used to investigate the effect of various parameters on the strength and absorption properties of fly ash-based geopolymer concrete. Reported that the optimum mix design by fly ash enhanced concrete parameters tested was 20% cement replacement (Mehta et al., 2017).

2014	Taguchi's approach with ANOVA analysis was used to determine crack properties and compressive strength of structural lightweight concrete, including fly ash exposed to high temperatures. The ideal parameters for structural lightweight concrete compressive strength and fracture characteristics were discovered to be 400 °C, 500 kg/m^3 cement dosage, and 20% fly ash (Tanyıldızı, 2014).
2012	Taguchi's approach with ANOVA analysis was used to determine Influence of various parameters on mechanical and durability properties of fly ash based geopolymer concrete. Findings show that the mechanical properties of the geopolymer concrete mixtures are competitive compared to OPC concrete and that they are more durable in a marine environment (Olivia & Nikraz., 2012).

According to the research listed in the table above, no study has been undertaken utilising Taguchi's approach with ANOVA analysis to determine the optimal durability properties of concrete containing local fly ash tested on various grades from a local ready-mixed concrete supplier.

2.7.3 Standardised Design of Experiments (DOE)

The technique of defining and examining all conceivable conditions in a multi-factor experiment is known as "design of experiments" (DOE) also known as factorial design. Chronological steps with description of 5-step DOE by Taguchi's approach according to the standardized version of DOE is shown in Table 2.32 (Roy, 2010).

Table 2.32: Chronological Steps with Description of a 5-step DOE by Taguchi's Approach

Step	Description
1	**Definition of quality:** Quality defined as consistency of performance and considered as a primary attribute should be measurable, as long as performance is close to the target with the least variation. The following two-step optimisation strategy is used to increase quality; a. Find the factor-level combination that reduces performance variability. b. Adjust the factor levels that bring performance closer to the target.
2	**Standardized DOE:** Orthogonal arrays (OAs) are used to implement the smallest fractional factorials as well as the most typical experiment designs.
3	**Robust design strategy:** Incorporates a formal method for including noise factors in the experiment layout by allowing the use of smaller-sized experiments to study the impacts of a larger number of noise factors. This results in better performance with the mean being nearer to the target and less variance around the mean.
4	**Loss function:** A mathematical formula associated with the loss function notion allows for an easy way to measure improvements in monetary units. in which monetary units reflect production costs, pollution, safety, and/or service duration.
5	**Signal-to-noise (S/N) analysis:** The use of S/N ratios instead of outcomes for analysing multiple-sample test results simplifies the interpretation of DOE data. Furthermore, the logarithmic transformation of the results in terms of S/N ratios enables the prediction of performance improvement in the analysis.

The selection of control factors (variables) is the most crucial stage in DOE. Thus, as many variables as possible should be included to determine non-significant variables at the earliest opportunity (Nian et al., 1999; Bayat & Eslami, 2022). Furthermore, a systematic and efficient work plan (flow chart) is necessary to investigate the optimum conditions that influence the experimental results as shown in Figure 2.15 (Ross, 1996). As such, the initial

nineteen steps of Taguchi's approach have been simplified into thirteen operational steps for easier achieving of design optimisation as summarised below (Tanyildizi & Sahin, 2015);

1. Determination of the problem.
2. Determination of the performance characteristics and the experimental system.
3. Determination of the variables affecting the performance characteristics of experimental.
4. Doing the screening design.
5. Determination of the number of the levels and values of the controllable and uncontrollable variables.
6. Determination of the interactions of experimental parameters.
7. Selection of appropriate OAs and appointing the variables to the suitable columns.
8. Determination of the loss functions for experimental work.
9. Recording of the experimental results.
10. Determination of the optimum value of the controllable variables.
11. Tests of the results.
12. Doing tolerance design.
13. Doing evaluation and implementation.

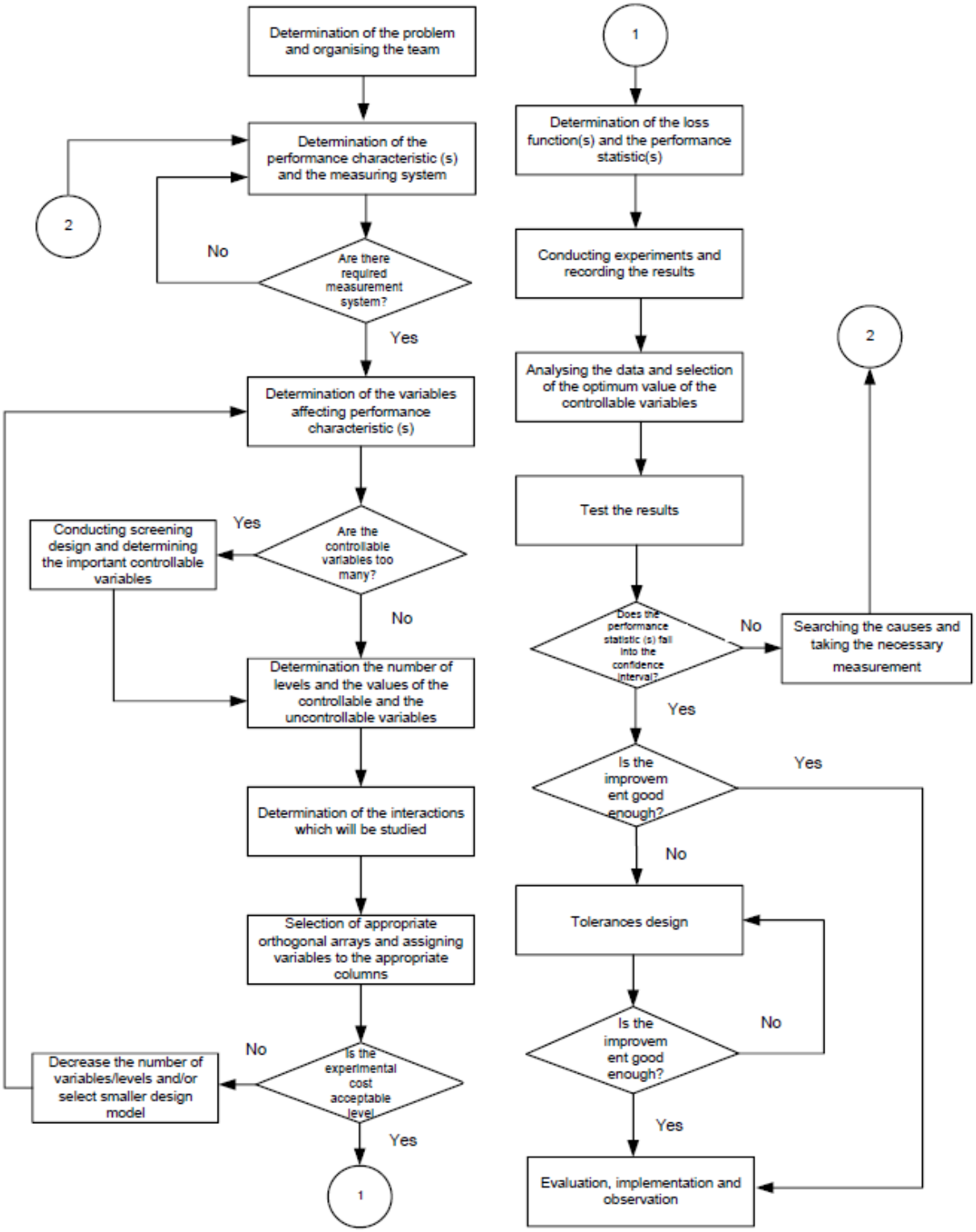


Figure 2.16: Flowchart of the Systematic and Efficient Work Plan to the Application of Taguchi's Approach

2.8 Summary of Research Gaps

The following is a summary of research gaps based on a literature review conducted in accordance with the objectives of the study;

1) To determine the perceptions of construction industry players on chloride-induced corrosion RC structures in Sarawak via survey questionnaires.

Section 2.2: The determination of the most severely corrosive environmental exposure (absorption) provides a clear scenario for the selection of PBDS indicators test methods for accurate corrosion treatment. Presently, most of the chloride-induced corrosion ingress test methods are based on diffusion, which obviously does not represent the local severe chloride-induced environmental exposure.

Sections 2.4 & 2.7: Control factors (variables) are extracted as much as possible from SSBW or SSRW and Eurocodes standards before perception of construction industry on chloride-induced corrosion assessed suit to local condition or practice as advocated by Eurocode 2. Currently, no study has been undertaken combining Taguchi's Approach with a survey questionnaires approach and field investigation to determine accurate variables contributing to the local chloride-induced environment problem.

2) To optimisation of ready-mixed concrete partially replaced of cement with Class-F fly ash.

Sections 2.2 & 2.3: Most of the capillary pore structures that contribute to the concrete's durability degradation are greatly improved by fly ash worldwide. Taking advantage of Sarawak holds nearly 70% of Malaysia’s coal reserves and result of no less than 2000 tonnes

of fly ash yearly production. Presently, there is no study conducted using local fly ash tested on local famous grade concretes.

Section 2.4: The allowable proportion of fly ash in the concrete mixture was only introduced in 2014, and it has not remained consistent across subsequent SSBWs. Presently, usage of fly ash as blended cement in the construction industry is still not seen due to unclear local guidelines and the lack of a study to determine the significant effectiveness of local fly ash tested on local ready-mixed concrete.

3) To correlate performance NDT guidelines between compressive strength (Cu) and ultrasonic pulse velocity (UPV).

Sections 2.4 to 2.6: SSBW's quality control assessment for concrete works clearly relies on prescriptive specification without incorporating any NDT techniques at any construction phase. Presently, no study has been undertaken by UPV correlation with Cu on famous grade concretes supplied by the dominant local ready-mixed concrete supplier in Sarawak for QA/QC monitoring purposes throughout the construction phases.

4) To formulate PBDS indicators model based on water absorption (WA), volume of permeable voids (VPV) and ultrasonic pulse velocity (UPV) tests.

Sections 2.2 & 2.6: Determination of the most dominant transport mechanism (absorption) based on local severely corrosive environmental exposure can lead to effective and efficient monitoring at low cost measurement, high level precession and QRDC indicators monitoring. Presently, most chloride-induced corrosion ingress test methods are based on diffusion, which is very expensive, lengthy in time, not user-friendly and does not meet the real local practices

CHAPTER 3

RESEARCH METHODOLOGY

3.1 Introduction

The chapter describes the research methodology, standard test methods, established material specifications and well-known guidelines or approaches for concrete performance optimisation. The discussion covers conceptual framework study, data sources, survey questionnaires, field investigation, ready-mixed concrete design mixtures, raw materials, standard test methods, Taguchi's Approach implementation and data analysis.

3.2 Conceptual Framework Study (CFS)

A total of thirteen operational steps involved in Conceptual Framework Study (CFS) is adapted from Taguchi's approach as summarised in Chapter 2 (Section 2.7.3) with minimal amendments by intro ducing survey questionnaires and field investigation approaches. All the explanations and headings in this chapter were concurrently applied to all objectives except for objective 1, which mainly used a survey questionnaires form as method of real data collection to serves objectives 2, 3, and 4 as shown in Table 3.8. Comprehensive explanation for methodology (inclusive data sources; materials and methods), results and discussion, findings and Taguchi's assessments were detailed out in chapters 4, 5, 6, and 7 specifically for objectives 1, 2, 3, and 4 respectively. Overall, a simplified research flow chart throughout the objectives study is shown in Figure 3.1.

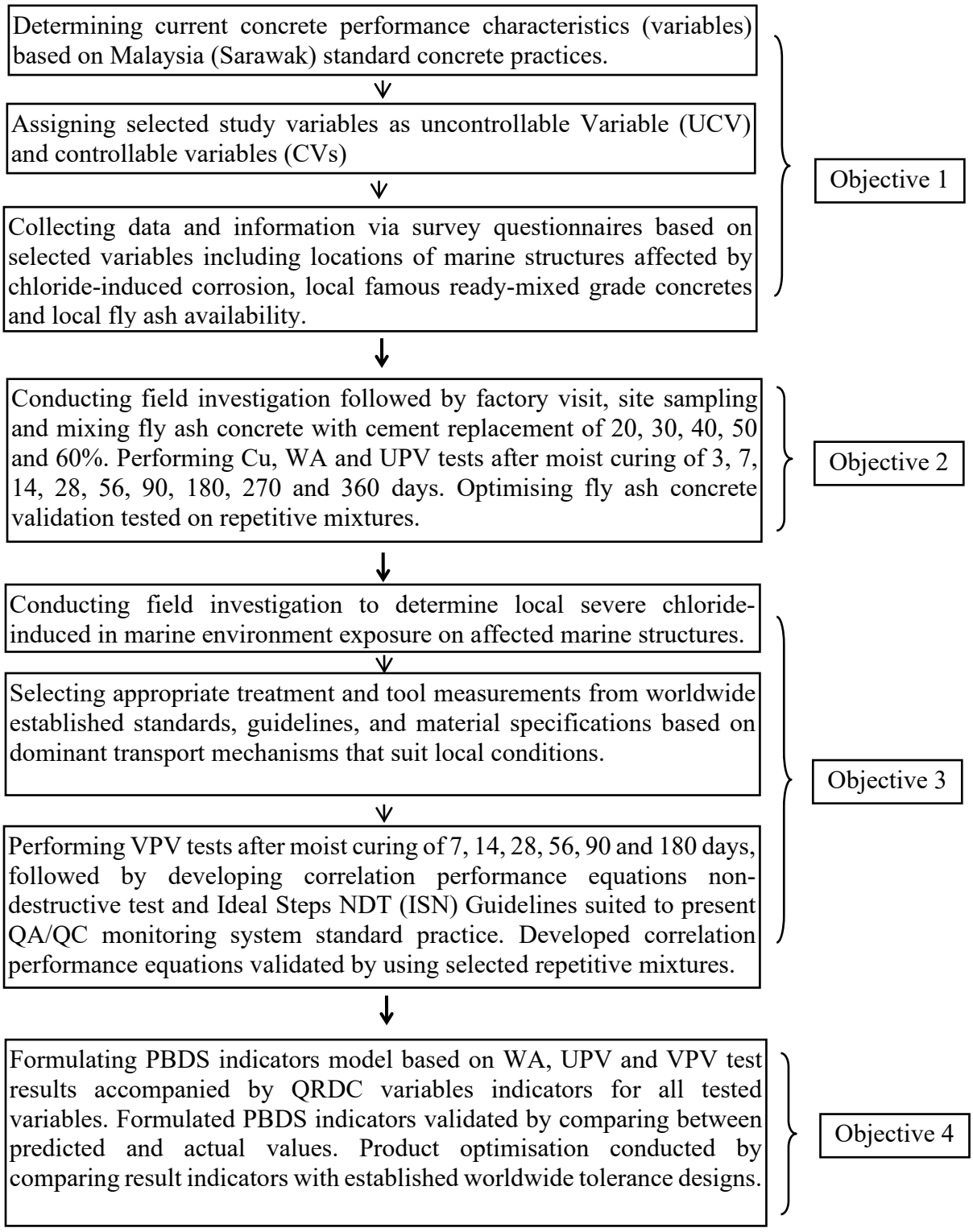


Figure 3.1: Simplified Flowchart

3.3 Data Sources

The required data in this study consist of primary, secondary, and tertiary data. Survey Questionnaires were used to collect primary data, which was then followed by a field investigation into the present condition. Meanwhile, secondary and tertiary data were obtained from several government organisations (authorities), non-governmental organizations and previous studies. All these data summaries are in Table 3.1.

Table 3.1: Data Sources

No.	Data or information Description	Data Category	Sources	Document Attachments
1	List of construction industry players with full addresses	Secondary	SSM and site visits	Letter to SSM (Appendix B)
2	List of gain-profit businesses for ready-mixed concrete suppliers in Sarawak		SSM	
3	Chloride-induced corrosion awareness and treatments	Primary	Survey questionnaires	Letter for survey questionnaires (Appendix C)
4	Local famous ready-mixed grade concretes usage			
5	SCM for chloride-induced corrosion treatment		Survey questionnaires and field investigation	
6	Structures affected by chloride-induced corrosion			

Table 3.1 Continued

7	Structures affected by severe chloride-induced corrosion environment (According to the survey questionnaire findings)	Secondary	JKR, DID & DBKU	Letters: • Request letter (Appendix D) • JKR (Appendix E) • DID (Appendix F) • DBKU (Appendix G)
8	Sejingkat's fly ash properties	Secondary	Fly ash supplier	Test results (Appendix H)
9	Raw material properties (other than fly ash)	Secondary	Ready-mixed concrete supplier	Letter (Appendix I) and test results (Appendix J and K)
10	SSBW and SSRW documents	Tertiary	Local consultant firms	Letter (Appendix L)
11	Malaysia's material specification documents			
12	Malaysia's standard test method documents	Tertiary	SIRIM Berhad	-
13	Various concrete standards, guidelines, specifications and studies focusing on developed countries including EN, USA, Australia, New Zealand, China, Japan and India with a high population	Secondary and Tertiary	Online sources	-

3.3.1 Desk Study

The desk study performed in this study was divided into two work activities, namely "brainstorming issues and treatments" and "research gaps resolutions". Brainstorming was conducted prior to the finalisation of the survey questionnaires form. The main objectives of the brainstorming activity were to explore variables based on problems and any available precautions or treatments provided by present standard concrete practices in Malaysia (Sarawak). The data and information required for this activity included items No. 1 till 2 and 10 till 13 as stated in Table 3.1. This data and information gave a lead on selecting useful questions in determining the most powerful variables and the most reliable tool measurements. Besides research gaps resolutions ensured the selected tool measurements were the most cost-effective and reliable for obtaining optimised performance throughout product development. The data and information required in this stage are all items in Table 3.1 except for items No. 1 and 2.

3.3.2 Survey Questionnaires

The selection of questions formulated in a survey questionnaires form was based on the desk study above as summarised in Table 3.2 with question numbers indicated accordingly. The data and information required for this stage were exactly the same as per the brainstorming issue stage.

Table 3.2: Variables Mapping to Question Numbers Accordingly

Variable Designation	Variable Description	Question Nos
Uncontrollable Variable		
UCV	Severe chloride-induced corrosion in marine environment exposure	Q14
Controllable Variable		
CV1	Chloride-induced corrosion awareness and treatments	Q6 till Q12 and Q15
CV2	Famous ready-mixed grade concretes usages	Q2, Q4 and Q5
CV3	SCM for chloride-induced corrosion treatment	Q13
CV4	Durability Performance and NDT measurements	Not assessed (Conducted by literature review of worldwide standard concrete documents)

The main objectives of the survey questionnaires approach conducted in this study were to determine the roots of the problems, important control variables, possible low-cost local treatment and provide an effective platform for data modelling. Required data and information are summarised as follows:

1. Level of seriousness for chloride-induced corrosion issue

2. On-site treatment implementation according to design guidelines

3. Famous ready-mixed grade concretes usages

4. Dominant ready-mixed concrete supplier

5. SCM availability and production

6. List of RC structures affected by chloride-induced corrosion

3.3.3 Field Investigation

Field investigation was conducted based on findings provided by survey questionnaires related to variable designation of UCV and CV3. The data and information required for this activity include items No. 5 till 9 as stated in Table 3.1. UCV was assigned to severe chloride-induced corrosion in marine environment exposure. This was the most useful for local verification of the most dominant transport mechanism affecting RC marine structures before selecting durability standard test methods.

3.4 Ready-mixed Concrete

Fresh concrete was provided by the dominant local ready-mixed concrete supplier in Sarawak who was identified based on the highest gain in profits from income data provided by SSM. Grade concretes supplied by the concrete supplier mentioned ranged from G25 to G50. However, the specific grade of concrete of ready-mixed concrete was not allowed to be revealed in this report as requested by the concrete supplier. Thus, the specific grade designations were denoted as M1 to M6 accordingly as shown in Table 3.3.

Table 3.3: Concrete Ready-mixed Designs

Grade Designations	Cement (kg/m^3)	Water (kg/m^3)	Water / cement ratio	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	M150 (litre)	M40RA (litre)	Slump (mm)
M1	320	175	0.55	809	1020	1.920	0.960	125
M2	350	176	0.50	721	1081	2.624	1.050	100
M3	375	170	0.45	756	1040	3.750	1.688	115
M4	400	160	0.40	660	1168	4.000	1.200	120
M5	422	148	0.35	621	1284	3.798	1.266	105
M6	500	165	0.33	621	1085	6.000	-	125

To ensure that the comparisons and optimisation of using fly ash analysis were valid for famous ready-mixed grade concretes, three control mixtures (M1, M3 and M5) for ready-mixed designs were adopted for cement replacement mixtures with target slump to be maintained ranging from 75mm to 125mm in accordance with manufacturing supplier conduct. The cement content of each grade of concrete was replaced with various fly ash percentages of 20, 30, 40, 50, and 60. All fly ash concrete mixtures were prepared under controlled environmental conditions in a laboratory. Table 3.4 provides a detailed breakdown of the concrete ingredients for the fly ash concrete optimisation testing.

Table 3.4: Modified Concrete Ready-mixed Designs Using Fly Ash Cement Replacement Method

Grade Designations	Fly Ash (kg/m^3)	Cement (kg/m^3)	Water (kg/m^3)	Water / cement ratio	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Slump (mm)
M1	0	320	175	0.55	809	1020	125
M1FA20	64	256	165	0.52			110
M1FA30	96	224	160	0.50			95
M1FA40	128	192	160	0.50			100
M1FA50	160	160	155	0.48			100
M1FA60	192	128	155	0.48			110
M3	0	375	170	0.45	756	1040	115
M3FA20	75	300	145	0.39			115
M3FA30	113	262	145	0.39			125
M3FA40	150	225	135	0.36			110
M3FA50	188	187	110	0.29			115
M3FA60	225	150	110	0.29			125
M5	0	422	148	0.35	621	1284	105
M5FA20	84	338	148	0.35			120
M5FA30	127	295	140	0.33			100
M5FA40	169	253	115	0.27			110
M5FA50	211	211	100	0.24			100
M5FA60	253	169	100	0.24			110

3.5 Raw Material

The raw materials used in the concrete mixtures were fully supplied by the identified ready-mixed concrete supplier (Appendix I), except for OPC and fly ash for mixture laboratory usages. OPC was obtained under similar manufacturing conditions for the batching plant usage. Meanwhile, fly ash was obtained from the sole fly ash supplier in Sarawak. The following sections explain in detail sources of material and properties of the ingredients used in this study.

3.5.1 Cement

The Ordinary Portland Cement (OPC) of CEM I 42.5 R Portland Cement in accordance with MS EN 197-1:2014 (MS, 2014a) was used in this study. CMS Portland Cement is produced by Sarawak's main cement supplier, namely CMS Cement Industries Sdn. Bhd., for use in pre-cast, ready-mixed, and other concrete works. The chemical compositions of CEM I 42.5 R OPC are shown in Table 3.5 (Sutan et al., 2014) while cement packaging is shown in Figure 3.2.

Table 3.5: Chemical Composition of OPC (CEM I 42.5)

Chemical properties	**OPC (CEM I 42.5), (%)**
Silicon dioxide (SiO_2)	22.8
Aluminium oxide (Al_2O_3)	5.8
Iron oxide (Fe_2O_3)	2.4
Calcium oxide, (CaO)	63.0
Magnesium oxide (MgO)	2.0
Sulphur trioxide (SO_3)	2.8

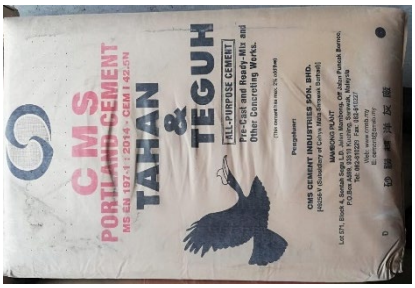


Figure 3.2: Packaging of OPC of CEM I 42.5 R

3.5.2 Fly Ash

Type Class-F fly ash was collected from a power plant owned by Sejingkat Power Corporation Sdn. Bhd., which is located in Pending, Sarawak. This power plant generates electric power by consuming coal up to 2000 tonnes annually as explained in detail in Section 2.3.2. Currently, Sejingkat's fly ash is being supplied by Gobel Industry Sdn. Bhd. for limited usages with chemical composition as summarised in Table 2.6 in accordance with MS EN450-1:2014 (MS, 2014b). Packaging of Sejingkat's fly ash is shown in Figure 3.3, while a test report of chemical composition is provided by the supplier as shown in Appendix H.



Figure 3.3: Packaging of Fly Ash (35 kg per Bag)

3.5.3 Fine Aggregate

Sadong's river sand with a specific gravity of 2.61 and water absorption of 0.69% tested as per BS812 was collected from the batching plant for use as fine aggregate. The gradation of the sand was determined by sieve analysis as per MS 30 and was found to fall under zone 2 with a silt content of 0.34%. Sample of fine aggregate is shown in Figure 3.4 and full test reports are attached in Appendix J.



Figure 3.4: Sample of Fine Aggregate

3.5.4 Coarse Aggregate

Penkuari's coarse aggregate of 20 mm microtonalite stone production at 9.5 Mile Kuching-Serian Road with a specific gravity of 2.63, water absorption of 1.30% and silt of 0.33% were collected from the batching plant to be used as coarse aggregate. Sample of coarse aggregates is shown in Figure 3.5. The gradation of the coarse aggregate was found to fall within the limit and full test reports are shown in Appendix K.



Figure 3.5: Sample of Coarse Aggregates

3.5.5 Admixtures

Both types of mixing concretes at the batching plant and laboratory used two types of admixtures and were fully supplied by a ready-mixed concrete supplier. For both M150 and M40RA, dosages for laboratory concrete mixtures remained unchanged as per control mixtures. The Mighty 150 (M150) is a synthetic oligomer-based additive which performs extremely well with various types of Portland cement to improve the strength of concrete while reducing water usage. Meanwhile, Mighty 40RA (M40RA) is a High-Performance Retarding Plasticizer, produced through chemical processes from Ligno Sulfate Formaldehyde sulfactant. It is a retarding type of water reducing concrete admixture or a developed retarding base concrete admixture of medium strength with good slump retention. Figure 3.6 shows M150 and M40RA admixtures.



Figure 3.6: M150 and M40RA Admixtures

3.6 Preparation of Concrete Specimens

The concrete specimens to be examined were obtained from a truck concrete mixer at a batching plant and cast in the laboratory by using a portable bowl concrete mixer machine. Concrete cubes from the batching plant consisted of the famous ready-mixed grade

concretes around the state. Meanwhile, prepared fly ash concrete specimens with various replacement levels to get the optimum performance were conducted by using the cement replacement method. Total concrete cube specimens according to tested parameters, excluding specimens for preliminary result identification of durability performances are summarised in Table 3.6.

Table 3.6: Total Concrete Cubes Specimens

Testing	**Quantity of Concrete Cubes**	
	150mm Cube	**100mm Cube**
Batching Plant (Including control mixture)		
Cu and UPV	200	-
WA and VPV	-	45
Laboratory		
Cu and UPV	400	-
WA and VPV	-	200

Mixing of all the materials for fly ash concrete was done in the laboratory. Fine aggregates with half the volume of the coarse aggregate were fed into a concrete bowl mixer machine and mixed for 1 minute, then fed with all the remaining coarse aggregate and mixed again for 1 minute. followed by adding cement together with fly ash and mixing for 1 minute. Finally, add water with admixtures and allowed it to continue mixing for about 3 to 4 minutes. Figure 3.7 shows the raw materials, machinery and samples of fly ash concrete mixed at the laboratory.

Prior to concrete moulding, slump tests was performed on site and in the laboratory. Slump tests were conducted by filling the cone mould in three equal layers, with each layer

been approximately one third of the height of the cone mould. Each layer was compacted in turn 25 times with the rounded end of the steel rod and each rod passed through one layer into the layer beneath before measuring the height of slump with a measuring tape or ruler from the highest point of the concrete to the underside of the trowel. Figure 3.8 shows the apparatus and various samples of slump tests conducted at the site and laboratory.



Figure 3.7: Raw Materials, Machineries and Samples of Mixing Fly Ash Concrete Conducted

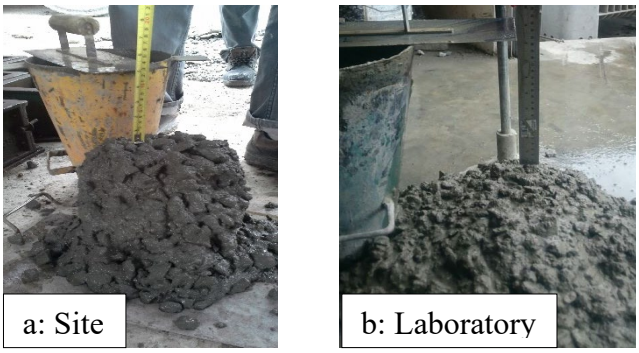


Figure 3.8: Apparatus and Various Samples of Slump Tests Conducted at Site and Laboratory

Immediately after the slump test, the fresh concrete was cast into the prepared 150 mm and 100 mm cube moulds at three layers and two layers by hand compactions respectively. The compaction of the concrete specimens was performed at 35 and 25 manual strokes per layer using a 25 mm square tamping rod for 150 mm and 100 mm cubes respectively. After casting, all the moulded specimens were covered with plastic sheets as per the manufacturing supplier's conduct, then left at the site and laboratory for 24 hours before been placed in a water curing tank at the laboratory. Figure 3.9 shows the preparation of concrete specimens before curing in water tanks.

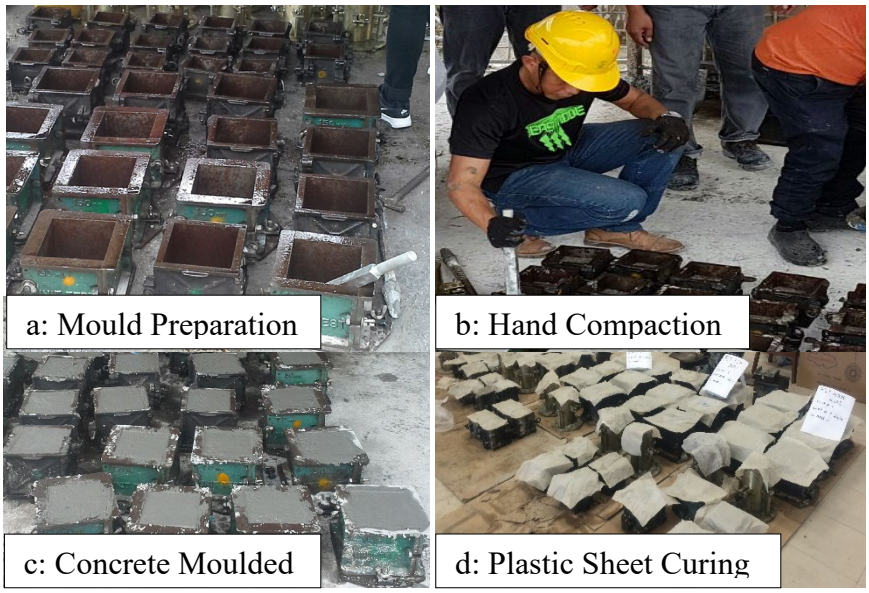
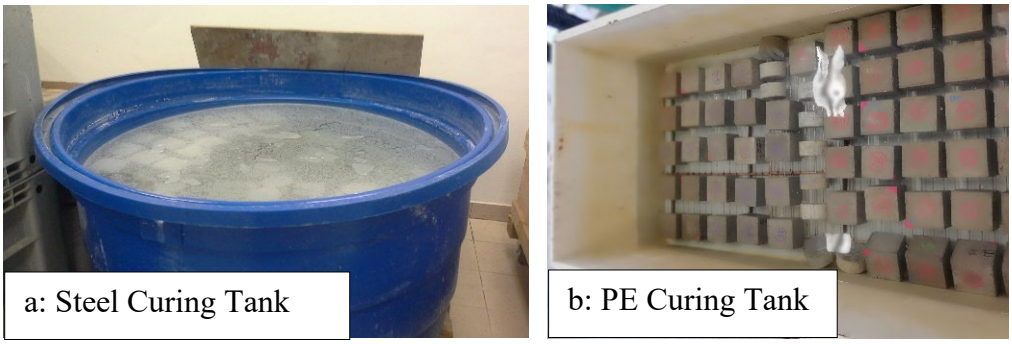


Figure 3.9: Preparation of Concrete Specimens

Finally, all specimens were demoulded a day after sampling and saturated by immersion in a water curing tank in the laboratory as shown in Figure 3.10, then removed from the water after the required moist curing periods for testing.



a: Steel Curing Tank

b: PE Curing Tank

Figure 3.10: Apparatus and Sample of Curing Specimens for Test Conducted

3.7 Testing Procedures

The concrete tests executed throughout the study included Slump, Compressive strength (Cu), Ultrasonic pulse velocity (UPV), water absorption (WA) and Volume of permeable voids (VPV) tests. Table 3.7 shows a list of all concrete tests according to standard test method reference. The testing forms for UPV and WA & VPV were developed based on MS EN 12504 and ASTM C642 respectively.

Table 3.7: List of Concrete Testing According to Standard Test Method Reference

Concrete Test	Standard Test Method
Slump	MS 26-1-2 (MS, 2009)
Compressive strength (Cu)	MS EN 12390-3 (MS, 2012)
Ultrasonic pulse velocity (UPV)	MS EN 12504-4 (MS, 2013)
Water absorption (WA) and Volume of permeable voids (VPV)	ASTM C642 (ASTM, 2006)

3.7.1 Slump

In order to suit a target slump ranging from 75mm to 125mm as per the manufacturing supplier's conduct, trial mixes for each mixture were conducted by maintaining all concrete ingredients except for water content. As such, water content was reduced as fly ash percentages increased accordingly. The workability of all fresh concrete at the batching plant and laboratory was measured immediately in accordance with MS 26-1-2, after mixing in a slump test.

3.7.2 Compressive Strength

The compressive load test of cubes of 150 mm concrete specimens was measured after 3, 7, 14, 28, 56, 90 and 180 days of moist curing for fly ash concrete in accordance with MS EN 12390-3. Meanwhile, moist curing was extended to 270 and 360 days for cubes made in batching plants. Both specimens from the batching plant and laboratory were tested by using an analogue compressive strength test machine with an ultimate capacity of 2000 kN in accordance with MS EN 12390-4 and as manufacturing supplier conduct. Each test cube was exposed to a force at a loading rate of 6.89 kN/s until failure occurred. For each day's compression tests, three cubes were left in the laboratory to allow drying at room temperature for 24 hours. Prior to testing, each cube was weighed and measured for the dimensions before UPV test took place, followed by a compressive test. The results of the three cubes' compressive load were recorded in Cu test form. Then, dividing the maximum load applied by the cross-sectional area of the specimen, the compressive strength value was calculated. Figure 3.11 shows machineries and compressive load test conducted.





a: Cu Test Machine b: Specimen Under Testing c: Specimen After Testing

Figure 3.11: Machineries Compressive Load Test Conducted

3.7.3 UPV

The velocity of the propagation of ultrasound pulses of 150mm cubes concrete was measured after 7, 14, 28, 56, 90 and 180 days of moist curing. Both specimens from the batching plant and the laboratory were tested by portable ultrasonic non-destructive digital indicator tester in accordance with MS EN 12504-4 using the direct transmission method. The main kit comprised of a Time Display Unit with a precision of 0.1 s, a Calibration Bar, two 54kHz transducers, transducer cables, and a calibration bar. The time (T) taken by a pulse to traverse a specimen of length (L) is known as transit time. The pulse velocity (V) is calculated by dividing the length of the specimen (L) by the average transit time (T) as shown in Equation 2.11. The average value of three specimens is considered as the UPV value of a particular mixture of the tested concrete specimen at selected age. Figure 3.12 shows the apparatus and UPV test conducted at the laboratory.

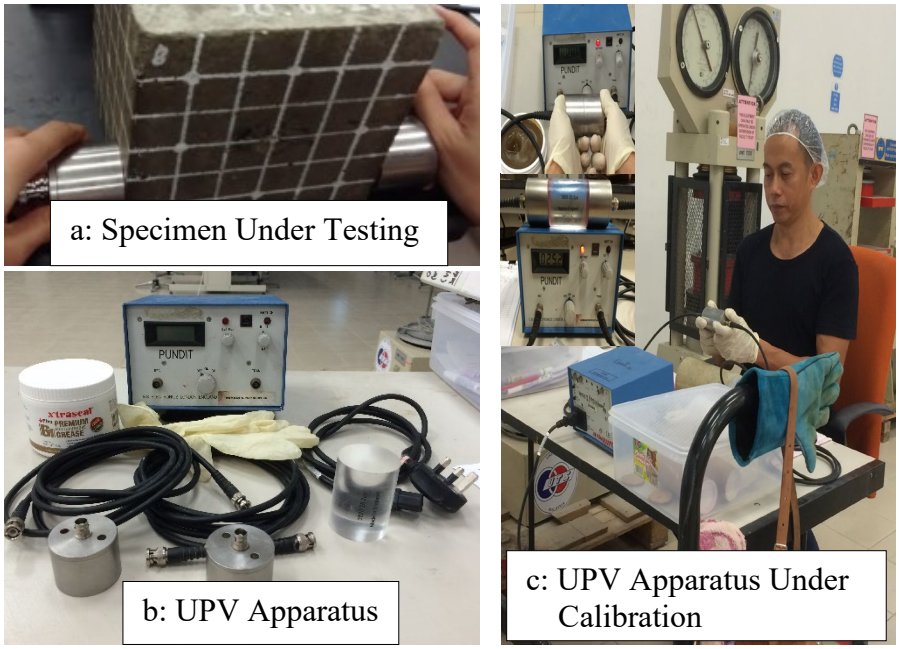


Figure 3.12: Apparatus and UPV Test Conducted

3.7.4 WA and VPV

The WA and VPV of 100mm cubes concrete specimens were measured after 7, 14, 28, 56, 90 and 180 days of moist curing for all concrete specimens. The WA and VPV determinations were carried out according to ASTM C642. The WA and VPV results were calculated based on Equation 2.12 and Equation 2.13. Figure 3.13 shows machineries, apparatus and VPV tests conducted at the laboratory.

3.8 Taguchi's Approach Implementation

Table 3.8 shows the summary of thirteen operational steps work programme after minimal amendment to suit local standard concrete practice and availability of determined important variables. The implementation of steps No. 3 till 6 on the flow chart from Figure 2.15 was conducted by using survey questionnaires and field investigation approaches. Meanwhile, Steps No. 7 till 10 were assigned for data operational activities. Followed by

Steps No. 11 till 13 were assigned for operational performance optimisation activities. Based on Table 3.8, Objective 1 was bound to operational Steps No. 1 till 9. While Objectives 2, 3, and 4 were implemented concurrently. Throughout, operational steps from No. 4 till 13 were subjected to the availability of established standard test methods identified in Section 2.5 and QRDC indicators provided in Section 2.6.



Figure 3.13: Machineries, Apparatus and VPV tests conducted

Table 3.8: Summary of Taguchi's Approach Implementation According to Thirteen Operational Steps

No.	Description of Operational Step	Objectives			
		1	2	3	4
1	Problem statement	✓	-	-	-
2	Brainstorming issues and treatments	✓	-	-	-
3	Variables identifications	✓	-	-	-
4	Research gaps resolutions	✓	✓	✓	✓
5	Selection of appropriate treatments and tool measurements	✓	✓	✓	✓
6	Cost benefits verification	✓	✓	✓	✓
7	Determination of performance tool measurements	✓	✓	✓	✓
8	Data collections	✓	✓	✓	✓
9	Data Analysis	✓	✓	✓	✓
10	Results validations (Hypothesis checking)	-	✓	✓	✓
11	Performance verification (Hypothesis checking) - Performance Statistic fall into the practice confidence interval)	-	✓	✓	✓
12	Product optimisation using QRDC indicators - Tolerances Design	-	-	-	✓
13	Product implementation	-	✓	✓	✓

3.9 Data Analysis and Modelling

Statistical analyses adopted in this study are a combination of descriptive and inferential statistical analyses as described in the following sections.

3.9.1 Descriptive Statistics

Descriptive statistical analyses were performed by using Microsoft Excel or SPSS software version 25 prior to inferential statistics (modelling). The descriptive statistical analyses involved in this study are summarised as follows;

1. Basic features description (tables, charts and graphs)
2. Central tendency (mean and median) measurement
3. Dispersion or variability (standard deviation, kurtosis and skewness) measurement
4. Outliers identification (box-plots)
5. Data Normality tests

Most of the normality of distribution data in this study was identified by using tables (consisting of mean, median, standard deviation, kurtosis and skewness) and graphical visualisation via box-plots to determine any outlier data. The data is considered as basically normally distributed if it complies with conditions as follows;

1. Mean and median values almost overlap at the centre.
2. Data comparatively, has less dispersion or variability as well as a lower standard deviation value.
3. Data has a skewness value within the range of -0.5 to +0.5
4. Data has a kurtosis value within the range of -2 to +2 (George and Mallery, 2010)
5. Data shown on Box-plot is contained within Whisker top and Whisker bottom

Meanwhile, data normality tests were conducted based on Kolmogorov-Smirnov and Shapiro-Wilk approaches subject to the number of samples (test results) involved (NIST, 2012). As such, the Kolmogorov-Smirnov approach was adopted for sampling more than 50 samples while Shapiro-Wilk approach was applied to sampling of equal or less than 50 samples. Both approaches might be considered as data normally distributed if the significance value was greater than 0.05.

3.9.2 Inferential Statistic

Inferential statistical analyses applied for modelling purposes included correlation and regression analyses were based on Analysis of Variance (ANOVA) using SPSS software version 25. Correlation among the variables was determined by using the Pearson approach. Meanwhile, rating of correlation analysis was interpreted based on Table 3.9 (Schober et al., 2018).

Table 3.9: Conventional Approach to Interpreting a Correlation Coefficient

Absolute Magnitude of the Observed Correlation Coefficient	Interpretation
0.00–0.10	Negligible correlation
0.10–0.39	Weak correlation
0.40–0.69	Moderate correlation
0.70–0.89	Strong correlation
0.90–1.00	Very strong correlation

Meanwhile, the model developed via regression analysis is considered significant if the regression analyses comply with modelling limitations according to at least any one of the significant levels as follows;

1. Significance (F) value is less than the confidence interval of 0.10, which is a model identified as a strong significant model with an accuracy of $\pm$10%.
2. Significance (F) value is less than the confidence interval of 0.05, which is a model defined as a very strong significant model with an accuracy of $\pm$5%.

In addition, selected variables for modelling are considered to have very strong significant for modelling if P-values are less than the confidence interval of 0.05.

CHAPTER 4

PERCEPTIONS OF CONSTRUCTION INDUSTRY PLAYERS ON CHLORIDE-INDUCED CORROSION RC STRUCTURES IN SARAWAK

4.1 Introduction

Chloride-induced attack is the main issue affecting RC structures, especially those built in marine environments in spray and splash zone areas. The structures constructed could be exposed to the possibility of chloride-induced corrosion that would reduce the strength and durability of RC structures. The main objective of this chapter is to determine the perceptions and opinions of construction industry players including local authorities, developers, consultants, contractors and other agencies, via survey questionnaires, in relation to the chloride-induced corrosion affecting RC marine structures in Sarawak. Other agencies included those from concrete suppliers and engineers of infrastructure maintenance.

4.2 Standardised Design of Experiments (DOE) on Locality Condition

According to Taguchi's approach, the selection of variables was the most crucial stage in DOE and should be developed to be as resistant to uncontrollable environmental (UCV) factors as possible at a low implementation cost as explained in detail in Chapter 2 (Section 2.7.3). In order to meet these requirements, it is critical to investigate the dominant transport mechanism affecting the local severe chloride-induced corrosion caused by uncontrollable environmental condition. Based on the present worst scenario, suitable treatment may be imposed on the famous ready-mixed grade concretes which used of available low-cost local fly ash waste as blended cement. In making the survey questionnaires workable to meet the objectives of study, the most relevant reviews are explained in this chapter summarised as (i) Chloride attack on RC marine structures, (ii) Fly

ash use, (iii) Sarawak's standard concrete practices and (iv) Optimisation of concrete durability properties using Taguchi's approach.

The significant findings from the survey questionnaires determined the roots of the local chloride-induced problems, important variables and possible low-cost local treatment. Thus, these data and information are the most useful in the study to achieve an excellent treatment at optimised level as required by the latest concrete standards.

4.3 Materials and Method

Data and information required to create a survey questionnaires form were gathered from SSM, local consulting firms, SIRIM Berhad and site visits. The method used in this chapter was based on the latest Taguchi's approach and other approaches. The following sections provide a detailed explanation of the data usage and method used in this chapter.

4.3.1 Materials

All the data and information required for this chapter were discussed in Chapter 3 (Section 3.3.1). Most of the data and information used for brainstorming in desk study were types of secondary and tertiary data. Some confidential data are not disclosed in this thesis report.

4.3.2 Method

The method used discussed in this chapter was a combination of the latest Taguchi's approach, the questionnaire approach and field investigation. As a result, work was more comprehensive to local conditions due to work been performed in sequences, consisting of brainstorming, optimising variables selection, research gaps resolutions, questionnaire

distribution, and ending with field investigation to verify the data collection or further clarification on the explained literature reviews.

The operational steps involved in this chapter were Steps No. 1 till 9 as stated in Table 3.8 of Chapter 3 (Section 3.8). Steps No. 1 till 3 were explained detail in this section. Meanwhile, research gap resolution was finalization of problem statements and variables that matched to the objectives of study. In addition, the selection of appropriate treatment was based on cost-effective material, as explained briefly in Section 2.3. Besides, the determination of performance tool measurements was based on the local real problem of chloride-induce environment, local available standard concrete practices and worldwide standard test methods that suit the local conditions as discussed detail in Sections 2.2, 2.4, and 2.5 respectively.

Immediately after the problem statement in Step 1 as stated in Table 3.8 (Chapter 3: Section 3.8), Step 2 was performed to determine problems and possible precautionary actions or treatments available from standard concrete practise (SSBW & SSRW), SIRIM standards and Eurocodes concrete standards. Overall, Step 2 was implemented according to the tasks work flow stated in Figure 4.1.

Meanwhile, Step 3 for operational performance optimisation, variable identification activities were selected based on a series of activities of known variables, identified variables, selection variables and screening variable processes as shown in Figure 4.2.

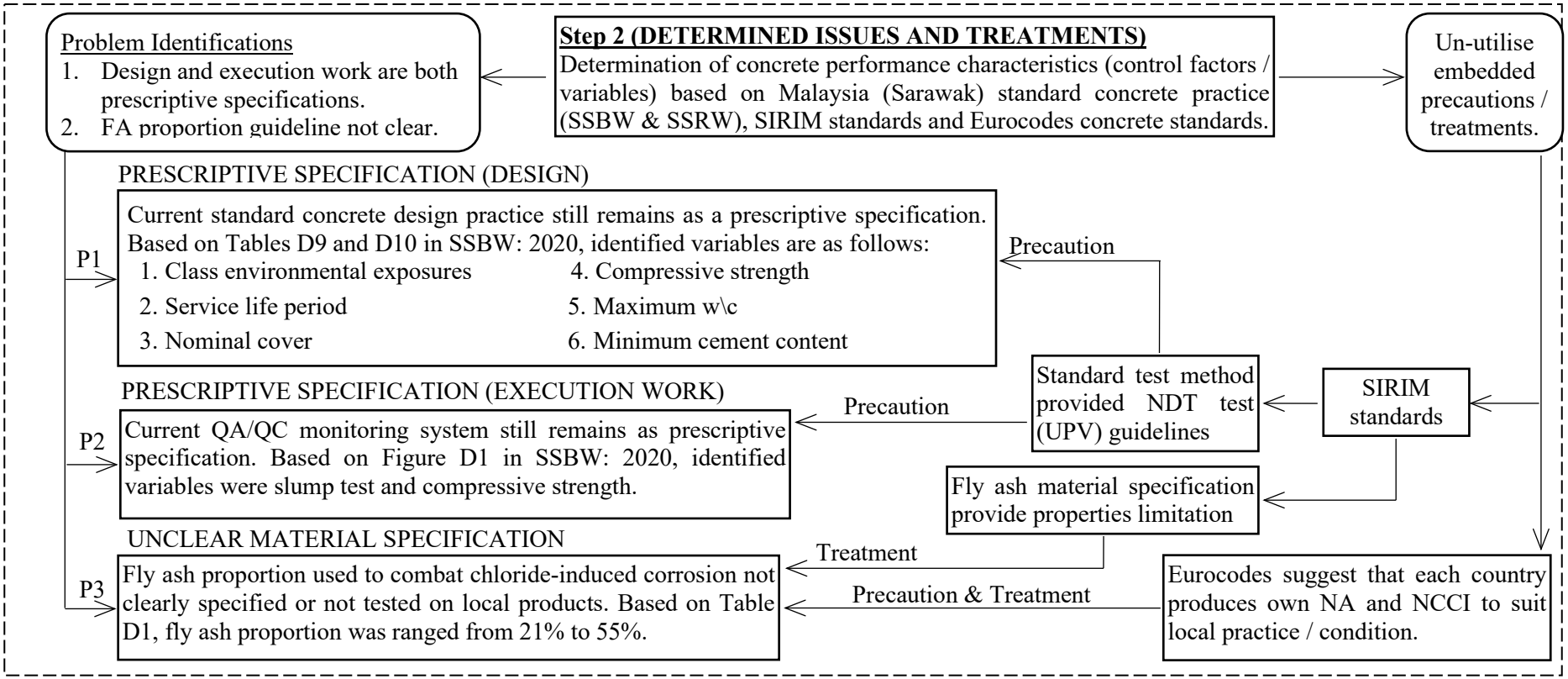


Figure 4.1: Overall Issues Determination and Treatments Conducted

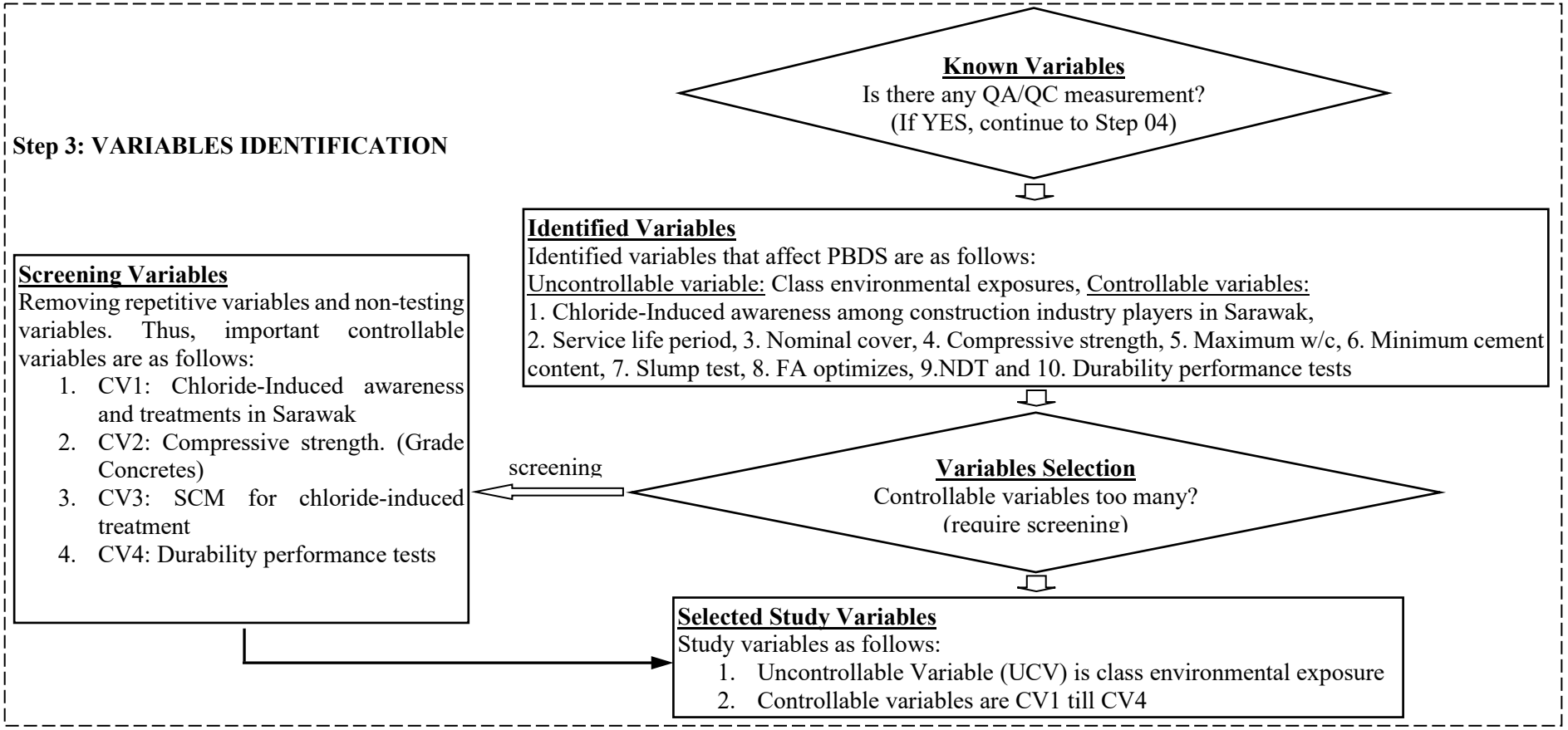


Figure 4.2: Operational Performance Optimisation Variables Identification Conducted

Research gap resolutions in this chapter was conducted to fulfil the main purposes listed in Chapter 3 (Section 3.3.2) until it successfully met all the following objectives as required by Taguchi's approach optimisation. A total of 15 finalised questions was listed in the survey questionnaires form as shown in Appendix C. Finally, a field investigation was carried out based on survey questionnaire findings to ensure that the developed Ideal Steps NDT (ISN) Guidelines QA/QC monitoring and formulated PBDS indicators models suit the local dominant transport mechanisms for severe chloride-induced environmental exposure.

4.4 Results and Discussion

All the results obtained from the survey questionnaires were based on written responses from 73 respondents around the state. The majority of the respondents were from the local authorities, which made up 38.36%; followed by contractors, developers and consultants, with compositions of 23.29%, 19.18% and 8.22%, respectively. The remaining 10.96% of the respondents were concrete suppliers and engineers of infrastructure maintenance. Figure 4.3 shows the percentages of respondents who participated in answering the survey questionnaires form. The explanations of the survey questionnaires and field investigation results are discussed in detail in the following sections.

4.4.1 Uncontrollable Variable

Uncontrollable variable (UCV) was assigned to Question No. 14 (Survey questionnaires form in Appendix C) and dealt with marine structures affected by chloride-induced corrosion. This question was the most important to determine the local severe chloride-induced corrosion that affecting RC structures as well as to clarify the review finding in Chapter 2 (Sections 2.2.2 and 2.2.3). This was followed by the determination of accurate standard test methods for NDT and PBDS indicators modelling. RC structures

affected by chloride-induced corrosion are shown in Table 4.1 (some information is not stated with full name or location to avoid any image interference of ownership).

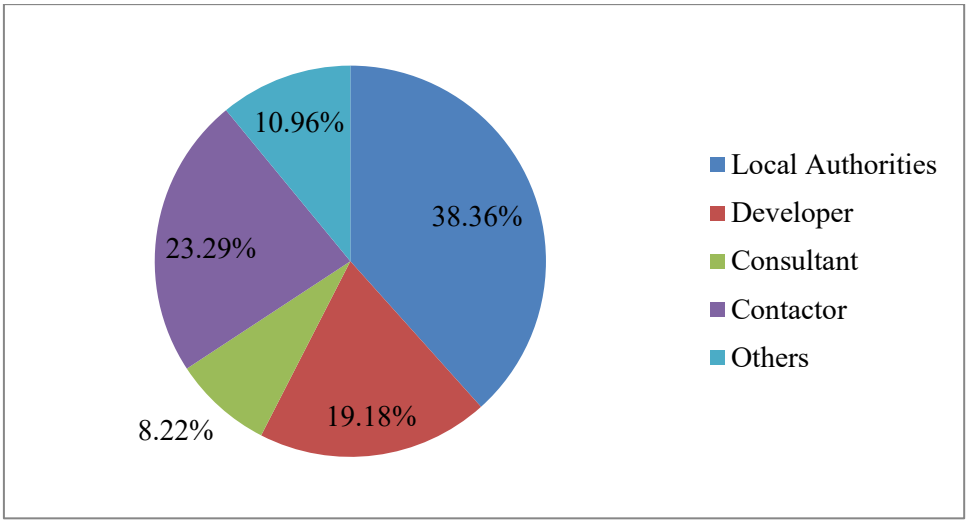


Figure 4.3: Percentages of Respondents Participating in Answering Questionnaires

Table 4.1: RC Structures Affected by Chloride-induced Corrosion

Marine Structures	Building	Others
a. Sambir RC wharf b. Sadong Jaya RC wharf c. Sebuyau RC Fisheries wharf d. Sebuyau Terminal Penumpang e. Sematan RC wharf f. Buntal Esplanade g. Water Intake Jetty, Bintulu h. Taman Selera Pier Deck i. LNG, Bintulu	a. Building Arcade b. Hostel at Serian c. Gourmet Flat Inn d. Old building, Bintangor e. Housing SPB, Lambir f. Building Inn	a. Water Front Esplanade Extension b. Daro Treatment Plant c. Waterworks Meradong

According to Table 4.1 above, 9 structures are classified as marine structures. From this list, 3 of the RC marine structures were chosen for detailed field investigation due to severe chloride-induced corrosion conditions. In addition, the Water Front Esplanade Extension was included for visitation structure as requested by the owner. Request letter for visiting and conducting chloride-induced corrosion study on the selected structures is shown in Appendix D. Meanwhile, response letters from JKR, DID and DBKU allow for exploration study of listed structures are shown in Appendixes E, F, and G respectively.

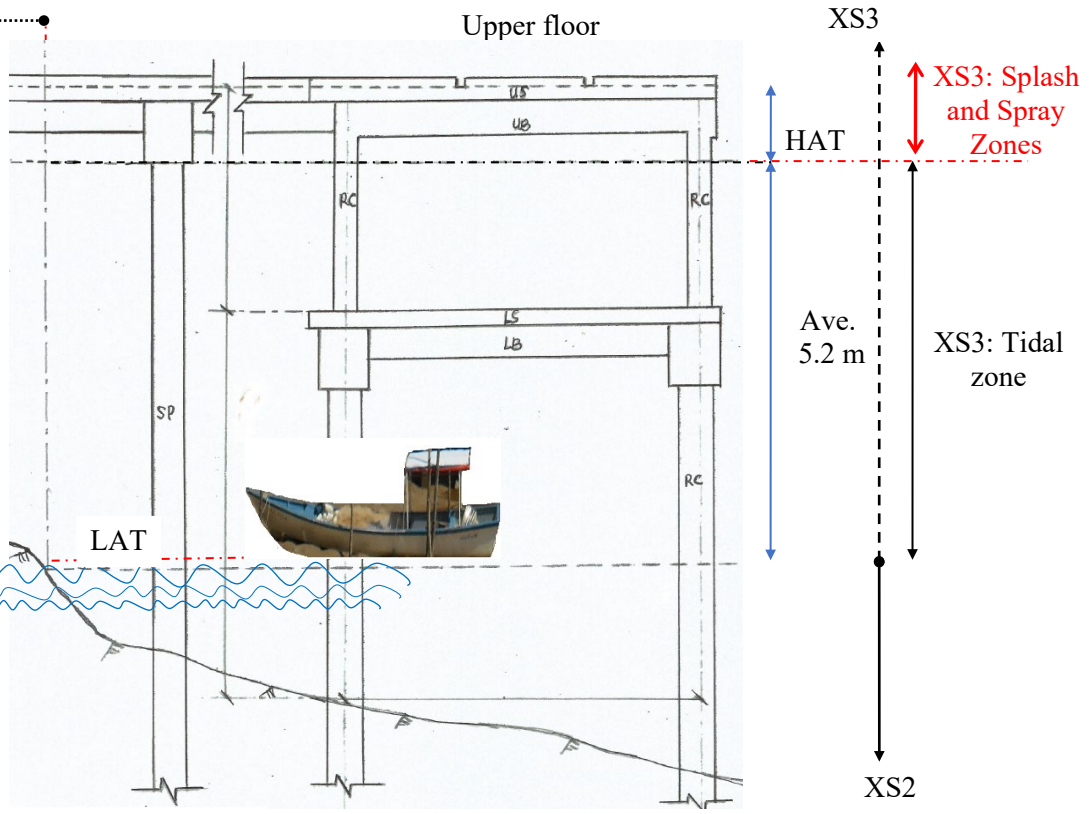
Among the marine structures selected for detail field investigation, Sambir RC wharf was identified as the most severely affected by chloride-induced corrosion in a marine environment exposure. For better interpretation of the identical transport mechanisms revealed in Table 2.2 (Chapter 2) and the similar chloride-induced corrosion environment diagram shown in Figure 2.6 (Chapter 2), the model diagram in Figure 4.4 should be used. This model diagram was developed based on actual dimensions and the lowest astronomical tide (LAT) and highest astronomical tide (HAT) data collected from DID, Sarawak website. In this case, the most critical HAT ever predicted was 6.5m.

Based on detailed inspection of the Sambir RC wharf, the most affected element structure was located in the splash and spray zones as shown in photos attached in Figure 4.5. Thus, it is clear that the most dominant local transport mechanism contributing to local severely affected chloride-induced corrosion in a marine environment exposure was capillary absorption as per earlier determination in Chapter 2 (Sections 2.2.2).



a: On-site King Tide Measurement





c: Local Model Diagram of Chloride-induced Marine Environment Exposure

Figure 4.4: Model Diagram for Local Chloride-induced Marine Environment Exposure Classes

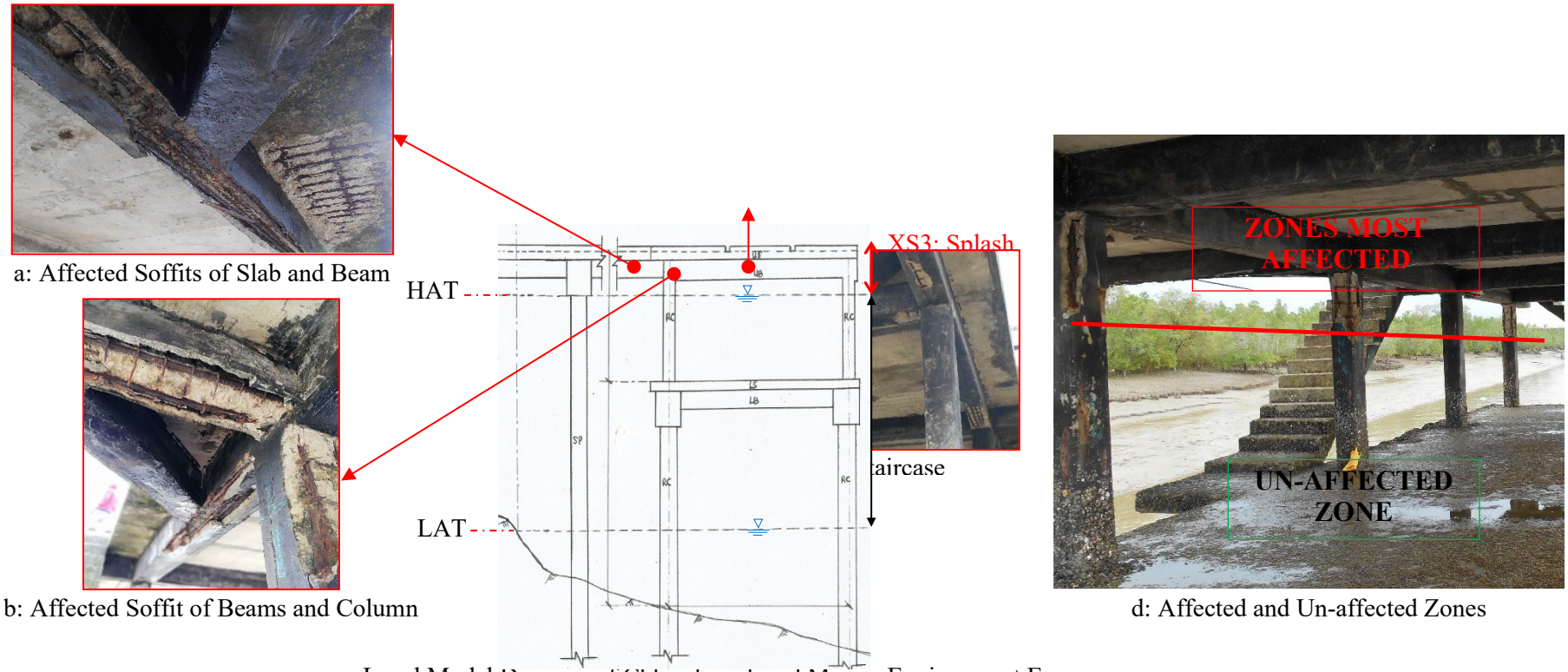


Figure 4.5: Splash and Spray Zones Most Severely Affected by Chloride-induced Corrosion at Sambir RC Wharf

In order to verify that similar phenomena of severe chloride-induced corrosion in a marine environment exposure occurred around the state, detailed visual inspections were made for Sematan RC wharf, Sebuyau RC Fisheries wharf and Water Front Esplanade Extension as shown in Figures 4.6, 4.7 and 4.8 respectively.

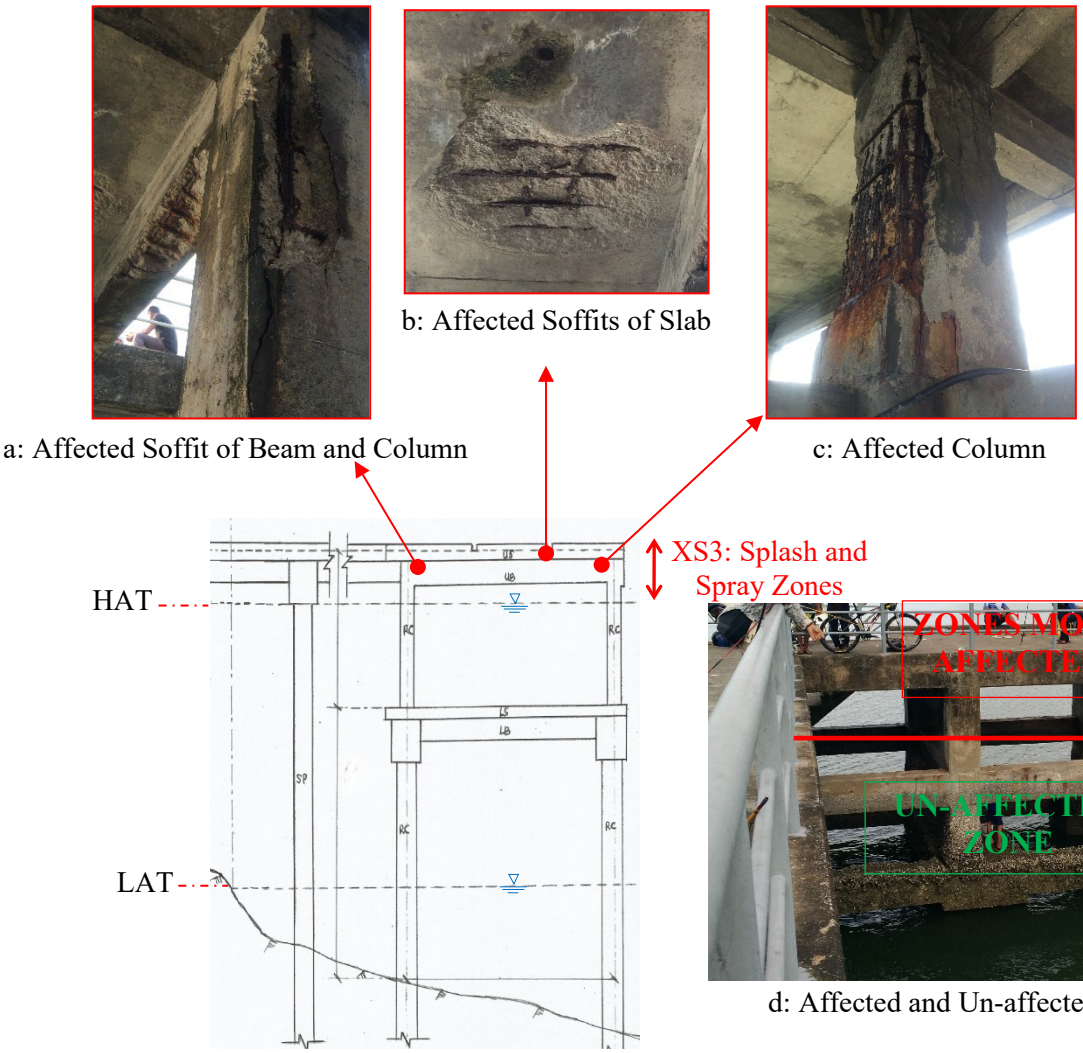


Figure 4.6: Splash and Spray Zones Most Severely Affected by Chloride-induced Corrosion at Sematan RC Wharf

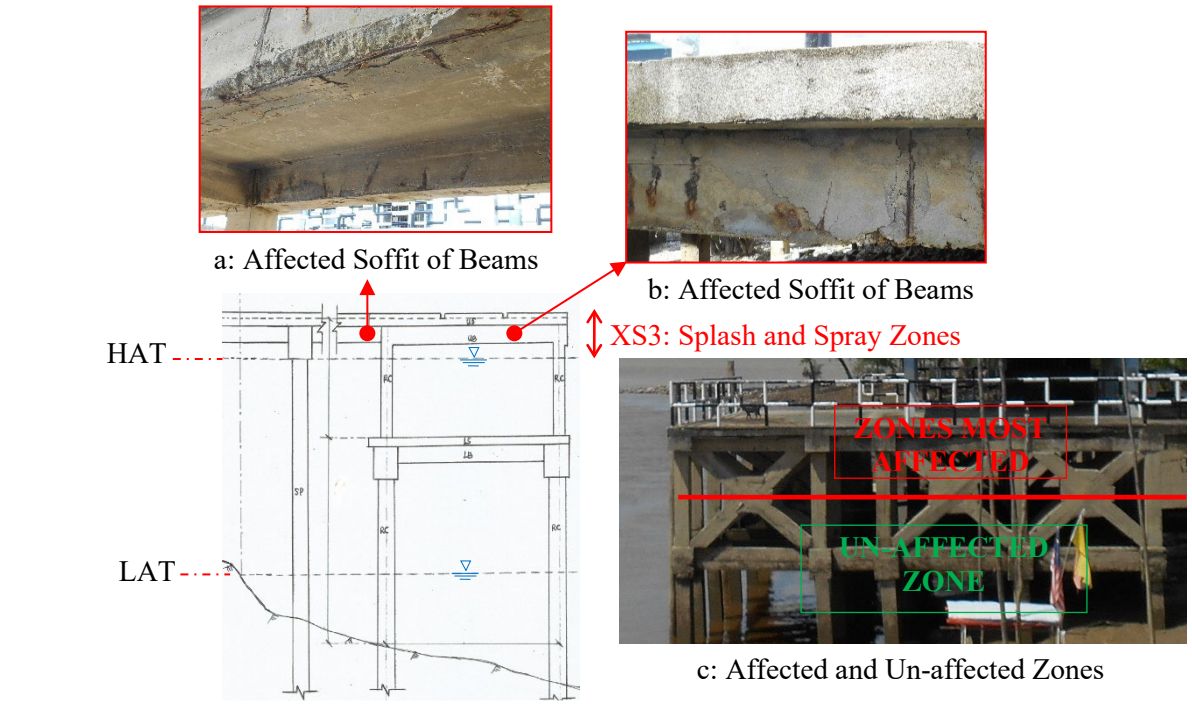


Figure 4.7: Splash and Spray Zones Most Severely Affected by Chloride-induced Corrosion at Sebuyau RC Fisheries Wharf

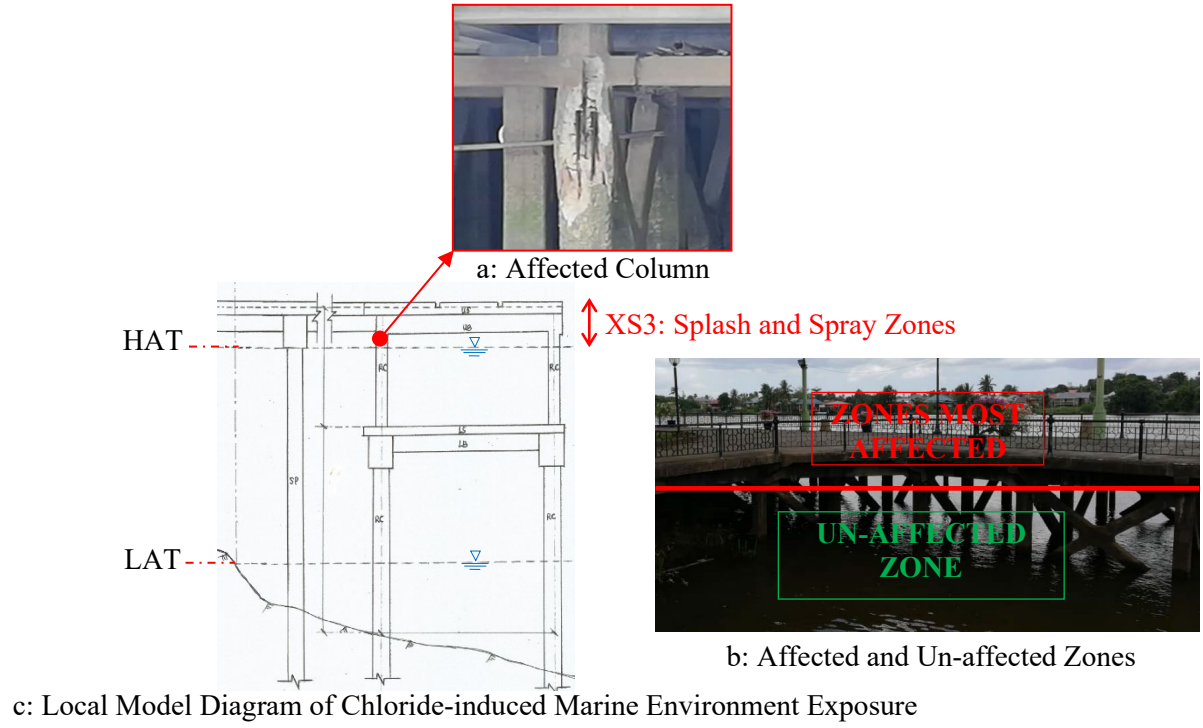


Figure 4.8: Splash and Spray Zones Most Severely Affected by Chloride-induced Corrosion at Water Front Esplanade Extension

All the findings from detailed field investigations conducted on the affected RC marine structures identified in Question No. 14 clearly prove that the earlier findings in Chapter 2 (Sections 2.2.2 and 2.2.3) were significant to the local chloride-induced corrosion problem condition. Thus, NDT guidelines and PBDS indicators based on capillary absorption transport mechanism under splash and spray zones conditions are very crucial to be developed.

4.4.2 Controllable Variable

A. Awareness on Chloride-induced Corrosion

Figure 4.9 shows the respondents' awareness of chloride-induced effects on RC structures. 74.0% of the respondents (mostly local authorities, consultants and contractors) were aware of the effects of chloride-induced corrosion on RC structures versus only 6.8% of the respondents who did not know. Meanwhile, 19.2% of the total respondents were not sure.

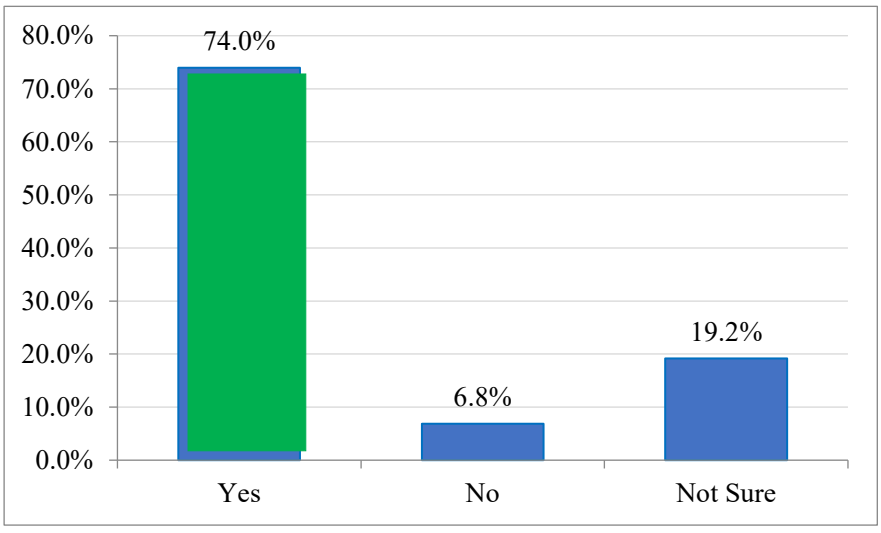


Figure 4.9: Percentages of Respondents' Awareness of Chloride Effects on RC Structures

Based on Figure 4.10, construction industry players stated that the highest percentage factors contributing to corrosion of RC structures was sea water, at a percentage of 84.8% compared to 6.1% and 9.1% stating carbonation process was from fresh water and chemical attacks respectively. About 69.7% of the respondents opined that carbonate was the medium factor for corrosion and all respondents completely agreed that chemical attacks contributed to the lowest corrosion factor.

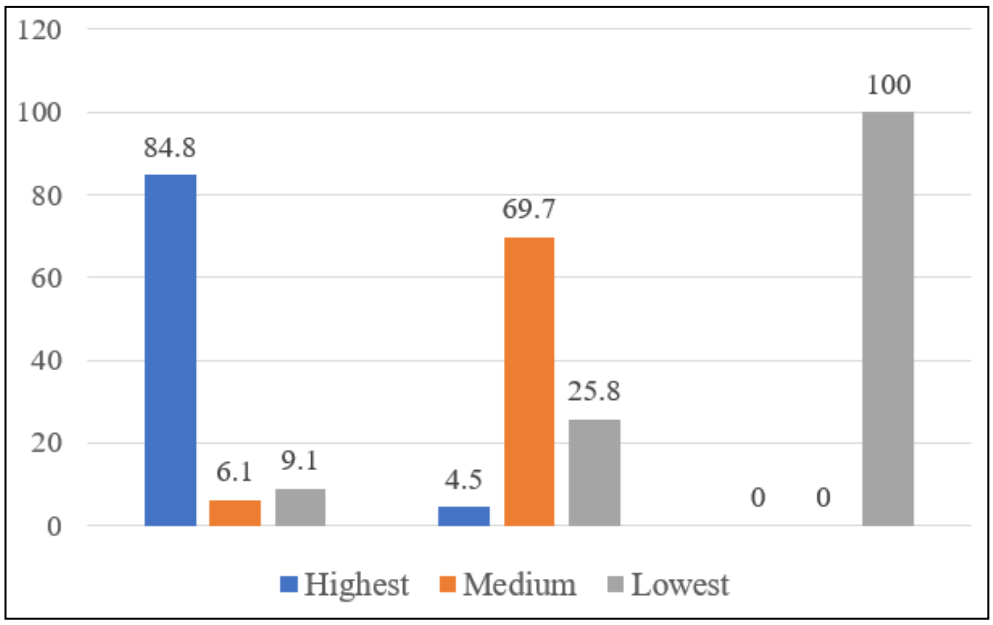


Figure 4.10: Respondent's Perception on Corrosion Factors

The opinions of the construction industry players on the importance of producing a guidelines for the chloride-induced resistance of RC structures in Sarawak are shown in Figure 4.11. 94.5% of respondents agreed that it is essential to produce this particular guideline, compared to only 5.5% of respondents who do not agree.

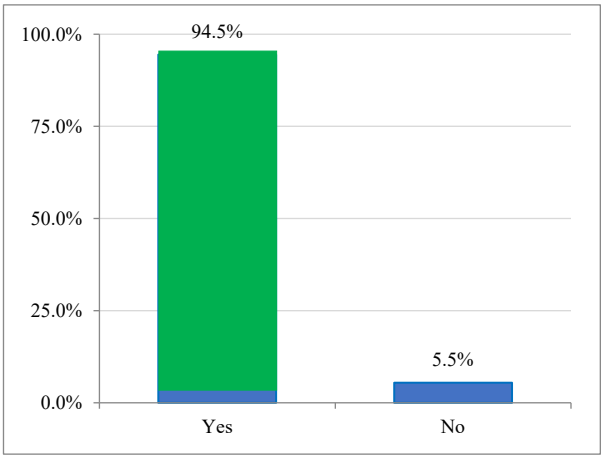


Figure 4.11: Respondents' Opinions on the Importance of Producing Guidelines on Chloride-induced Resistance for RC Structures

Based on Figures 4.9, 4.10 and 4.11, it is very clear that 94.5% of construction industry players agreed to produce guidelines for chloride-induced resistance for RC structures built under marine environment exposure in Sarawak as supported by 84.8% of respondents who agreed that the main causes of chloride-induced corrosion were from sea water (Figure 4.10). Local authorities, consultants, concrete suppliers and engineers of infrastructure maintenance concurred with these two opinions.

The acuteness of developing guidelines through performance-based durability specifications (PBDS) was aligned with records of burden cost maintenance published by Department of Statistic Malaysia (DSM) due to chloride-induced attack on RC Marine Structure. In which, total number of bridges and wharfs maintained by Jabatan Kerja Raya (JKR) has increase significantly from 1180 to 1437 (2014 to 2018).

B. Design Consideration on Chloride-induced Treatment

Figure 4.12 shows the percentages of construction industry players considering chloride-induced exposure designs on RC structures within maximum distances from the seashore or main river. The highest percentage of respondents at 27.4% (mostly from local authorities and consultants) stated that the maximum distance was 5 km. This was followed by 2 km, 15 km, 20 km, 30 km and 25 km with percentages of 17.8%, 13.7%, 9.6%, 8.2% and 4.1% respectively. Meanwhile, 19.2% of the respondents (mostly from concrete suppliers and developers) were unsure or did not respond to the survey question.

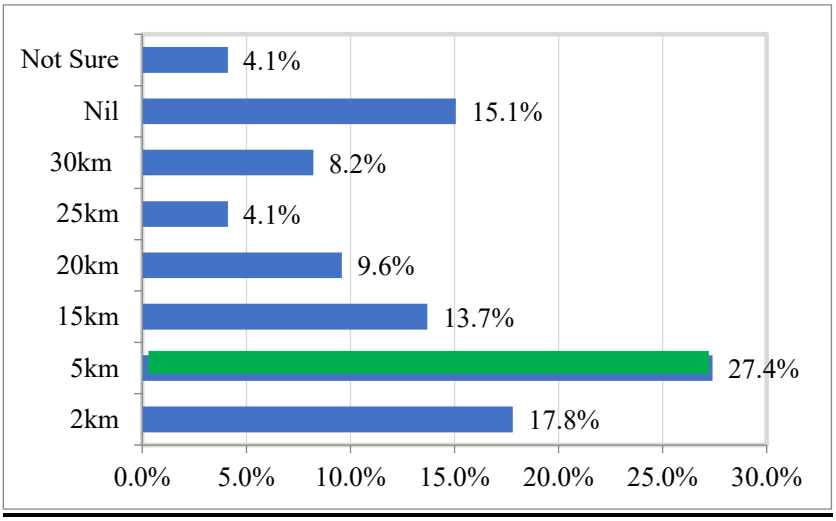


Figure 4.12: Percentage of Maximum Distances Considered for Chloride-induced Exposure Designs on RC Structures

Figure 4.13 shows the percentages of respondents selecting minimum grade concrete to combat chloride deterioration. The highest percentage of respondents (mostly contractors and consultants) at 21.9% stated that the minimum grade of concrete required was 30 MPa. This was followed by 35 MPa, 25 MPa, 40 MPa, 45 MPa and 50 MPa with percentages of 19.2%, 15.1%, 13.7%, 5.5% and 4.1% respectively. Meanwhile, 8.2% to 12.3% of the

respondents (mostly developers and others) were unsure and did not respond to the survey question respectively.

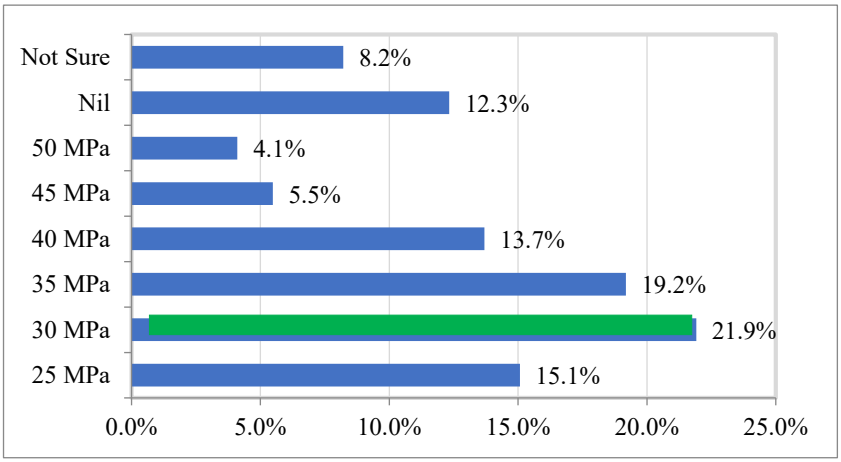


Figure 4.13: Percentages of Respondents Selecting Minimum Grade Concretes to Combat Chloride Deterioration

Figure 4.14 shows that most of the respondents at 45.2% (mostly from local authorities and contractors) recommended thickness of concrete cover to combat chloride by using 50 mm. This was followed by 75 mm, 25 mm and 100 mm with percentages of 20.5%, 17.8% and 2.7% respectively. Meanwhile, a total of 13.7% of respondents were unsure or did not respond to the survey question.

Figure 4.15 shows the highest percentage of respondents at 28.8% (mostly from local authorities and consultants) adopted service life for RC design at 100 years. This was followed by 50 years, 25 years and 75 years with percentages of 27.4%, 15.1% and 11.0% respectively. Meanwhile, a total of 17.8% of the respondents was unsure or did not respond to the survey question.

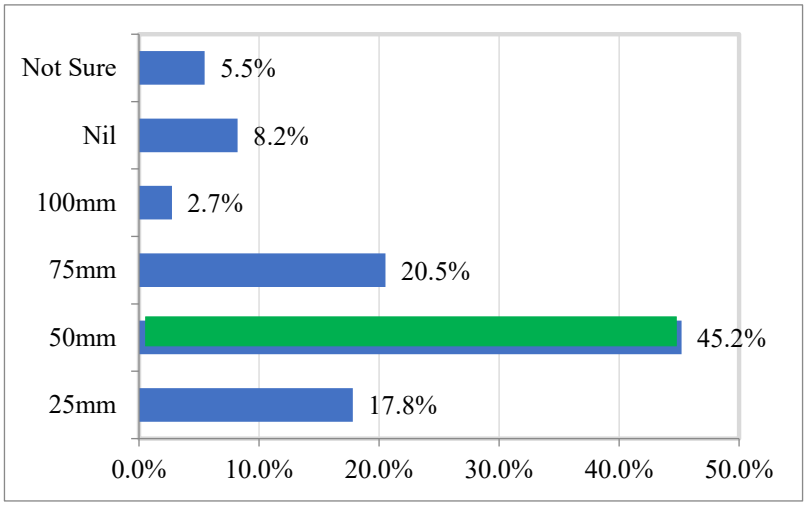


Figure 4.14: Percentages of Respondents Recommending Minimum Thicknesses of Concrete Cover to Combat Chloride Deterioration

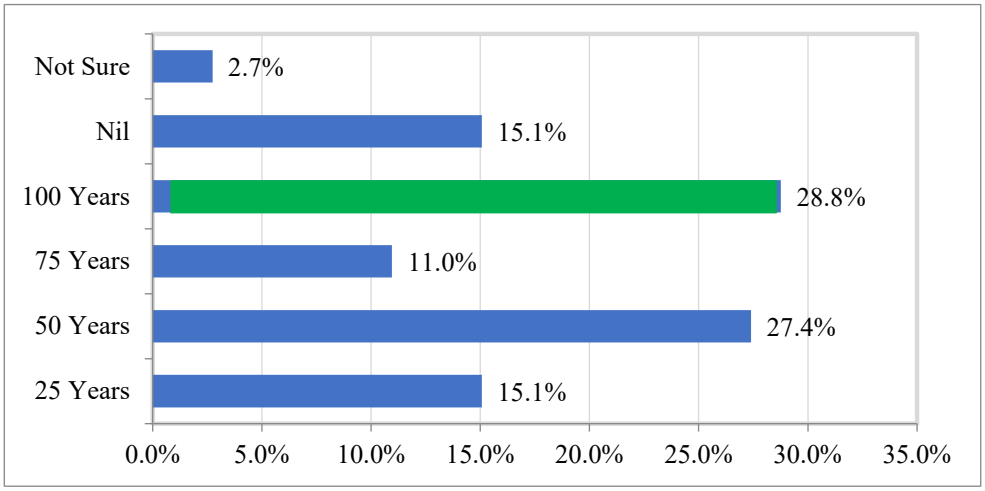


Figure 4.15: Percentages of Respondents Adopting Design Service Life

Based on Figures 4.12, 4.13, 4.14 and 4.15, it is clear that local treatments comply with the existing prescriptive specifications for combating chloride deterioration of XS3 class exposure (Splash and Spray Zones) as commented in Table 4.2. Based on comments attached to this table, the minimum grade of concrete and the required thickness of concrete

cover do not meet the present standard specifications. Thus, PBDS as effective quality monitoring implementation becomes more crucial throughout the construction phases.

Table 4.2: Status of Local Treatments Compliance to Present Standard Specifications

Local Treatments Practice Description	Finding (Survey Questionnaire)	SSBW (SSBW, 2020) / Eurocodes (MS, 2010a; MS, 2010b)	Remarks
Maximum distances from the seashore or main river	5 km	Not stated	Not related due to current standard compliance based on exposure classes.
Minimum grade concrete	30 MPa	25 to 50 MPa, mainly subjected to concrete cover	Mostly above 30 MPa, except for concrete mixtures with w/c (0.55) and minimum cement content (320 kg/m^3), but concrete cover must be above 75 mm. Thus, FAIL at all
Required thickness of concrete covers	50 mm	60 to 80 mm; subjected to compressive strength class, w/c ratio and cement content	FAIL at all
Maximum design service life	100 years	50 / 100 years	Fulfil requirements

C. Famous Grade Concretes Usages

Figure 4.16 shows the various grades of concrete supplied by ready-mixed concrete (RMC) and non-ready-mixed concrete (NRMC) suppliers to the construction industry in Sarawak. The most common grades of concrete supplied by RMC suppliers are 25, 30, 35, 40, 45 and 50 MPa, with a percentage of 14.3% for each grade. Meanwhile, the percentages of graded concrete of 55 MPa and 60 MPa are both at only 7.1% each. Besides, the largest amount supplied by NRMC is graded at 30 MPa, followed by 25 MPa, 40 MPa, 50 MPa and 45 MPa. In addition, highest usages of this grade concrete were aligned with result shown by Figure 4.13. In which, both results shown the most grade concrete used by NRMC was grade concrete of 30 MPa.

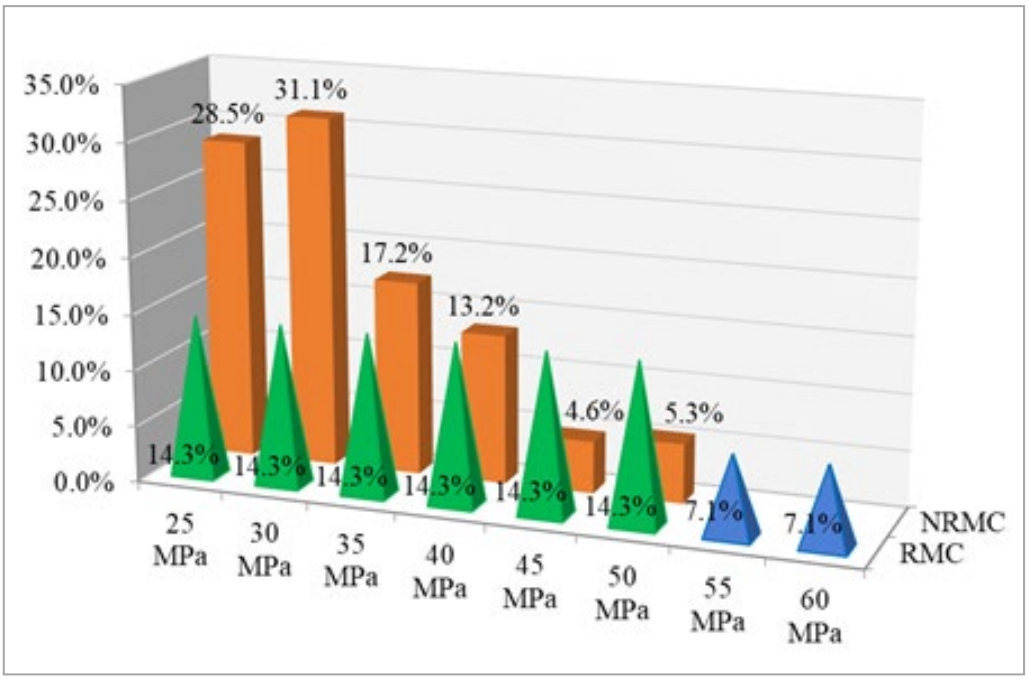


Figure 4.16: Percentages of Various Concrete Grades Supplied by RMC and NRMC in Sarawak

Based on the findings above, it is clearly shown that common grade concrete supplied by RMC are 25, 30, 35, 40, 45, and 50 MPa. At the same time, NRMC also shows similar grades of concrete around the state. In addition, Figure 4.13 also shows similar ranges of graded concrete chosen by respondents to combat chloride deterioration. As a result, the famous ready-mixed grade concretes used and supplied by local ready-mixed concrete suppliers in Sarawak consist of grade concrete of 25, 30, 35, 40, 45, and 50 MPa.

D. Treating Chloride-induced Corrosion with Supplement Cementitious Material or Other Material

Figure 4.17 shows the recommended types of cement/material that may reduce chloride deterioration. Most of the respondents did not respond to the survey question or were unsure of the available cement/material to combat chloride-induced corrosion in RC structures. These two groups of respondents represented percentages of 57.5% and 16.4% respectively. The rest, 26% (mostly from consultant, concrete suppliers and local authorities) recommended fly ash (FA) and silica fume with percentages of 11.0% and 8.2% respectively. Meanwhile, those who recommended carbon fibre sheets/glass (CFG), high alumina cement with low w/c ratio (HAC), water reducer (WR), high strength concrete (HSC) and waterproof mixture, only showed 1.4% for each.

According to the finding in Figure 4.17, only a few people knew about the availability of fly ash in Sarawak. This is believed to be due to un-familiarised usage of SCM, unclear guidelines, and the lack of a study to determine the significant effectiveness of local fly ash tested on local ready-mixed concrete as discussed in Chapter 2 (Section 2.4.3). In fact, Sarawak holds nearly 70% of Malaysia's coal reserves as explained in Chapter 2 (Section 2.3.2). In addition, based on test reports provided by the supplier, the Sejingkat Fly Ash is qualified for use in concrete mixtures and is currently on sale at only RM 9.50

per bag of 35 kg net weight. Unfortunately, field investigation shows that the ash pond (landfill) is still being used as a dump area for excessive fly ash. The nearest location of ash pond is near to Sejingkat Power Plant as shown in Figure 4.18.

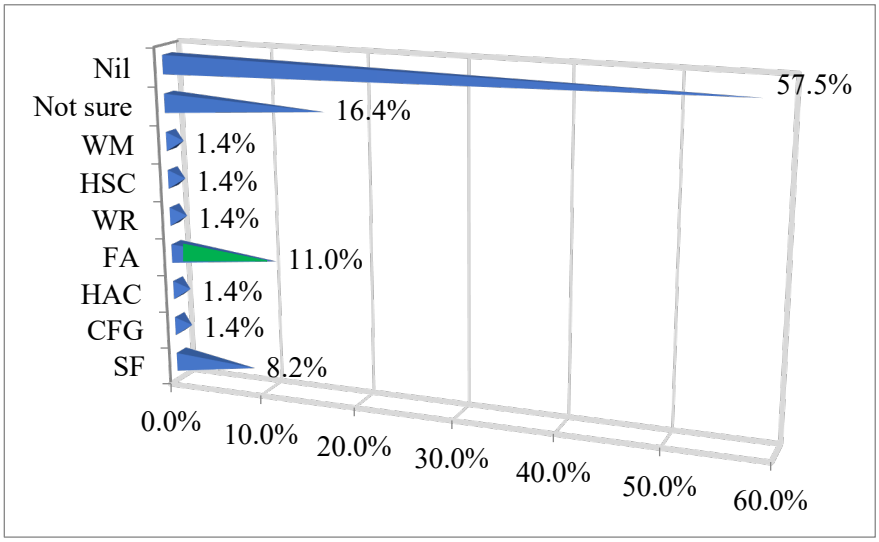


Figure 4.17: Percentages of Recommended Type of Cement/Material that May Reduce Chloride Deterioration



Figure 4.18: Location of Ash Pond Near to Sejingkat Power Plant

4.5 Chapter Summary

Based on simple statistical analysis on survey questionnaires data and detailed field investigations, the data and information most useful for this study are summarised as follows;

Uncontrollable Variable (UCV)

a. Capillary absorption due to splash and spray zone conditions was the dominant transport mechanism for chloride ions suit to local conditions.

b. Model diagram for Local Chloride-Induced Marine Environment Exposure is shown in Figure 4.19.

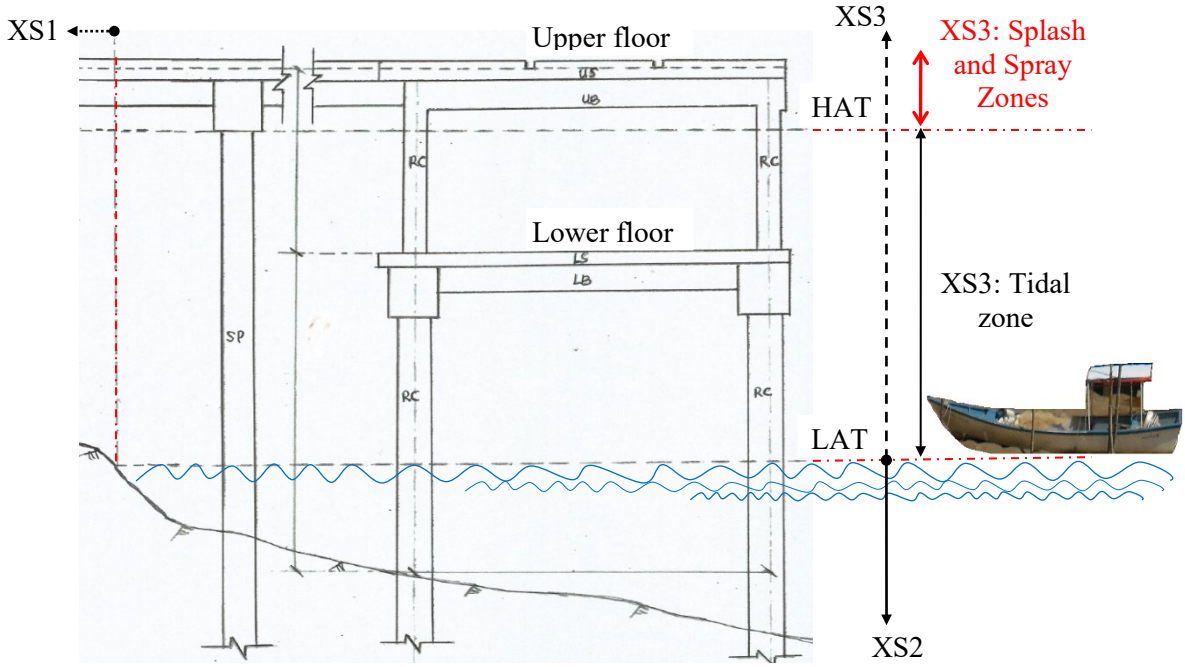


Figure 4.19: Proposed Local Model Diagram of Chloride-induced Marine Environment Exposure

Controllable Variable (CV1)

c. 74.0% of the respondents (mostly local authorities, consultants and contractors) are aware of the effects of chloride-induced corrosion on RC structures.

d. 84.8% of the respondents stated that the highest factor contributing to the corrosion of RC structures was sea water.

e. 94.5% of the respondents agreed that it is essential to produce chloride-induced resistance guidelines for RC structures.

f. The highest percentage of respondents (mostly local authorities and consultants) at 27.4% stated that the maximum distance is 5 km from the seashore or main river, to avoid chloride-induced corrosion attack.

g. The highest percentage of respondents (mostly contractors and consultants) at 21.9% stated that the minimum grade of concrete required to combat chloride-induced corrosion was 30 MPa.

h. The highest percentage of respondents (mostly local authorities and contractors) at 45.2% recommended that the thickness of concrete cover to combat chloride-induced corrosion was 50 mm.

i. The highest percentage of respondents (mostly local authorities and consultants) at 28.8% adopted 100 years as service life for RC design.

Controllable Variable (CV2)

j. Famous concrete grades included 25, 30, 35, 40, 45, and 50 MPa.

Controllable Variable (CV3)

k. The highest percentage of the respondents (mostly local authorities and consultants) at 11.0% recommended fly ash to be used to mitigate chloride-induced corrosion.

CHAPTER 5

OPTIMISATION OF READY-MIXED CONCRETE PARTIALLY REPLACED OF CEMENT WITH CLASS-F FLY ASH

5.1 Introduction

Performance of local concrete in chloride-induced environment that affecting RC marine structures built in splash and spray zones can undoubtedly be improved by using fly-ash replacement method, which has proven workable worldwide as shown in Table 2.8 (Chapter 2). This leads to testing and analysing the optimum percentage of fly-ash blended into local ready-mixed concrete, until it reaches the maximum strength and durability with valuable cost-effectiveness. The main objective of this chapter is to optimise the concrete performance of local ready-mixed concrete partially replaced with fly ash.

5.2 Concrete Optimisation Via Taguchi's Approach

According to Taguchi's approach as stated in Table 3.8 (Chapter 3) on the operational Step No. 6, the selection of treatment must be cost-effective and reasonable. Its cost can be in terms of reducing the cost of production; low maintenance costs; promoting environmental sustainability and enhanced safety for public users.

There is a present concrete technology practise to utilise fly ash waste as determined in Chapter 4 to optimise the performance of local ready-mixed concrete. Currently, an excessive amount of local fly ash is being dumped into the ash pond nearby power plants with no commercial use for construction. More crucial, present standard concrete practice does not clearly specify of optimised proportion of fly ash that may be used to combat chloride-induced corrosion in marine environment. In addition, there is no study conducted to determine the significant effectiveness of fly ash tested on local famous ready-mixed

grade concretes. In fact, Eurocode 2 has been advocated for each country' members to produce its own NA and NCCI to suit local practice and background material respectively. With the excessive availability of fly ash, it is time to optimise concrete performance of local ready-mixed concrete against chloride-induced attack by incorporating fly ash as successfully conducted by established guidelines stated in Table 1.3 (Chapter 1). The most relevant reviews are explained in this chapter and are similar as per Chapter 4's references.

5.3 Concrete Work Specifications Improvement

The main contribution provided in this chapter is to determine the accurate optimised percentage of local fly ash replacement tested on famous ready-mixed grade concrete supplied by the dominant concrete supplier in Sarawak. These data are useful for improving Table D1 in SSBW:2020 by indicating the actual fly ash optimised proportion replacement. In order to combat chloride-induced corrosion in XS3 class exposure for marine environment, Tables D2, D9 and D10 in SSBW:2020 or Eurocode 2 are also affected indirectly.

5.4 Materials and Method

Ready-mixed concrete design mixtures, raw materials, standard test methods, Taguchi's approach implementation and data analyses are explained in Chapter 3. Data and materials required to gauge optimised concrete performance of local ready-mixed concrete obtained from Chapter 4, namely as class environment exposure, available supplementary cementitious material (SCM) for chloride-induced treatment and famous grade concrete usages in Sarawak.

The operational steps involved in this chapter were Steps No. 4 till 11 and No. 13. Steps No. 4 till No. 7 were identical to Objective 1 as explained in Section 4.3. Meanwhile,

Steps No. 8 and 9 were explained detail in Section 5.5 to 5.7. Performance verification and concrete standard specifications improvement were detailed out in Sections 5.8 and 5.9 respectively.

5.5 Famous Ready-mixed Grade Concretes Without Fly Ash

Compression test results for famous ready-mixed grade concretes supplied by the dominant local ready-mixed concrete supplier are shown in Figure 5.1 (full test results are attached in Appendix M). All grade concretes showed normal strength development up to 360 days in ascending order. Based on the error bars attached to Figure 5.1, it is clearly shown that only grade concretes M1 till M3 provided concentrated and more reliable results, while other grade concretes were only able to comply after 90-days of curing age. M1 and M4 grade concretes exhibited strength development in their respective compressive strength classes. Throughout the strength development, M2 and M3 almost merged. This condition occurred was suspected to be due to the lesser usage of coarse aggregate in M3 concrete mixture, which was only 1040 kg/m^3 versus 1081 kg/m^3 in M2. Similarly, M5 and M6 tended to completely merge at 360-day of strength development due to an ingredient constituent factor, which was that M6 only consumed 1085 kg/m^3 compared to 1280 kg/m^3 in M5. Due to this uncertainty in compressive strength result conditions, detailed descriptive statistical analyses are required to determine the appropriate optimised performance offered by local fly ash for all grade concretes in Sarawak.

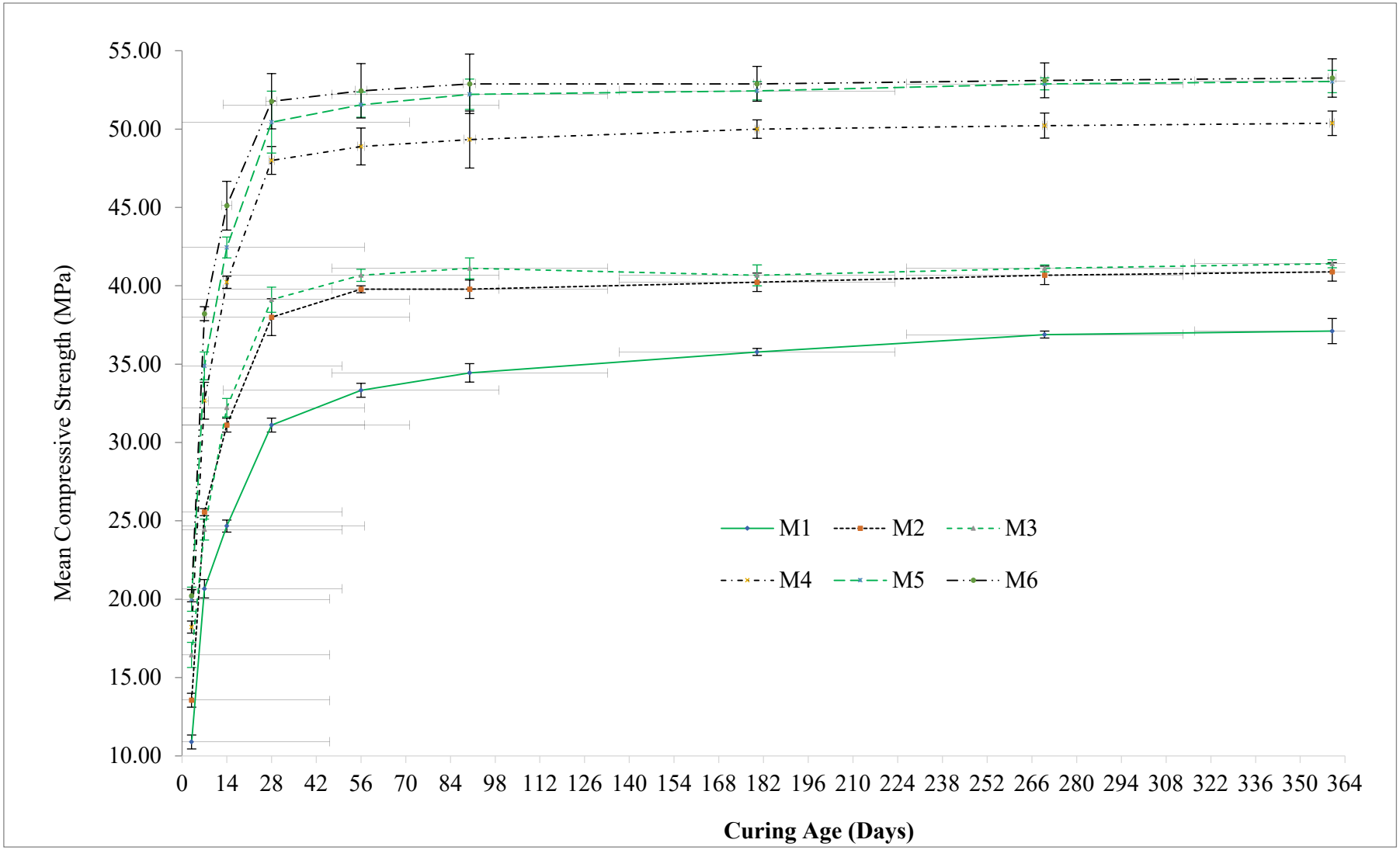


Figure 5.1: Famous Ready-mixed Grade Concretes Compressive Strength Development

The results of descriptive data analyses for famous ready-mixed grade concretes are summarised in Table 5.1. Descriptive data analysis was conducted on individual and a few combinations of grade concretes as per methods specified in Chapter 3 (Section 3.9.1) by assessing standard deviation, mean, median, kurtosis, and skewness values to determine any approximately symmetrical distributed data before outlier data improvement was shown by using box-plot.

M1, M2, and M3 standard deviations were considered slightly less dispersed than others, with recorded ranges from 8.954 to 9.081 versus ranges from 11.088 to 11.391. Meanwhile, all types of combination grade concretes showed almost the same values of standard deviation, with ranges from 11.443 to 11.683. Besides, skewness for all of the data series was shown to be negatively skewed with unsymmetrical distributed data except for grade concrete combination of M1-M3-M5. This was recorded to have a skewness value of -0.416 as well as defined as approximately symmetric distributed data. In addition, kurtosis values for all individual grade levels except M6 were shown to be less than 3, which was considered flat distributed data. Thus, the appropriate and reliable combination for the determination of outliers' data prior to optimising concrete performance was combination grade concretes of M1-M3-M5 due to approximately symmetric distributed data shown by skewness, kurtosis and almost overlapped values between mean and median.

Based on the statistical data provided in Table 5.1 and the discussion above, the total calculated percentage of outlier data for grade concretes combination of M1-M3-M5 was 4%, or exactly 1 out of 27 data compressive strengths participated in the outlier's determination as shown in Figure 5.2. Clearly showed that the value of compressive strength for grade concrete M1 at 3 days was slightly less than the Whisker bottom value of about

0.22 MPa. Finally, the outlier data was removed by replacing it with a value of 16.33 MPa. This value was a little bit higher than the lower bond but less than the G35 tested at the same curing age. As shown in Figure 5.3, the new skewness, mean, and median after improving the outlier were -0.27, 36.94 MPa, and 37.11 MPa respectively. Thus, the appropriate grade of concrete that was proven statistically could proceed with optimising concrete performance by local fly ash was a combination grade concretes of M1-M3-M5 as shown by box-plot. Ready-mixed concrete design mixtures are shown individually in Table 3.4 (Chapter 3).

Table 5.1: Summary of Descriptive Data Analysis for Individual and Combination Grade Concretes

Grade Designations	Standard Deviation	Mean	Median	Kurtosis	Skewness
M1	8.954	29.43	33.33	1.000	-1.308
M2	9.418	34.4	39.78	2.277	-1.674
M3	9.081	35.24	40.67	1.112	-1.484
M4	11.088	43.1	48.81	2.622	-1.761
M5	11.391	45.55	51.56	2.605	-1.755
M6	11.152	46.66	52.44	4.121	-2.053
M1 to M6	11.683	39.66	40.44	-0.3701	-0.663
M2-M4-M6	11.443	41.39	40.84	0.283	-1.029
M1-M3-M5	11.666	36.74	37.11	-0.3698	-0.416
Limitation values as per guidelines stated in Chapter 3 (Section 3.9.1)		Both values almost overlapped		-2 to +2	-0.5 to +0.5

Compressive Strength		OUTLIER
G25	10.89	TRUE
	20.67	FALSE
	24.67	FALSE
	31.11	FALSE
	33.33	FALSE
	34.44	FALSE
	35.78	FALSE
	36.89	FALSE
	37.11	FALSE
G35	16.44	FALSE
	24.44	FALSE
	32.22	FALSE
	39.11	FALSE
	40.67	FALSE
	41.11	FALSE
	40.67	FALSE
	41.11	FALSE
	41.41	FALSE
G45	20.00	FALSE
	34.89	FALSE
	42.44	FALSE
	50.44	FALSE
	51.56	FALSE
	52.22	FALSE
	52.44	FALSE
	52.89	FALSE
	53.04	FALSE
Percentage Outliers (%)		4%

M1-M3-M5	
Mean	36.74
Standard Error	2.25
Median	37.11
Mode	#N/A
Standard Deviation	11.67
Sample Variance	136.09
Kurtosis	-0.37
Skewness	-0.42
Range	42.15
Minimum	10.89
Maximum	53.04
Sum	992.00
Count	27.00
MIN	10.89
Q1	31.67
MEDIAN	37.11
Q3	41.93
MAX	53.04
BOX 1-HIDDEN	31.67
BOX 2-LOWER	5.44
BOX 1-UPPER	4.81
WHISKER BOTTOM	11.11
WHISKER TOP	20.78

Q1	Q3	IQR	UPPER BOND	LOWER BOND
31.67	41.93	10.26	57.31	16.28

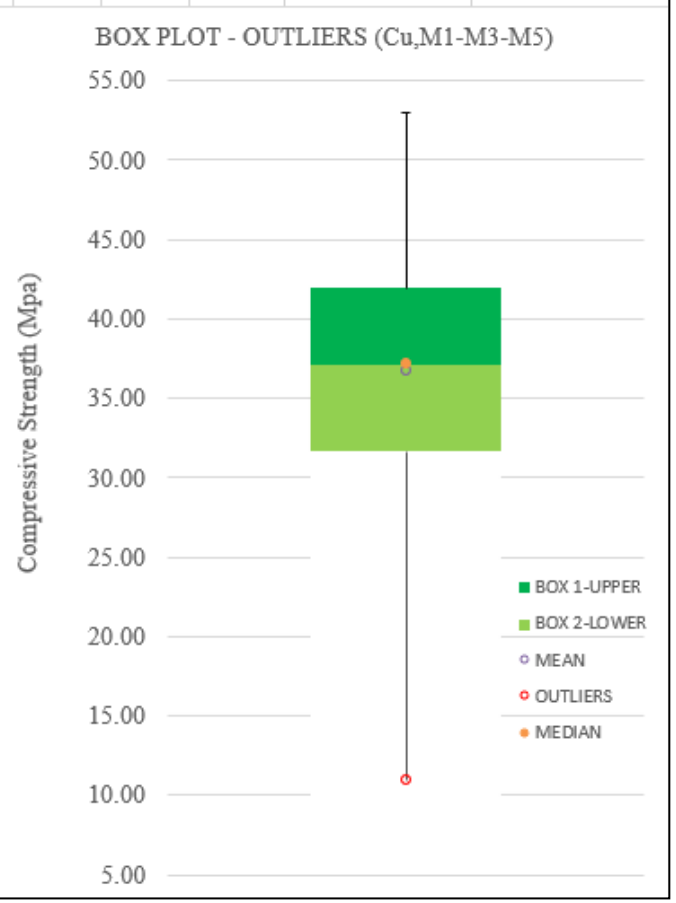


Figure 5.2: Grade Concretes Combination of M1-M3-M5 with 4% Outliers Data

Compressive Strength		OUTLIER
G25	16.33	FALSE
	20.67	FALSE
	24.67	FALSE
	31.11	FALSE
	33.33	FALSE
	34.44	FALSE
	35.78	FALSE
	36.89	FALSE
	37.11	FALSE
G35	16.44	FALSE
	24.44	FALSE
	32.22	FALSE
	39.11	FALSE
	40.67	FALSE
	41.11	FALSE
	40.67	FALSE
	41.11	FALSE
	41.41	FALSE
G45	20.00	FALSE
	34.89	FALSE
	42.44	FALSE
	50.44	FALSE
	51.56	FALSE
	52.22	FALSE
	52.44	FALSE
	52.89	FALSE
	53.04	FALSE
Percentage Outliers (%)		0%

M1-M3-M5	
Mean	36.94
Standard Error	2.16
Median	37.11
Mode	#N/A
Standard Deviation	11.24
Sample Variance	126.41
Kurtosis	-0.70
Skewness	-0.27
Range	36.74
Minimum	16.30
Maximum	53.04
Sum	997.41
Count	27.00
MIN	16.30
Q1	31.67
MEDIAN	37.11
Q3	41.93
MAX	53.04
BOX 1-HIDDEN	31.67
BOX 2-LOWER	5.44
BOX 1-UPPER	4.81
WHISKER BOTTOM	11.11
WHISKER TOP	15.37

Q1	Q3	IQR	UPPER BOND	LOWER BOND
31.67	41.93	10.26	57.31	16.28

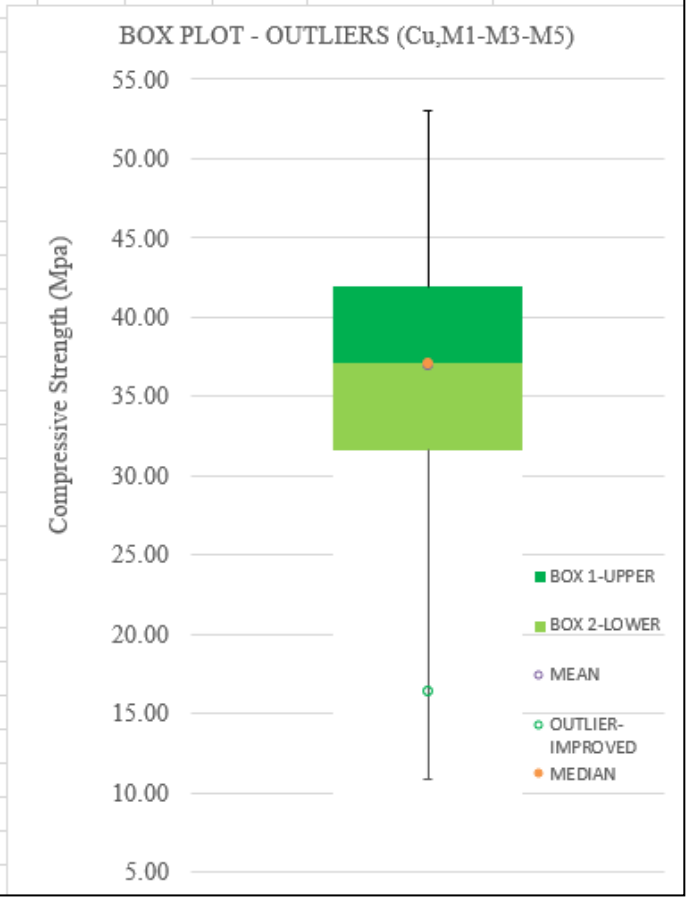


Figure 5.3: Grade Concretes Combination of M1-M3-M5 with Improved Outliers Data

5.6 Ready-mixed Concrete Optimised by Fly Ash

Optimized concrete performance for identified grade concretes in Section 5.5, namely M1, M3 and M5, was conducted by using cement replacement method with percentages as detailed in Chapter 3 (Section 3.4). All specimens were tested for compressive strength, ultrasonic pulse velocity, water absorption and volume of permeable voids. All test results went through descriptive data analyses at individual grade and separate group parameter to determine the pattern of data distribution and the existence of any outlier data throughout 3, 7, 14, 28, 56, 90 and 180-day curing ages.

For M1 and M5 optimised performance evaluation, only compressive strength test results were used for assessment. Meanwhile, ultrasonic pulse velocity and water absorption test results were used for detailed analyses on the confirmation of optimisation performance for grade concrete M3. The results of the descriptive data analyses and outlier determination for compressive strength are shown in Table 5.2.

Table 5.2: Summary of Descriptive Data Analysis of Compressive Strength Test Results

Grade Designations	Kurtosis	Skewness	Outlier (%)
M1	- 0.830	- 0.206	0
M3	- 0.968	- 0.035	0
M5	- 0.909	- 0.404	0

Table 5.2 clearly shows that skewness values representing the data distribution were approximately symmetric and none detected any outlier data at all grade levels. Meanwhile, kurtosis values for all grade concretes showed more than -1 but less than +2, which was considered flat distributed data and acceptable.

Reporting optimised concrete performance in this chapter is presented in two parts. The first part is concrete with grade designations of M1 and M5 for which laboratory test results clearly shows optimum compressive strength with fly ash replacement of 30%. The second part is concrete with a grade designation of M3, which has a slightly different percentage of optimum compressive strength compared to M1 and M5.

A. Concrete Grade Designations of M1 and M5

Based on Figures 5.4 and 5.5, optimum compressive strengths with fly ash replacement to fulfil the study's Objective 2 are summarised as follows;

1. The optimum compressive strength of local concrete grade designations M1 and M5 partially replaced with local fly-ash was 30% of the cement replacement.
2. The strength development of the concrete mixtures enhanced with fly-ash replacements became more pronounced at 56, 90-day and the later ages.

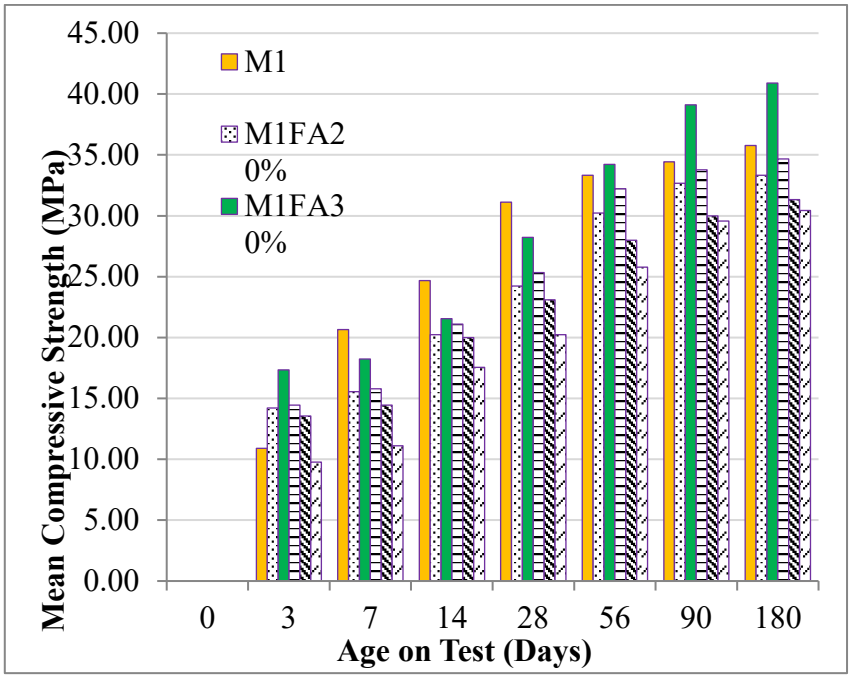


Figure 5.4: Effect of Fly Ash on Concrete Compressive Strength by Age (Grade Designation M1)

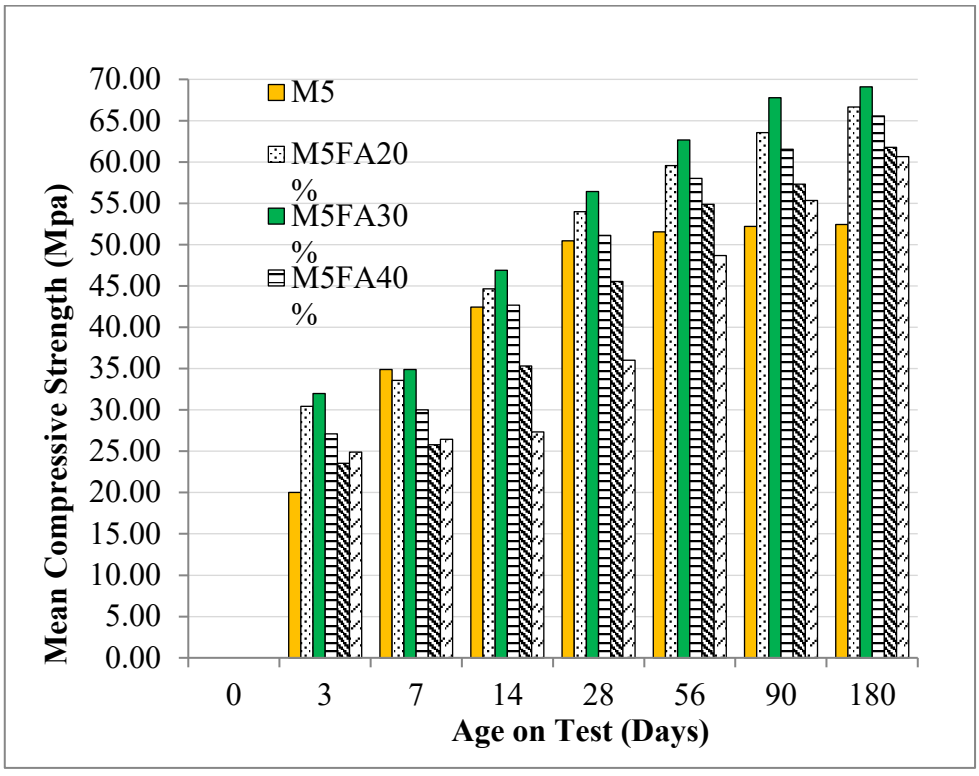


Figure 5.5: Effect of Fly Ash on Concrete Compressive Strength by Age (Grade Designation M5)

B. Concrete Grade Designation of M3

Figure 5.6 shows that the compressive strength development for grade concrete M3 was of similar trend to those of M1 and M5. However, all fly ash mixtures recorded inconsistent strength development from 3 days up to 14 days, followed by developing strength higher than the control mixture up to 56 days. Afterwards, strength development was inconsistent again, with 20% and 60% of replacements slightly recording lower strength development, while 40% of replacements showed abnormal strength development. Subsequently, optimised fly ash concrete for grade concrete M3 was 40% cement replacement. However, due to test results grade concrete M3 which was does not bounded in between grade concretes M1 and M5 recorded optimum 30% cement replacement. Thus, it is very crucial to clarify the accurate percentage of fly ash replacement by assessing the results of durability testing conducted on the affected specimens.

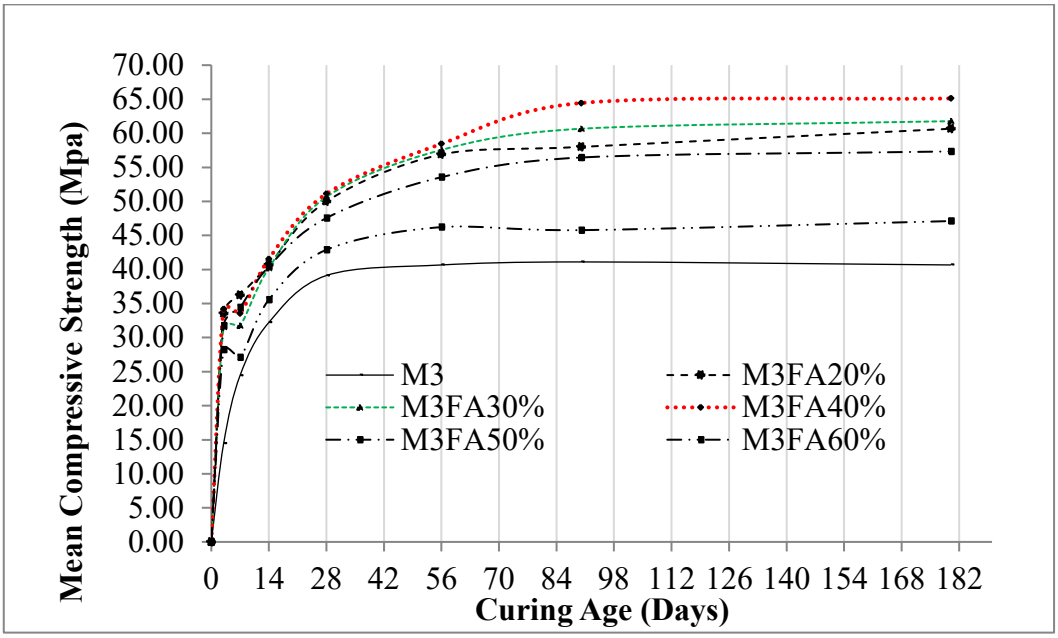


Figure 5.6: Effect of Fly Ash on Concrete Compressive Strength by Age (Grade Designation M3)

Based on the concrete performance of M1 and M5, it is stated that the strength development of the concrete mixtures enhanced with fly ash replacements became more pronounced at 56, 90 and the later ages. Thus, the following assessments were mainly based on these curing ages.

Figure 5.7, clearly shows ultrasonic pulse velocity had inconsistent trends in performance development with compressive strength at 56 days of curing age. In that case, the compressive strength recorded was almost similar to the values for all 20%, 30% and 40% cement replacements. However, ultrasonic pulse velocity records progressively increased in ascending order. Thus, further assessment is required by limiting the number of specimens to 30% and 40% cement replacement only for clear and easy interpretation.

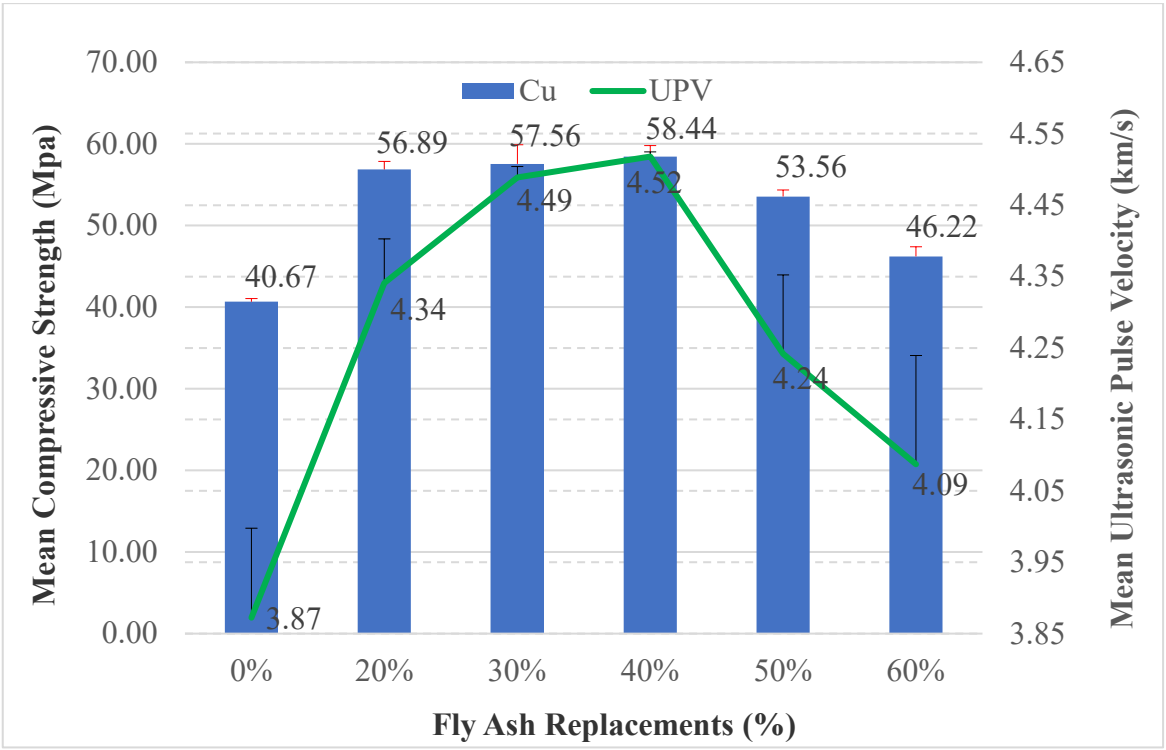


Figure 5.7: Comparison Between Concrete Compressive Strength and Ultrasonic Pulse Velocity at 56 Days Age (Grade Designation M3)

Based on the red horizontal dashed lines in Figure 5.8, which were drawn from error bars at 40% towards 30%, it is ambiguously shown that 40% was significant took over from 30% specimens. However, the difference in ultrasonic pulse velocity for both fly ash replacements only differed by about 0.66%. This value was too small and was likely to be roughly the same for both curing ages.

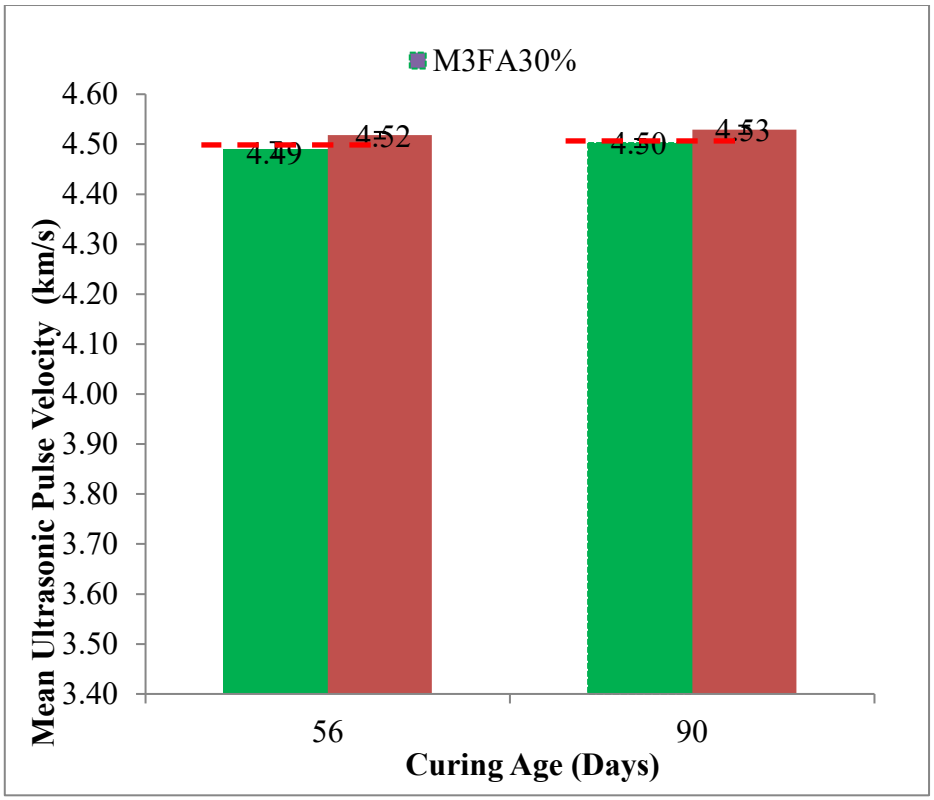


Figure 5.8: Effect of Fly Ash on Ultrasonic Pulse Velocity at 56 and 90-days Age (Grade Designation M3)

Based on ultrasonic pulse velocity test results recorded in Figure 5.9, it is clearly shown that 30% trend performance development represented by the green linear line would take over against 40% at a later age. This finding was agreed to the results of M1 and M5, in which 30% of cement replacements had pronounced strength development at 56 days, 90 days and the later ages.

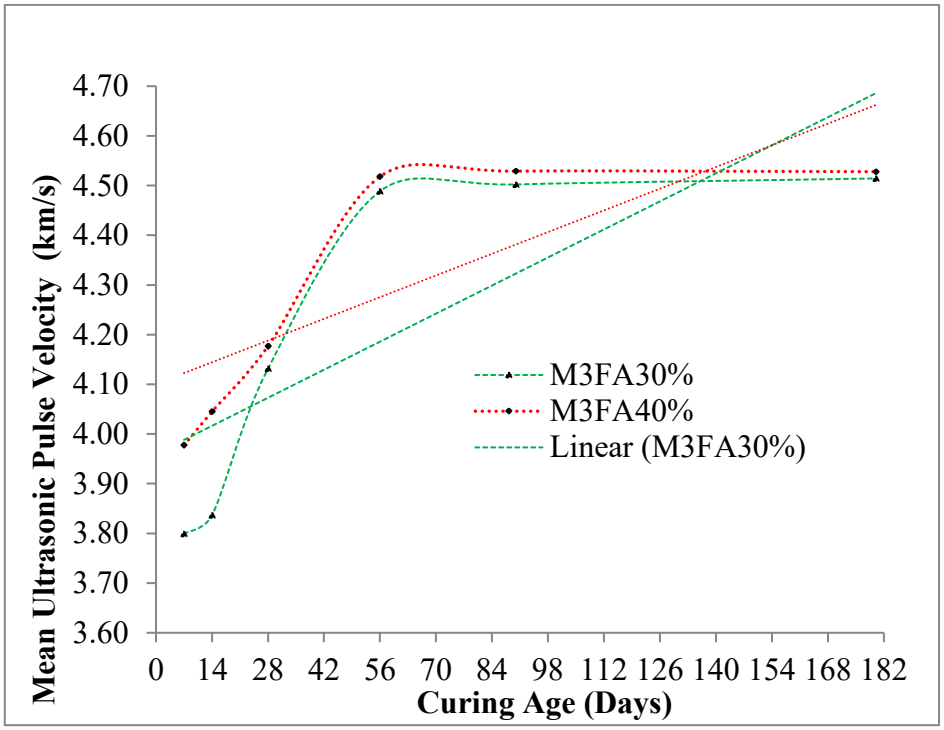


Figure 5.9: Effect of Fly Ash on Ultrasonic Pulse Velocity Throughout 180 days (Grade Designation M3)

Besides, water absorption performance development in Figure 5.10 was inconsistent with ultrasonic pulse velocity performance in Figure 5.8. This clearly shows that 40% was not significantly different from 30% at a curing age of 56-days. Fortunately, Figure 5.11 clearly shows that 30% trend performance development represented by the green linear line was similar to Figure 5.9, which takes over against 40% at a later age. Indeed, for grade concretes M1 and M5, it was previously concluded that the strength development of concrete mixtures enhanced with fly ash replacements became more pronounced at 56 days, 90 days and later ages.

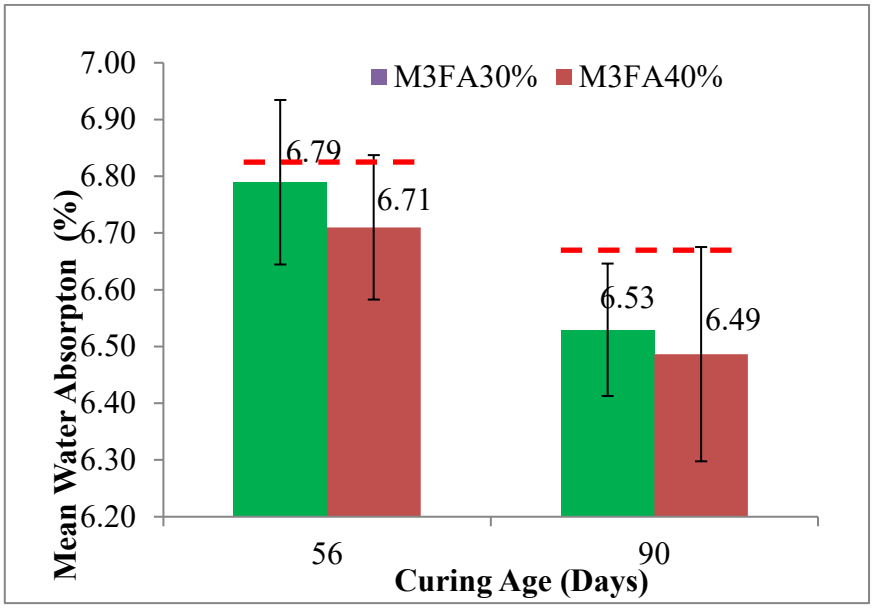


Figure 5.10: Effect of Fly Ash on Water Absorption at 56 and 90-days Age (Grade Designation M3)

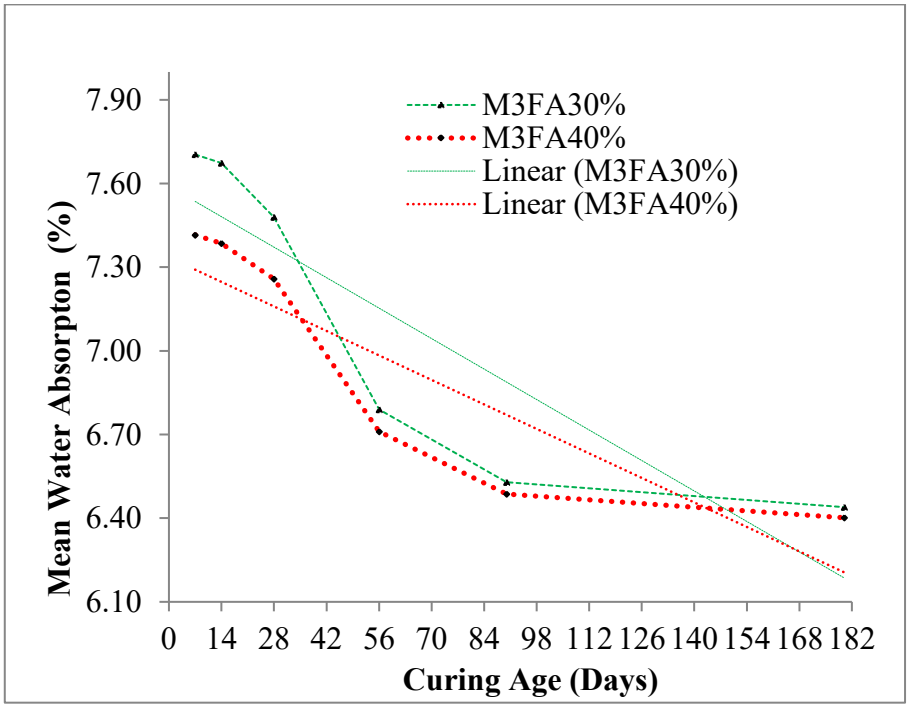


Figure 5.11: Effect of Fly Ash on Water Absorption Throughout 180 days (Grade Designation M3)

Based on the detailed analyses conducted above on clarification of optimised concrete performance either effected by 30% or 40% cement replacement, it can be concluded that the optimum compressive strength of grade designation M3 partially replaced with fly ash was 30% of cement replacement similar with grade designations of M1 and M5.

5.7 Results Validation

The optimum compressive strength was validated with additional concrete samples prepared with 30% fly-ash replacement for all grade concretes tested. Prepared samples were tested for compressive strength simultaneously at the ages of 56 and 90 days. The error ranges for grade designations M1 and M5 were 9.67% to 10.40% and 5.66% to 6.88% respectively.

Table 5.3: Validation of Compressive Strength for Grade Designation M3 with 30% Fly Ash Replacement

Age (days)	Sample No.	Compressive Strength of Samples Validation (MPa)		Study Mean Compressive Strength (MPa)	Error (%)
		Value	Mean		
56	1	60.00	60.52	57.56	5.15
	2	61.33			
	3	60.22			
90	1	65.56	65.70	60.67	8.30
	2	65.33			
	3	66.22			

Meanwhile, for grade designation M3, validation test results ranged from 5.15% to 8.3% as shown in Table 5.3. All recorded ranges of error values above were not more than 15% as maximum range value recommended by JKR (SSBW, 2020). Thus, optimisation laboratory testing considered acceptable.

5.8 Performance Verification

Prior to product improvement, optimised performance of tested fly ash is ensured fall into the confidence interval stated in national specifications, guidelines or studies integrating fly ash in concrete works as suggested by Taguchi's approach. Thus, the 30% of optimised local fly ash cement replacement were compared with established worldwide available optimised performance of fly ash data. Table 5.4 shows the summary of percentage ranges and optimised fly ash tested worldwide. Data from Tables 1.3 (Chapter 1), 2.8, and 2.31 (Chapter 2) were compiled based on normal concrete partially replaced with Class-F fly ash only and proven performance was tested from a marine environment perspective.

Based on the Table 5.4, the usage of fly ash for RC structures ranges from 15 to 55%, in such a large gap in fly ash percentages of about 40% will cause the client, designer or decision maker facing difficulties to determine the accurate optimised fly ash percentage replacement that should be applied to local concrete products. Thus, some developed countries have been conducting local fly ash performance optimisation testing on concrete mixtures as advocated by most concrete work standards. As a result, Belgium, United States, Canada, Turkey and Australia are optimising fly ash in concrete mixtures with cement replacement percentages of 40%, 25%, 15% and 30% respectively. Meanwhile, Canada and New Zealand, which have almost similar climatic exposure on USA and Australia optimised fly ash in concrete mixtures with cement replacement at 25% and 30% respectively. Overall, the present and the most valuable optimised fly ash percentage replacement around the world ranges from 25% to 30% (UFGS, 2010; BS, 2016).

Table 5.4: Summary of Worldwide Available Data Based on Percentage Ranges of Optimised Fly Ash to Combat Chloride-induced Attack for RC Structures in Marine Environment

No.	Country	Code of Standard / Designation	Ranges / Optimise Fly Ash Class-F (%)
1	CEN	BS 8500-2:2015+A1:2016 (BSI, 2016)	21 - 55%
2	USA	UFGS-03 31 29: 2010 (UFGS, 2010)	20 – 40%
3		ACI 318-08 (ACI, 2005)	Limited to 25%
4	Australia	Specification Guide NB80:2012 (RMS, 2012a)	20 - 40%
5		Chloride Resistance of Concrete:2009 (CCAA, 2009)	Optimised at 30%
6	New Zealand	NZS 3101.1:2006 (NZS, 2006)	Optimised at 30%
7	Belgium	Strength and durability of high-volume fly ash concrete (Baert et al., 2008)	Optimised at 40%
8	Canada	Effect of Curing on the Compressive Strength, Resistance to Chloride-Ion Penetration and Porosity of Concretes Incorporating SCM (Ramezanianpour and Malhorta, 1995)	Optimised at 25%
9	Turkey	Influence of fly ash on corrosion resistance and chloride ion permeability of concrete (Boga and Topcu, 2012)	Optimised at 15%

Locally, Sejingkat's Class-F fly ash tested on famous local ready-mixed concrete was proven experimentally optimised at 30% cement replacement for grade designations M1, M3 and M5. This discovery also corresponded to the earlier discussion in Chapter 2 (Section 2.3.5) on fly ash concrete optimisation among developed countries, followed by Sarawak's standard concrete practice dealing with fly ash usage as detailed in Section 2.4. In such a condition, it was truly verified by survey questionnaire form and detailed field

investigation under procedure work of Chapter 4. Thus, the reliable optimised dosage of fly ash percentage replacement should be accommodated in SSBW and SSRW as part of the contractual construction documents to eliminate chloride-induced attack on RC marine structures was 30% cement replacement.

5.9 Concrete Standard Specifications Improvement

All the results obtained in this chapter were planned according to Taguchi's philosophy principles as shown in Table 2.30 (Chapter 2) and implemented according to Table 3.8 (Chapter 3). Quality and long-term cost-saving were priorities, thus the various stages included collecting data, conducting field investigations and testing were carried out to ensure quality was really embedded and to minimise variation from a target for products that have more resistance to chloride-induced attack. As a result, it is crucial to improve the present JKR's concrete standard specifications (SSBW, 2020) with the valuable findings from this study to suit local conditions as advocated by Eurocodes standards (BSI, 2016).

Cement broad designation types IIB-V and IVB-V, with fly ash composition ranges of 21 to 35% and 36 to 55% respectively, shall be merged into a single optimised value of 30% fly ash cement replacement. Significant changes must be made to the existing fly ash composition on Table D1 in SSBW 2020 (Page D/45 or equivalent to Figure 2.10) by introducing fly ash optimised value as Shown in Figure 5.12. In order to combat chloride-induced corrosion under XS3 class exposure, Tables D2, D9 and D10 in SSBW 2020 are fully subjected to the changes in fly ash composition stated in the proposed amended Table D1.

Broad Designation[b]	Composition	Comprises cement and combination types (see Table D2)
CEM I	Portland cement	CEM I
CEM I-SR 0 CEM I-SR 3	Sulphate-resisting Portland cement	CEM I-SR 0 CEM I-SR 3
IIA	Portland cement with 6 % to 20 % fly ash, ground granulated blastfurnace slag, limestone, or 6 % to 10 % silica fume[c]	CEM II/A-L, CIIA-L, CEM II/A-LL, , CIIA-LL, CEM II/A-S, CIIA-S, CEM II/A-V, CIIA-V, CEM II/A-D
IIB-S	Portland cement with 21 % to 35 % ground granulated blastfurnace slag	CEM II/B-S, CIIB-S
IIB-V	Portland cement with 21 % to 35 % fly ash	CEM II/B-V, CIIB-V
IIB+SR	Portland cement with 25 % to 35 % fly ash	CEM II/B-V + SR, CIIB-V + SR
IIIA[d]	Portland cement with 36 % to 65 % ground granulated blastfurnace slag	CEM III/A, CIIIA
IIIA + SR	Portland cement with 36 % to 65 % ground granulated blastfurnace slag with additional requirements that enhance sulphate resistance	CEM III/A + SR[e], CIIIA + SR[e]
IIIB[f]	Portland cement with 66 % to 80 % ground granulated blastfurnace slag	CEM III/B, CIIIB
IIIB+ SR	Portland cement with 66 % to 80 % ground granulated blastfurnace slag with additional requirements that enhance sulphate resistance	CEM III/B + SR[e], CIIIB + SR[e]
IVB-V[g]	Portland cement with 36 % to 55 % fly ash	CEM IV/B-V, CIVB-V

LEGEND: **single optimised value of 30% fly ash**

Figure 5.12: Proposed Amended Table D1 on Fly Ash Optimise Composition

5.10 Chapter Summary

Based on experimental laboratory test results for Cu, UPV and WA accompanied by statistical analyses in accordance with Taguchi's approach work program, it was clearly determined that the accurate optimised percentage of Class-F fly ash replacement tested on famous ready-mixed grade concretes supplied in Sarawak was 30%.

In addition, the combination of this valuable finding on UCV, CV1, and CV2 provides an effective platform in developing Ideal Steps NDT (ISN) guidelines and PBDS indicators for real concrete quality monitoring systems, as explained in detail in Chapters 6 and 7 respectively.

CHAPTER 6

PERFORMANCE NDT GUIDELINES FOR CORRELATION BETWEEN CU AND UPV

6.1 Introduction

Presently, NDT has become the most powerful sophisticated standard test method widely used for quality monitoring system throughout construction phases due to greater value for money and guarantee on the safety of public users. Principle of performance-based stated that the construction of RC structures must be monitorable on a regular basis and strictly comply with durability indicators other than those specified in prescriptive specification during pre-qualification testing. In-line with Taguchi's approach, the quality of the product should be designed into the product and not to be inspected for it. In order to meet these requirements, it is critical to develop Ideal Steps NDT (ISN) Guidelines suited to present QA/QC monitoring system standard practice with greater cost-effective implementation and enhanced safety builds up public users' trust.

6.2 Quality Assessment / Quality Control (QA/QC) Monitoring Improvement

The significant findings in this chapter were to develop Ideal Steps NDT (ISN) guidelines based on NDT technique identified in Chapter 2 (Section 2.5.4). Concrete testing flow chart of Figure D1 in SSBW (2020) was improved from prescriptive specification to the performance QA/QC monitoring system with the help of NDT throughout the construction phases. The QA/QC monitoring system indirectly integrated structural sustainable health monitoring by lengthening the infrastructure lifespan and gaining the confidence of public users. Overall operational steps involved in this chapter were steps No. 4 till No.13 as stated in Table 3.8. Steps No.4 till No.7 was repetitive steps in objective 1.

Meanwhile, steps No.8 and No.9 were explained detail in Sections 6.3 and 6.4 respectively. Performance enhancement and Quality Assessment/Quality Control monitoring Improvement as explained detail in Sections 6.5 and 6.6 respectively.

6.3 Results and Discussion

All laboratory test results, including Cu, UPV, WA and VPV were analysed by using SPPS software version 25 prior to NDT modelling towards the development of Ideal Steps NDT (ISN) guidelines. Identifications of normalised distribution data were carried out using graphical method or/and normalised tests on each variable at individual and combined grade designations. Overall, the operational steps involved in this chapter were Steps No. 4 till 13 as stated in Table 3.8 of Chapter 3 (Section 3.8). The explanations of the results of the analyses and NDT modelling are discussed in detail in the following sections.

6.3.1 Normalise Test Analyses

Combined grade designations normality tests summarised in Table 6.1 shows that only VPV data was not normally distributed when tested by the Kolmogorov-Smirnov approach, with significance value of less than 0.05. Unfortunately, without VPV involvement, the determination of significant variables at the earliest opportunity under DOE conditions will be more affected due to the limited involvement of variables as explained in Chapter 2 (Section 2.7.3). Thus, further normalisation tests on individual grade designation are required as encouraged by Taguchi's approach to include as many variables as possible before any correlation and regression analyses take place.

Table 6.1: Summary of Normality Tests by Combined Grade Designations of Cu, UPV, WA and VPV Test Results

Variables	Kolmogorov-Smirnov (Significance)	Conclusion of Normality Test
Cu	0.200	Data normally distributed
UPV	0.200	Data normally distributed
WA	0.120	Data normally distributed
VPV	0.030	Data NOT normally distributed
Limitation values as per guidelines stated in Chapter 3 (Section 3.9.1)	Significance value is greater than 0.05	Data normally distributed

According to Table 6.2, all skewness and kurtosis values lay within allowable ranges of -0.5 to 0.5 and -2 to 2 respectively. This could lead to the assumption that all of the group data were approximately symmetric distributed data. However, for correlation and modelling purposes, the data should be proven statistically normally distributed with a significance value greater than 0.05.

According to Table 6.3, only UPV test results showed normally distributed data tested by Kolmogorov-Smirnov and Shapiro-Wilk at all grade designations, followed by VPV employing normally distributed data tested by Kolmogorov-Smirnov. Meanwhile, WA showed not normally distributed data by Shapiro-Wilk for all grade designations as well as M5WA not normally distributed data tested by Kolmogorov-Smirnov. In addition, only

M1Cu showed significance for normally distributed data tested by both approaches. To collaborate between the requirements of quality control stated in Figure D1 in SSBW (2020) and the objective study by transforming prescriptive specification to PBDS with the assistance of NDT, Cu became the most important variable to be estimated throughout the construction phases without causing damage to RC structures. Thus, data screening was required for variables M3Cu and M5Cu before proceeding with correlation and NDT modelling.

Table 6.2: Summary of Descriptive Data Analyses of UPV, WA and VPV Test Results

Grade Designation	Variables	Kurtosis	Skewness	Outlier (%)
M1	UPV	- 0.886	- 0.155	0
	WA	-1.431	0.123	0
	VPV	-1.583	- 0.067	0
M3	UPV	-1.037	0.173	0
	WA	- 0.910	- 0.164	0
	VPV	-1.074	- 0.022	0
M5	UPV	-1.246	- 0.121	0
	WA	- 0.808	0.113	0
	VPV	-1.001	0.048	0
Limitation values as per guidelines stated in Chapter 3 (Section 3.9.1)		-2 to +2	-0.5 to +0.5	0

Notes: Summary of descriptive data analysis of Cu test results referred in Table 5.2 (Chapter 5).

.

Table 6.3: Summary of Normality Tests by Individual Grade Designation of Cu, UPV, WA and VPV Test Results

Variables	Kolmogorov-Smirnov[a] (Significance)	Shapiro-Wilk (Significance)	Conclusion of Normality Test
M1Cu	0.200	0.418	Data normally distributed
M1UPV	0.200	0.103	Data normally distributed
M1WA	0.063	0.020	Data normally distributed
M1VPV	0.125	0.148	Data normally distributed
M3Cu	0.001	0.014	Data NOT normally distributed
M3UPV	0.200	0.064	Data normally distributed
M3WA	0.062	0.023	Data normally distributed
M3VPV	0.200	0.039	Data normally distributed
M5Cu	0.017	0.043	Data NOT normally distributed
M5UPV	0.144	0.565	Data normally distributed
M5WA	0.006	0.016	Data NOT normally distributed
M5VPV	0.200	0.030	Data normally distributed

Note: Data only treated as normally distributed if the significance value was greater than 0.05

(Chapter 3; Section 3.9.1)

Table 6.4 shows group data for M3Cu and M5Cu after screening have been transformed into normally distributed data as proven by the Shapiro-Wilk significance values. Thus, correlation could appropriately take place to determine the most significant NDT variable before proceeding with NDT modelling.

Table 6.4: Summary of Normality Tests by Individual Grade Designation of Cu Test Results (After Data Screening)

Variables	Kolmogorov-Smirnov[a] (Significance)	Shapiro-Wilk (Significance)	Remarks
M3Cu	0.016	0.065	Removed 6 out of 36 samples to provide data normally distributed
M5Cu	0.137	0.353	Removed 2 out of 36 samples to provide data normally distributed

Note: Data only treated as normally distributed if the significance value is greater than 0.05 (Chapter 3; Section 3.9.1)

6.3.2 Correlation Test Results

Table 6.5 shows all coefficient of determination (R-squared or R^2) and correlation coefficient (R) results for Cu versus UPV, WA or VPV determined by using the Pearson approach (full SPSS test results attached in Appendix N).

Table 6.5: Summary of R and R-square for Cu versus UPV, WA and VPV Respectively on Grade Designations M1, M3 and M5

Variables	Regression Statistics	M1	M3	M5
Cu Vs. UPV	R	0.979**	0.944**	0.955**
	R^2	0.959	0.892	0.912
Cu Vs. WA	R	-0.912**	-0.838**	-0.861**
	R^2	0.832	0.702	0.741
Cu Vs. VPV	R	-0.920**	-0.840**	-0.866**
	R^2	0.846	0.705	0.750

Note: **. Correlation was significant at the 0.01 level (2-tailed)

Cu showed a positive relationship with UPV and negative relationships with both variables of WA and VPV. Cu versus UPV recorded the highest R values among the tested variables for all grade designations, followed by Cu versus VPV and lastly by Cu versus WA. Similarly, the condition of R^2 which had the highest values was employed by Cu versus UPV and considered as a very strong correlation with 96%, 89% and 91% of the variation in Cu was explained well by UPV for grade designations M1, M2 and M3 respectively. In addition, all the R values shown were acceptable for modelling purposes with significant correlation at the level of 0.01 as indicated as R**. Thus, the most significant correlation could be NDT models that could be adopted to Figure D1 in SSBW 2020 for QA/QC monitoring purposes with the availability of the local standard test method guideline as stated in Chapter 2 (Section 2.4.4) was Cu versus UPV.

6.3.3 NDT Modelling by ANOVA analyses

All simple linear regressions produced by the ANOVA analyses stated in Table 6.6 were represented as very good NDT models, in which significance (F) values were less than the confidence interval of 0.05.

Table 6.6: Summary of Simple Linear Regression for Cu Versus UPV on Grade Designations M1, M3 and M5

Grade Designation (MPa)	Model	Significance, F (< 0.05)	P-values (< 0.05)
M1(25)	$Cu_1 = 32.651UPV_1 - 88.157$	3.871E-25	2.109E-21
M3(35)	$Cu_2 = 37.118\ UPV_2 - 106.058$	4.654E-15	2.259E-11
M5(45)	$Cu_3 = 44.994\ UPV_3 - 137.898$	1.926E-18	1.447E-14

Meanwhile, selected variables of UPV representing NDT for modelling were shown to have very strong variable modelling at all grade designations as well as P-values were less than the confidence interval of 0.05 (full SPSS test results attached in Appendix O).

6.4 Results Validation

The NDT models were validated with additional concrete samples prepared with 30% fly-ash replacement. The prepared samples were tested for Cu and UPV simultaneously at the ages of 28 and 56-days suited to JKR practice and strength maturity of fly ash concrete respectively. Actual UPV results were used for the prediction of Cu values by using models available in Table 6.6. Meanwhile, actual Cu results from similar cube concrete specimens were used for modelling validation by complying with the requirement for significant value at the 0.01 level ($\pm$10% errors). The validation analyses result including sources of data are represented detail in the following sections.

6.4.1 Grade Designations M1 and M3 (Primary finding)

Based on the results obtained from the primary findings (publication No. 3 shown in Appendix A) provided along with proof validation to fulfil the study are as listed below;

1. Grade designations M3(35) and M5(45) recorded strong correlation relationships between Cu and UPV of about 0.776 and 0.807 respectively.
2. Different results (errors) between model predictions and actual testing were in the ranges of -8.55 to 2.31% and -4.91 to 7.01% for grade designations M3(35) and M5(45) respectively.

These primary findings were based on raw data from tested specimens aged 14, 28, 56, 90, and 180 days. Based on the findings, NDT models are still reliable with significant standard errors of less than ±10%.

6.4.2 Final NDT models

The final NDT models shown in Table 6.6 were validated based on the UPV results for tested specimens from primary findings. Calculated values for validation results were indicated graphically to demonstrate clearly that the NDT models in the study complied with the ±10% modelling limitation.

Table 6.7 shows 17% of individual raw data errors computed did not comply with the requirement of significant of level of 10%. However, it was just slightly higher than 10%. Meanwhile, mean errors computed only ranged from -9.15 to 7.48% which complied with significant level modelling requirements. In addition, it is clearly shown in Figure 6.1 that all mean errors computed are within ±10% of the modelling limitation. Thus, all models in Table 6.6 are ready to be used on-site for NDT monitoring with an accuracy of ±10%. Besides, similar results of validation correlation modelling between Compressive Strength (Cu) and Ultrasonic Pulse Velocity (UPV) were recorded ± 10% deviation from the true value of the actual experiment works (Torrent and Luco, 2007).

Table 6.7: Validation Test Results of Simple Linear Regression for Cu versus UPV on Grade Designations M1, M3 and M5

Grade Designation (MPa)	Age	No.	Measured UPV, km/s	Predicted Cu, MPa		Actual Tested Cu, MPa		Errors (%)	
				Raw	Mean	Raw	Mean	Raw	Mean
M1(25)	28	1	3.536	27.30	27.44	29.78	29.63	-8.33%	-7.40%
		2	3.533	27.20		28.89		-5.85%	
		3	3.552	27.82		30.22		-7.95%	
	56	1	3.824	36.70	37.39	34.67	35.04	5.87%	6.70%
		2	3.865	38.04		34.89		9.03%	
		3	3.846	37.42		35.56		5.24%	
M3(35)	28	1	4.157	48.24	47.73	53.09	52.54	-9.13%	-9.15%
		2	4.195	49.65		53.71		-7.56%	
		3	4.078	45.31		50.82		-10.84%	
	56	1	4.524	61.86	61.78	61.37	59.67	0.80%	3.53%
		2	4.530	62.09		59.26		4.77%	
		3	4.511	61.38		58.39		5.12%	
M5(45)	28	1	4.265	54.00	58.94	56.35	60.12	-4.17%	-1.96%
		2	4.481	63.72		63.64		0.13%	
		3	4.378	59.09		60.36		-2.11%	
	56	1	4.545	66.60	67.23	60.10	62.55	10.81%	7.48%
		2	4.561	67.32		66.12		1.81%	
		3	4.571	67.77		61.43		10.32%	

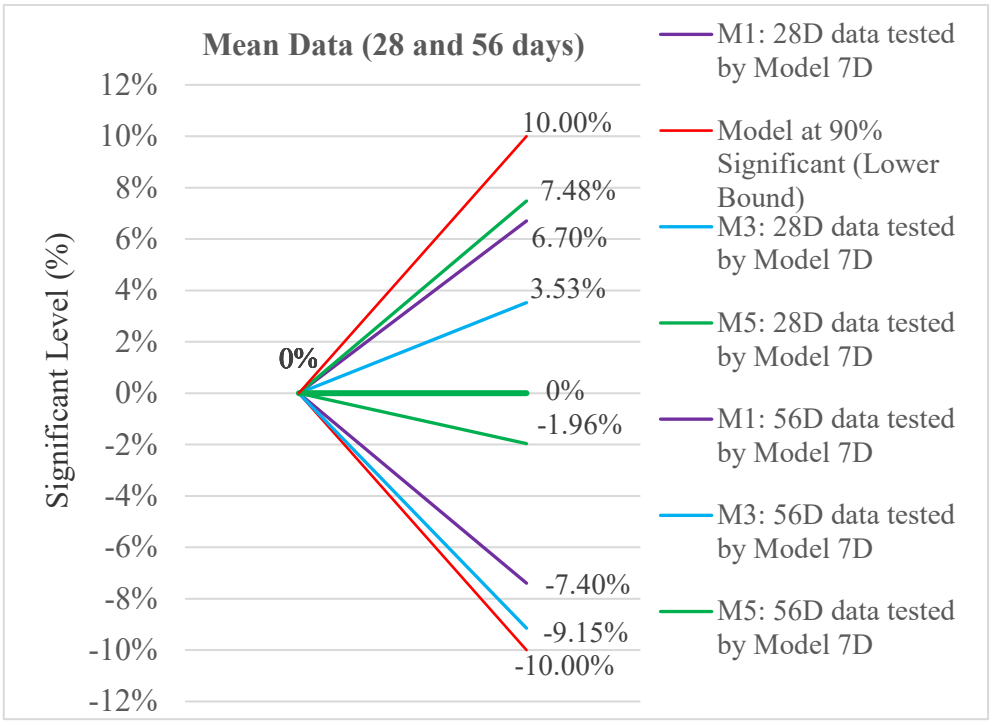


Figure 6.1: 7D Model Complies with ±10% of Modelling Limitation

6.5 Performance Modelling Enhancement

The mean result errors computed in Section 6.4.2, which range from -9.15 to 7.48% is categorised as an accuracy of ±10%. There is a gap for improvement by narrowing down the ranges of errors into ±5%, thus making the models approach the significant level of 95%. In addition, procedure steps involved for improvement can be the basis of guidelines for ideal NDT modelling throughout the construction phases as recommended by Taguchi approach to designed quality monitoring into the product (Roy, 2010).

In order to develop NDT models approaching the significant level of 95%, additional 14D and 28D NDT models were generated based on existing data used in the 7D NDT models as well as by studying the trend of errors based on curing ages. 14D model indicated that the data used for modelling started at 14 days of test results and it applied accordingly

to the 28D model as well. Unfortunately, the 56D NDT model was rejected due to data not normally distributed for grade designation M3.

According to Table 6.8 (SPSS result in Appendix P), most of the models generated were unable to fully comply with the accuracy of ±5%. However, overall mean error results have shown great improvement. As such, mean errors computed were enhanced to the ranges of -7.57 to 5.84% and -6.90 to 6.29% provided by the 14D and 28D models respectively, which initially ranged from -9.15 to 7.48% in the 7D model.

Table 6.8: Summary of Simple Linear Regression for 14D and 28D Models on Grade Designations M1, M3 and M5

Grade Designation (MPa)	Age	Model	Significance, F- (< 0.05)	P-values (< 0.05)	Errors (%)	
					28 Days	56 Days
M1(25)	14D	$Cu_{1,14D} = 30.784UPV_1 - 81.283$	3.575E-18	9.051E-15	-6.50	5.84
M3(35)		$Cu_{2,14D} = 32.951UPV_2 - 87.966$	6.839E-15	5.412E-11	-7.57	2.27
M5(45)		$Cu_{3,14D} = 37.193UPV_3 - 103.668$	7.232E-16	1.342E-11	-2.19	4.95
M1(25)	28D	$Cu_{1,28D} = 31.699UPV_1 - 84.641$	7.632E-12	2.706E-9	-6.90	6.29
M3(35)		$Cu_{2,28D} = 30.998UPV_2 - 79.275$	2.084E-11	3.867E-8	-6.43	2.03
M5(45)		$Cu_{3,28D} = 36.438UPV_3 - 100.337$	3.365E-10	5.515E-7	-1.75	5.17

Based on Figure 6.2, it is clearly shown that all models generated on grade designation M1 complied with ±10% but were still beyond ±5% of the modelling limitation.

However, additional models were proven to be more precise than 7D models. Which, the most significant model was created by the 14D model with significant levels of -6.50 and 5.84% based on data validation of 28 days and 56 days respectively, followed by 28D and 7D. The significant levels were enhanced from -7.4 to -6.50% and 6.70 to 5.84%.

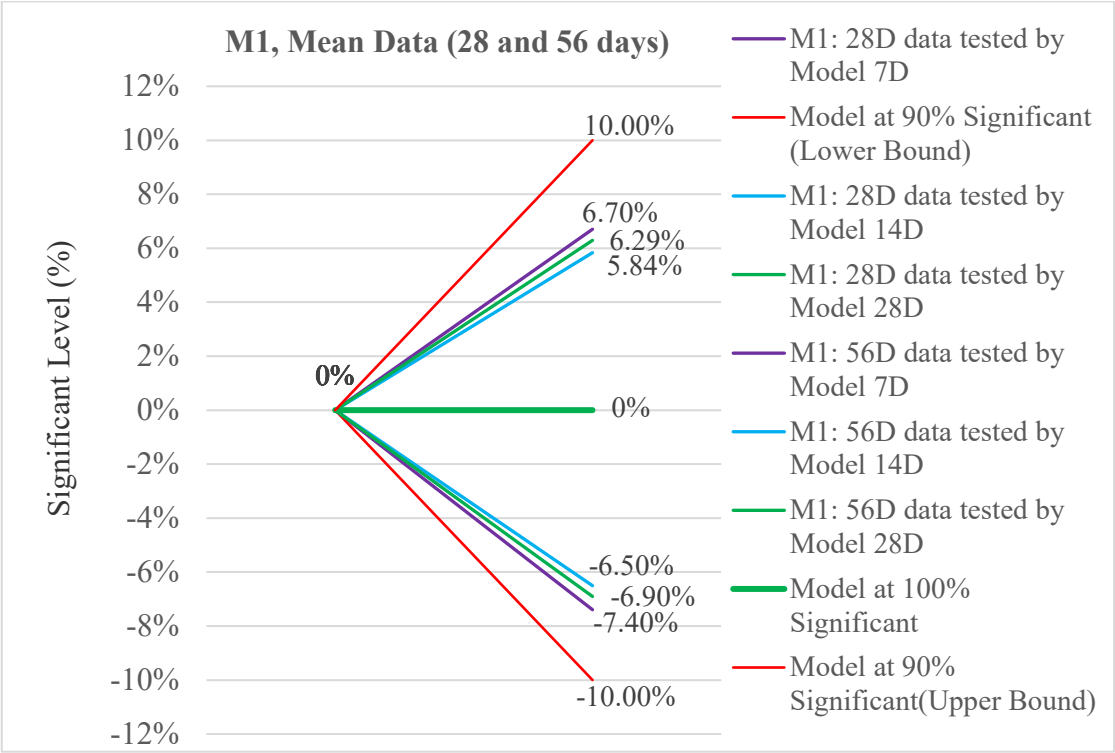


Figure 6.2: Grade Designation M1 for 7D, 14D and 28D Models Compliance to ±10% of Modelling Limitation

Based on Figure 6.3, it is clearly shown half of the models generated on grade designation M3 complied with +5% of the modelling limitation. The most significant model was determined by the 28D model with significant levels of -6.43% and 2.03% based on data validation of 28 days and 56 days respectively, followed by 14D and 7D. The significant levels were enhanced from -9.15 to -6.43% and from 3.53 to 2.03%. In fact, these figures'

enhancement was of lower values than the results shown in Figure 6.2. Thus, it can be confirmed that the 28D model was more precise compared to the 14D and 7D models.

In addition, Figure 6.4 clearly shows all models generated on grade designation M5 showed the compliance combination trend results of M1 and M3 models. The most significant models were the 28D model and the 14D model for data validations of 28 days and 56 days respectively. The significant levels were enhanced from -1.96 to -1.75% and from 7.48 to 4.95%.

Based on modelling enhancement test error results shown in Figures 6.2, 6.3 and 6.4, it can be concluded that the 28D model was the most significant compared to the 14D and 7D models. Thus, the real NDT modelling (Ideal Steps NDT (ISN) Guidelines) throughout the construction phases can be more precisely developed concurrently with 28 days compressive strength tests conducted accordingly to SSBW (2020). The most reliable developed NDT models (stated in Table 6.8) and ISN's three main steps (according to clauses in SSBW) are summarised in Section 6.7.

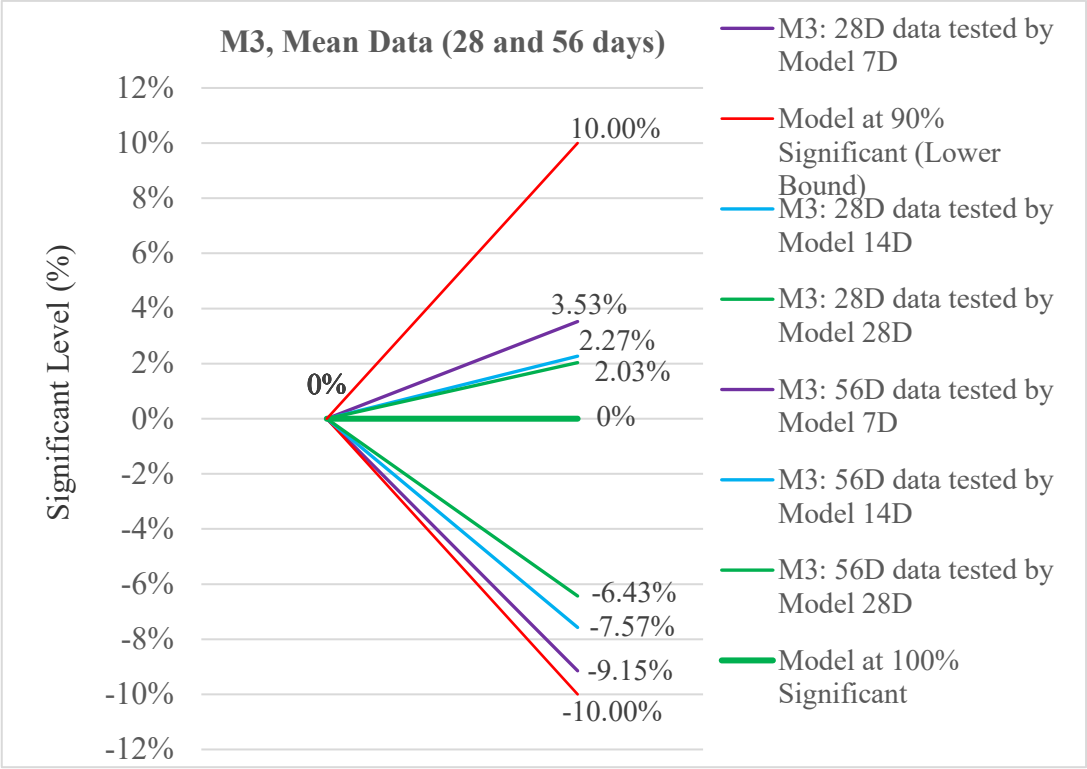


Figure 6.3: Grade Designation M3 for 7D, 14D and 28D Models Compliance to +10% of Modelling Limitation

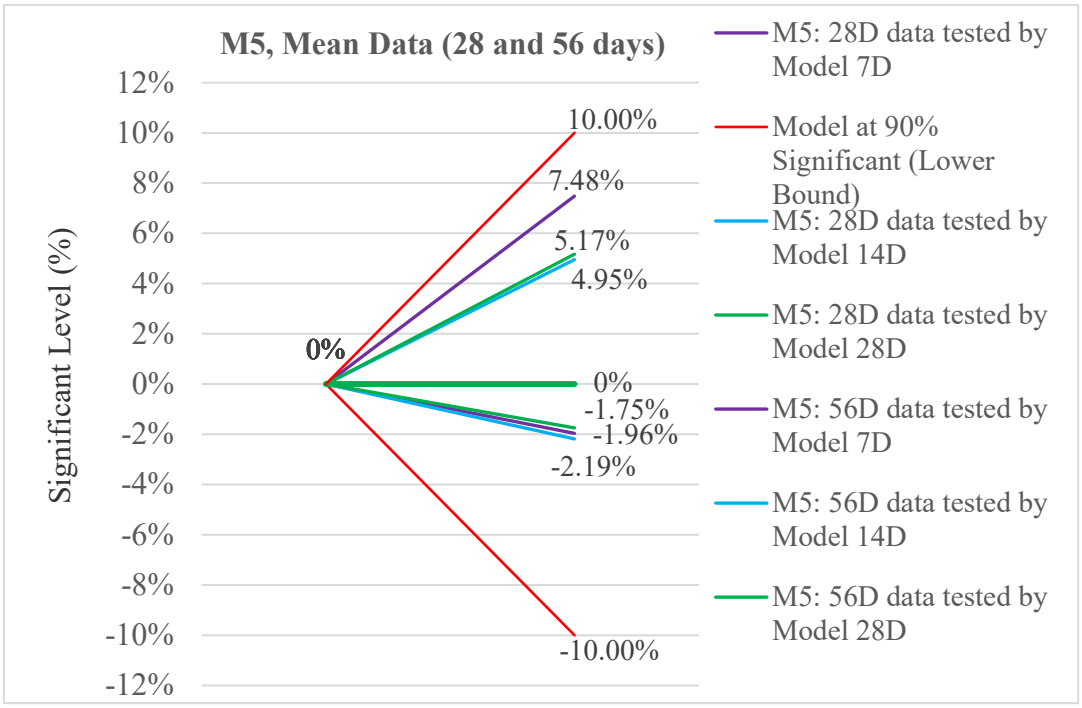


Figure 6.4: Grade Designation M5 for 7D, 14D and 28D Models Compliance to +10% of Modelling Limitation

6.6 Quality Assessment / Quality Control (QA/QC) Improvement

As a result, implementing the Taguchi approach through processes of variable identification up to product improvement implemented by taking advantage the Concrete Testing Flow Chart of Figure D1 in SSBW (2020), will ensure the lifespan design period is fulfilled by any of two (2) valuable alternative NDT approaches. In addition to the developed NDT stated in Table 6.8, an ideal NDT QA/QC monitoring model can be developed concurrently in accordance with clauses available in SSBW:2020 before being able to be utilised as a regular maintenance inspection sophisticated tool during service lifespan. Thus, the Concrete Testing Flow Chart in Figure 2.9 on Page 58 is to be improved by accommodating developed NDT models or implementing Ideal Steps NDT (ISN) Guidelines QA/QC monitoring on the identified testing activities as shown overlapped in Figure 6.5. Ultrasonic pulse velocity (UPV) and Compressive Strength (Cu) tests must be conducted

simultaneously during the construction phase for data collection toward the development of an Ideal Steps NDT.

6.7 Chapter Summary

Based on experimental laboratory test results of Cu and UPV accompanied with modelling using statistical ANOVA in accordance to Taguchi's approach work programme, findings of two (2) valuable alternatives NDT approaches were finalised as follows;

1. The most significant developed NDT models were based on 28D modelling as shown in Table 6.8. Developed NDT models according to grade designations might be applied to Figure D1 in SSBW:2020 as stated below;

   $Cu_1 = 31.699UPV_1 - 84.641$, and R2 = 0.886 Equation 6.1

   $Cu_2 = 30.998UPV_2 - 79.275$, and R2 = 0.933 Equation 6.2

   $Cu_3 = 36.438UPV_3 - 100.337$, and R2 = 0.853 Equation 6.3

   Where Cu_1, Cu_2 and Cu_3 represented compressive strengths of 25, 35 and 45 MPa.

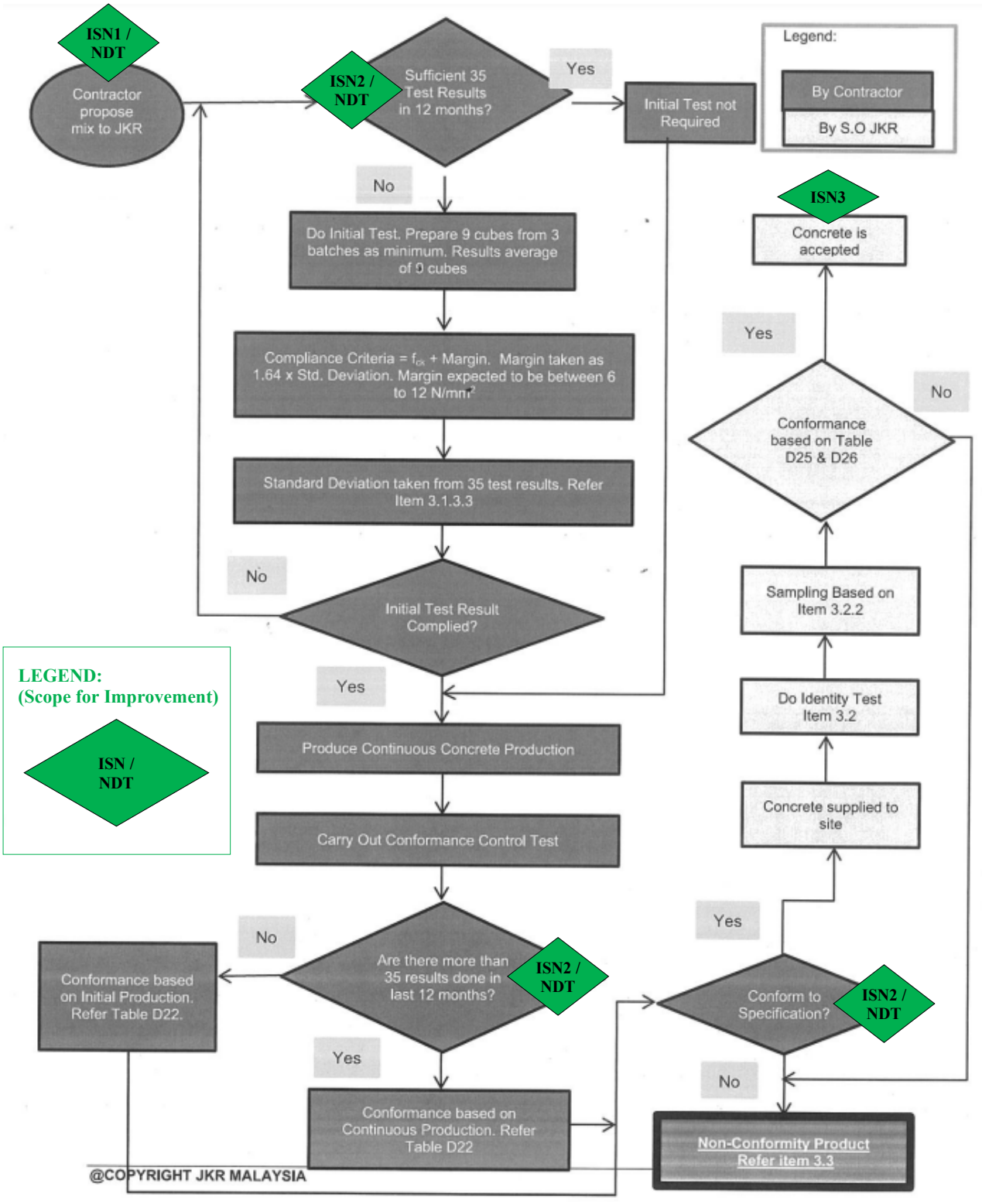


Figure 6.5: Proposed Embedding of a Real NDT Monitoring System into JKR's Concrete Testing Flow Chart

2. Alternative NDT, designed as Ideal Steps NDT (ISN) Guidelines QA/QC monitoring model may be accommodated in Figure D1 (Figure 2.9) as a series of step procedures in accordance with clauses available in SSBW:2020. ISN's three main steps are summarised below;

ISN1 : Primary NDT model developed at a pre-qualification testing level by preparing at least 9 test results in accordance to clause 3.1.2 as a requirement for initial compressive strength tests.

ISN2 : Continuous NDT model improvement conducted concurrently with continuous production in accordance with Clause 3.1.3 for at least 35 test results as a requirement for continuous compressive strength tests.

ISN3 : High accuracy NDT model developed based on real data contributed by ISN2 throughout the construction period can be utilised as structural sustainable health monitoring for completed RC structures under a chloride-induced environment with the assistant of PBDS indicators explained in Chapter 7.

CHAPTER 7

PERFORMANCE-BASED DURABILITY SPECIFICATIONS

7.1 Introduction

After several decades since the 1950's, Malaysia's standard specifications for concrete works have still relied on prescriptive specification by referring to Concrete of Practice (CP), British Standards (BS) and presently Eurocodes directly. The local concrete works practice for most of the time assume that the target mean strength based on material proportion and workmanship in preparing the test specimen is the same as as-built structures. This assumption is seldom true and the prescriptive method-based cannot guarantee a satisfactory "performance" of hardened concrete throughout its lifespan. Nowadays, a few developed countries have produced Performance-Based Durability Specifications (PBDS) guidelines suited to local conditions for sustainable health monitoring of structure based on developed Quality Rating Durability Compliance (QRDC). Thus, the main objective of this chapter is to formulate a PBDS indicators accompanied with QRDC indicators for quality monitoring purposes using the most low-cost sophisticated testing tools at a high level of precession.

7.2 Preliminary Results

Prior to the development of the PBDS model, several grade designations namely M4, M5 and M6 were tested to determine the capability and ease of implementation of durability standard test methods identified in Chapter 2 (Section 2.5.3). Indirectly, the tested variable also confirmed the contribution of grade concrete to concrete durability properties. Thus, selected concrete grade designations were made in gradually increasing order as concrete price increased accordingly. Trial durability tests conducted were WA, VPV and sorptivitiy

tests. Durability standard test methods for WA and VPV are explained in Chapter 3 (Section 3.7), while sorptivity tests were conducted in accordance with ASTM C1585 (ASTM, 2013).

The concrete specimens used for these durability tests were obtained from similar ready-mixed concrete supplier identified in Chapter 3 (Section 3.4) and ready-mixed concrete designs are shown in Table 7.1.

Table 7.1: Ready-mixed Concrete Designs (Primary tests)

Concrete Designation	Cement (kg/m^3)	Water (kg/m^3)	Water / cement ratio	Fine Agg. (kg/m^3)	Coarse Agg. (kg/m^3)	Slump (mm)
M4	400	160	0.40	660	1168	120
M5	460	175	0.38	540	1150	110
M6	422	148	0.35	621	1284	100

Prior to the curing procedure, 150 mm concrete cubes were cut horizontally into three equal pieces by using a heavy-duty cutter machine and specimens were named as Top, Middle and Bottom as shown in Figure 7.1.

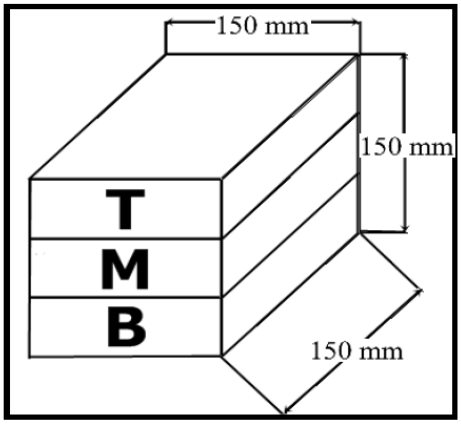


Figure 7.1: 150 mm Concrete Cube Cut Horizontally into Three Equal Pieces (Parts)

7.2.1 Water Absorption Test

Based on the grade designations evaluated, most of the water absorption values decreased as the grade of the specimen increased. However, there was only a little difference between M4 and M5 for the middle zone at all ages on tests as shown in Figure 7.2. Thus, the increase in the grade designations did not guarantee the reduced volume of capillary pores as well as the high expenditure for higher grade concrete. In fact, the middle zone was just 50 mm from the surface of concrete, which did not comply with standards specifying concrete cover at XS3 class exposure with an intended lifespan of 100 years (SSBW, 2020). Water absorption is defined in such cases as the transport of liquid through porous solids (concrete cover) due to capillary absorption (Khatib et al., 1995). Thus, the water absorption test represented more accurately compared to concrete grade as a durability indicator.

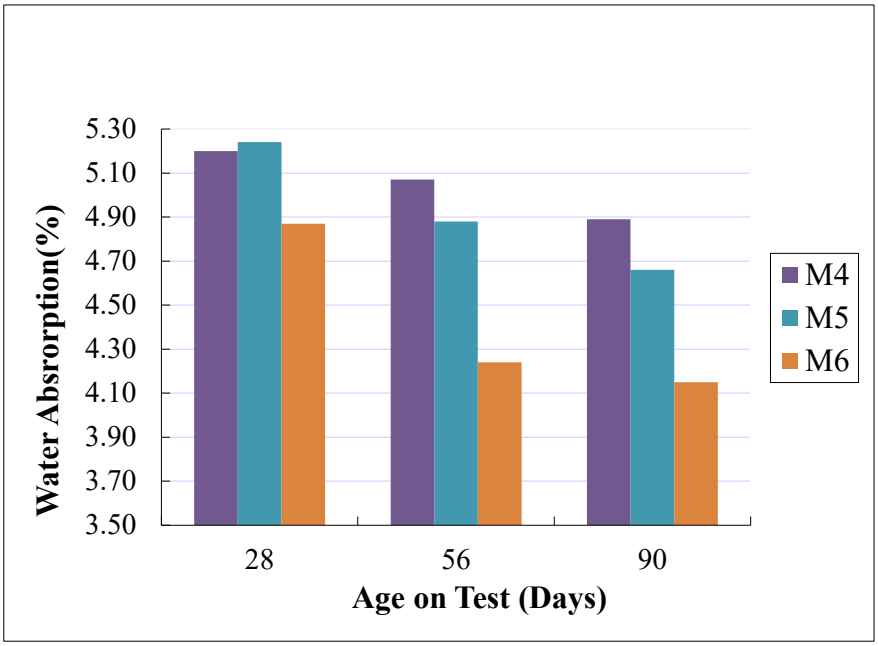


Figure 7.2: WA Values in the Middle Part of M4, M5, and M6 at Different Ages

7.2.2 Volume of Permeable Voids Test

The VPV result was directly proportional to the water absorption result, whereas the water absorption increased as permeable voids increased (Dinakar et al., 2008) as similar agreements were explained in Chapter 2 (Section 2.2.2). Figure 7.3 shows that grade designations were not consistent with VPV performance. In such, VPV values between M4 and M5 were almost half compared to the difference between M5 and M6 at all ages. Conclusively, VPV had a similar capability to water absorption and the availability of QRDC indicators stated in Section 2.6.2 was an advantage for VPV to be considered as a QRDC indicator measurement.

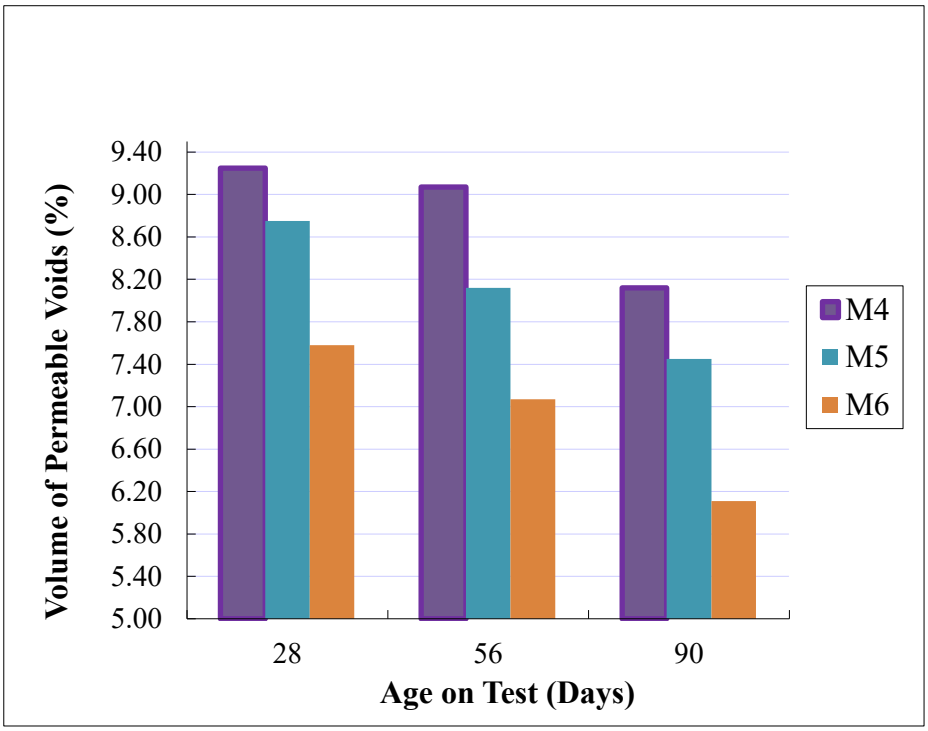


Figure 7.3: VPV Values in the Middle Part of M4, M5, and M6 at Different Ages

7.2.3 Sorptivitiy Test

Sorptivity is defined as the rate of movement of water on the surface of the concrete under the action of capillary force (Mannan and Idris, 2013). As the age and degree of hydration of the specimen increased, the sorptivity as well as the porosity decreased (Mehta, 1991). All results showed that the sorptivity decreased as the grade designation increased. However, there was only a minimal difference in performance between M4 and M5 at all ages on tests as shown in Figure 7.4. Overall, the durability performance of the sorptivity test is good, as are the WA and VPV capabilities. Unfortunately, it was identified in Chapter 2 (Section 2.5.3) sorptivity was unable to suit JKR's qualification age test for the earlier 7-day compressive strength test. As such, 7-day compliance testing was the time frame required for the striking of formwork on some element structures.

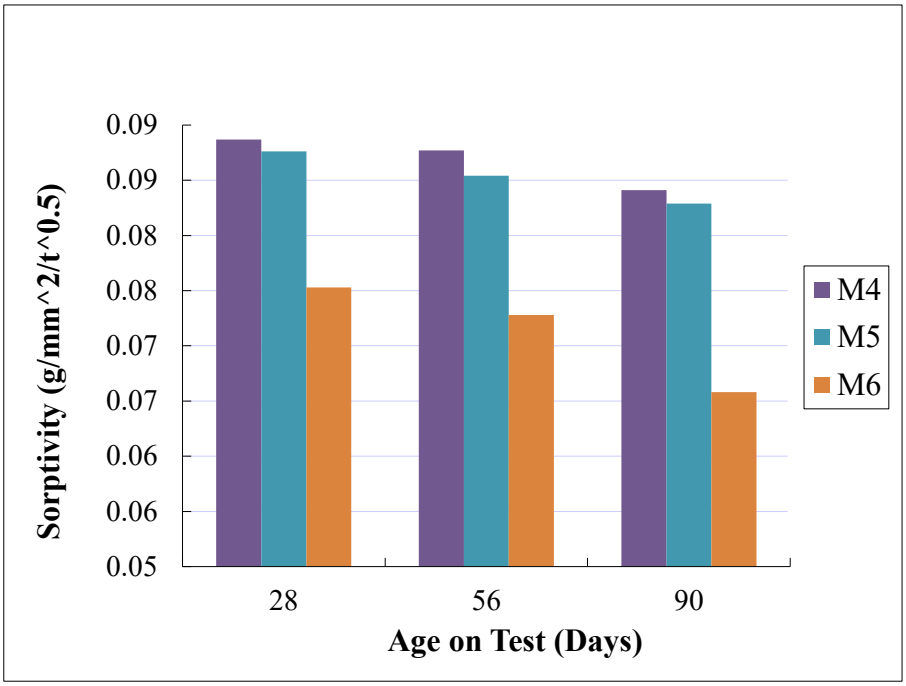


Figure 7.4: Sorptivity Values in the Middle Part of M4, M5, and M6 at Different Ages

7.3 Performance-based Durability Modelling

Based on Section 7.2 above, WA and VPV were selected to proceed with performance-based durability modelling due to the advantages and availability of QRDC indicators as explained in Chapter 2 (Section 2.6.2). Meanwhile, UPV was included as a durability testing indicator due to NDT advantages and the availability of QRDC indicators as explained in Chapter 2 (Section 2.6.1). In addition, Cu was incorporated for analyses of performance-based durability modelling due to mandatory concrete testing requirements as explained in detail in Chapter 2 (Section 2.4.3). Overall, the operational steps involved in this chapter were step No. 4 till 13 as explained in Chapter 3 (Section 3.8). The results of the analyses and performance-based durability modelling are discussed in detail in the following sections.

7.3.1 Normalise Test Analyses

For the purpose of performance-based durability modelling prior to production of QRDC indicators, data used for normalised test analyses in Table 6.1 (Chapter 6) were screened out to provide normally distributed data. Data screening has been conducted in accordance with number of specimens' limitations required by JKR's standard practice and the Kolmogorov–Smirnov test. In that case, JKR and Kolmogorov–Smirnov tests required at least 35 and 50 test results respectively. Each data variable was screened from 108 to 78 test results and the final normalised test analysis results are shown in Table 7.2. The Kolmogorov-Smirnov significance values for all the tested variables were greater than 0.05 value, which means they complied with the modelling limitation. Thus, performance-based durability modelling could take place to establish QRDC indicators suited to local conditions.

Table 7.2: Summary of Normality Tests for Combined Grade Designations of Cu, UPV, WA and VPV Test Results (After Screening)

Variables	Kolmogorov-Smirnov (Significance)	Conclusion of Normality Test
Cu	0.200	Data normally distributed
UPV	0.200	Data normally distributed
WA	0.200	Data normally distributed
VPV	0.200	Data normally distributed
Limitation values as per guidelines stated in Chapter 3 (Section 3.9.1)	Significance value was greater than 0.05	Data normally distributed

7.3.2 Performance-based Durability Modelling by ANOVA analyses

According to the variables stated in Table 7.2 above, a total of ten (10) models were generated by SPSS software based on Orthogonal Arrays (OAs) (full SPSS test results are attached in Appendix Q). Only two models were successfully generated under ANOVA analysis selection as Multiple Linear Regression (MLR) as shown in Table 7.3. Meanwhile, six of which were excluded due to not fulfil modelling requirements, and two of which were only generated as Single Linear Regression (SLR).

Based on Table 7.3, Model 1 was inappropriate to include in the performance-based durability modelling due to UPV having been assigned as NDT assessment to avoid destructing the structure member. According to the chapter's objective, UPV and other NDT determined in Section 2.5.4 (Chapter 2) are utilised as NDT QA/QC monitoring system for concrete works throughout the lifespan of the built structure.

Table 7.3: Summary of Performance-based Durability Models

Model	Variable / Model	Significance, F (< 0.05)	P-Values (< 0.05)
UPV = n1Cu – n2WA + n3 Where; n1, n2 and n3 are no. decimal points	Model 1	0.000	-
	UPV	-	0.000
	Cu	-	0.000
	WA	-	0.000
WA = 0.843VPV – 0.078UPV + 0.104	Model 2	0.000	-
	WA	-	0.006
	VPV	-	0.000
	UPV	-	0.033

Besides, Model 2 statistically met the requirements of modelling, in which significance (F) values were less than the confidence interval of 0.05. Meanwhile, WA, VPV and UPV variables were found to have very strong significant variable modelling, with all P-values recorded less than the confidence interval of 0.05. Thus, the developed PBDS indicators model has successfully qualified and is capable of projecting QRDC indicators for the purpose of the performance verification process as required by the Taguchi approach.

7.3.3 Local Quality Rating Durability Compliance

Proposed QRDC indicators were projected on the basis of performance-based durability modelling (Model 2) include UPV, VPV, WA, and Cu variables. As such, the concrete quality rating used in the proposed QRDC indicator is directly referenced to the available rating categories in BS1881 (1986) as well as provided in Chapter 2 (Section 2.6.1: Table 2.28). Based on the proposed QRDC indicators shown in Table 7.4, suitable concrete

quality should have at least a "GOOD" quality rating for non-aggressive environment exposure. Meanwhile, for aggressive chloride-induced environments, an "EXCELLENT" quality rating should be used. Besides, any RC structure that falls under QRDC indicators with a condition of "DOUBTFUL" concrete quality should be rejected. Conclusively, proposed QRDC indicators are applicable to all types of performance testing specified in Chapter 2 (Section 2.5.2: Table 2.17) subjected to the client's desired concrete quality adopted from Table 7.4.

Table 7.4: Proposed QRDC Indicators for UPV, VPV, WA and Cu Variables

BS1881:1986		**Developed PBDS Indicators Model (Proposed QRDC Indicators)**			
UPV (km/s)	**Concrete Quality**	**UPV, Rodded Cube 150mm (km/s)**	**VPV, Rodded Cube 100mm (%)**	**WA, Rodded Cube 100mm (%)**	**Cu, Rodded Cube 150mm (MPa)**
Above 4.5	Excellent	> 4.5	< 10	< 7	≥ 55
3.5 – 4.5	Good	3.5 – 4.5	10 - 12	7 – 8	30 - 50
3 – 3.5	Medium	3.0 – 3.5	12 - 14	8 – 9	20 - 25
Below 3	Doubtful	< 3.0	> 14	> 9	≤ 15

In-place performance testing may use Model 2 for concrete quality rating assessment based on UPV and VPV test results directly measured on the built structures. The UPV test may be carried out in accordance with the method of measurement specified in Chapter 2 (Section 2.6.1(A): Table 2.25) or MS EN 12504-4:2013, and the VPV cored sampling in

accordance with MS EN 12504-1:2013. Durability concrete quality rating assessment based on Model 2 is represented by Equation 7.1 below.

$$WA = 0.843VPV - 0.078UPV + 0.104 \quad \text{Equation 7.1}$$

Where;

WA = Water absorption is predicted for built structures by Model 2.

VPV = Volume of permeable voids is directly tested on core samples extracted from built structures.

UPV = Ultrasonic pulse velocity is directly measured on the surfaces of built structures.

7.4 Results Validation

The PBDS indicators model in the study shown in Equation 7.1 was validated by using the raw data of UPV, VPV and WA test results from all grade designations that were not used in the modelling process. Total of 216 predicted WA values were computed by using a developed model, and then compared with the actual test results to estimate the different (error) values. The average of maximum and minimum errors for each grade designation was almost constant with ranges from 5 to -5% are shown in Table 7.5 (full validation test results and data used are attached in Appendix R).

Table 7.5: Summary of Validation Test Results of Predicted and Actual WA

Grade Designation (MPa)	Errors (%)	
	Maximum	Minimum
M1(25)	4	-4
M3(35)	5	-3
M5(45)	5	-5

In such, all validation test results were compliant with a very strong significant level modelling requirements at a fulfilment rate of 95% of the confidence interval. As a result, the formulated PBDS indicators model presented in Equation 7.1 is ready for use on-site for concrete quality rating assessment with a $\pm$ 5% accuracy.

7.5 Performance Verification

Table 7.6 shows the comparison of recommended VPV values between CCAA 2009 and the PBDS indicators in the study. CCAA 2009 has five categories for rating concrete quality versus only four categories provided by the proposed QRDC indicators.

Table 7.6: Comparison of Recommended VPV Values between CCAA 2009 and Study on QRDC Indicators

Cement Concrete & Aggregates Australia (Chloride Resistance of Concrete)		**Study's PBDS Indicators (Proposed QRDC indicators)**	
Durability Classification Indicator	**Rodded* Cylinders (VPV %)**	**Concrete Quality**	**VPV, Rodded** Cube 100mm (%)**
Excellent	<12	Excellent	< 10
Good	12-14	Good	10 - 12
Normal	14-15	Medium	12 - 14
Marginal	15-17	Doubtful	> 14
Bad	>17		

Notes:

* Rodded by 16 mm diameter tamping rod

** Rodded by 25 mm square tamping rod

However, both agreed on the first and second categories, which are denoted by "EXCELLENT" and "GOOD" concrete quality. In addition, both performance indicators agreed that to combat chloride-induced attack on RC structure, concrete quality should be in "EXCELLENT" condition.

Table 7.7 shows a summary of minimum compressive strengths to combat chloride-induced environment for RC marine structures. It was recorded that the highest minimum compressive strength was assigned to concrete grade of 50 MPa, by Australian and Indian standards. Meanwhile, the USA only assigned a minimum compressive strength of at least about 35 MPa. In addition, New Zealand's utilised compressive strength ranged from 40 to 100 MPa depending on the thickness of concrete cover and type of SCM. Besides, JKR implementation fully relies on Eurocodes which range from 30 to 50 MPa subjected to W/C, minimum cement content and types of SCM.

Overall, the compressive strengths that were used to combat chloride-induced attack for RC structures ranged from 30 to 100 MPa. Thus, the proposed QRDC indicators with a minimum compressive strength of 55 MPa is reasonable to be utilised for quality control monitoring in concrete works that are exposed to a chloride-induced environment.

More crucial, most practicing engineers have adopted Eurocode guidelines based on CEN conditions. As revealed by the results of survey questionnaires, most grade concretes used to combat chloride-induced deterioration was 30 MPa. As such, clearly identified by the detailed field investigation which was described in Chapter 4 (Section 4.4.1) that the chosen grade of concrete was not workable in combating chloride-induced environment deterioration in Sarawak.

Based on the concrete quality rating categories and the compressive strength performance confidence interval discussed above, it can be concluded that the value provided by the proposed QRDC indicators is reliable. Thus, it is acceptable for use as a QA/QC monitoring system for concrete work during construction and throughout the life of the built structure.

Table 7.7: Summary of Worldwide Available Data Based on Minimum Compressive Strengths to Combat Chloride-Induced Attack for RC Structures

No.	Country	Code of Standard / Designation	Minimum Compressive Strengths (MPa)	Remarks
1	JKR	JKR's Standard specifications for building works (SSBW, 2020)	30 - 50	Depending on W/C, minimum cement content and types of SCM.
2	CEN	MS EN 1992-1-1:2010 (NA) (MS, 2010b)		
3	USA	UFGS-03 31 29: 2010 (UFGS, 2010)	$\geq$ 35	-
4		ACI 201.2R-08 (ACI, 2008)		
5	Australia	Specification Guide NB80:2012 (RMS, 2012a)	$\geq$ 50	-
6		Chloride Resistance of Concrete:2009 (CCAA, 2009)		
7	New Zealand	NZS 3101.1:2006 (NZS, 2006)	40 - 100	Depending on concrete cover and types of SCM.
8	India	IS 456:2000 (Kulkarni, 2009)	$\geq$ 50	-

7.6 Performance-based Durability Specifications Indicators Optimisation

In order to optimise the performance of the developed PBDS indicators model according to established national specifications or guidelines, the proposed QRDC indicator values were compared with established QRDC indicator data from around the world. Currently, only UPV and VPV provide QRDC indicators as shown in Chapter 2 (Section 2.6.1: Table 2.28) and Chapter 2 (Section 2.6.2: Table 2.29) respectively. However, the UPV rating value (BS 1881:1986) has been set as the reference basis for the local QRDC assessment. Besides, presently there is no QRDC indicator provided for WA by established concrete standards to combat chloride-induced attack for RC structures. Therefore, formulated PBDS model indicator optimisation verification can only be made on VPV rating values.

Most of the VPV values in proposed QRDC indicators shown in Table 7.6 above are less than 2% compared to CCAA 2009. It just indicates that these indicators have lower number values compared to CCAA 2009 due to the usage of rodded 25 mm square tamping rod versus 16 mm diameter tamping rod. As such, rod of 25 mm square is more effective in compacting fresh concrete compared to 16 mm in diameter. In fact, it is well known that compression strength tests on cylinder concrete are always lower compared to cube concrete. It can be concluded that the VPV values provided by the proposed QRDC indicators in this study are lower than VicRoads Australia's which provide more factors of safety indicator and thus acceptable.

7.7 Performance-based Durability Specifications Indicators Implementation

Presently, there is no durability indicator based on capillary absorption assessment embedded in the present Sarawak standard concrete practice as revealed in Chapter 2 (Section 2.4). Therefore, for an accurate assessment of RC structures effected by the chloride-induced attack, it is necessary to embed the proposed QRDC indicators shown in Table 7.4 into the contractual document construction as a basis for concrete durability acceptances criteria under clauses listed as follows (SSBW 2020);

1) Clause 1.1.1: Designed Concrete
2) Clause 3.1: Evaluation Conformity
3) Clause 3.2: Identify Test
4) Clause 7.5: Inspection and Making Good

QRDC indicators monitoring was proven among the developed countries to provide more benefits to the RC marine structures, clients and environment as detailed out in Chapter 2 (Section 2.5). Thus, proposed QRDC indicators provide a very flexible interface to the clients, local authorities, designers or decision makers to make an accurate decision based on the optimum concrete performance, concrete treatment and financial capacity.

7.8 Chapter Summary

Based on experimental laboratory test results of Cu, UPV, WA and VPV accompanied with modelling using statistical ANOVA in accordance to Taguchi's approach work programme, the chapter's findings are finalised as follows;

1. Formulate PBDS indicators model in this study based on VPV and UPV is stated below.

   $$WA = 0.843VPV - 0.078UPV + 0.104 \quad \text{Equation 7.1}$$

2. Developed QRDC indicators should be applied to RC marine structures under aggressive chloride-induced environment with UPV, VPV, WA and Cu values of more than 4.5 km/s, less than 10%, less than 7% and at least 55 MPa respectively. OR classified as "EXCELLENT" concrete quality in Table 7.4.

3. Developed QRDC indicators should be applied to RC structures under non-aggressive chloride-induced environment with UPV, VPV, WA and Cu values not less than 3.5 km/s, 10%, 7% and 30 MPa respectively. OR classified as "GOOD" concrete quality in Table 7.4.

4. Any RC structure that falls under QRDC indicators with a condition of "DOUBTFUL" concrete quality as stated in Table 7.4 should be rejected. Rejected indicator values for UPV and Cu are less than 3.0 km/s and equal to or less than 15 MPa. Meanwhile, VPV and WA values are more than 14% and 9% respectively.

CHAPTER 8

CONCLUSION AND RECOMMENDATIONS

8.1 Conclusion

Study based on real-world local problem scenarios investigated with Taguchi's approach and a combination of survey questionnaires, detailed field investigation, experimental work, and Statistical Product and Service Solutions (SPSS) modelling has resulted in a greater durability specification for the local environment. Performance NDT guidelines and a model of PBDS indicators adapted to local products or practises were developed from existing prescriptive specifications into Performance-based Durability Specifications (PBDS), as advocated by Eurocode 2.

The perceptions of construction industry players among local authorities, developers, consultants, contractors, concrete suppliers and maintenance engineers on chloride-induced corrosion affecting RC structures in Sarawak had been assessed using survey questionnaires form. In general, 74.0% are aware of the effects of chloride-induced corrosion, and 84.8% believe that sea water is the most significant contributor to this problem. While 94.5% of the respondents, mostly from the local authorities, consultants, concrete suppliers, and engineers of infrastructure maintenance, agreed essentially to produce chloride-induced corrosion guidelines. Besides, it was revealed by survey questionnaires that the minimum grade of concrete and the required thickness of concrete cover did not meet the present standard specifications by construction industry players. 45.2% (mostly local authorities and contractors) only adopted a 50 mm thickness of concrete cover versus 60 to 80 mm and 21.9% (mostly contractors and consultants) only used 30 MPa versus 25 to 50 MPa of grade concrete to combat chloride-induced deterioration.

Based on the Cu, UPV and WA test results accompanied by descriptive statistical analyses and performance verification, it was certainly determined that local Class-F fly ash optimisation tested on famous ready-mixed grade concretes supplied in Sarawak was 30% of cement replacement. Thus, cement broad designation types of IIB-V and IVB-V with fly ash composition ranges from 21 to 55% in SSBW (2020) that recommended to combat chloride-induced corrosion, should be merged into 30% to provide a quantified optimised proportion to designers, concrete suppliers or decision makers.

Based on the Cu and UPV test results accompanied by SPSS modelling and performance verification, it was revealed that grade designations of 25 and 45 MPa were recorded as strong correlations, whereas grade designation 35 MPa was recorded as a very strong correlation. Developed NDT models Specific for grade designations of 25, 35 and 45 MPa were as represented by equation correlations of Cu1 = 31.699UPV1 – 84.641, Cu2 = 30.998UPV2 – 79.275 and Cu3 = 36.438UPV3 – 100.337 with recorded R2 values of 0.886, 0.933 and 0.853 respectively. In addition, Ideal Steps NDT (ISN) Guidelines developed to suit JKR's Concrete Testing Flow Chart implementation and represented using three main steps as shown in Chapter 6 (Section 6.7). Adopting medical check-up by using NDT correlation between Cu and UPV developed throughout construction phases or utilising any equation correlation stated above ensures the sustainability of RC structures and guarantees the safety of public users.

Based on the durability variable test results accompanied by SPSS modelling, performance verification and durability indicator optimisation, the formulated PBDS indicators model tested on famous ready-mixed grade concretes was represented with a model equation of WA = 0.843VPV – 0.078UPV + 0.104. A significance (F) value of 0.000

was recorded, which was less than the confidence interval of 0.05 (limitation of modelling verification) and proved through result validation that this model provided a highly significant measurement of $\pm$ 5% accuracy. In addition, WA, VPV and UPV variables were found to have very strong significant variable modelling, with all P-values settled below the confidence interval limitation of 0.05 with values of 0.006, 0.000 and 0.033 respectively. Meanwhile, the dependent variable (WA) recorded very strong correlations with independent variables (VPV and UPV) with R^2 values of 0.982 and 0.983 respectively. Furthermore, QRDC indicators to combat chloride-induced corrosion at XS3 class exposure should be complied to “EXCELLENT" concrete quality as provided in Table 7.4. Whereas the QRDC indicator values for UPV, VPV, WA and Cu should be more than 4.5 km/s, less than 10%, less than 7% and at least 55 MPa, respectively. Adopting the proposed QRDC indicators accordingly to "EXCELLENT" concrete quality compliance will enhance the service lifespan of RC marine structures, provide greater value for money due to less maintenance cost and guarantee the safety of public users.

8.2 Recommendations

Currently, the implementation of local concrete standards practice is still based on prescriptive specifications by choosing exposure classes to reflect compressive strength, w/c ratio, cement content and concrete cover during pre-qualification tests. Furthermore, the quality of concrete is solely determined by workability on fresh concrete and compressive strength tested at maximum of 28 days with the assumption that test results would be the same as the as-built structure. Thus, for better performance of RC structures against chloride-induced attack, it is recommended that developed Performance-based Durability Specifications (PBDS) indicators be included as part of the contractual document construction as a QA/QC monitoring system. Meanwhile, for the purpose of real NDT

monitoring on the specific RC structures after construction, it is recommended to develop an NDT correlation by using the developed Ideal Steps NDT (ISN) Guidelines.

A number of future research areas, currently beyond the scope of this study are recommended as follows;

1. Determine the optimise performance of other supplementary cementitious materials (SCM) includes ground granulated blastfurnace slag (GGBS), silica fume, rice hush ask and palm oil fuel ash (POFA) as stated in Table D1 of SSBW (2020) or advocated by Eurocode 2.

2. Develop a service life model based on water absorption tests exposed to XS3 class exposure using an accelerated test corrosion-induced environment.

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APPENDICES

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Appendix

A: Journal Publications

1. **Matarul, J.,** Mannan, M. A., Safawi, M. Z. M. I., Ibrahim, A., Jainuddin, N. A. & Yusuh, N. A. (2016) Performance-based Durability Indicators of Different Concrete Grades Made by the Local Ready Mixed Company: Preliminary Results. *Procedia-Social and Behavioural Sciences, 224*, 620-625.
2. **Matarul, J.,** Chiew, F. H., Mannan, M. A, Ibrahim, A. & Yusof, E. E. M. (2019). Relationship Between Compressive Strength and Ultra-Sonic Velocity Pulse (UPV) of Local Fly Ash. *Journal of Engineering and Applied Sciences, 14*(3), 6085-6088.
3. **Matarul, J.,** Mannan, M. A., Yussop, N., Endut, M. Z. & Ibrahim, A. (2019). Optimising concrete enhancement of local ready-mix concrete partially replaced with local fly-ash. *Journal of Physics: Conference Series, International Conference Nanomaterials: Sciences, Engineering and Technology (ICoNSET), 1349.*
4. **Matarul, J.,** Mannan, M. A., Jainuddin, N. A., Nazaruddin, A. & Fhaeizdhayall, A. (2020). The Perceptions among the Construction Industry on the Induced Chloride Corrosion for Reinforced Concrete Structure in Sarawak. *Journal of Advanced Research in Social and Behavioural Sciences, 21*(1), 11-18.

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3 November 2014

Pengarah
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93450 Kuching
Sarawak
(U.P: Tuan Hairul Anuar bin Yasin)

Tuan,

Memohon Maklumat bagi Pelajar Siswazah untuk Tujuan Kajian *'Chloride-Induce Corrosion'*

Dengan segala hormatnya perkara tersebut dirujuk.

Untuk makluman, penama seperti yang dinyatakan di bawah adalah merupakan pelajar siswazah (Doktor Falsafah) di Fakulti Kejuruteraan, UNIMAS dan sedang menjalankan kajian menyeluruh berhubung keadaan *'Chloride-Induce Corrosion'* di Sarawak secara Kaji Soal Selidik dan kerahsiaan maklumat tersebut akan dijaga sepenuhnya.

Nama	**: Ir Jamil bin Matarul**
No. Matrik	**: 15010039**
No. Telefon	**: 019-3117552**
E-mail	**: jamsrul@gmail.com**
Tajuk Kajian	**: *Enhancing Service Life of RC Structures for Chloride Belt Area Through Durability-Based Concrete Properties***
Penyelia	**: Prof Dr Md Abdul Mannan**

Maklumat berkaitan alamat penuh berserta e-mel dan nombor telefon bagi firma-firma berikut adalah diperlukan:

a) Pemaju Hal Tanah (*Developer*)
b) Perunding Reka Bentuk (*Consultant*)
c) Kontraktor Pembinaan (*Contractor: Sdn Bhd & Bhd*)
d) Pembekal Konkrit Sedia Bancuh (*Ready Mix Concrete*)

SURUHANJAYA SYARIKAT MALAYSIA
DI TERIMA
18 DEC 2014
Pengarah Negeri Sarawak
COMPANIES COMMISSION OF MALAYSIA

HZ/nj

MSC-Status

Diharap pihak tuan dapat berkongsi maklumat seperti yang dinyatakan untuk menjayakan kajian ini. Segala kerjasama dan perhatian pihak tuan amatlah dihargai dan diucapkan ribuan terima kasih.

Yang benar,

Dr Hushairi Zen
Timbalan Dekan (Pascasiswazah & Penyelidikan)
Fakulti Kejuruteraan, UNIMAS

s.k : Penyelia, Prof Dr Md Abdul Mannan

This survey is carried out as a part of the researcher's on-going PhD study with research title of "Performance-based Durability Specifications (PBDS) for Concrete Chloride-induced in Marine Environment" Survey objective is to obtain the respondent's opinion on the standard concrete practice works expose to chloride-induced (Marine structure) for the purpose of concrete durability specification improvement.

Kindly answer all the questions in the questionnaire and return it to the enumerator. Please note that all the responses are confidential and only aggregate data is used in the analysis.

Your confidentiality is assured.

Thank you for your assistance.

Yours Faithfully,

.....

Ir. Jamil Bin Matarul
(Researcher)
Faculty of Civil Engineering
Universiti Teknologi Mara Cawangan Sarawak
94300 Kota Samarahan, Sarawak.

Copy to;

1. **Prof. Dr. Mohammad Abdul Mannan**
   (Supervisor)
   Faculty of Civil Engineering
   Universiti Malaysia Sarawak
   94300 Kota Samarahan, Sarawak.

2. **Prof. Dr. Azmi Bin Ibrahim**
   (Co-Supervisor)
   Faculty of Civil Engineering
   Universiti Teknologi Mara Shah Alam
   40450 Selangor

Please answer by placing a tick (√) at the appropriate box and/or by writing your best response.

1. Town/District: _____ (e.g.: Kota Samarahan, Kuching, Sibu, Bintulu, Miri, Lawas etc.)
2. Area of responsibility:
   ☐ Local Authority ☐ Developer ☐ Architect ☐ Consultant ☐ Contractor
   ☐ Ready-mixed Concrete Supplier ☐ Others: _____
3. Position: Please specify _____
4. **IF READY-MIXED CONCRETE SUPPLIER**, what are the concrete grades you have been supply for construction?
   ☐ 25 ☐ 30 ☐ 35 ☐ 40 ☐ 45 ☐ 50 ☐ 55 ☐ 60 ☐ Others: _____
5. **OTHER THAN READY-MIXED CONCRETE SUPPLIER**, what are the concrete grades you have been used for construction?
   ☐ 25 ☐ 30 ☐ 35 ☐ 40 ☐ 45 ☐ 50 ☐ 55 ☐ 60 ☐ Others: _____
6. Do you know what is the effect of chloride to reinforced concrete structure?
   ☐ Yes ☐ No ☐ Not Sure
7. Based on your work place / knowledge, rate the corrosion factor below accordingly.

Corrosion Factors	Rating
Chloride (Sea water)	
Carbonate (fresh water)	
Chemical attacks	

RATING GUIDE;

Factor Description	Rate Indicators
Highest factor	1
Medium factor	2
Lowest factor	3

8. What is the design code/specification/standard used in your reinforced concrete design to manage chloride deterioration?
   ☐ BS8110 ☐ EN206 ☐ Not Sure ☐ Others: _____
9. What is the maximum distance consideration chloride exposure design adopted in your reinforced concrete design?
   ☐ 2km ☐ 5km ☐ 15km ☐ 20km ☐ 25km ☐ 30km above
10. What is the minimum requirement for CONCRETE GRADE adopted in your reinforced concrete design to manage chloride deterioration?
    ☐ 25 ☐ 30 ☐ 35 ☐ 40 ☐ 45 ☐ 50 ☐ 55 ☐ 60 ☐ Others: _____
11. What is the recommended CONCRETE COVER adopted in your reinforced concrete design to manage chloride deterioration?
    ☐ 25 ☐ 50 ☐ 75 ☐ 100 ☐ Others: _____
12. What is the design service life adopted in your reinforced concrete design?
    ☐ 25 Years ☐ 50 Years ☐ 75 Years ☐ 100 Years ☐ Others: _____
13. What is the recommended type of cement/materials to reduce chloride deterioration?
    Please specify: _____
14. Have you seen any other building/structure damaged by corrosion at your place?
    ☐ Yes ☐ No ☐ Not Sure
    IF YES: please, list the name of the buildings, location and completion year
    i. _____, _____ & _____.
    ii. _____, _____ & _____.
    iii. _____, _____ & _____.
15. In your opinion, is it important to produce own GUIDELINE TO CHLORIDE RESISTANCE OF REINFORCED CONCRETE STRUCTURES?
    ☐ Yes ☐ No ☐ Not Sure

Ir. Jamil Bin Matarul

Kepada Sesiapa Yang Berkenaan

26 Disember 2018

Tuan,

TO DETERMINED CRITICAL CORROSION THRESHOLD VALUE OF EXISTING MARINE STRUCTURES IN SARAWAK BY SITE CHLORIDE CONTENT MEASUREMENT.

Perkara berhubung kajian di atas adalah dirujuk.

2. Saya ingin memohon kebenaran pihak tuan untuk mengambil sedikit sampel konkrit dari senarai jambatan seperti berikut;

a. Shambir RC wharf
b. Sadong Jaya RC wharf
c. Sebuyau RC Fisheries wharf
d. Terminal Penumpang Sebuyau
e. Sematan RC wharf
f. Buntal Espalanade

3. Tatacara pengambilan sampel adalah dengan kaedah "Non-destructive" seperti perincian pada Lampiran 1. Sampel jambatan kajian adalah tidak terbatas kepada senarai di atas, pihak tuan juga boleh mencadangkan sebarang jambatan di bawah kuasa pentadbiran tuan untuk tujuan kajian di atas terutama jambatan terbiar atau perlukan kajian yang sama.

4. Besar harapan saya agar pihak tuan dapat memberi kebenaran untuk menjayakan kajian ini dan didahulukan dengan ucapan ribuan terima kasih.

Sekian.

Yang Benar

.....

Ir. Jamil Bin Matarul
Pelajar Sambilan, Fakulti Kejuruteraan Awam, UMIMAS

DEWAN BANDARAYA KUCHING UTARA
28/12/2018

s.k.: Prof. Dr. Md. Abdul Mannan – Penyelia PhD, Fakulti Kejuruteraan Awam, UMIMAS

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Tel: 082-677200 Fax: 082-677300

Tuan/Puan,

TO DETERMINED CRITICAL CORROSION THRESHOLD VALUE OF EXISTING MARINE STRUCTURES IN SARAWAK BY SITE CHLORIDE CONTENT MEASUREMENT.

Merujuk kepada surat daripada pihak tuan bertarikh 26.12.2018 dan perbincangan dengan pihak tuan pada tarikh yang sama berhubung perkara tersebut di atas .

2. Untuk makluman pihak tuan, pihak kami tiada bantahan untuk pihak tuan menjalankan kajian seperti yang dipohon bergantung kepada terma dan syarat yang berikut;

i. Menghantar lakaran/gambar lokasi sampel yang akan diambil dan selepas persampelan. Sebarang persampelan hendaklah dibaikpulih kepada keadaan asal.
ii. Maklumat produk seperti SIKA yang digunakan untuk menampal semula lokasi sampel.
iii. Menyalurkan salinan keputusan kajian kepada pihak kami sebagai rekod.
iv. Isu keselamatan adalah dibawah prerogatif pihak tuan.

3. Sila berhubung dengan Pihak Lembaga Sungai Sarawak bagi jeti d, e dan f.

Sekian, harap maklum.
Terima kasih.

"CEPAT, EKONOMI DAN BERKUALITI"
"BERSATU BERUSAHA BERBAKTI"
"AN HONOUR TO SERVE"

.....
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Tuan,

TO DETERMINED CRITICAL CORROSION THRESHOLD VALUE OF EXISTING MARINE STRUCTURES IN SARAWAK BY SITE CHLORIDE CONTENT MEASUREMENT

Perkara di atas dan surat tuan bertarikh 26.12.2018 adalah dirujuk.

2. Adalah dimaklumkan bahawa pihak kami tiada halangan untuk pihak tuan mengambil sampel konkrit dari jambatan - jambatan seperti dinyatakan pada surat tuan di atas, walaubagaimanapun jambatan tersebut adalah dibawah seliaan Lembaga Sungai-Sungai Sarawak (S.R.B) dan pihak tuan bolehlah memohon kebenaran daripada mereka.

3. Sehubungan dengan perkara di atas, pihak kami berbesar hati sekiranya pihak tuan dapat mengambil sampel untuk struktur konkrit bagi pihak kami seperti di bawah:

i. Jambatan Segali, Simunjan
ii. Ramp Kokrit, Kpg. Sageng Simunjan.

Sebarang maklumat lanjut sila berhubung terus dengan pihak kami seperti dinyatakan di atas.

Sekian terima kasih.

"BERSATU BERUSAHA BERBAKTI"
"An Honour To Serve"

[IR. IRWANDEE B. REDUAN]
Jurutera Pengairan Dan Saliran
Bahagian Kuching/Samarahan

Mak/.....

DEWAN BANDARAYA KUCHING UTARA
(Commission of the City of Kuching North)
BUKIT SIOL, JALAN SEMARIANG, PETRA JAYA,
93050 KUCHING, SARAWAK.
TEL : 082-446688 HOTLINE : 082-446644 FAKS : 082-446414
Laman Web: www.dbku.gov.my : Dewan Bandaraya Kuching Utara
E-mel: pro@dbku.gov.my

Bil. Tuan :

Tarikh : 9 Jan. 2018

Bil. Kami : DBKU/IMT(A)/45/19(/)

Universiti Teknologi MARA (UITM) Sarawak
Jalan Meranek
94300 Kota Samarahan
(Ir. JAMIL BIN MATARUL)

Tuan

TO DETERMINED CRITICAL CORROSION THRESHOLD VALUE OF EXISTING MARINE STRUCTURES IN SARAWAK BY SITE CHLORIDE CONTENT MEASUREMENT

Dengan hormatnya surat bertarikh 28 Disember 2018 adalah dirujuk.

2. Dimaklumkan bahawa, pihak kami tiada halangan bagi pengambilan sampel di lokasi dibawah seliaan DBKU :-

(i)	Sambir RC Wharf	}
(ii)	Sadong Jaya RC Wharf	} Dibawah Pihak Berkuasa
(iii)	Sebuyau RC Fisheries Wharf	} Tempatan yang lain
(iv)	Terminal Penumpang Sebuyau	}
(v)	Sematan RC Wharf	}
(vi)	Buntal Espalanade – dibawah penyeliaan DBKU	

3. Walaubagaimanapun, pihak kami ingin memberi lokasi iaitu Esplanade, Lebuh Java sebagai tambahan lokasi baru pengambilan sampel tersebut.

4. Pihak tuan boleh berhubung terus dengan pegawai kami Encik Mohamad Dahlan bin Haji Maderi di talian 082-448899 jika pihak tuan mula mengambil sampel tersebut.

Sekian. Harap maklum dan terima kasih.

"INTEGRITI DAN INOVASI BUDAYA KAMI"
"AN HONOUR TO SERVE"

Ir. ZAIDI BIN HAJI PATHI
Ketua Bahagian
Bahagian Penyelenggaraan Infrastruktur

CHEMSAIN KONSULTANT SDN BHD *(130904-U)*
No. 41, 1st Floor, Wisma Ko-Perkasa, Jalan Simpang Tiga,
93350 Kuching, Sarawak, Malaysia.
Tel: +60-82-422736 / 422737 **Fax:** +60-82-415506
Email: laboratory@chemsain.com

TEST REPORT

* NOT FOR ADVERTISEMENT PURPOSES *

Customer	:	Gobel Industry Sdn Bhd Lot 1165 (P.L 1153) Block 8, Muara Tebas L.D, Demak Laut Industrial Park, Jalan Bako Petra Jaya, Kuching	Lab No. Type (No.) of Sample Date Received Date of Report Service Order	: CK/CL105/76319/13 : Fly Ash (1) : 6th May 2013 : 14th May 2013 : -
Attn	:	Mr. Patrick Hii Tai Soon		

Parameter (s)	Fly Ash	*Method*
Loss of Ignition, %	0.5	*Gravimetric*
Silica (as SiO_2), %	58.8	
Aluminium Oxide (as Al_2O_3), %	21.0	*AAS*
Magnesium Oxide (as MgO), %	2.7	
Iron (as Fe_2O_3), %	7.4	
Calcium Oxide (as CaO), %	4.6	
Calcium Hydroxide (as $Ca(OH)_2$), %	6.1	*By Calculation*
Sulphuric Anhydride (as SO_3), %	0.2	*Gravimetric*

WINNIE LING SIEW KIONG
B.Sc., AMIC (2749/4716/05/2008)
SENIOR CHEMIST

CHEMSAIN KONSULTANT SDN. BHD. Laboratory Kuching (130904-U)

NOTE: 1) This Test Report shall not be reproduced, except in full, without the written approval of the laboratory.
2) The above relates to the sample(s) tested.

Fakulti Kejuruteraan
Faculty of Engineering

www.unimas.my

Tarikh: 26 Disember 2016

Pengarah,
CMS Concrete Product
Lot 212, Block 17, KLCD
Jalan Old Airport,
93250, Kuching Sarawak.
(U.P: Mr. Lim Wee Han)

Tuan,

Memohon Sampel *'Ready Mixed Concrete'* beserta bahan mentah untuk Tujuan Kajian *'Concrete Durability Due to Chloride-Induced Corrosion'*

Dengan segala hormatnya perkara di atas dan perbualan pelajar dengan wakil pihak tuan (Mr. Lim Wee Han) pada 10hb Jun 2016 adalah dirujuk.

Untuk makluman, penama seperti yang dinyatakan di bawah adalah merupakan pelajar siswazah (Doktor Falsafah) di Fakulti Kejuruteraan, UNIMAS dan sedang menjalankan kajian menyeluruh berhubung 'Concrete Durability due to Chloride-Induced Corrosion'.

Nama	: Ir Jamil bin Matarul
No. Matrik	: 15010039
No. Telefon	: 019-3117552
E-mail	: jamsrul@gmail.com
Tajuk Kajian	: Enhancing Service Life of RC Structure for Chloride Belt Area Through Durability-Based Concrete Properties.
Penyelia	: Prof Dr Md Abdul Mannan Prof Dr Azmi Ibrahim

Untuk makluman juga, kerahsiaan maklumat hasil daripada ujikaji yang dijalankan akan dijaga sepenuhnya dan menjadi milik bersama CMS Concrete Product.

Sampel *'Ready Mixed Concrete'* yang diperlukan adalah sebanyak 0.123 m^3 bagi setiap gred G25, G30, G35, G40, G45 dan G50 untuk tujuan ujikaji seperti di Lampiran 1. Manakala bahan mentah yang diperlukan untuk tujuan penambah baikan gred konkrit adalah seperti silica fume, simen, pasir, batu agregat dan bahan tambah. Kos pengangkutan, penyediaan acuan dan tenaga kerja akan disediakan oleh pelajar sendiri.

Diharap pihak tuan dapat memberikan sampel dan bahan mentah seperti yang dinyatakan untuk menjayakan kajian ini. Segala kerjasama dan perhatian pihak tuan amatlah dihargai dan diucapkan ribuan terima kasih.

Yang Benar

AP Ir Dr Siti Noor Linda Bt Taib
Timbalan Dekan (Pascasiswazah & Penyelidikan)
Fakulti Kejuruteraan, UNIMAS

s.k. Prof. Dr. Md. Abdul Mannan
Prof Dr Azmi Ibrahim

J/1

Job No.: 2013GP12

Subject: Testing of Sand Sample from Sg. Sadong, Kuching

Sample Ref.: Sand from Sg. Sadong (Dated 01.10.2013)

Sample Submitted By: Jing Hing Sand & Stone Supplier Sdn. Bhd., Sibu

Test Report 07.11.2013

Item	Type Of Test		Test Method	Results
1	Sieve Analysis		MS 30:Part 4: 1975	Data & Gradation Plots attached
2	Relative Densities	Relative density on an oven-dried basis	BS 812:Part 2: 1995	2.566 Mg/m^3
		Relative density on a saturated and surface-dried basis		2.584 Mg/m^3
		Apparent relative density		2.613 Mg/m^3
3	Water Absorption		BS 812:Part 2: 1995	0.69%
4	Clay, Silt And Dust Content		BS 812:Part 1: 1996	0.34%
5	Soundness Test by Sodium sulphate		ASTM C88	0.42%
6	Organic Matter Content		BS 1377:Part 3: 1990	0.2%
7	Chloride Content		BS 1377:Part 3: 1990	<0.01%
8	Total Sulphate Content		BS 1377:Part 3: 1990	0.02%
9	pH Value		BS 1377:Part 3: 1990	6.7

J/2

SIEVE ANALYSIS - WET SIEVING METHOD
(MS30 : Part 4 : 1995)

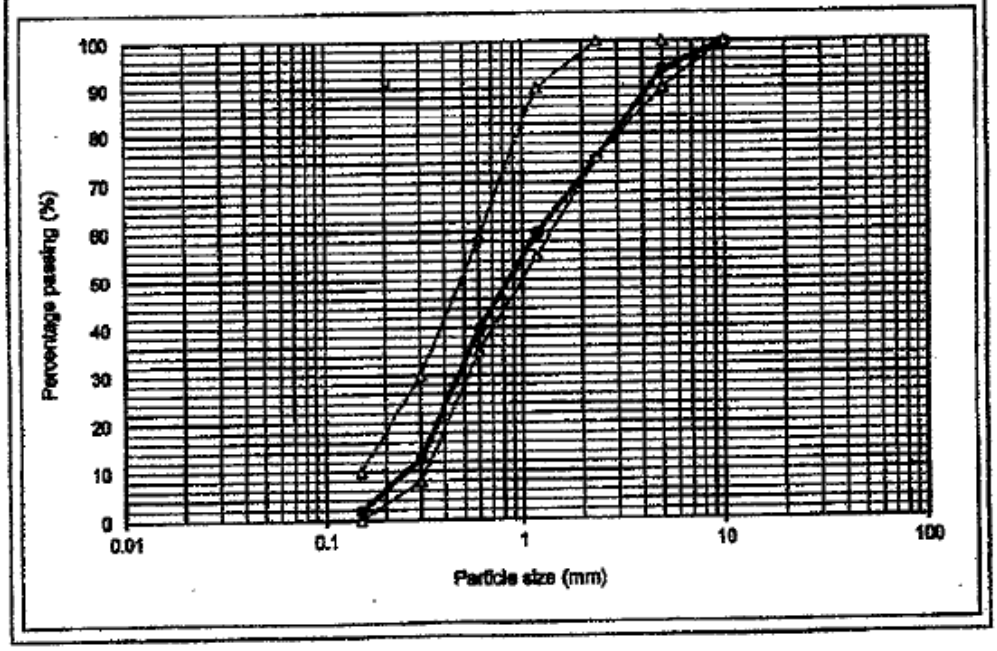
Subject: Testing of Sand Sample from Sg. Sadong, Kuching — Job No.: 2013GP12

Sample Ref.: Sand from Sg. Sadong (Dated 01.10.2013) — Tested Date: 03.10.2013

Sample Submitted By: Jing Hing Sand & Stone Supplier Sdn. Bhd., Sibu — Tested By: AC

BS sieve size (mm)	Mass Retained (g)	Total Mass Retained (g)	Cumulative Percentage Passing (%)
10	1.9	1.9	100
5	64.2	66	94
2.36	210.1	276	75
1.18	167.6	444	60
0.6	221.4	665	40
0.3	298.6	962	13
0.15	121.7	1084	2
Pan	18.9	1102	0

JKR/SPJ/1988 - Table 9.2 Gradation Limits for Fine Aggregate (Grading Zone 2)		
BS sieve size (mm)	% Passing by Weight	
10	100	100
5	90	100
2.36	75	100
1.18	55	90
0.6	35	59
0.3	8	30
0.15	0	10
-	-	-



K/1

OFFICIAL TEST REPORT

REPORT NO.: WATIMA/OTR/2013/04	PAGE: 2 OF 15

Note:
The test result is obtained from test done on the sample(s) received. We are not responsible for the reliability of the sample(s) submitted. This report shall not be reproduced, except in full and shall not be used for advertising purposes by any means or forms without written approval from Managing Director of our company.

SUMMARY OF TEST REPORT (20mm Aggregate)

Item	Type of Test		Test Method	Results
1	Moisture Content Determination		*BS 812 : Part 109 : 1990*	0.56%
2	Grading Analysis		*MS 30 Part 4 : 1995*	Please refer data & Graph
3	Clay / SILT & Dust Content		*MS 30 : 1971: Section 3, Method B*	0.33%
4	Flakiness Index (FI)		*MS 30 Part 5 : 1995*	21.19%
5	Aggregate Crushing Value (ACV)		*MS 30 Part 8 : 1995*	17.11%
6	Aggregate Impact Value (AIV)		*MS 30 : Part 10 : 1995*	14.3%
7	Elongation Index		*MS 30 : Part 5 : 1995*	23.14%
8	Ten Percent Fines Value		*MS 30 : Part 9 : 1995*	294.60 kN
9	Los Angeles Abrasion Value (LAAV)		*MS 30 : Part 11 : 1995*	17.46%
10	Specific Gravity	Sp. Gravity on Oven-dried basis	*BS 812 Part 2 : 1995*	2.545 Mg/m^3
		Sp. Gravity on SSD basis		2.579 Mg/m^3
		Apparent Specific Gravity		2.633 Mg/m^3
11	Water Absorption		*BS 812 Part 2 : 1995*	1.301%
12	Sodium Sulphate Soundness Test (5 Cycles)		*AASHTO Test Method T104*	0.85%
13	Total Sulphate Content		*BS 1377 : 1990*	0.137%
14	Chloride Content Determination		*BS 812 : 1976*	0.010%

Approved by:

PHANG TZE SHING
Managing Director

1/14

K42

OFFICIAL TEST REPORT

REPORT NO.: WATIMA/OTR/2013/04	PAGE: 4 OF 15

Note:
The test result is obtained from test done on the sample(s) received. We are not responsible for the reliability of the sample(s) submitted. This report shall not be reproduced, except in full and shall not be used for advertising purposes by any means or forms without written approval from Managing Director of our company.

TEST RESULT : ***GRADING ANALYSIS***

TEST METHOD : ***MS 30 Part 4 : 1995***

TESTED BY: Amy/Yong

DATE TESTED: 09/01/2013
TEMPERATURE: 27°C
RELATIVE HUMIDITY: -

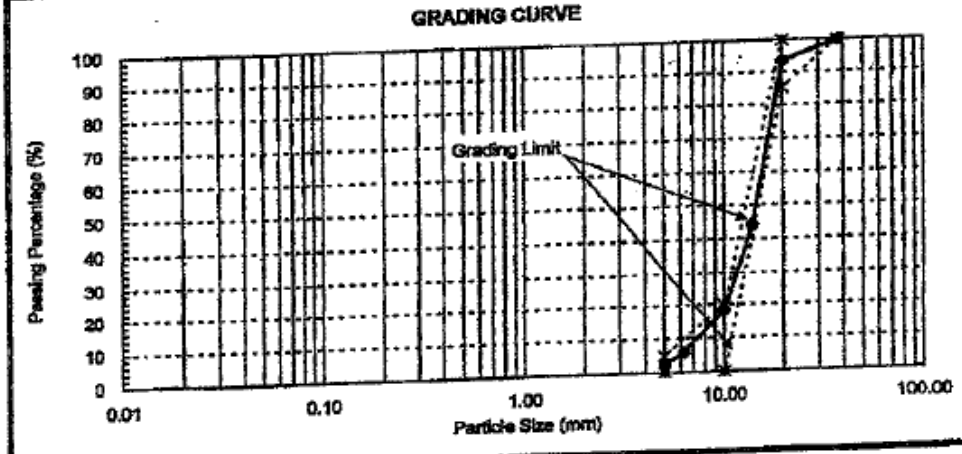
(a) Weight of Sample before wet sieving (g): *10526* *g*
(b) Weight of Sample after wet sieving (g): *10491* *g*
(c) Weight of Silt and Clay Content (g): *35* *g*

CLAY & SILT CONTENT: *0.33%*

B.S. SIEVE SIZE (mm)	MASS RETAINED (g)	MASS RETAINED (%)	PERCENTAGE PASSING
37.500	0	0.00	100
20.000	696	6.88	93
14.000	5199	49.39	44
10.000	2704	25.69	18
6.300	1308	12.43	6
5.000	347	3.30	3
Pan	270	2.57	0
TOTAL	10526.00	100.00	

B.S. SIEVE SIZE (mm)	SPECIFICATION	
	JKR/SPJ/1988 (Table 9.1) - 20mm	
37.500	100	100
20.000	86	100
10.000	0	20
5.000	0	5

GRADING CURVE



REMARKS: (JKR/SPJ/1988 Specification Requirement Clause 9.2.2.3 [Pg. S9-2]

Approved by:

PHANG TZE SHING
Managing Director

3/14

L/1

Acknowledge Receipt

Name:
Date:
Chop:

Tarikh: 20hb Ogos 2015

Pengarah,
Perunding TRA Sdn. Bhd
Lot 6810, Level 2, Synergy Square Block,
Matang Jaya Commercial Centre,
Jalan Matang, 93050 Kuching, Sarawak.
(U.P: Ir. Tairini Bin Abin)

Acknowledge Receipt
Name:
Date:
Chop:

Tuan,

MEMOHON PERKONGSIAN DOKUMEN-DOKUMEN BERKAITAN AMALAN-AMALAN REKA BENTUK KERJA-KERJA KONKRIT BERTETULANG.

Dengan segala hormatnya perkara di atas adalah dirujuk.

2. Saya meminta jasa baik pihak tuan untuk berkongsi maklumat berkaitan amalan-amalan reka bentuk kerja-kerja konkrit bertetulang seperti berikut:

a) "JKR's Standard Specification for Building Works (SSBW)".
b) "JKR's Standard Specification for Road Works (SSRW)".
c) "Malaysia's material specification documents for Fly Ash".
d) "Malaysia's standard test methods documents".
e) "Quality assessment and Quality Control (QA/QC) monitoring concrete works".
f) Lain-lain yang berkaitan dengan kerja-kerja konkrit bertetulang.

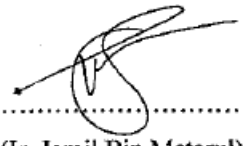
3. Untuk pengetahuan tuan, maklumat di atas adalah perlu untuk menjalankan kajian secara menyeluruh berhubung kajian "Performance-based Durability Specifications (PBDS) for Concrete Chloride-induced in Marine Environment" di Sarawak.

L/2

4. Oleh yang demikian, saya amat berharap agar pihak tuan dapat berkongsi maklumat seperti yang dinyatakan di atas untuk menjayakan kajian ini. Segala Kerjasama dan perhatian daripada pihak tuan, saya dahulukan dengan ucapan ribuan terima kasih.

Sekian.

Yang Benar



.....

(Ir. Jamil Bin Matarul)
Pensyarah Fakulti Kejuruteraan Awam UiTM Sarawak

s.k. Prof. Dr. Md. Abdul Mannan – Penyelia PhD, Fakulti Kejuruteraan Awam, UMIMAS

Appendix M: Raw Data for The Averages of Compressive Strength Test Results.

Table 1: Compressive Strength of Normal Concrete (Average of 3 cubes)

Age	M1	M2	M3	M4	M5	M6
3	10.89	13.56	16.44	18.22	20.00	20.22
7	20.67	25.56	24.44	32.67	34.89	38.22
14	24.67	31.11	32.22	40.22	42.44	45.11
28	31.11	38.00	39.11	48.00	50.44	51.78
56	33.33	39.78	40.67	48.89	51.56	52.44
90	34.44	39.78	41.11	49.33	52.22	52.89
180	35.78	40.22	40.67	50.00	52.44	52.89
270	36.89	40.67	41.11	50.22	52.89	53.11
360	37.11	40.89	41.41	50.37	53.04	53.26

Appendix M: Continued.

Table 2: Compressive Strength of Fly Ash Concrete – M1 (Average of 3 cubes)

Age	M1	M1FA20	M1FA30	M1FA40	M1FA50	M1FA60
3	10.89	14.22	17.33	14.44	13.56	9.78
7	20.67	15.56	18.22	15.78	14.44	11.11
14	24.67	20.22	21.56	21.11	20.00	17.56
28	31.11	24.22	28.22	25.33	23.11	20.22
56	33.33	30.22	34.22	32.22	28.00	25.78
90	34.44	32.67	39.11	33.78	30.00	29.56
180	35.78	33.33	40.89	34.67	31.33	30.44

Appendix M: Continued.

Table 3: Compressive Strength of Fly Ash Concrete – M3 (Average of 3 cubes)

Age	M3	M3FA20	M3FA30	M3FA40	M3FA50	M3FA60
3	14.44	33.56	31.56	34.22	31.78	28.22
7	24.44	36.22	31.78	33.56	34.44	27.11
14	32.22	40.67	40.22	41.56	40.44	35.56
28	39.11	50.00	50.67	51.11	47.56	42.89
56	40.67	56.89	57.56	58.44	53.56	46.22
90	41.11	58.00	60.67	64.44	56.44	45.78
180	40.67	60.67	61.78	65.11	57.33	47.11

Appendix M: Continued.

Table 4: Compressive Strength of Fly Ash Concrete – M5 (Average of 3 cubes)

Age	M5	M5FA20	M5FA30	M5FA40	M5FA50	M5FA60
3	20.00	30.44	32.00	27.11	23.56	24.89
7	34.89	33.56	34.89	30.00	25.78	26.44
14	42.44	44.67	46.89	42.67	35.33	27.33
28	50.44	54.00	56.44	51.11	45.56	36.00
56	51.56	59.56	62.67	58.00	54.89	48.67
90	52.22	63.56	67.78	61.56	57.33	55.33
180	52.44	66.67	69.11	65.56	61.78	60.67

Appendix N1: Correlations (M1)

Correlations

[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Write-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M1.sav

Correlations

		M1Cu	M1UPV	M1WA	M1VPV
M1Cu	Pearson Correlation	1	.979**	-.912**	-.920**
	Sig. (2-tailed)		.000	.000	.000
	N	36	36	36	36
M1UPV	Pearson Correlation	.979**	1	-.890**	-.898**
	Sig. (2-tailed)	.000		.000	.000
	N	36	36	36	36
M1WA	Pearson Correlation	-.912**	-.890**	1	.992**
	Sig. (2-tailed)	.000	.000		.000
	N	36	36	36	36
M1VPV	Pearson Correlation	-.920**	-.898**	.992**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	36	36	36	36

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix N2: Correlations (M5)

Correlations

```
[DataSet0] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.sav
```

Correlations

		M5Cu	M5UPV	M5WA	M5VPV
M5Cu	Pearson Correlation	1	.955**	-.861**	-.866**
	Sig. (2-tailed)		.000	.000	.000
	N	34	34	34	34
M5UPV	Pearson Correlation	.955**	1	-.906**	-.914**
	Sig. (2-tailed)	.000		.000	.000
	N	34	34	34	34
M5WA	Pearson Correlation	-.861**	-.906**	1	.974**
	Sig. (2-tailed)	.000	.000		.000
	N	34	34	34	34
M5VPV	Pearson Correlation	-.866**	-.914**	.974**	1
	Sig. (2-tailed)	.000	.000	.000	
	N	34	34	34	34

**. Correlation is significant at the 0.01 level (2-tailed).

Appendix N3: ModellingCu Vs. UPV

Curve Fit

Model Description

Model Name		MOD_2
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	36
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1UPV
Number of Positive Values		36	36
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.979	.959	.958	1.538

The independent variable is M1UPV.

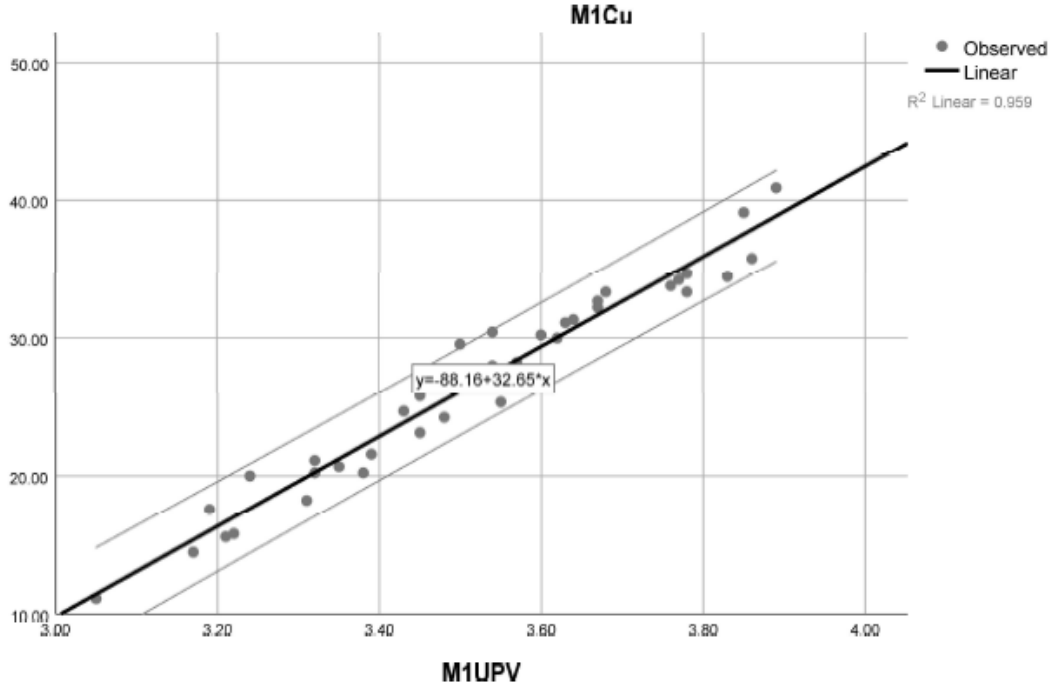
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1872.737	1	1872.737	792.033	.000
Residual	80.392	34	2.364		
Total	1953.129	35			

The independent variable is M1UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1UPV	32.651	1.160	.979	28.143	.000
(Constant)	-88.157	4.091		-21.550	.000




```
DATASET ACTIVATE DataSet2.
* Curve Estimation.
```

```
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3.sav
```

Model Description

Model Name		MOD_3
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	30
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent	Independent
		M3Cu	M3UPV
Number of Positive Values		30	30
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.944	.892	.888	3.407

The independent variable is M3UPV.

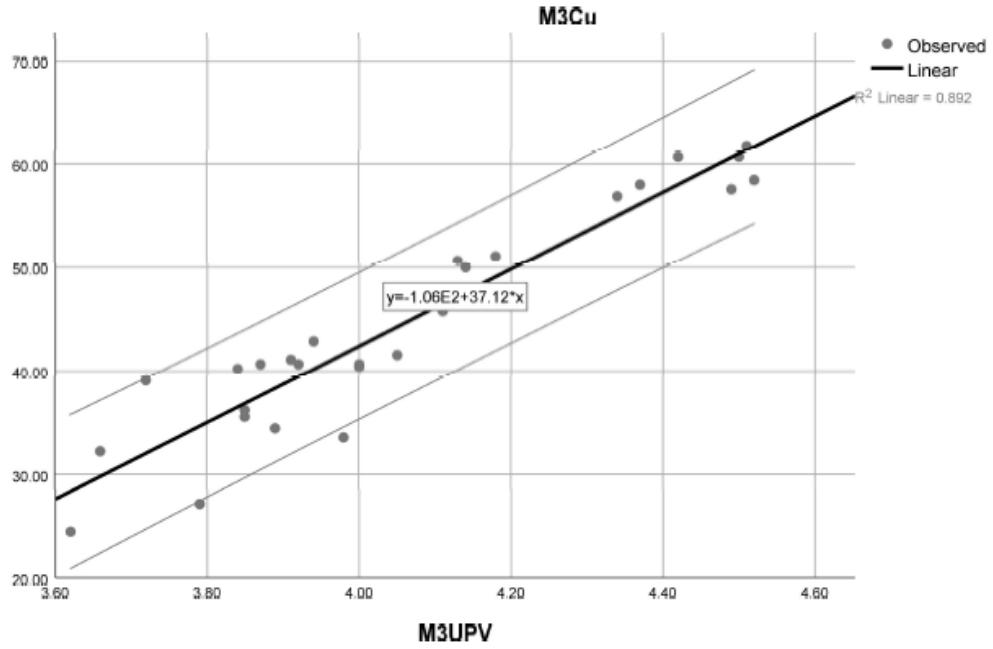
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2683.208	1	2683.208	231.162	.000
Residual	325.009	28	11.607		
Total	3008.217	29			

The independent variable is M3UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3UPV	37.118	2.441	.944	15.204	.000
(Constant)	-106.058	9.940		-10.670	.000




```
DATASET ACTIVATE DataSet0.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet0] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.s
```

Model Description

Model Name		MOD_4
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	34
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5UPV
Number of Positive Values		34	34
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.955	.912	.909	3.674

The independent variable is M5UPV.

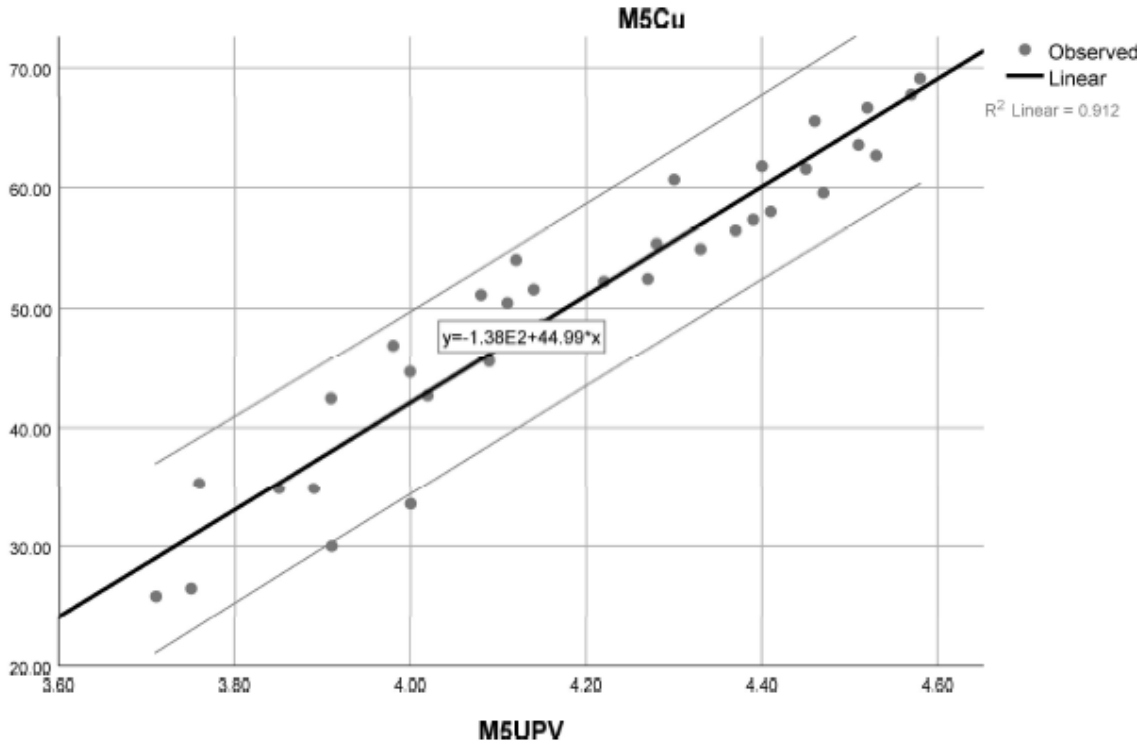
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	4470.355	1	4470.355	331.212	.000
Residual	431.903	32	13.497		
Total	4902.258	33			

The independent variable is M5UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5UPV	44.994	2.472	.955	18.199	.000
(Constant)	-137.898	10.383		-13.281	.000



Appendix N4: ModellingCu Vs. WA & VPV

Curve Fit

[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_W
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M1.sav

Model Description

Model Name		MOD_5
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1WA
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	36
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1WA
Number of Positive Values		36	36
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.912	.832	.827	3.111

The independent variable is M1WA.

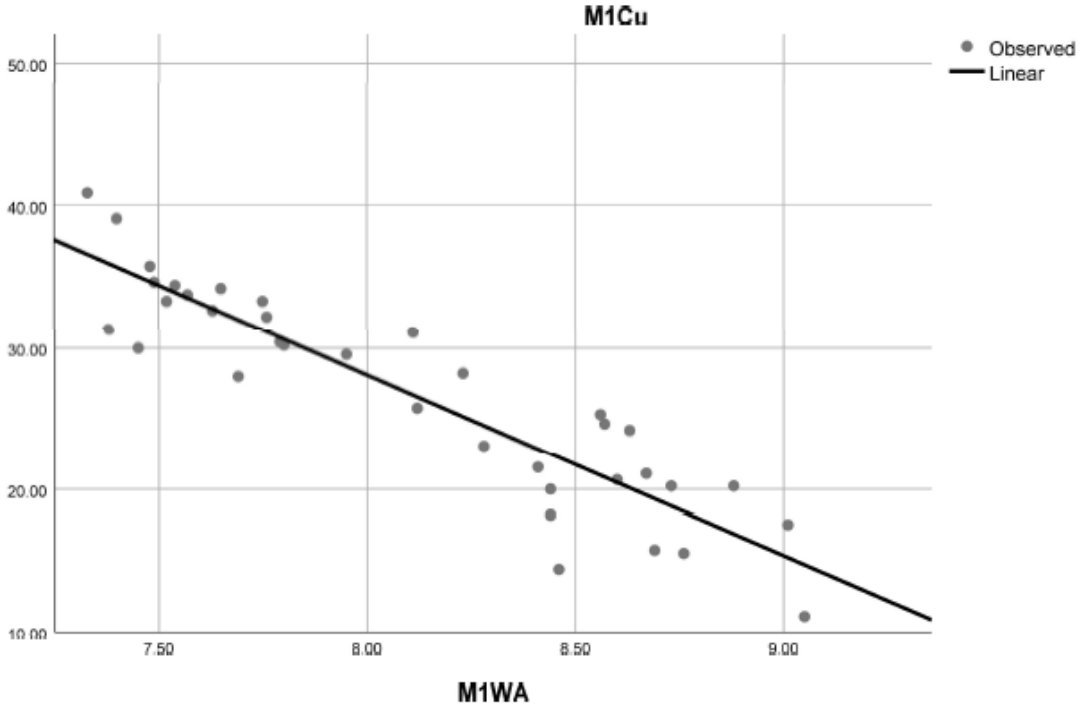
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1624.163	1	1624.163	167.864	.000
Residual	328.967	34	9.675		
Total	1953.129	35			

The independent variable is M1WA.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1WA	-12.705	.981	-.912	-12.956	.000
(Constant)	129.731	7.966		16.287	.000



```
DATASET ACTIVATE DataSet2.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3WA
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3.sav
```

Model Description

Model Name		MOD_6
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3WA
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	30
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent	Independent
		M3Cu	M3WA
Number of Positive Values		30	30
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.838	.702	.692	5.657

The independent variable is M3WA.

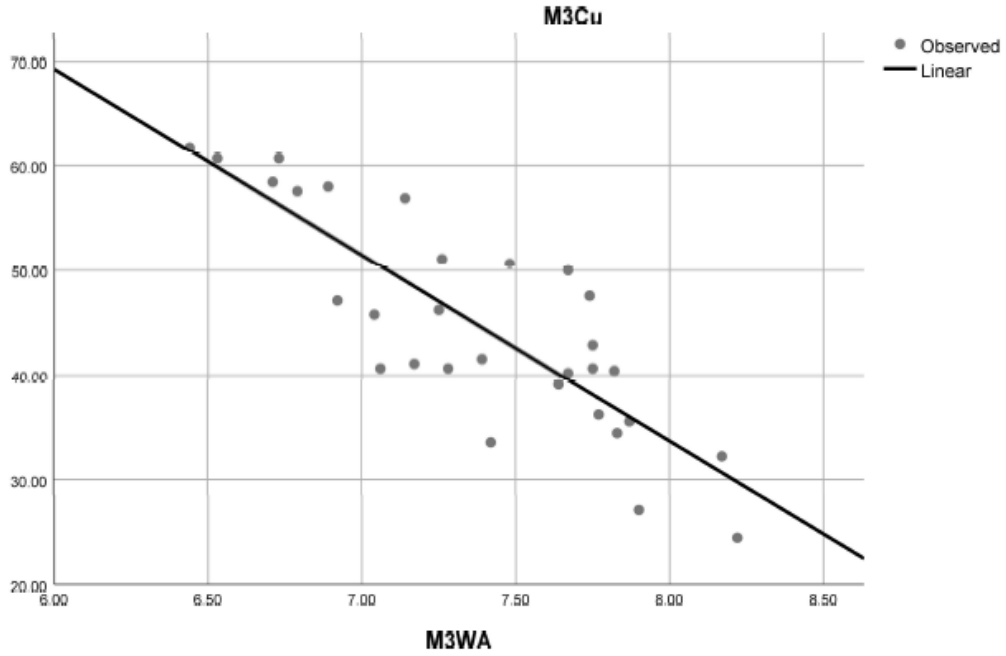
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2112.327	1	2112.327	66.018	.000
Residual	895.890	28	31.996		
Total	3008.217	29			

The independent variable is M3WA.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3WA	-17.786	2.189	-.838	-8.125	.000
(Constant)	175.981	16.181		10.876	.000




```
DATASET ACTIVATE DataSet0.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5WA
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet0] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.
```

Model Description

Model Name		MOD_7
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5WA
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	34
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5WA
Number of Positive Values		34	34
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.861	.741	.733	6.299

The independent variable is M5WA.

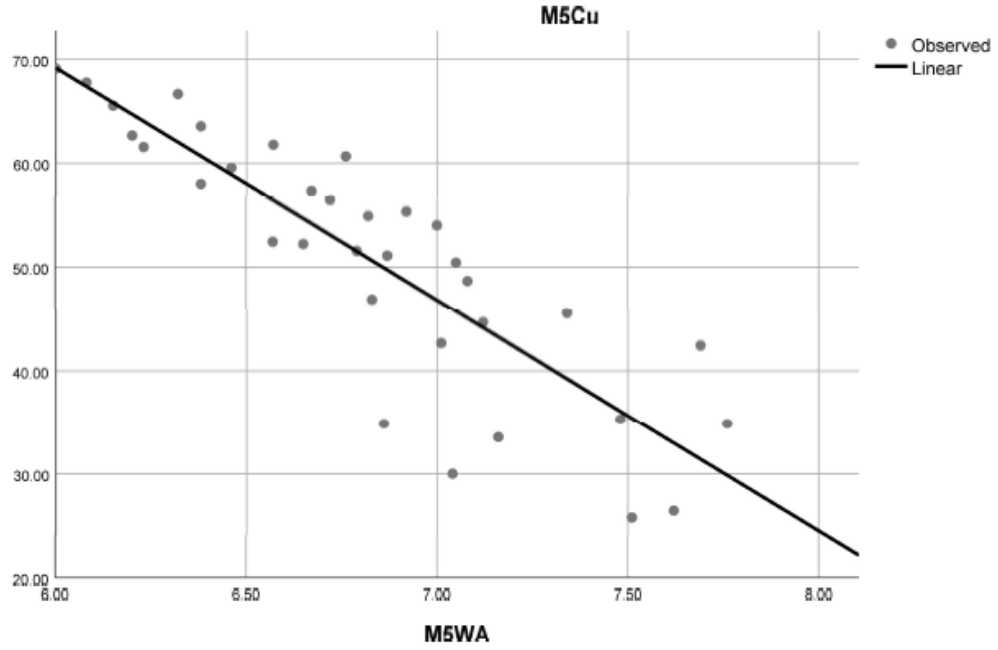
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3632.435	1	3632.435	91.539	.000
Residual	1269.823	32	39.682		
Total	4902.258	33			

The independent variable is M5WA.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5WA	-22.341	2.335	-.861	-9.568	.000
(Constant)	203.224	15.976		12.720	.000




```
DATASET ACTIVATE DataSet3.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M1Cu WITH M1VPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M1.
```

Model Description

Model Name		MOD_8
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1VPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	36
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1VPV
Number of Positive Values		36	36
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.920	.846	.841	2.975

The independent variable is M1VPV.

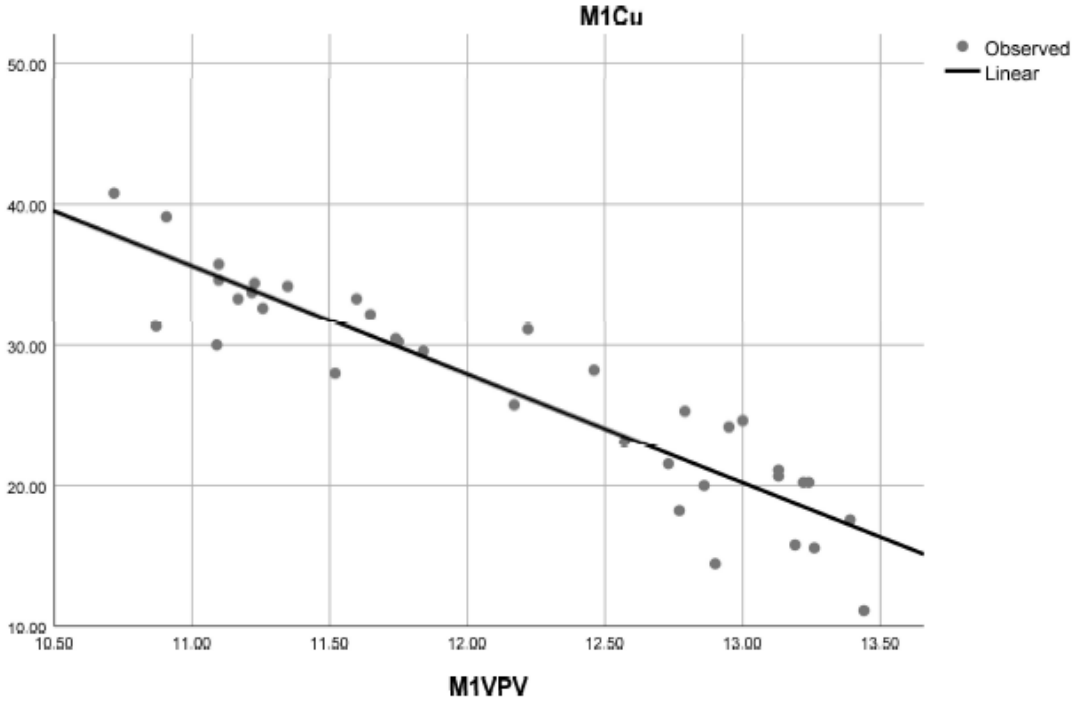
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1652.251	1	1652.251	186.709	.000
Residual	300.878	34	8.849		
Total	1953.129	35			

The independent variable is M1VPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1VPV	-7.733	.566	-.920	-13.664	.000
(Constant)	120.728	6.896		17.507	.000




```
DATASET ACTIVATE DataSet2.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3VPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
```

```
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3.sav
```

Model Description

Model Name		MOD_9
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3VPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	30
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M3Cu	Independent M3VPV
Number of Positive Values		30	30
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.840	.705	.695	5.627

The independent variable is M3VPV.

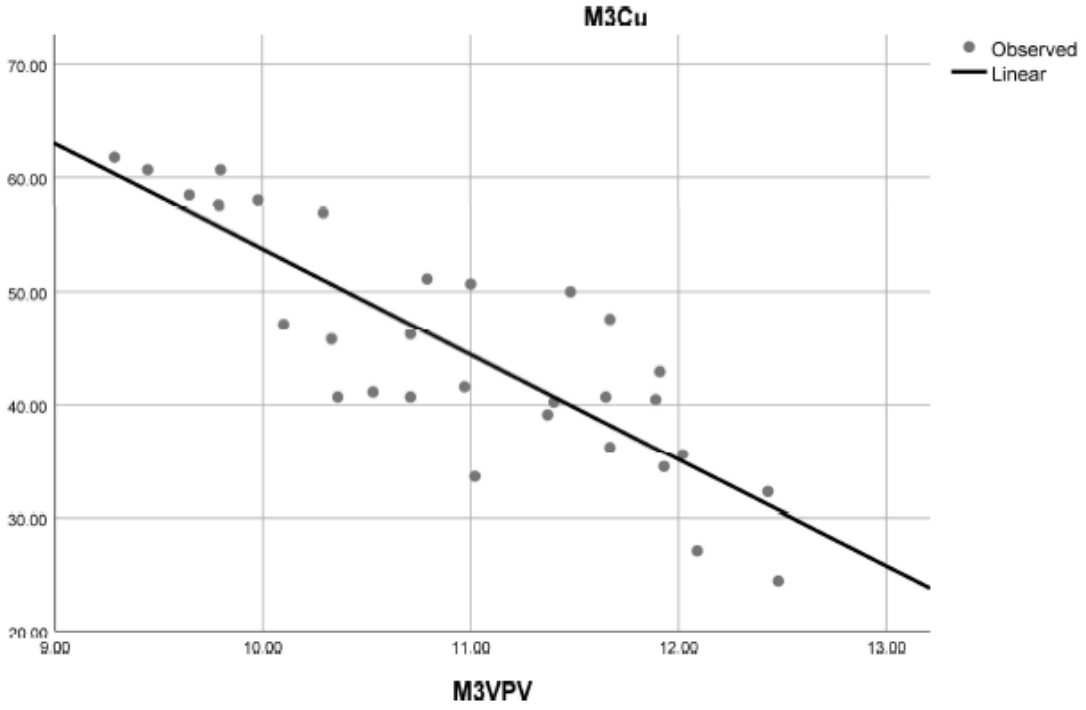
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2121.625	1	2121.625	67.004	.000
Residual	886.592	28	31.664		
Total	3008.217	29			

The independent variable is M3VPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3VPV	-9.316	1.138	-.840	-8.186	.000
(Constant)	146.870	12.514		11.736	.000



```
DATASET ACTIVATE DataSet0.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5VPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet0] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.sav
```

Model Description

Model Name		MOD_10
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5VPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	34
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5VPV
Number of Positive Values		34	34
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.866	.750	.742	6.189

The independent variable is M5VPV.

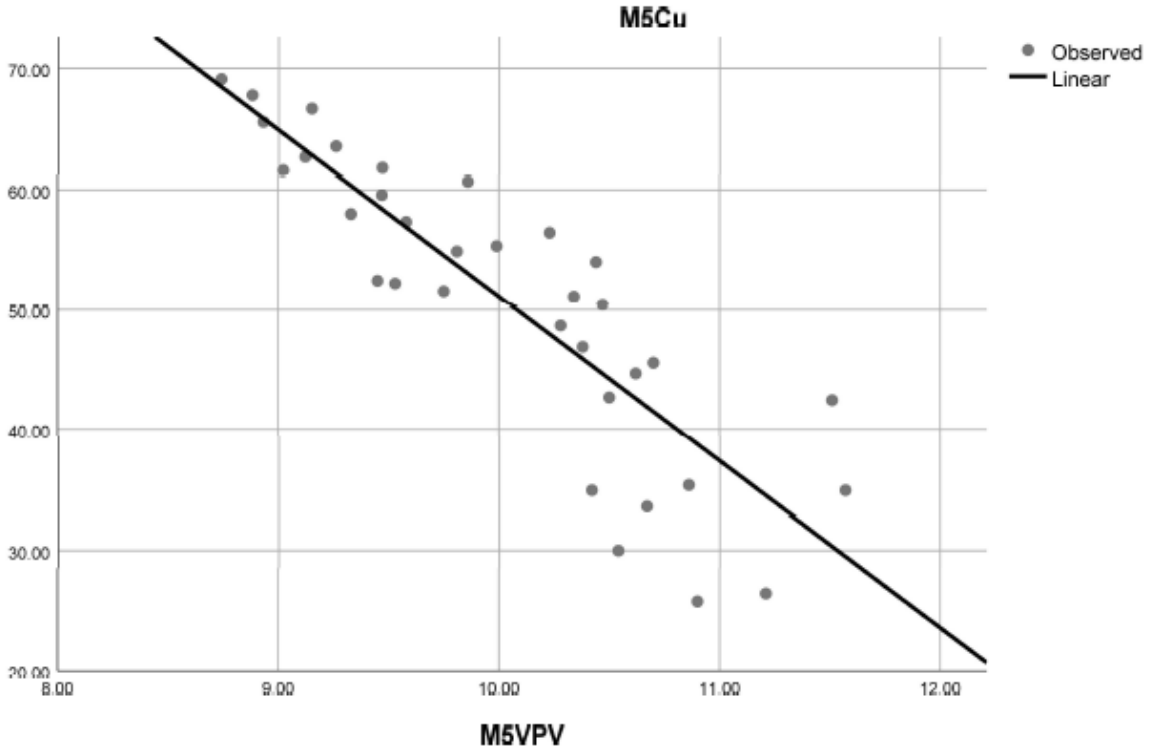
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	3676.607	1	3676.607	95.991	.000
Residual	1225.651	32	38.302		
Total	4902.258	33			

The independent variable is M5VPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5VPV	-13.767	1.405	-.866	-9.797	.000
(Constant)	188.788	14.132		13.359	.000


M5Cu
Observed
Linear
70.00
60.00
50.00
40.00
30.00
20.00
8.00
9.00
10.00
11.00
12.00
M5VPV

Appendix O: ModellingCu Vs. UPV (7D)

Curve Fit

[DataSet1] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Write-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M1.sav

Model Description

Model Name		MOD_1
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	36
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1UPV
Number of Positive Values		36	36
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.979	.959	.958	1.538

The independent variable is M1UPV.

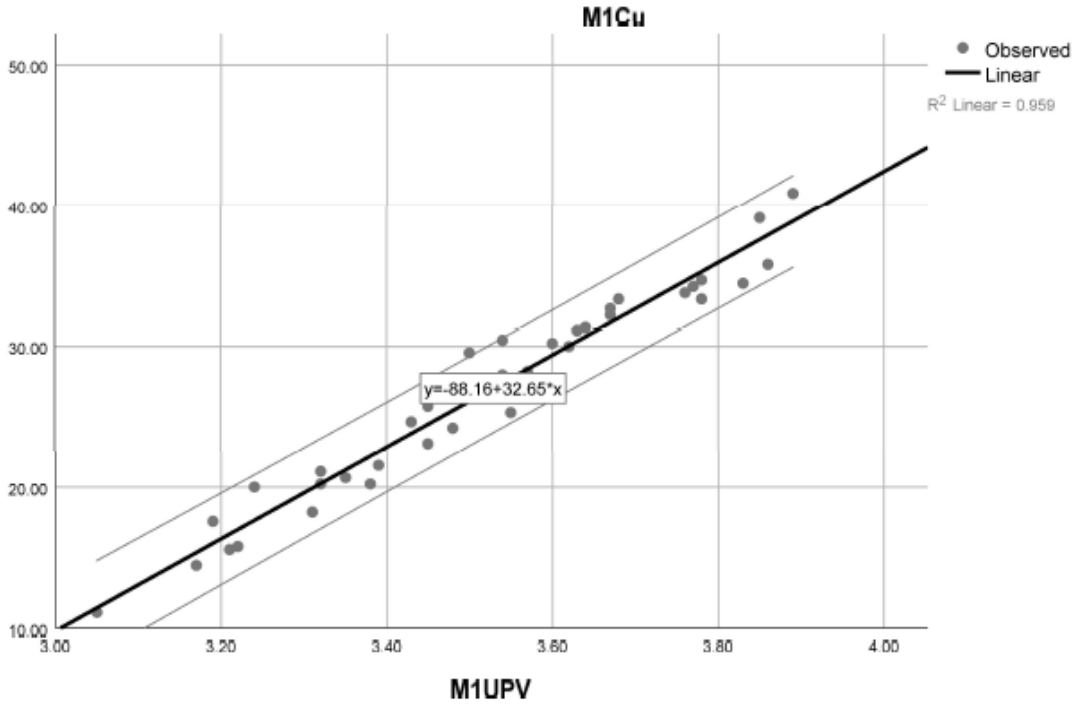
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1872.737	1	1872.737	792.033	.000
Residual	80.392	34	2.364		
Total	1953.129	35			

The independent variable is M1UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1UPV	32.651	1.160	.979	28.143	.000
(Constant)	-88.157	4.091		-21.550	.000



```
GET
  FILE='C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Write
-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3.sav'.
DATASET NAME DataSet2 WINDOW=FRONT.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3.sav
```

Model Description

Model Name		MOD_2
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	30
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M3Cu	Independent M3UPV
Number of Positive Values		30	30
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.944	.892	.888	3.407

The independent variable is M3UPV.

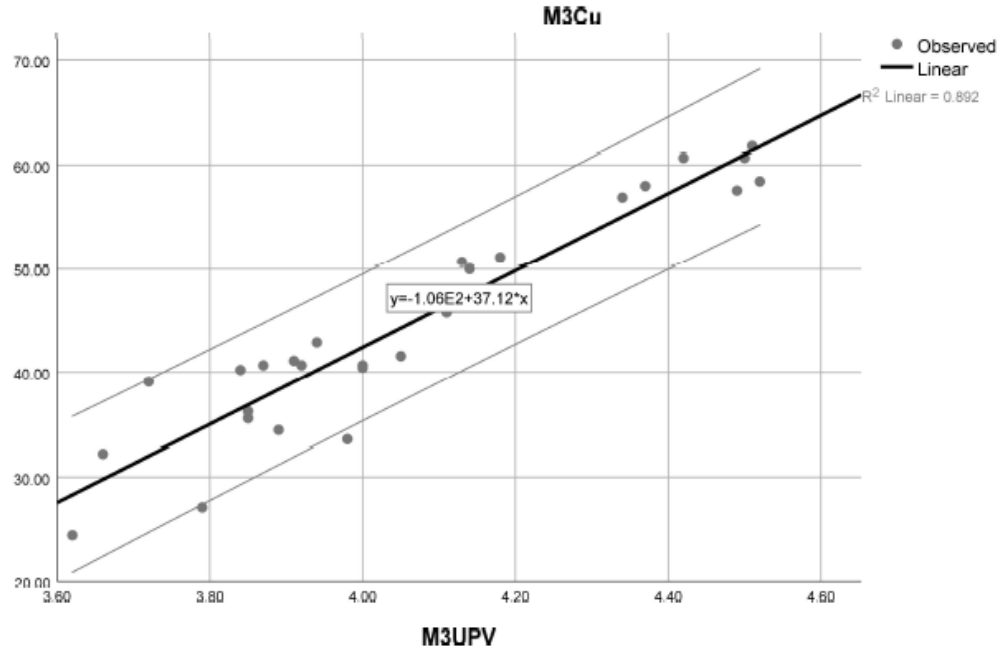
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	2683.208	1	2683.208	231.162	.000
Residual	325.009	28	11.607		
Total	3008.217	29			

The independent variable is M3UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3UPV	37.118	2.441	.944	15.204	.000
(Constant)	-106.058	9.940		-10.670	.000




```
GET
  FILE='C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_W
-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.sav
DATASET NAME DataSet3 WINDOW=FRONT.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5.
```

Model Description

Model Name		MOD_3
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	34
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5UPV
Number of Positive Values		34	34
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.955	.912	.909	3.674

The independent variable is M5UPV.

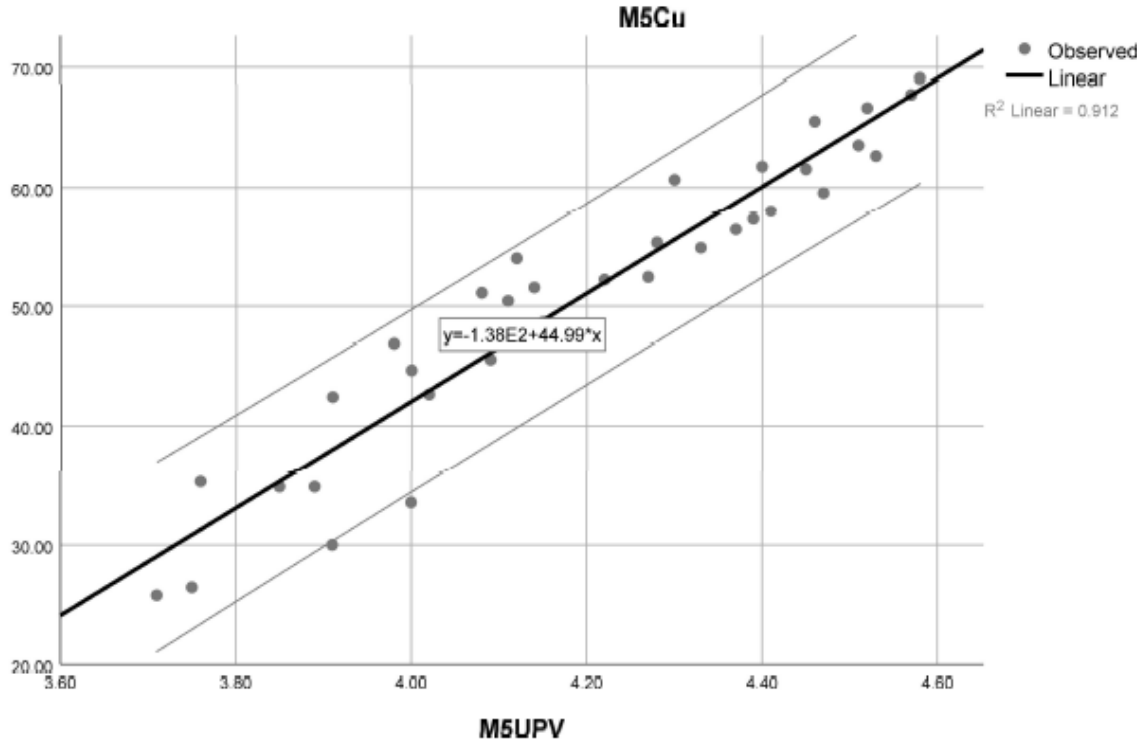
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	4470.355	1	4470.355	331.212	.000
Residual	431.903	32	13.497		
Total	4902.258	33			

The independent variable is M5UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5UPV	44.994	2.472	.955	18.199	.000
(Constant)	-137.898	10.383		-13.281	.000



Appendix P1: ModellingCu Vs. UPV (14D)

Curve Fit

Model Description

Model Name		MOD_2
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	30
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1UPV
Number of Positive Values		30	30
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.967	.935	.933	1.569

The independent variable is M1UPV.

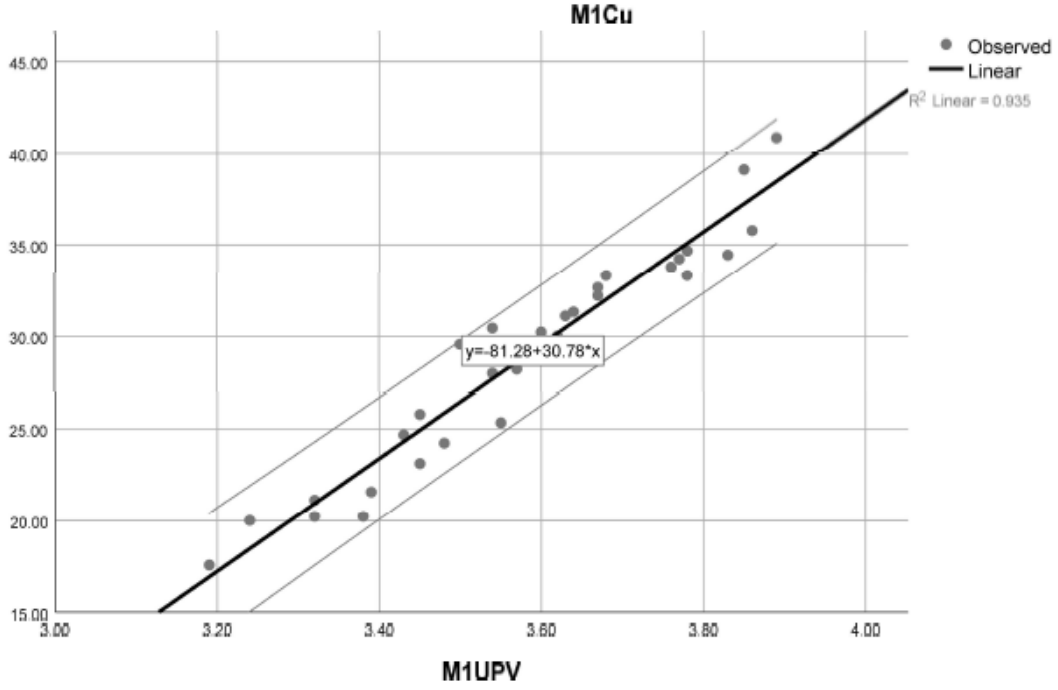
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	993.703	1	993.703	403.875	.000
Residual	68.892	28	2.460		
Total	1062.594	29			

The independent variable is M1UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1UPV	30.784	1.532	.967	20.097	.000
(Constant)	-81.283	5.490		-14.805	.000




```
DATASET ACTIVATE DataSet2.
* Curve Estimation.
```

```
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Wr
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3-14D.
sav
```

Model Description

Model Name		MOD_3
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	25
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M3Cu	Independent M3UPV
Number of Positive Values		25	25
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.965	.932	.929	2.308

The independent variable is M3UPV.

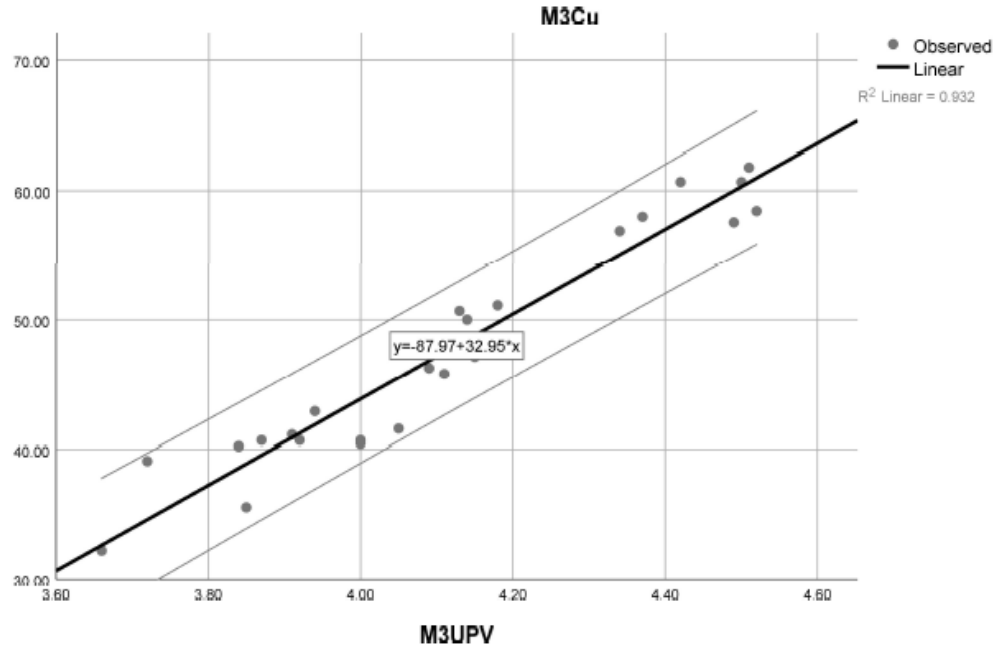
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1668.276	1	1668.276	313.167	.000
Residual	122.524	23	5.327		
Total	1790.799	24			

The independent variable is M3UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3UPV	32.951	1.862	.965	17.697	.000
(Constant)	-87.966	7.669		-11.470	.000




```
DATASET ACTIVATE DataSet3.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5-
sav
```

Model Description

Model Name		MOD_4
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	28
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5UPV
Number of Positive Values		28	28
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.960	.921	.918	2.438

The independent variable is M5UPV.

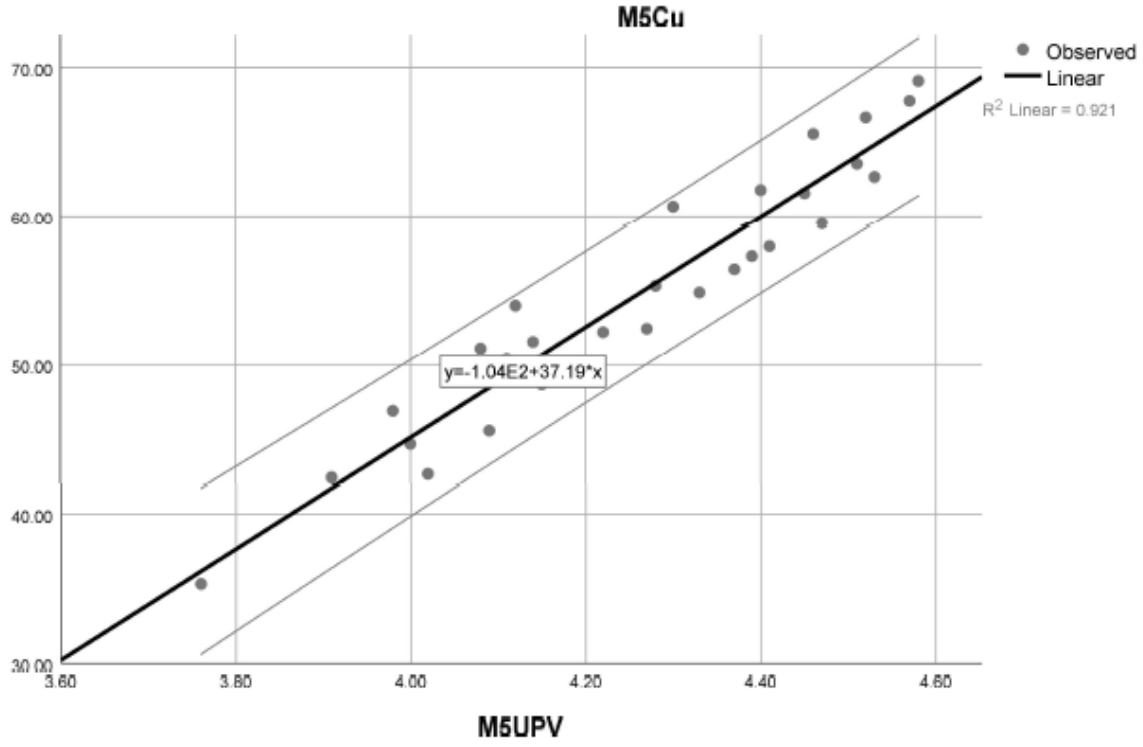
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1807.595	1	1807.595	304.088	.000
Residual	154.552	26	5.944		
Total	1962.147	27			

The independent variable is M5UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5UPV	37.193	2.133	.960	17.438	.000
(Constant)	-103.668	9.108		-11.382	.000



Appendix P2: ModellingCu Vs. UPV (28D)

Curve Fit

[DataSet1] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_Write-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M1-28D.sav

Model Description

Model Name		MOD_1
Dependent Variable	1	M1Cu
Equation	1	Linear
Independent Variable		M1UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	24
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M1Cu	Independent M1UPV
Number of Positive Values		24	24
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M1Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.941	.886	.881	1.689

The independent variable is M1UPV.

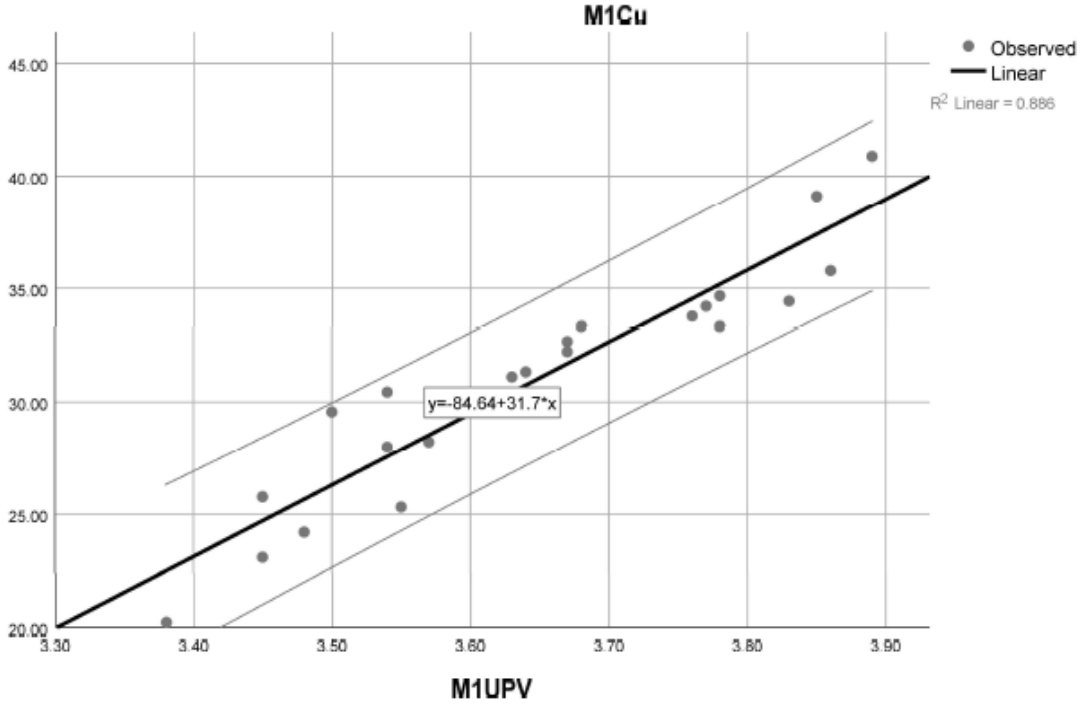
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	486.739	1	486.739	170.705	.000
Residual	62.729	22	2.851		
Total	549.468	23			

The independent variable is M1UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M1UPV	31.699	2.426	.941	13.065	.000
(Constant)	-84.641	8.851		-9.563	.000



```
DATASET ACTIVATE DataSet2.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M3Cu WITH M3UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet2] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\1_W
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M3-28D
sav
```

Model Description

Model Name		MOD_2
Dependent Variable	1	M3Cu
Equation	1	Linear
Independent Variable		M3UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	19
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M3Cu	Independent M3UPV
Number of Positive Values		19	19
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M3Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.966	.933	.929	2.058

The independent variable is M3UPV.

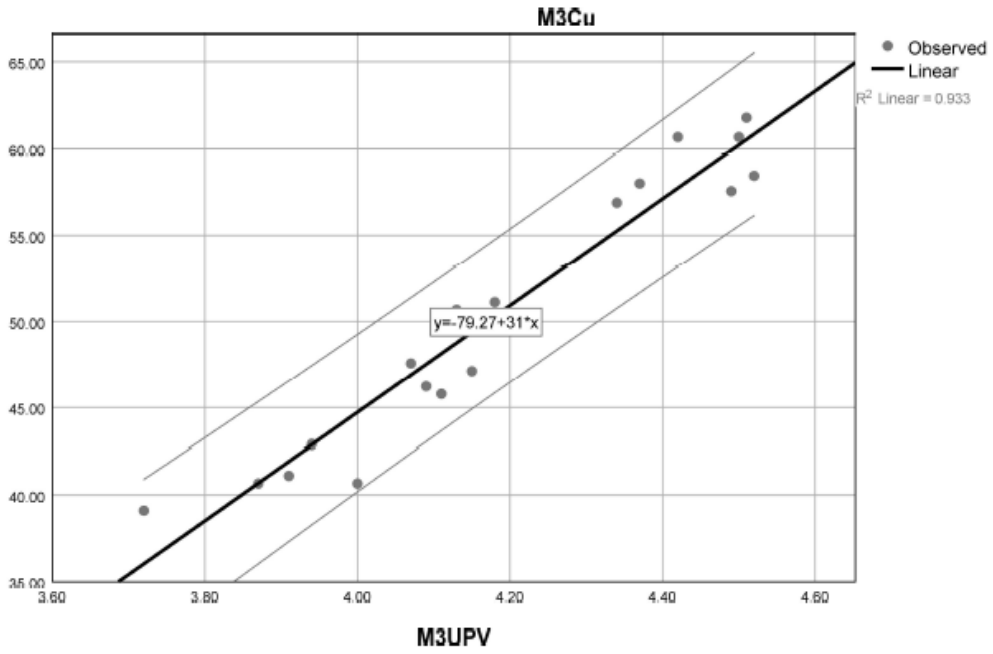
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	1002.134	1	1002.134	236.498	.000
Residual	72.036	17	4.237		
Total	1074.170	18			

The independent variable is M3UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M3UPV	30.998	2.016	.966	15.378	.000
(Constant)	-79.275	8.443		-9.389	.000




```
DATASET ACTIVATE DataSet3.
* Curve Estimation.
TSET MXNEWVAR=3.
CURVEFIT
  /VARIABLES=M5Cu WITH M5UPV
  /CONSTANT
  /MODEL=LINEAR
  /PRINT ANOVA
  /PLOT FIT
  /CIN=95
  /SAVE=PRED CIN .
```

Curve Fit

```
[DataSet3] C:\Users\User\Desktop\PhD Lenovo_220606\Bismillah-PhD220120\
ite-up PhD_220118\Chapter 6a_Objective 3\SPSS\Remove Un-Normal data\M5-2
sav
```

Model Description

Model Name		MOD_3
Dependent Variable	1	M5Cu
Equation	1	Linear
Independent Variable		M5UPV
Constant		Included
Variable Whose Values Label Observations in Plots		Unspecified

Case Processing Summary

	N
Total Cases	23
Excluded Cases[a]	0
Forecasted Cases	0
Newly Created Cases	0

a. Cases with a missing value in any variable are excluded from the analysis.

Variable Processing Summary

		Variables	
		Dependent M5Cu	Independent M5UPV
Number of Positive Values		23	23
Number of Zeros		0	0
Number of Negative Values		0	0
Number of Missing Values	User-Missing	0	0
	System-Missing	0	0

M5Cu

Linear

Model Summary

R	R Square	Adjusted R Square	Std. Error of the Estimate
.924	.853	.846	2.547

The independent variable is M5UPV.

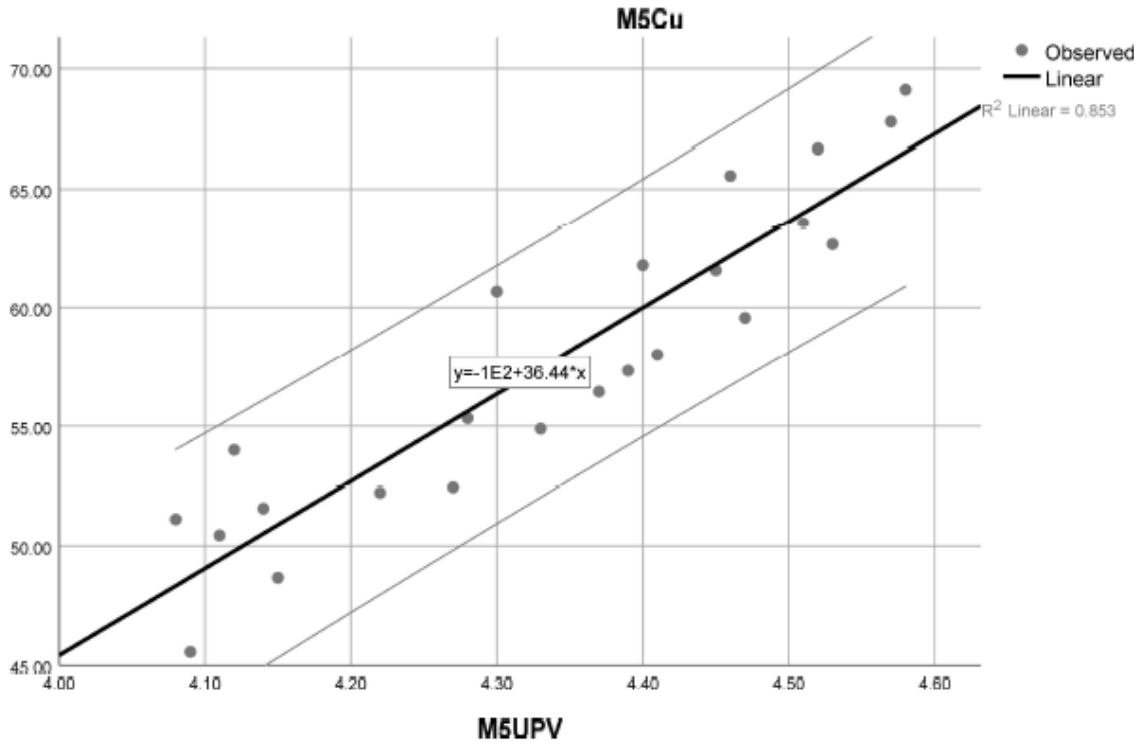
ANOVA

	Sum of Squares	df	Mean Square	F	Sig.
Regression	790.102	1	790.102	121.760	.000
Residual	136.270	21	6.489		
Total	926.372	22			

The independent variable is M5UPV.

Coefficients

	Unstandardized Coefficients		Standardized Coefficients		
	B	Std. Error	Beta	t	Sig.
M5UPV	36.438	3.302	.924	11.034	.000
(Constant)	-100.337	14.331		-7.001	.000



Appendix Q: Performance-based Durability Modelling

Regression

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	UPV	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: Cu

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.965[a]	.932	.931	.063368153	.932	1035.941

Model Summary

Model	Change Statistics		
	df1	df2	Sig. F Change
1	1	76	.000

a. Predictors: (Constant), UPV

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.160	1	4.160	1035.941	.000[b]
	Residual	.305	76	.004		
	Total	4.465	77			

a. Dependent Variable: Cu

b. Predictors: (Constant), UPV

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-.052	.019		-2.703	.008
	UPV	.984	.031	.965	32.186	.000

Coefficients[a]

Model		95.0% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	-.091	-.014		
	UPV	.923	1.045	1.000	1.000

a. Dependent Variable: Cu

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics	
						Tolerance	VIF
1	WA	-.024[b]	-.310	.757	-.036	.155	6.448
	VPV	-.035[b]	-.467	.642	-.054	.164	6.092

Excluded Variables[a]

Model		Collinearity ...
		Minimum Tolerance
1	WA	.155
	VPV	.164

a. Dependent Variable: Cu

b. Predictors in the Model: (Constant), UPV

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions	
				(Constant)	UPV
1	1	1.929	1.000	.04	.04
	2	.071	5.195	.96	.96

a. Dependent Variable: Cu

```
REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA COLLIN TOL CHANGE
  /CRITERIA=PIN(.05) POUT(.10)
  /NOORIGIN
  /DEPENDENT UPV
  /METHOD=STEPWISE Cu WA VPV.
```

Regression

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	Cu	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2	WA	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: UPV

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.965[a]	.932	.931	.062155236	.932	1035.941
2	.974[b]	.949	.947	.054216340	.017	24.887

Model Summary

Model	Change Statistics		
	df1	df2	Sig. F Change
1	1	76	.000
2	1	75	.000

a. Predictors: (Constant), Cu

b. Predictors: (Constant), Cu, WA

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.002	1	4.002	1035.941	.000[b]
	Residual	.294	76	.004		
	Total	4.296	77			
2	Regression	4.075	2	2.038	693.213	.000[c]
	Residual	.220	75	.003		
	Total	4.296	77			

a. Dependent Variable: UPV

b. Predictors: (Constant), Cu

c. Predictors: (Constant), Cu, WA

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.090	.017		5.275	.000
	Cu	.947	.029	.965	32.186	.000
2	(Constant)	.356	.055		6.422	.000
	Cu	.696	.056	.709	12.315	.000
	WA	-.295	.059	-.287	-4.989	.000

Coefficients[a]

Model		95.0% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	.056	.123		
	Cu	.888	1.005	1.000	1.000
2	(Constant)	.246	.467		
	Cu	.583	.808	.206	4.848
	WA	-.413	-.177	.206	4.848

a. Dependent Variable: UPV

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics	
						Tolerance	VIF
1	WA	-.287[b]	-4.989	.000	-.499	.206	4.848
	VPV	-.270[b]	-4.665	.000	-.474	.211	4.736
2	VPV	.022[c]	.111	.912	.013	.018	55.858

Excluded Variables[a]

Model		Collinearity ...
		Minimum Tolerance
1	WA	.206
	VPV	.211
2	VPV	.017

a. Dependent Variable: UPV

b. Predictors in the Model: (Constant), Cu

c. Predictors in the Model: (Constant), Cu, WA

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	Cu	WA
1	1	1.910	1.000	.04	.04	
	2	.090	4.608	.96	.96	
2	1	2.641	1.000	.00	.00	.00
	2	.351	2.742	.00	.05	.06
	3	.008	18.595	1.00	.95	.93

a. Dependent Variable: UPV

```
REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA COLLIN TOL CHANGE
  /CRITERIA=PIN(.05) POUT(.10)
  /NOORIGIN
  /DEPENDENT WA
  /METHOD=STEPWISE Cu UPV VPV.
```

Regression

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	VPV	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).
2	UPV	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: WA

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.991[a]	.982	.982	.031082572	.982	4136.826
2	.991[b]	.983	.983	.030351078	.001	4.708

Model Summary

Model	Change Statistics		
	df1	df2	Sig. F Change
1	1	76	.000
2	1	75	.033

a. Predictors: (Constant), VPV

b. Predictors: (Constant), VPV, UPV

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	3.997	1	3.997	4136.826	.000[b]
	Residual	.073	76	.001		
	Total	4.070	77			
2	Regression	4.001	2	2.001	2171.670	.000[c]
	Residual	.069	75	.001		
	Total	4.070	77			

a. Dependent Variable: WA

b. Predictors: (Constant), VPV

c. Predictors: (Constant), VPV, UPV

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	.026	.008		3.384	.001
	VPV	.910	.014	.991	64.318	.000
2	(Constant)	.104	.037		2.823	.006
	VPV	.843	.034	.917	24.703	.000
	UPV	-.078	.036	-.081	-2.170	.033

Coefficients[a]

Model		95.0% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	.011	.041		
	VPV	.882	.939	1.000	1.000
2	(Constant)	.031	.177		
	VPV	.775	.911	.164	6.092
	UPV	-.150	-.006	.164	6.092

a. Dependent Variable: WA

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics	
						Tolerance	VIF
1	Cu	-.051[b]	-1.538	.128	-.175	.211	4.736
	UPV	-.081[b]	-2.170	.033	-.243	.164	6.092
2	Cu	.023[c]	.393	.695	.046	.068	14.673

Excluded Variables[a]

Model		Collinearity ...
		Minimum Tolerance
1	Cu	.211
	UPV	.164
2	Cu	.053

a. Dependent Variable: WA

b. Predictors in the Model: (Constant), VPV

c. Predictors in the Model: (Constant), VPV, UPV

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions		
				(Constant)	VPV	UPV
1	1	1.885	1.000	.06	.06	
	2	.115	4.057	.94	.94	
2	1	2.657	1.000	.00	.00	.00
	2	.337	2.807	.00	.06	.03
	3	.005	22.074	1.00	.94	.97

a. Dependent Variable: WA

```
REGRESSION
  /MISSING LISTWISE
  /STATISTICS COEFF OUTS CI(95) R ANOVA COLLIN TOL CHANGE
  /CRITERIA=PIN(.05) POUT(.10)
  /NOORIGIN
  /DEPENDENT VPV
  /METHOD=STEPWISE Cu UPV WA.
```

Regression

Variables Entered/Removed[a]

Model	Variables Entered	Variables Removed	Method
1	WA	.	Stepwise (Criteria: Probability-of-F-to-enter <= .050, Probability-of-F-to-remove >= .100).

a. Dependent Variable: VPV

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics	
					R Square Change	F Change
1	.991[a]	.982	.982	.033835137	.982	4136.826

Model Summary

Model	Change Statistics		
	df1	df2	Sig. F Change
1	1	76	.000

a. Predictors: (Constant), WA

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	4.736	1	4.736	4136.826	.000[b]
	Residual	.087	76	.001		
	Total	4.823	77			

a. Dependent Variable: VPV

b. Predictors: (Constant), WA

Coefficients[a]

Model		Unstandardized Coefficients		Standardized Coefficients		
		B	Std. Error	Beta	t	Sig.
1	(Constant)	-.019	.009		-2.229	.029
	WA	1.079	.017	.991	64.318	.000

Coefficients[a]

Model		95.0% Confidence Interval for B		Collinearity Statistics	
		Lower Bound	Upper Bound	Tolerance	VIF
1	(Constant)	-.036	-.002		
	WA	1.045	1.112	1.000	1.000

a. Dependent Variable: VPV

Excluded Variables[a]

Model		Beta In	t	Sig.	Partial Correlation	Collinearity Statistics	
						Tolerance	VIF
1	Cu	-.026[b]	-.759	.450	-.087	.206	4.848
	UPV	-.022[b]	-.556	.580	-.064	.155	6.448

Excluded Variables[a]

Model		Collinearity ...
		Minimum Tolerance
1	Cu	.206
	UPV	.155

a. Dependent Variable: VPV

b. Predictors in the Model: (Constant), WA

Collinearity Diagnostics[a]

Model	Dimension	Eigenvalue	Condition Index	Variance Proportions	
				(Constant)	WA
1	1	1.894	1.000	.05	.05
	2	.106	4.236	.95	.95

a. Dependent Variable: VPV

Appendix R1: Modelling Validation Test Results M1

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
8.70	0.7746	8.66	0%
8.51	0.7162	8.54	0%
9.05	0.9070	8.92	1%
8.47	0.6705	8.45	0%
8.72	0.6458	8.40	4%
8.16	0.6686	8.45	-4%
8.91	0.9086	8.92	0%
8.47	0.6326	8.38	1%
8.72	0.8380	8.78	-1%
8.21	0.5650	8.24	0%
9.10	0.8738	8.85	3%
9.00	0.8284	8.76	3%
8.64	0.7282	8.56	1%
8.50	0.6775	8.46	0%
9.00	0.8811	8.87	1%
8.47	0.6541	8.42	1%
8.70	0.8771	8.86	-2%
8.12	0.3826	7.88	3%
8.88	0.8725	8.85	0%
8.45	0.6223	8.36	1%
8.70	0.8085	8.72	0%
8.19	0.5508	8.22	0%
9.08	0.8559	8.82	3%
8.95	0.8029	8.71	3%
8.49	0.6073	8.33	2%
7.74	0.3648	7.85	-1%
8.85	0.7789	8.66	2%
8.41	0.5902	8.29	1%
8.52	0.8045	8.71	-2%
7.93	0.3021	7.73	3%
8.78	0.7777	8.66	1%
8.34	0.4873	8.09	3%
8.52	0.7181	8.54	0%
8.04	0.4541	8.02	0%
8.90	0.9136	8.93	0%
8.70	0.6266	8.36	4%

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
8.10	0.4194	7.96	2%
7.40	0.2012	7.53	-2%
7.85	0.3883	7.89	-1%
7.75	0.3400	7.80	-1%
7.90	0.4838	8.08	-2%
7.40	0.0306	7.19	3%
7.85	0.3431	7.81	1%
7.67	0.3261	7.77	-1%
7.95	0.4582	8.03	-1%
7.43	0.1673	7.46	0%
8.24	0.5501	8.21	0%
8.01	0.4384	7.99	0%
7.91	0.3320	7.78	2%
7.17	0.0966	7.32	-2%
7.72	0.4211	7.96	-3%
7.55	0.0482	7.22	4%
7.50	0.2228	7.57	-1%
7.30	0.0449	7.22	1%
7.68	0.2825	7.69	0%
7.47	0.1556	7.44	1%
7.53	0.2351	7.59	-1%
7.36	0.1659	7.46	-1%
8.00	0.4470	8.01	0%
7.89	0.3509	7.82	1%
7.83	0.2939	7.71	2%
7.13	0.0644	7.26	-2%
7.68	0.3575	7.83	-2%
7.37	0.0709	7.27	1%
7.45	0.0998	7.33	2%
7.20	0.0615	7.25	-1%
7.63	0.2780	7.68	-1%
7.34	0.0924	7.31	0%
7.47	0.1980	7.52	-1%
7.28	0.0812	7.29	0%
7.89	0.4213	7.96	-1%
7.69	0.3241	7.77	-1%

Appendix R2: Modelling Validation Test Results M3

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
8.28	0.9470	8.17	1%
8.16	0.8912	8.07	1%
7.83	0.7303	7.76	1%
7.71	0.6722	7.65	1%
8.00	0.7712	7.84	2%
7.41	0.5357	7.38	0%
7.48	0.5558	7.42	1%
7.35	0.5269	7.37	0%
7.85	0.7906	7.87	0%
7.81	0.7321	7.76	1%
8.00	0.8434	7.97	0%
7.81	0.7685	7.83	0%
8.25	0.9283	8.14	1%
8.08	0.8692	8.02	1%
7.83	0.8972	8.08	-3%
7.68	0.4893	7.29	5%
7.96	0.7726	7.84	2%
7.39	0.5150	7.34	1%
7.44	0.5317	7.38	1%
7.33	0.4974	7.31	0%
7.84	0.7499	7.80	1%
7.80	0.7449	7.79	0%
7.99	0.8407	7.97	0%
7.75	0.7336	7.76	0%
7.98	0.7369	7.77	3%
7.29	0.5565	7.42	-2%
7.75	0.6876	7.68	1%
7.58	0.5976	7.50	1%
7.74	0.8089	7.91	-2%
7.13	0.2423	6.82	4%
7.30	0.4872	7.29	0%
7.22	0.4480	7.21	0%
7.79	0.7087	7.72	1%
7.69	0.6741	7.65	0%
7.89	0.8424	7.97	-1%
7.60	0.6743	7.65	-1%

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
7.59	0.5834	7.47	2%
6.97	0.3787	7.08	-2%
7.19	0.3649	7.05	2%
7.09	0.3217	6.97	2%
6.89	0.1710	6.68	3%
6.69	0.2480	6.83	-2%
6.80	0.2060	6.75	1%
6.62	0.1423	6.63	0%
7.41	0.4475	7.21	3%
7.27	0.3734	7.07	3%
7.31	0.4871	7.29	0%
7.19	0.4476	7.21	0%
7.45	0.5559	7.42	0%
6.88	0.3027	6.94	-1%
6.97	0.2840	6.90	1%
6.80	0.2502	6.83	-1%
6.61	0.1613	6.66	-1%
6.45	0.0937	6.53	-1%
6.62	0.1420	6.63	0%
6.35	0.0485	6.45	-1%
7.13	0.3875	7.10	0%
6.93	0.2731	6.88	1%
7.13	0.4103	7.14	0%
6.95	0.3255	6.98	0%
7.39	0.5249	7.36	0%
6.74	0.2379	6.81	-1%
6.78	0.2352	6.81	0%
6.67	0.1970	6.73	-1%
6.49	0.1446	6.63	-2%
6.39	0.0270	6.40	0%
6.45	0.0768	6.50	-1%
6.35	0.0468	6.44	-1%
6.95	0.3110	6.95	0%
6.86	0.2585	6.85	0%
6.98	0.3313	6.99	0%
6.86	0.2870	6.90	-1%

Appendix R3: Modelling Validation Test Results M5

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
7.96	0.9351	7.83	2%
7.55	0.7232	7.39	2%
7.22	0.6160	7.17	1%
7.10	0.5686	7.08	0%
6.93	0.5791	7.10	-2%
6.78	0.5048	6.95	-2%
7.05	0.5764	7.09	-1%
7.04	0.5635	7.07	0%
7.70	0.7285	7.40	4%
7.33	0.6201	7.18	2%
7.89	0.8422	7.64	3%
7.35	0.6558	7.26	1%
7.84	0.9076	7.77	1%
7.54	0.7095	7.37	2%
7.22	0.8168	7.58	-5%
7.00	0.3500	6.63	5%
6.86	0.5357	7.01	-2%
6.81	0.5108	6.96	-2%
7.03	0.5571	7.05	0%
7.00	0.5486	7.04	-1%
7.65	0.7133	7.37	4%
7.30	0.6081	7.16	2%
7.85	0.8199	7.59	3%
7.33	0.6520	7.25	1%
7.31	0.5973	7.14	2%
6.80	0.4606	6.86	-1%
7.19	0.6179	7.18	0%
6.82	0.4331	6.80	0%
6.78	0.4848	6.91	-2%
6.67	0.4190	6.77	-2%
6.94	0.5205	6.98	-1%
6.81	0.4941	6.93	-2%
7.40	0.6039	7.15	3%
7.28	0.5823	7.11	2%
7.82	0.7944	7.54	4%
7.22	0.6130	7.17	1%

WA Laboratory Test	WA = 0.843VPV - 0.078UPV + 0.104	WA Model Predicted	Errors (%)
7.10	0.4658	6.87	3%
6.49	0.2440	6.41	1%
6.50	0.3118	6.55	-1%
6.43	0.2051	6.33	1%
6.27	0.1927	6.31	-1%
6.13	0.1415	6.20	-1%
6.41	0.2306	6.39	0%
6.35	0.2312	6.39	-1%
6.92	0.3755	6.68	3%
6.73	0.3302	6.59	2%
7.26	0.5433	7.03	3%
6.90	0.4275	6.79	2%
7.04	0.4199	6.77	4%
6.26	0.1663	6.25	0%
6.44	0.2321	6.39	1%
6.32	0.1720	6.27	1%
6.12	0.1180	6.16	-1%
6.05	0.0881	6.10	-1%
6.28	0.1583	6.24	1%
6.19	0.1293	6.18	0%
6.72	0.2988	6.53	3%
6.62	0.2875	6.50	2%
7.08	0.4269	6.79	4%
6.76	0.3668	6.66	1%
7.00	0.3898	6.71	4%
6.15	0.1525	6.23	-1%
6.39	0.2145	6.35	1%
6.25	0.1433	6.21	1%
6.09	0.1164	6.15	-1%
5.92	0.0324	5.98	-1%
6.21	0.1461	6.21	0%
6.10	0.1087	6.14	-1%
6.61	0.2857	6.50	2%
6.53	0.2503	6.43	2%
6.81	0.3903	6.71	1%
6.72	0.3529	6.64	1%