Climate Resilient Concrete Structures in Marine Environment of Bangladesh

Final Field and Laboratory Testing Report

Mott MacDonald Ltd.

Mott MacDonald

AsCAP Project Reference Number BAN2077A

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Cover Photo: Photo showing concrete trial mixing at LGED Central Laboratory

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Mott MacDonald,
Mott MacDonald House,
8-10 Sydenham Road,
Croydon CR0 2EE,
United Kingdom
T +44 (0)20 8774 2000
F +44 (0)20 8681 5706
W www.mottmac.com

ReCAP Project Management Unit
Cardno Emerging Market (UK) Ltd
Oxford House, Oxford Road
Thame
OX9 2AH
United Kingdom

Project Summary

Bangladesh has a vast coastal infrastructure seriously affected by climate change and associated extreme environmental conditions. Reinforced concrete structures in the coastal regions can deteriorate rapidly (within 5-10 years of construction) due to exposure to aggressive marine environment, issues related to poor workmanship, limited availability of good quality materials and lack of awareness on good construction practices.
LGED maintains around 380,000 linear metres of concrete bridges/culverts in the rural coastal areas and are planning to build more than 200,000 linear metres during the next ten years. In order to construct durable concrete structures to withstand the aggressive coastal environment for the intended design life, there is a need to study the local factors that influence the durability of reinforced concrete structures. This project will examine the major factors that contribute to premature deterioration of concrete structures, develop cost effective concrete mix design to enhance the durability of future structures and make recommendations on improvements in construction practice and workmanship considered necessary to improve service life.

Final Field and Laboratory Testing Report

Following the approval of Laboratory Testing Report 1 and Interim Field and Laboratory Testing Report 2, this Final Laboratory testing report is submitted to fulfil the objectives of milestone 5 agreed in the terms of reference of the contract. This report essentially combines the Interim laboratory testing report 1 & 2 along with the interpretative discussions on phase II experimental work undertaken to study the durability of various concrete mixes. The outcome of the phase I testing helped in establishing the inter-relationship between various factors such as W/C ratio, cement content, strength, workability and corrosion inhibitors for local materials available in Bangladesh. The inter-relationship established in Phase I study was used to develop the research matrix for Phase II study, which deals with durability testing of various concrete mixes. The outcome of the phase II study on durability testing of concrete clearly demonstrates the improvement in performance of concrete with flyash or slag additions. The study concludes that the concrete mix with at least 30% addition of flyash as cementitious content produced more durable concrete mix for aggressive marine exposure conditions in the coastal regions of Bangladesh.

Key words

Condition survey, Testing, Concrete durability, Corrosion, Carbonation, Bangladesh, Chloride content, Coastal infrastructure, Marine structures

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Acronyms, Units and Currencies

£	British Pound
RECAP	Research for Community Access Partnership
UK	United Kingdom (of Great Britain and Northern Ireland)
UKAid	United Kingdom Aid (Department for International Development, UK)
LGED	Local Government Engineering Department
DFID	Department of International Development
MML	Mott MacDonald Ltd.
BDT	Bangladesh Taka
BNBC	Bangladesh National Building Code
SCM	Supplementary Cementitious Material
CI	Corrosion Inhibitor
SSD	Saturated Surface Dry
W/C	Water/Cement or Water/Cementitious ratio

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Safe and sustainable transport for rural communities

AsCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Asia. The AsCAP partnership supports knowledge sharing between participating countries in order to enhance the uptake of low cost, proven solutions for rural access that maximise the use of local resources. AsCAP is brought together with the Africa Community Access Partnership (AfCAP) under the Research for Community Access Partnership (ReCAP), managed by Cardno Emerging Markets (UK) Ltd.

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1 Introduction

1.1 Background

Following a competitive tendering process, Mott MacDonald Limited was awarded the contract to undertake the Research for Community Access Partnership (ReCAP) project, "Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh" (the Project). The ReCAP programme is funded by the Department for International Development (DfID) and managed by Cardno Emerging Markets (UK) Ltd.

The original tender documentation set out the context of the Project, describing how Bangladesh is seriously affected by climate change. In particular, excessive intrusion of seawater, air borne chlorides and the high humidity of the coastal belt cause the rapid deterioration of concrete structures within 5 to 10 years of construction.

LGED maintains around 380,000 linear metres of concrete bridges/culverts at the rural coastal areas, with plans to build more than 200,000 linear metres during the next ten years. This has created an urgency to undertake a study on the durability of concrete structures in the marine environment of Bangladesh.

1.2 Inception report

The outcome and deliverables for each phase of the project is presented in the form of technical reports as agreed in terms of reference in the contract. An Inception Report was submitted to Cardno on 22nd Aug 2016, which provided a comprehensive review of background information on locally available concrete materials, durability of concrete, workmanship issues and gaps identified in literature review. The inception report also provided an outline of the plan of work for the condition survey phase and a research matrix for the mix design development and laboratory testing phase.

1.2.1 Identified gaps in literature review

Although information on environment, materials and performance of concrete structures are available from the coastal regions of Bangladesh, the following major gaps were identified, which needed to be addressed to enable the design and assessment of concrete structures:

- Very little information on the benefits of locally available fly ash and slag as cement replacement on long-term strength and corrosion resistance of concrete.
- Numerous studies on the comparison of stone aggregates vs brick aggregates mainly focussed on the strength characteristics, however limited information was available on the variability in quality of brick aggregates, measures to improve quality of brick aggregates and corrosion resistance of brick aggregate concrete.
- Some of the previous surveys of concrete structures in the coastal regions identified that corrosion of reinforcement and workmanship issues are the major reasons for deterioration of concrete structures based on visual observations, however no testing data is available. No condition survey of concrete structures that involved information related to local exposure conditions, extent of chloride and carbonation levels in concrete, extent of corrosion activity by half-cell surveys and in-situ strength and condition of concrete.
- Most of the available literature on durability studies of concrete using locally available materials focussed on influence of strength; very little on permeation properties of concrete and no information/data on corrosion resistance of concrete and steel type.

- Chloride induced corrosion models are widely used as a tool to predict the service life of concrete structures in marine environment. These models need crucial information on the durability properties such as chloride migration coefficient, maturity/strength development characteristics, surface chloride and climatic information of local environment. This information obtained at different exposure zones in the coastal regions of Bangladesh will be invaluable for the design and service life assessment of concrete structures in the region.

1.3 Condition survey

The Condition survey report submitted to Cardno on 21st Nov 2016, provided a factual information on the condition of various concrete structures surveyed in identified coastal districts viz., Bagerhat, Noakhali, Gopalganj and Cox's Bazar. Based on the observations from the condition survey of concrete structures it is believed that the major causes of deterioration of concrete in coastal regions are as follows:

- exposure to aggressive marine environment,
- poor workmanship
- use of brick aggregates
- use of chloride contaminated aggregates and water in construction
- limited availability of good quality materials
- lack of awareness on good construction practices.
- lack of quality control mechanism for small construction projects

A mix design programme was planned to explore the possibility of developing cost effective mix design(s) that will enhance the durability of concrete used in the rural marine environment. While it is easy to recommend that only clean aggregates or clean water be used, in some areas these materials are simply not available. Bangladesh has little natural resources with most cement and aggregates being imported. While major infrastructure projects are able to use the imported aggregate, much of the smaller, rural market relies on crushed bricks. The mix design programme needs to gauge the effect of using bricks and contaminated water, assess whether there are opportunities to enhance durability with these materials and contrast potential service life improvements if quality materials can be sourced.

2 Strategy for Achieving Durability

As described in the inception report, best practice for ensuring durability of reinforced concrete elements are:

- Structural design that avoids non-durable features that are vulnerable to deterioration and details which are likely to make concrete placement and full compaction difficult to achieve, particularly overly-congested reinforcement;
- Full consideration of the factors that are likely to influence or control durability, based on a knowledge of the structure, its required performance level, and a thorough assessment of the service environment (requiring adequate site data);
- Specification, development and production of a concrete mix that has fresh characteristics which allow it to be readily placed and compacted, and on hardening to produce a high quality dense, impermeable concrete (of particular importance are aggregate quality and grading, selection of a cement/combination type with suitable characteristics, appropriate minimum cement content and low maximum water/cement ratio, and appropriate use of admixtures to modify fresh and hardened properties);
- Specification and achievement of a suitable nominal cover depth (comprising the minimum depth for durability plus a reasonable allowance for deviation in practice);

- Where appropriate, specification and provision of additional means of protection which enhance intrinsic resistance to deterioration, or modify/reduce exposure to the factors that may cause deterioration;
- Ensure appropriate methods and standards of placement, compaction and curing to achieve high quality finished concrete product.

Therefore, based on the consideration of available methods the optimal approach to providing the required service life with an adequate degree of confidence and in terms of economy of design and cost, should involve the following strategy:

- The primary means of providing the required level of durability will be the provision of high quality, dense, low permeability concrete that is inherently resistant to the most likely deterioration mechanisms, with a sufficient minimum cover depth to reinforcement.
- Secondary measures for further enhancing the durability of the structures especially to protect the reinforcement from corrosion in salt environment by means of adding corrosion inhibitor in the concrete mix.

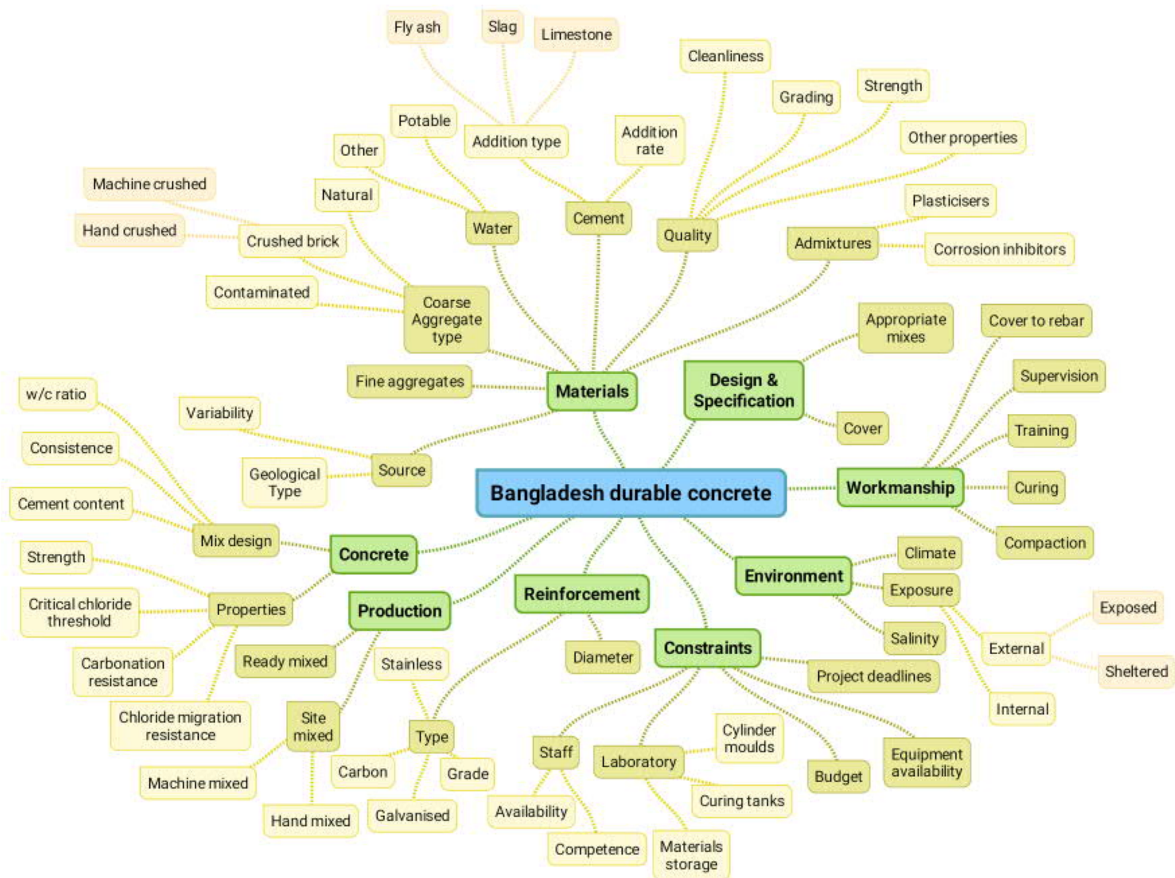


Figure 1 Inter-relationship between variables influencing durability of concrete

3 Rationale behind variable selection

3.1 Selection of variables

There are many variables that could be considered as illustrated in Figure 1. Many of these could be broken down into much more detail but the nature of the project is a high-level look at factors affecting the poor performance and what practical steps can be made to enhance the service life. Due to the generally low level of control and supervision of the rural projects, it will be difficult to exercise control over aggregate quality, water quality, workmanship etc. The only source of material that is reliably controlled is the cement as it is factory produced and is bagged. Discussions with cement manufacturers have indicated that replacement levels are typically 20% (fly ash or slag) but they have a willingness to increase the addition content. No admixtures are currently blended with cements but again the industry expressed a willingness to incorporate them if required.

Table 1 Categorisation of selected variables

Unquantifiable	Specifiable	• Supervision of construction • Competency of workforce • Curing • Compaction • Source of materials
	Unspecifiable	• Critical chloride threshold • Diligence of workforce • Effectiveness of supervision • Effectiveness of curing • Climate • Exposure environment
Quantifiable	Specifiable	• Characteristic strength • Fine aggregate type • Coarse aggregate type • Target grading • Cement type • Percentage addition (fly ash /slag) • Max chloride content • Minimum cement content, • Maximum free water/cement ratio • Consistence • Water quality • Admixture type • Admixture dosage • Target cover to rebar • Type of rebar
	Unspecifiable	• Actual grading • Aggregate absorption • Actual w/c ratio • Admixture performance • Actual cover • Actual strength

The mix design programme will therefore be developed to:

- Utilise the opportunities of developing a bagged cement for the rural market designed to enhance service life
- Limit the variables considered in order that it can be delivered within timescales and budget

Service life will be assessed using NT Build 492 to determine the chloride migration coefficient of different concrete mixes in conjunction with a probabilistic model based on fib bulletin 34. To limit the variables in the experimentation the identified variables can be categorised into specifiable and unspecifiable variables as listed in Table 1 and among these variables critical variables as highlighted in red are selected for the mix design programme.

3.2 Selection of levels among variables

Two types of cement are in widespread use in Bangladesh, CEM I, CEM IIA-M. The 'M' classification permits any addition (e.g. slag or fly ash). Throughout the laboratory testing programme, the terminology for CEM II will use the following descriptions to clarify the cement composition.

- CEM IIA-S: Cement with 80% CEM I and 20% slag.
- CEM IIA-V: Cement with 80% CEM I and 20% Fly ash.
- CEM IIB-V Cement with 70% CEM I and 30% Fly ash.
- CEM IIIA; Cement with 60% CEM I and 40% slag.

Since local producers only offer IIA-M cements, Fly ash and slag were blended in the concrete mix with CEM I. to produce the required combinations.

Given that the increase in blend levels will most likely improve the durability performance of concrete, it is necessary to consider all cements with at least two addition levels. CEM I is often perceived as the "quality" cement and has been frequently specified on major government contracts, whereas European specifications and standard BS 8500-1:2015+A1:2016 would use blended cements in more aggressive environments, particularly when exposed to chlorides. The increased dosage of SCMs in cement should improve the durability, sustainability and potentially reduce the cost of concrete.

It is unlikely that multiple sources of coarse aggregate will be available at the rural sites under consideration in this project, therefore blends of material will not be tested, instead the options trialled will be 100% natural aggregate, 100% hand-crushed brick and 100% machine processed brick.

Three free water cement ratios is considered which will reflect the range of mixes used and act as a proxy for the effect of adding a water-reducing plasticiser.

Mixes are prepared with potable water and contaminated water at two different concentrations, which mainly helps to study the influence of use of contaminated water caused by issues related to poor workmanship on the durability performance of concrete. It is anticipated that using contaminated water will reduce the binding capacity of the concrete, accelerating the ingress of external chlorides. The selected concentration of contaminated water is based on the concentration level of local water tested in the four coastal districts.

Mixes are also prepared with two levels of corrosion inhibitor (CI) and without any CI as a control. While corrosion inhibitors are unlikely to be added on site, consideration is being given to incorporating them into the bagged cement products. While calcium nitrite (commonly used CI) is an expensive constituent, which would preclude it from widespread application, there is evidence (Baghabra et al., 2003) that the significantly cheaper calcium nitrate can also be effective at extending the propagation period of the housing process.

Fine aggregate tends to be natural sand and will not be treated as a variable. Although the sand may be contaminated with chlorides and possibly clay/silts, these effects can be assessed using contaminated water and varying the w/c ratio (the main effect of excessive fines in the sand will be to increase water demand).

Based on the above discussion, the final variable matrix is presented in Table 2.

Table 2 Variables matrix

Material	Measurand	Variable type	No of Variables
Cement type	Categorical	CEM I CEM IIA-V (20% FA) CEM IIB-V (30% FA) CEM IIB-S (20% slag) CEM IIIA (40% slag)	5
Cement content (free w/c ratio)	Quantitative	0.6, 0.5, 0.4	3
Coarse aggregate type	Quantitative	Natural aggregate (NA) Machine crushed Brick (MCB) Cement Coated Brick (CCB)	3
Water	Quantitative	Potable Contaminated level 1 (0.5% Cl^-) Contaminated level 2 (1.0% Cl^-)	3
Corrosion Inhibitor	Quantitative	0 Type 1 Type 2	3

4 Laboratory testing

The mix design and laboratory testing phase of the project was planned based on the gaps identified in the Inception stage of the project and findings obtained in the condition survey stage of the project. The experimental programme for the laboratory testing is divided in two phases; the Phase-I deals with establishing the relationship between various factors that control the performance of concrete construction by using locally available materials and phase-II focusses on optimising the concrete mix for durable performance in marine exposure conditions by studying the corrosion resistance characteristics and service-life assessment of reinforced concrete elements.

4.1 Phase – I Laboratory testing

The phase-I study involves various trial mixes for optimising the concrete mix constituents to produce workable, good strength and low permeable concrete. The experimental research matrix for phase I study is shown in Table 3, which mainly focuses on establishing relationships between W/C ratio, Cement content and compressive strength; increasing the SCM proportion in concrete, improving the properties of brick aggregates; and identify optimum proportions of combined graded stone and brick aggregates.

The study to establish relationship between W/C ratio, Cement content and compressive strength, mainly focusses on understanding the performance of materials in producing a workable concrete. The relationship established in this study will help to identify appropriate cement content for a given W/C ratio in the Phase-II testing of concrete.

Table 3 Experimental Research Matrix

Study	Variables	Techniques of analysis
To establish relationship between W/C ratio, Cement Content and Strength	Stone aggregates vs Brick Aggregates No Chemical Admixture vs Chemical Admixture	Fresh properties of concrete (slump, cohesion of mix and density) Strength (7 and 28 days)
To increase the proportion of SCMs in concrete	Binder content and W/C ratio: Approximate binder content 350, and 400 corresponding to 0.5 and 0.4 W/C ratio Flyash (30-40% cement replacement) Slag (30-50% cement replacement) Combination of flyash and slag (>30% cement replacement)	Fresh properties of concrete (slump, cohesion of mix and density) Strength development (7, 28 and 56 days)
Feasibility study on improving the properties of brick aggregates	Coated vs uncoated brick aggregates	Preliminary Testing: Specific Gravity Absorption Capacity (%) Unit Weight (kg/m3) Los Angles Abrasion (%) Secondary Testing: Fresh properties of concrete (slump, cohesion of mix and density of concrete) Compressive Strength (7, 28 and 56 days)
To study the effect of Calcium Nitrate Corrosion inhibitor on fresh and hardened properties of concrete	Dosage of Corrosion Inhibitor: 3%, 3.5% and 4% W/C ratio: 0.4, 0.5 and 0.6	Cement Testing: Setting time Normal consistency Compressive strength Concrete testing: Slump loss Compressive strength

Compressive strengths were measured at 28 days and 56 days and an optimum SCM content was obtained by taking into consideration the later age strength development (56 days strength).

One of the novel features of the Phase-I study was examining the feasibility of improving the properties of brick aggregates by pre-treating them with a cement slurry mix. A recent research study by Sarkar and Pal, 2016, suggests that addition of cement coating in over burnt brick aggregate has reduced the aggregate impact value, Los Angeles Abrasion value, water absorption and increased the specific gravity of aggregates. This study shows a potential scope for improving the properties of brick aggregates, which can be trialled in concrete mixes to check the improvement in durability properties of concrete.

4.2 Phase – II Laboratory testing

The phase-II of the study builds on the outcome of phase-I and focusses on investigating the corrosion resistance of reinforced concrete by studying the corrosion resistance related properties of concrete and steel. The experimental research matrix for phase-II study has been planned based on design of experiments methodology as detailed below.

4.2.1 Design of experiment

In the traditional approach for experimentation, one parameter is varied and all the other parameters are kept constant. To study different factors and its interactions, factorial experiments and response surface design methods are available. In the case of full factorial design, where interactions between different factors and parameters are individually tested, it will result in numerous experiments. The variable matrix identified in section 3 and presented in Table 2, when investigated in full factorial design would require 5 x3x 3x3x3 =405 mixes.

In design of experiment methodology, each cement type will be compared against the other four variables as listed in Table 4 based on a Taguchi L9 Orthogonal Array giving a total of 45 mixes required as presented in Table 5.

Table 4 Experimental Variables – L9 Orthogonal Array

Experiment number	Free w/c ratio	Coarse aggregate type	Contamination level	Corrosion Inhibitor type
1	0.4	NA	0	0
2	0.4	CCB	1	1
3	0.4	MCB	2	2
4	0.5	NA	1	2
5	0.5	CCB	2	0
6	0.5	MCB	0	1
7	0.6	NA	2	1
8	0.6	CCB	0	2
9	0.6	MCB	1	0

To remove unintended bias from the mix designs the sequence of mixes will be randomised and the following order has been created using Microsoft Excel RandBetween function.

Table 5 Experimental matrix for phase-II testing

Run number	Cement type	w/c ratio	Coarse aggregate type	Contamination level	Cl dose
1	CEM I	0.6	MCB	1	0
2	CEM I	0.4	CCB	1	1
3	CEM IIIA	0.4	CCB	1	1
4	CEM IIA-S	0.5	CCB	2	0
5	CEM IIA-V	0.6	CCB	0	2
6	CEM IIIA	0.5	MCB	0	1
7	CEM IIB-V	0.5	CCB	2	0
8	CEM IIA-S	0.5	NA	1	2
9	CEM IIB-V	0.4	CCB	1	1
10	CEM IIA-V	0.4	NA	0	0
11	CEM IIIA	0.6	MCB	1	0
12	CEM IIA-V	0.5	NA	1	2
13	CEM I	0.5	CCB	2	0
14	CEM IIA-V	0.4	MCB	2	2
15	CEM IIA-V	0.5	MCB	0	1
16	CEM IIIA	0.5	NA	1	2
17	CEM IIA-S	0.5	MCB	0	1
18	CEM IIA-V	0.6	MCB	1	0
19	CEM IIA-S	0.6	CCB	0	2
20	CEM IIA-S	0.4	MCB	2	2
21	CEM IIA-V	0.4	CCB	1	1
22	CEM I	0.6	CCB	0	2
23	CEM IIB-V	0.4	NA	0	0
24	CEM IIB-V	0.5	NA	1	2
25	CEM IIIA	0.6	CCB	0	2
26	CEM IIA-S	0.6	MCB	1	0
27	CEM I	0.5	NA	1	2
28	CEM IIB-V	0.4	MCB	2	2
29	CEM IIIA	0.4	NA	0	0
30	CEM IIIA	0.5	CCB	2	0
31	CEM IIIA	0.4	NA	0	0
32	CEM IIIA	0.6	NA	2	1
33	CEM IIA-S	0.4	CCB	1	1
34	CEM IIB-V	0.6	MCB	1	0
35	CEM IIIA	0.4	MCB	2	2

Run number	Cement type	w/c ratio	Coarse aggregate type	Contamination level	Cl dose
36	CEM I	0.6	NA	2	1
37	CEM IIB-V	0.5	MCB	0	1
38	CEM IIA-V	0.5	CCB	2	0
39	CEM IIB-V	0.6	CCB	0	2
40	CEM I	0.4	MCB	2	2
41	CEM IIA-V	0.6	NA	2	1
42	CEM IIA-S	0.4	NA	0	0
43	CEM IIA-S	0.6	NA	2	1
44	CEM IIB-V	0.6	NA	2	1
45	CEM I	0.5	MCB	0	1

The experimental work for phase-II involves concrete mixing with variables as detailed in Table 5, testing of fresh concrete properties, tests to study chloride migration of concrete through NT Build 492 test method and corrosion rates of steel in reinforced concrete slabs subjected to accelerated corrosion environment.

5 Material Selection and Testing

This part of the study involves testing representative materials that will be used in the study in accordance with the list of testing specified in Table 6.

Table 6 Specification for material sampling and testing

Material	Comparison of samples	Laboratory testing of chosen sample
Cement	At least 3 no popular selling cement – CEM I	• Chemical analysis • Blaine fineness • Setting time (Initial & Final) • Specific Gravity • Compressive Strength (3, 7 and 28 days)
Fly ash	At least 3 no from most popular cement companies in coastal region	• Chemical analysis • Blaine fineness • Specific Gravity
Slag	At least 3 no from most popular cement companies in coastal region	• Chemical analysis • Blaine fineness • Specific Gravity
Aggregates	Locally available sand, brick chips, ‘Machine Made’ aggregates and stone aggregates should be sampled	• Specific Gravity • Absorption Capacity (%) • Unit Weight (kg/m3)

Material	Comparison of samples	Laboratory testing of chosen sample
	at Bagerhat, Noakhali, Gopalganj and Cox's Bazar	• Los Angles Abrasion Value (%) • Ten Percent fines value (%) • Flakiness Index (%) • Elongation Index (%) • Fineness Modulus • Chloride content
Water	Locally available drinking water and untreated water at Bagerhat, Noakhali, Gopalganj and Cox's Bazar	• Chloride content

5.1.1 Cement, Flyash and Slag

The local market information and discussions with LGED suggested that Bashundhara cement company is the most popular cement used in the country. Therefore, as a representative cement sample of the market, Bashundhara cement products were used in this study.
Chemical testing of the cement was undertaken by Bashundhara Cement and the results are

The chemical testing of the cement was done at testing facility of Bashundhara Cement and the results are presented in Table 7. The physical testing of the cement was conducted at LGED laboratory and the test results are presented in

Table 8.

Table 7: Chemical characteristics of OPC (CEM I) cement

Chemical parameter	Result (% mass)	BS EN 197-1:2011 or BDS 197-1 requirements
Loss on Ignition (LOI)	0.48	≤ 5.0%
Magnesium Oxide (MnO)	1.68	-
Sulphuric Anhydrate (SO3)	2.40	≤ 4.5%
Insoluble Residue	0.40	≤ 5.0%
Free Lime	0.45	-
Sodium Oxide (Na_2O)	0.07	-
Pottasium Oxide (K_2O)	0.53	-
Total Alkalies	0.42	-
Chloride (Cl-)	0.019	≤ 0.1%

Table 8: Physical characteristics of OPC (CEM I) cement

Physical parameter	Result	BS EN 197-1:2011 or BDS 197-1 requirements

Specific Surface (m^2/kg)	385	-
Setting time (mins)		
Initial Setting Time	102	≥ 60
Final Setting Time	250	-
Soundness (mm)	0.50	≤ 10
Compressive Strength (MPa)		
3 days	24.48	-
7 days	27.88	-
28 days	45.38	≥ 42.5

The flyash sample supplied by Bashundhara cement was imported from India, the physical and chemical characteristics of the flyash are given in Table 9.

Table 9 Chemical and Physical characteristics of flyash

Elements	Result (% mass)	BS EN 450-1: 2012 requirements
Calcium Oxide (CaO)	1.25	≤ 1.5%
Silicon dioxide (SiO2)	59.60	SiO2+Al2O3+Fe2O3 ≥ 70%
Aluminium oxide (Al2O3)	28.70	SiO2+Al2O3+Fe2O3 ≥ 70%
Iron Oxide (Fe2O3)	6.64	SiO2+Al2O3+Fe2O3 ≥ 70%
Magnesium Oxide (MgO)	0.97	≤ 4.0%
Sulphuric Anhydride (SO3)	0.11	≤ 3.0%
Loss of Ignition (LOI)	1.12	≤ 5.0% by mass (Cat A)
Moisture	0.32	-
Blaine Surface area	283	-
Bulk Density	0.806	-

The slag sample supplied by Bashundhara cement was imported from Japan, the physical and chemical characteristics of the sample are presented in Table 10. The test results show that the moisture content of the slag is higher than the limits specified in EN 15167-1:2006.

Table 10 Chemical and Physical characteristics of Slag

Elements	Result (% mass)	BDS 197-1	EN 15167-1:2006 requirements
Loss on Ignition (LOI)	0.09		≤ 3.0%

Insoluble Residue (IR)	0.14		-
Sulphur trioxide (SO_3)	0.05		≤ 2.5%
Alluminium oxide (Al_2O_3)	16.30		-
Iron oxide (Fe_2O_3)	0.91		-
Calcium oxide (CaO)	42.60	(CaO + MgO) / SiO_2≥ 1 CaO+MgO+SiO_2 ≥ 66.67%	-
Silicon dioxide (SiO_2)	34.10		-
Magnesium oxide (MgO)	5.53		≤ 18.0%
Moisture	7.81		≤ 1.0%

5.1.2 Coarse Aggregate

Most of the stone aggregates used in infrastructure projects are imported from neighbouring countries. The source of these stone aggregates is quite variable depending on the availability and cost of transporting to the construction location. Although locally quarried stone aggregates are available in some regions of the country, the quality of the aggregates were observed to be variable. For example, some of the samples of local aggregates collected from Gaptoli in Dhaka had LA abrasion value varying between 35 and 50 (well above maximum LA limit of 30 as per LGED standard).

The stone aggregates used in this study were a combination of local aggregates (10 mm nominal size) and imported Vietnam aggregates (20mm nominal size) collected from Gaptoli in Dhaka. The brick aggregates were also collected from Gaptoli in Dhaka, where a combination of first class bricks and picked Jhama brick were selected and machine crushed, such that the combined aggregates has an LA Abrasion value close to LGED limit of 40.. The physical properties of all the sampled aggregates were tested at LGED Central Laboratory. The physical characteristics of the stone aggregates and brick aggregates are presented in Table 11 and Table 12.

Table 11 Physical characteristics of stone aggregates

Test Parameter (units)	Result
Specific Gravity 20 mm 10mm	 2.74 2.65
Water Absorption (%) 20 mm 10 mm	 0.40 0.73
Unit weight (kg/m^3) 20 mm 10 mm	 1667 1472
LA Abrasion Combined aggregates (50% of 20 mm and 50% of 10 mm)	 30.0

Test Parameter (units)	Result
Ten percent fines (%) Combined aggregates	 9.96
Flakiness Index (%) 20 mm 10 mm	 14.84 36.22
Elongation Index (%) 20 mm 10 mm	 33.33 41.22

Table 12 Physical characteristics of brick aggregates

Test parameter (units)	Result
Specific Gravity	2.06
Water Absorption (%)	14.99
Unit weight (kg/m^3)	
LA Abrasion	42.26
Ten percent fines (%)	12.19
Flakiness Index (%)	23.03
Elongation Index (%)	44.34
Fineness modulus	7.03

5.1.3 Fine Aggregate

The fine aggregate used in this study was Sylhet sand collected from Gaptoli in Dhaka. The physical properties of the fine aggregate are presented in Table 13.

Table 13 Physical characteristics of fine aggregate

Test parameter (units)	Result
Specific Gravity	2.57
Water Absorption (%)	1.28
Unit weight (kg/m^3)	1587
Fineness modulus	2.98

5.1.4 Water

The water used in the study was tap water available at LGED central laboratory.

5.1.5 Water-reducing admixture (Superplasticiser)

Sikament 2002 NS, which is a high range water reducing chemical admixture manufactured by Sika India Ltd was used in this study. This is a modified Naphthalene Formaldehyde Sulphanate (SNF) based water reducing admixture that has a relative density of 1.17 kg/l and pH greater than 6.

5.1.6 Corrosion Inhibitor

Corrosion inhibitors are often used to prolong the initiation period to corrosion of reinforcement in concrete. In the context of this project, while corrosion inhibitors are unlikely to be added on-site in rural infrastructure projects, it is considered that there could be an opportunity to incorporate them in the bagged cement products. While calcium nitrite (commonly used CI) is an expensive constituent, which would preclude it from widespread application, there is evidence (Baghabra et al., 2003) that the significantly cheaper calcium nitrate can be effective at extending the propagation period of the corrosion process. Moreover, calcium nitrate based corrosion inhibitors are available in granules, which can be easily inter-ground with clinker/cement to produce bagged cement product. In the phase-I stage of laboratory testing, concrete trial mixes using corrosion inhibitors are tested to study the influence of this admixture on fresh and hardened concrete properties. The calcium nitrate corrosion inhibitor used in this study was kindly contributed by Yara Intl ASA, Norway. The chemical and physical characteristics of calcium nitrate corrosion inhibitor as given in the manufacturer's test certificate is provided in Table 14.

Table 14 Chemical composition and density of Calcium Nitrate Corrosion Inhibitor

Test parameter	Result (%)
Total Nitrogen	2.57
Ammonium-N	1.28
Nitrate-N	1587
Total CaO	2.98
Chlorine	0.0
Iron	0.03
Water insoluble >3µm	500 ppm
Bulk density	1.10 kg/l

6 Phase I Study - Concrete mix design, Optimisation and Testing

6.1 To establish relationship between free W/C ratio, Cement content and Strength

This part of the phase-I study involves trial mixes to determine free W/C ratio and cement content for a constant slump, ensure mixes are cohesive and yield 1.0m3. The study focusses on establishing relationship between free W/C ratio, cement content and strength of concrete at a target slump of 75-100mm for both stone and brick aggregate concretes. To get a good correlation curve between the free W/C ratio and cement content of concrete, concrete mixes with four different cement content was tested. In the trial testing, the final free W/C ratio of each concrete mix with given cement content was determined based on total amount of water added to the mix to attain target slump of 75-100mm. The free total water in the mix is determined after moisture correction compensating for the water contributed by wet aggregates or water absorbed by dry aggregates. The final saturated surface dry (SSD) batch weights of concrete mixes tested with stone aggregates are given in Table 15.

Table 15 Mix proportions of concrete mixes with stone aggregates

Mix Ref	Free w/c ratio	Cement (kg)	Coarse Aggregate (60%) (kg)		Total Coarse Aggregate (60%) (kg)	Sand (40%) (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
			20 mm (50% of CA)	10 mm (50% of CA)					
T-01	0.84	250	555.83	555.83	1111.66	741.11	211	90	2337.72
T-02	0.63	350	542.17	542.17	1084.34	722.89	219	80	2384.64
T-03	0.51	450	522.43	522.43	1044.86	696.57	231	90	2360.86
T-04	0.46	500	491.26	491.26	982.52	655.02	229	75	2389.46
T-05	0.44	550	460.1	460.1	920.2	613.47	241	90	2375

In the case of concrete mixes with brick aggregates, the aggregates were pre-soaked for a period of 1 hour such that the brick aggregates do not absorb any additional water at the time of mixing and testing of concrete for slump. The moisture content of pre-soaked aggregates was measured prior to the trial mixing and the batch weights for each mix were corrected for moisture contributed by the aggregates to the mix. The final SSD batch weights of concrete mixes with brick aggregates are given in Table 16.

Table 16 Mix proportions of concrete mixes with brick aggregates

Mix Ref	w/c ratio	Cement (kg)	Coarse Aggregate (50%) (kg)	Sand (50%) (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
T-07	0.93	250	855	856	232	70	2087
T-08	0.65	350	790	791	227	90	2084
T-09	0.52	450	748	749	180	100	2018
T-10	0.47	500	708	709	236	80	2119
T-11	0.45	550	667	668	248	95	2123

6.1.1 Use of water reducing admixture

The water reducing chemical admixtures are quite widely used in larger infrastructure projects in Bangladesh and less predominant in rural projects. The major benefit of using these chemical admixtures will help in improving the workability and homogeneity of concrete mix, however it needs stringent quality control practices at sites. The increased workability of the mix will also help in better compaction of concrete at site. It is envisaged that for the next ten years in Bangladesh there will be high amount of construction activity and it is more likely that chemical admixture will be predominantly used in concrete.

In this part of the study, high range water reducing admixture was used in four different concrete mixes containing stone aggregates. Similar to the methodology adopted in T01 to T05 mixes, the W/C ratio of the mixes was determined such that the concrete mix attains a target slump of 75-100mm. The final SSD batch weights of the concrete mixes are given in Table 17.

Table 17 Mix proportions of concrete mixes with stone aggregates and superplasticiser

Mix Ref	w/c ratio	Cement (kg)	Coarse Aggregate (60%) (kg)		Sand (40%) (kg)	Sikaplast 2002NS (1%)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
			20 mm (50% of CA)	10 mm (50% of CA)					
T-15	0.74	250	616.65	616.65	822.21	2.825	185	70	2339
T-16	0.49	350	570.55	570.55	760.74	3.955	173	90	2365
T-17	0.38	450	540.67	540.67	720.9	5.085	171	90	2433
T-18	0.42	400	569.81	569.81	759.74	4.52	169	90	2407

The relationship between W/C ratio and cement content was determined for the three-different type of concrete mixes viz., stone aggregates, brick aggregates and stone aggregates with superplasticiser (SP) as shown in Figure 2.

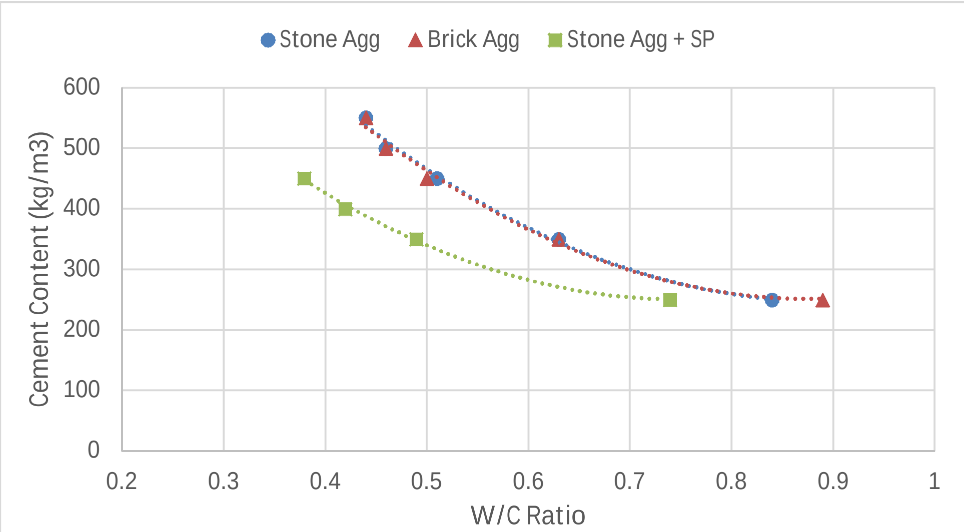


Figure 2 The relationship between W/C ratio and cement content of concrete

It can be observed from Figure 2 that the free W/C ratio required by brick aggregate concrete to produce constant slump concrete was higher than the stone aggregate concrete at 250 kg/m3 cement content, however the relationship curve between free W/C ratio and cement content of the concrete mix almost overlapped. On the other hand the concrete mixes with stone aggregate and superplasticiser required less cement in the mix to produce similar workability. The relationship presented in Figure 2 helps to identify the required cement content for a given free W/C ratio and can therefore be used in mix design of concrete for phase II laboratory testing.

Table 18 Compressive strength results of concrete mixes with stone and brick aggregates

Mix Ref	Free W/C ratio	Cement (kg)	Variable	Compressive Strength (MPa)	
				7 days	28 days
T-01	0.84	250	Stone Aggregate	17.49	21.51
T-02	0.63	350	Stone Aggregate	26.69	32.60
T-03	0.51	450	Stone Aggregate	38.13	38.90
T-04	0.46	500	Stone Aggregate	39.95	41.55
T-05	0.44	550	Stone Aggregate	42.28	47.45
T-07	0.93	250	Brick Aggregates	12.343	17.24
T-08	0.65	350	Brick Aggregates	20.813	26.78
T-09	0.52	450	Brick Aggregates	28.387	37.46
T-10	0.47	500	Brick Aggregates	30.057	37.82
T-11	0.45	550	Brick Aggregates	34.66	39.97
T-15	0.74	250	Stone Agg + SP	18.5	22.76
T-16	0.49	350	Stone Agg + SP	36.48	43.79
T-17	0.38	450	Stone Agg + SP	46.4	53.67
T-18	0.42	400	Stone Agg + SP	42.44	46.01

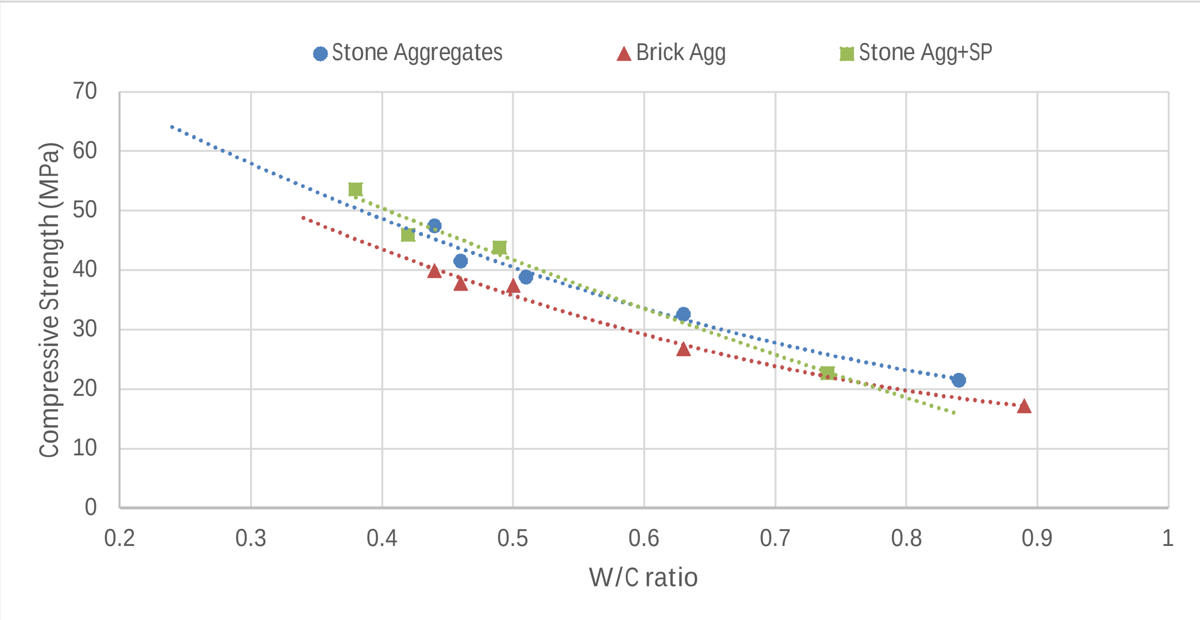


Figure 3 Relationship between W/C ratio and 28 days compressive strength of concrete

The 7-day and 28-day compressive strength results of the concrete mixes with stone and brick aggregates are presented in Table 18. A general trend in variation of 28 day strength of concrete at different W/C ratio can be observed in Figure 3 and presented in Table 18. The curve showing the relationship between W/C ratio and 7-day compressive strength of concrete for stone and brick aggregate concrete suggest that at similar cement content and workability, the 7-day strength of brick aggregate concrete mixes are around 20% less than the stone aggregate concrete mixes. The 28-day compressive strength results are presented in Figure 5, which suggests that the rate of strength gain with increase in cement content is low in the case of brick aggregate concrete as compared with stone Agg + SP concrete mixes. This suggests that the concrete with brick aggregates is reaching its strength limit due to the use of low strength brick aggregates. It can also be observed from Figure 3 that the concrete mixes with stone aggregates and stone aggregates+SP show a similar W/C ratio and strength relationship.

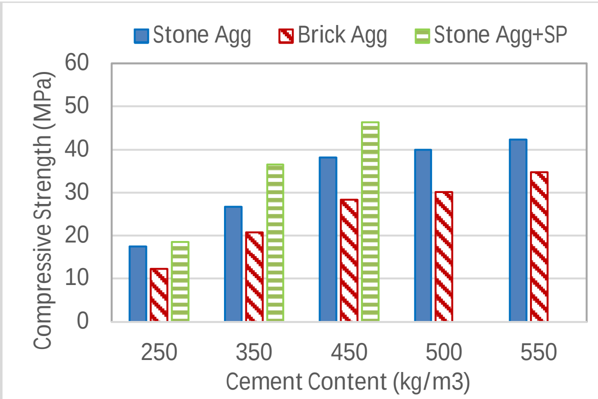


Figure 4 Comparison of 7 day compressive strength between brick and stone aggregate concrete

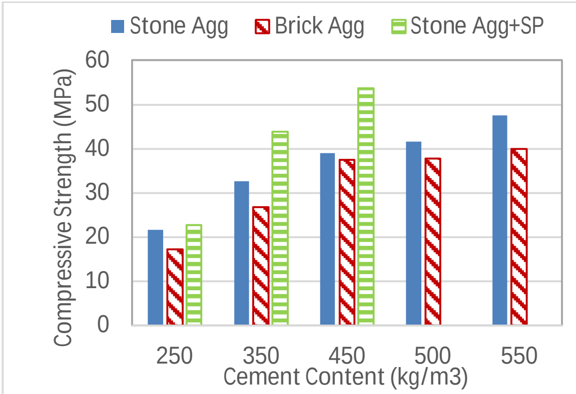


Figure 5 Comparison of 28 day compressive strength between brick and stone aggregate concrete

6.2 To increase the proportion of SCMs in concrete

Based on the literature review at the inception stage and discussions with local cement manufacturers, it is understood that the quality of Fly ash and slag available in Bangladesh is lower than those available in Europe and therefore optimum replacement levels were expected to be lower.

In this study three Fly ash replacement levels (20%, 25% and 30%) and four slag replacement levels (20%, 30%, 40% and 50%) were investigated. The influence of Fly ash/slag on the strength development of concrete are studied at target slump of 75-100mm, 0.5 W/C ratio and 450 kg/m^3 cementitious content. The mix details of concrete trial mixes with different replacement levels of Fly ash and slag are given in in Table 19 and Table 20 respectively.

Table 19 Mix details of concrete with different proportions of flyash

Mix Ref	w/c ratio	Cem I (kg)	Flyash (kg)	Stone Aggregate (60%) (kg)		Sand (40%) (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
				20 mm	10 mm				
T-12 (70% Cem I + 30% Flyash)	0.50	315	135	489	489	652.37	225	100	2328
T-13 (75% Cem I & 25% Flyash)	0.47	337.5	112.5	492	492	655.68	225	100	2341
T-14 (80% Cem I & 20% Flyash)	0.47	360	90	494	494	659	225	70	2332

Table 20 Mix details of concrete with different proportions of slag

Mix Ref	w/c ratio	Cem I (kg)	Slag (kg)	Stone Aggregate (60%) (kg)		Sand (40%) (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
				20 mm	10 mm				
T-19 (80% Cem I & 20% Slag)	0.50	360	90	501	501	668	223	90	2389
T-20 (70% Cem I & 30% Slag)	0.50	315	135	500	500	667	223	80	2356
T-21 (60% Cem I & 40% Slag)	0.49	270	180	499	499	665	220	85	2350
T-22 (50% Cem I & 50% Slag)	0.50	225	225	497	497	663	226	85	2325

The results of compressive strength tests of concrete with different replacement levels of flyash and slag are presented in Table 21 and shown in Figure 6. Based on the strength results it can be concluded that concrete mixes with slag additions produced slightly higher strength in comparison with 100% OPC concrete mix. In the case of concrete mixes with flyash addition, although the strength results are lower than 100% OPC concrete mix, however the increase in strength after 28 days was observed to be higher than the slag concrete mixes.

Table 21 Compressive strength results of concrete mixes with different proportions of flyash and slag replacements

Mix Ref	w/c ratio	Cement (kg)	Cement composition	Compressive Strength (MPa)		
				7 days	28 days	56 days
T-12	0.50	450	70% Cem I + 30% Flyash	17.97	25.28	27.60
T-13	0.47	450	75% Cem I & 25% Flyash	20.54	24.82	30.20
T-14	0.47	450	80% Cem I & 20% Flyash	22.91	27.90	32.80
T-19	0.50	450	80% Cem I & 20% Slag	27.15	40.20	42.50
T-20	0.50	450	70% Cem I & 30% Slag	32.09	41.80	42.40
T-21	0.49	450	60% Cem I & 40% Slag	26.44	42.30	42.20
T-22	0.50	450	50% Cem I & 50% Slag	24.40	37.58	43.20

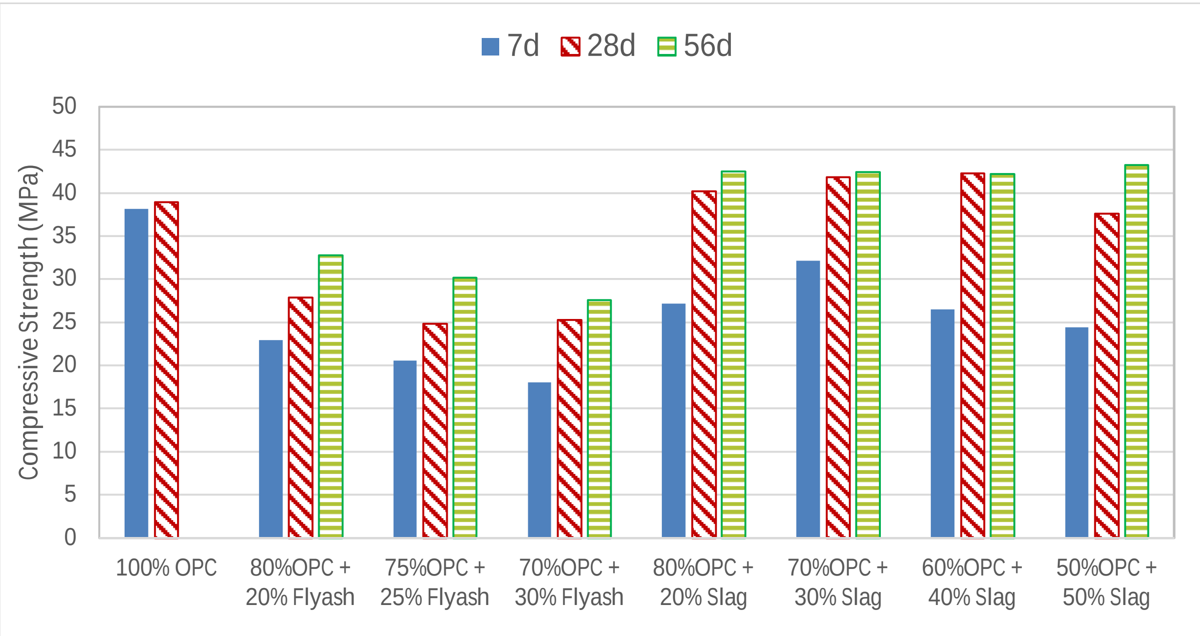


Figure 6 Comparison of strength development in concrete with different replacement levels of flyash and slag

6.3 Feasibility study on improving the properties of brick aggregates

This feasibility study deals with improving the properties of brick aggregates by cement coating. The preliminary testing involved coating of brick aggregates with cement paste containing 4%, 6% and 8% cement (by weight of aggregate) at 0.50 and 0.40 W/C ratio. The cement used for coating the brick aggregates was varied with two different proportions of flyash replacements. For each mix, the brick aggregates were initially conditioned to saturated surface dry and coated with cement paste in a laboratory concrete mixer for a period of 2-3 mins. The coated brick aggregates were cured for a period of 7-day and the aggregates were tested for specific gravity and water absorption. The results of testing of brick aggregates with varied proportions of cement paste coating are presented in Table 22. The specific gravity and water absorption results presented in Table 22 suggests that the cement paste coating has increased the water absorption of brick aggregates. The specific gravity of coated brick aggregates did not change much in comparison to uncoated brick aggregates. Although no clear explanation on the increase of water absorption of coated brick aggregates could be made due to the limited testing data, it can be assumed that one possible reason for this increased water absorption would be caused due to un-hydrated cement particles on the surface of brick aggregates. Among the varied proportions of cement coating tests, the 8 % cement coating mix at 0.4 W/C ratio was observed to have the lowest water absorption value.

Table 22 Physical properties of brick aggregates with varied coating proportions

Coating proportions			Specific gravity	Water absorption (%)
Cement content (% by weight of aggregates)	Cement	W/C ratio		
Uncoated	-	-	2.06	15.0
4%	100% OPC	0.5	2.05	17.3
6%	100% OPC	0.5	2.04	17.0
6%	100% OPC	0.4	2.04	17.2
8%	100% OPC	0.4	2.02	15.8
6%	60% OPC + 40% Flyash	0.5	2.01	16.3
6%	80% OPC+20% Flyash	0.5	2.00	16.6
8%	100% OPC	0.5	2.01	17.3

Although a clear improvement in brick aggregate properties has not been observed with coated bricks, however the 100% OPC mixed coated bricks were further tested in a concrete mix at two different cement content and W/C ratios. The mix proportions of concrete mix with three different coated brick aggregates are presented in Table 23.

Table 23 Mix proportion of concrete with different types of cement coated brick aggregates

Coating Type	Trial No.	w/c ratio	Cement (kg)	Coated Brick Aggregate (50%) (kg)	Sand (50%) (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
4% CC (100%-OPC), w/c-0.5	T-23	0.6	350	766.29	766.29	211	65	2097
	T-24	0.44	450	712.6	712.6	199	70	2117
6% CC (100%-OPC), w/c-0.4	T-25	0.55	350	764.2	764.2	192	85	2110
	T-26	0.43	450	710.65	710.65	192	80	2131
8% CC (100%-OPC), w/c-0.4	T-27	0.59	350	759.98	759.98	205	70	2095
	T-28	0.47	450	706.73	706.73	211	90	2134

The 7-day strength results of concrete mixes with three different types of coated brick aggregate are compared with uncoated brick aggregate and stone aggregate as shown in Figure 7.

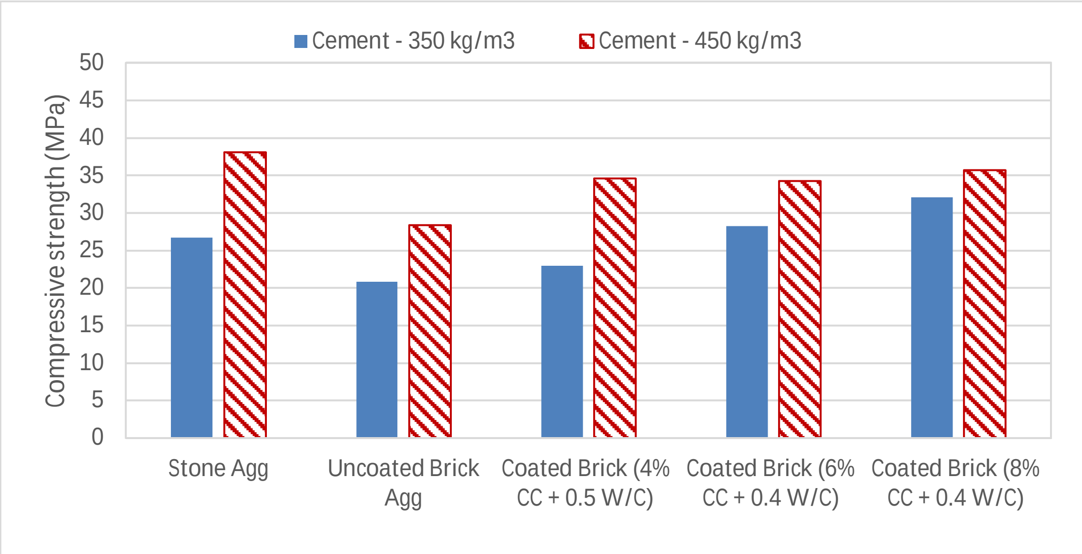


Figure 7 Compressive strength (7-day) of stone aggregate vs uncoated brick aggregate vs coated brick aggregate

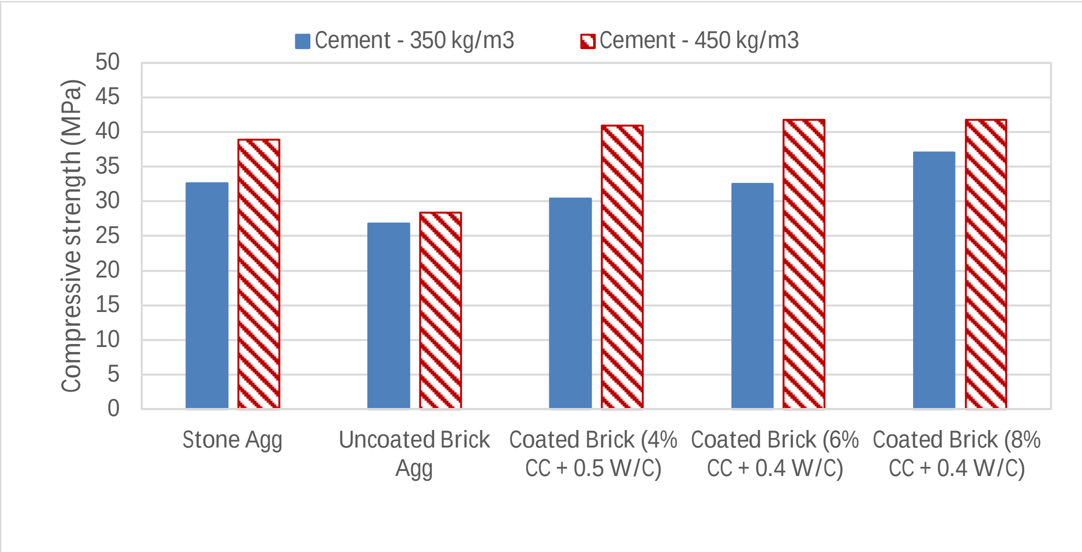


Figure 8 Compressive strength (28-day) of stone aggregate vs uncoated brick aggregate vs coated brick aggregate

The comparison of 7 day and 28 days strength results as shown in Figure 7 and Figure 8 suggest that the concrete strength of brick aggregate concrete increased with increase in cement coating. The coated brick aggregates with 8% cement content and 0.4 W/C ratio produced concrete with compressive strength greater than the stone aggregate concrete. The 6% cement coated brick aggregates produced 28-day compressive strength similar to the stone aggregate concrete. Therefore, for cost-effective concrete production brick aggregates coated with 6% cement content and 0.4% W/C ratio can be used to enhance the strength properties of concrete. This suggests that there is potential in improving the strength of concrete by use of coated brick aggregates. However, further testing is needed to get clear conclusions on the enhancement of both strength and durability properties of concrete with coated brick aggregates.

6.4 To study Influence of Calcium Nitrate Corrosion inhibitor on fresh and hardened properties of concrete

Previous studies on calcium nitrate corrosion inhibitor suggests that it acts as a set accelerator at lower dosage (1-3%) and as corrosion inhibitor (CI) at higher dosage (3-4%). The accelerating effect of calcium nitrate CI affects the fresh concrete properties such as slump and setting time of concrete. In order to counter the set acceleration of calcium nitrate, additional set retarding admixture needs to be added to the concrete mix. The effect of calcium nitrate CI on setting properties were initially studied on cement paste by testing standard consistency, initial setting time and final setting time of cement with varied proportions of CI. The optimum dosage of set retarding admixture to counter the set acceleration of CI was determined by testing the delay in setting time at different dosages of retarder and the results presented in Table 24 show that the combination of 3.5% CI and 1.8% retarder extends the setting time of cement to acceptable limits. The final durability performance of calcium nitrate based corrosion inhibitor is compared with commercial Sikagaurd corrosion inhibitor in the phase II (durability) testing.

Table 24 Comparison of setting time of cement with different proportions of CI and retarder dosages

Cement composition	Normal consistency	Setting time	
		Initial Setting Time (mins)	Final Setting Time (mins)
100% OPC	0.27	102	250
97% OPC + 3% CI	0.26	33	60
96.5% OPC + 3.5% CI	0.26	32	60
96% OPC + 4% CI	0.26	34	60
97% OPC + 3% CI + 1.2% Retarder	0.23	39	75
97% OPC + 3% CI + 1.5% Retarder	0.23	58	120
97% OPC + 3% CI + 1.8% Retarder*	0.22 *	126*	225*
96.5% OPC + 3.5% CI + 1.8% Retarder	0.215	78	180
96% OPC + 4% CI + 1.8% Retarder	0.21	37.5	105

* High Air voids observed in the cement paste

6.5 Conclusions – Phase I study

The outcome of the various experimental studies pursued in phase-I testing gives the following conclusions:

- The relationship between W/C ratio, cement content and strength of concrete containing three different variables viz., stone aggregates, brick aggregate and stone aggregate + superplasticiser has been established. This relationship helps in identifying appropriate cement content for a given W/C ratio and target slump, which is needed for the mix design of concrete mixes planned for phase II.
- The study to increase the proportion of flyash and slag used in composite cements suggests that the concrete mixes produced with varied proportions of flyash and slag produced homogenous and cohesive concrete. The comparison of 100% OPC concrete mix with flyash and slag mixes suggest that at a given cementitious content and target slump of 75-100mm, the required W/C ratio was almost similar between the mixes. The 7-day strength of different concrete tested in this study suggests that the strength drops with increase in

flyash/slag levels in concrete. However, it is a well-established fact that due to slower pozzalanic and hydration reactions in flyash/slag based concretes, strength development more than 100% OPC mix will be observed in later age (>56 days).

- The feasibility study on improving the brick aggregate properties by coating them with cement paste suggest that the specific gravity of aggregate has not changed much and the water absorption of coated brick aggregates has slightly increased as compared with uncoated aggregates. However, the early age strength results of concrete containing coated brick aggregates has showed increase in strength with increase in coating proportions. The 7-day strength of 8% cement coated brick aggregate with 350 kg/m3 cement content was higher than equivalent stone aggregate concrete. Therefore, the initial results suggest that there is a potential for improving the strength of brick aggregate concrete by using pre-coated brick aggregates. However more testing is needed to get a better evidence on the improvement of strength properties of concrete with coated brick aggregates.
- The study on use of calcium nitrate corrosion inhibitor suggests that at recommended 3-4% dosage of corrosion inhibitor has accelerated the setting time of cement drastically. However, with the use of set retarders, the accelerating effect of calcium nitrate corrosion inhibiter can be counter acted. The experimental trials at different dosages of corrosion inhibitor and set retarder suggested optimum combination at 3.5% corrosion inhibitor and 1.8% set retarder resulted in acceptable setting time results in cement samples.

7 Phase-II study – Durability testing of concrete for marine environment

The purpose of the phase II testing is to study the durability performance of concrete by varying various factors such as W/C ratio (or cement content), Cement type, aggregate type, salt contamination and use of corrosion inhibitors. The influence of change in W/C ratio, cement type and aggregate type on the durability of concrete has been studied using standard NT Build 492 test that measures the chloride migration coefficient of concrete. The effect of salt contamination of concrete and use of corrosion inhibitors in the concrete has been studied using standard salt ponding tests viz., modified ASTM G109 salt ponding test.

7.1 Materials

The materials used in the concrete mix for Phase II study is same as in Phase I study and as described in Section 5.

7.2 Batching, Mixing and Casting

Material proportioning was done by pre-weighing bulk materials in a container on a digital scale to the nearest 0.01kg. Prior to batching of ingredients for each concrete mix, the moisture content of the aggregates was measured, moisture correction was applied to the aggregates and water content of the mix is adjusted to achieve the saturated surface dry (SSD) mix proportioning. In addition to this, where liquid based chemical admixtures are used in the concrete mix the water contributed by the admixture solution is compensated in the total water content of the mix. Liquid based chemical admixtures were measured volumetrically using a volumetric cylinder to a nearest millilitre.
All the ingredients of the concrete mix were mixed in a 10/7 concrete mixer with a maximum capacity of 100 litres. Prior to each mixing, the concrete mixer is wetted using a wet cloth to prevent the absorption of water from the mix.

All the concrete mixes were designed for a target slump of 75-100mm and therefore the Water/Cement ratio for each mix was adjusted during the trial mixing to achieve this target slump. Each concrete mix was tested for fresh concrete density, nine concrete cylinders (100mm diameter and 200mm height) were cast for strength and durability testing and two slab samples (200mm X 200 mm X 100 mm) were cast for accelerated corrosion testing.

7.3 Curing

All the cylinder moulds were cured by immersing in water containing saturated calcium hydroxide solution in large plastic drums until the age of testing. Concrete cylinders containing salt additions are cured in separate curing drums to avoid contamination on other concrete specimens. The slab moulds are cured by wrapping them in wet hessian cloth for a period of 7 days and air cured under laboratory conditions until the specimens were 28 days old.

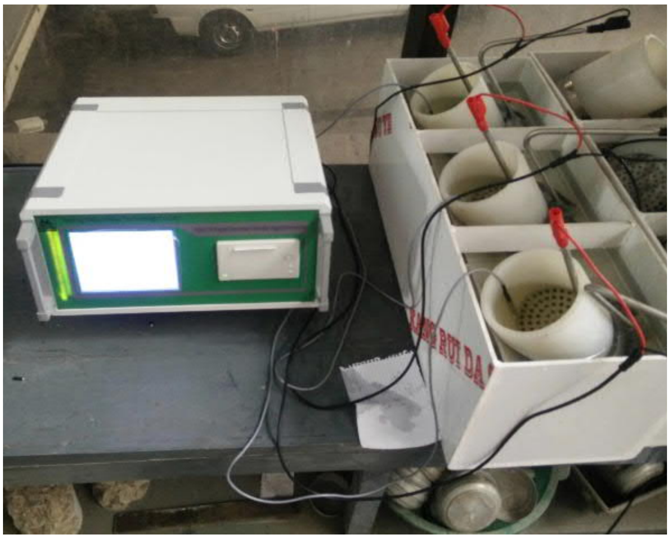
7.4 Durability Testing

7.4.1 NT Build 492 – Chloride migration test

(a) Concrete saw cutting

(b) Concrete specimen 100mm diameter and 50mm height

(c) Concrete vacuum saturation apparatus



(d) Chloride migration test apparatus

Figure 9 Different stages of sample preparation and testing in NT Build 492 chloride migration test

The chloride migration test was carried out in accordance with Nordic standard NT Build 492. The migration coefficient value for the concrete mix gives an indication on the ability of concrete to resist chloride ions, so lower values of migration coefficient indicates more durable concrete mix. Although there are number of tests available to assess the durability property of a concrete mix, the NT Build 492 chloride migration test was selected because of its widespread acceptance within the industry and its output is suitable for use in durability models. The service life models use the non-steady state migration coefficient in the calculations to assess the remaining service life for an existing structure or compute cover needed for a new structure for a given design life.

The concrete specimens used for the test were sliced from concrete cylinder samples, by eliminating top and bottom 50mm depth of concrete and the samples were prepared in accordance to the procedure described in NT Build 492 standard. The different stages of sample preparation prior to testing the concrete is shown in Figure 9.

After subjecting the concrete specimens to chloride migration test in the apparatus for an exposure period of 24 hrs, the test specimens were split into two halves and 0.1 N Silver Nitrate ($AgNO_3$) was sprayed at the cross section to indicate the depth of penetration of chloride ions into the concrete specimen. The chloride penetration depth is the average of seven different measurements along the cross-section of the specimen, which is then used to calculate the non-steady state migration coefficient D_{nssm} of concrete using equation (1).

$$D_{nssm} = \frac{0.0239(273+T)L}{(U-2)t}\left(x_d - 0.0238\sqrt{\frac{(273+T)L\,x_d}{U-2}}\right) \tag{1}$$

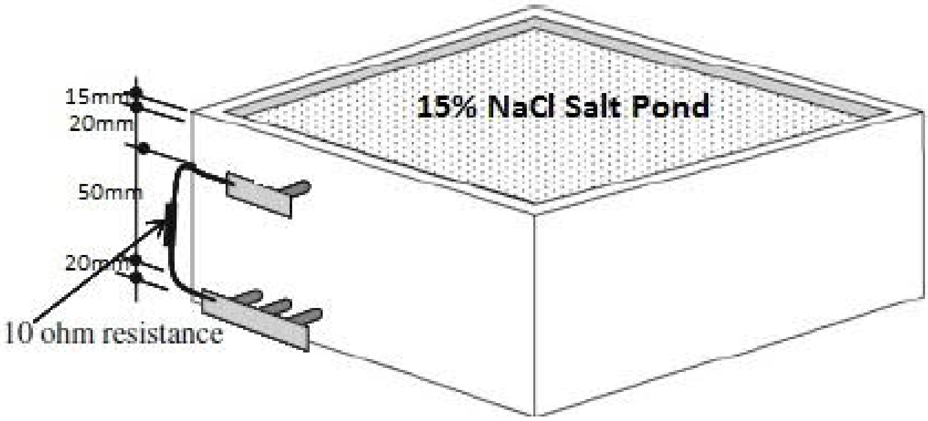
Where

D_{nssm} : non-steady state migration coefficient x 10^{-12} m^2/s
U : absolute value of the applied voltage, V
T : average value of the initial and final temperatures in the anolyte solution Deg C
L : thickness of the specimen, mm
X_d : average value of the penetration depths, mm
T : test duration, hour

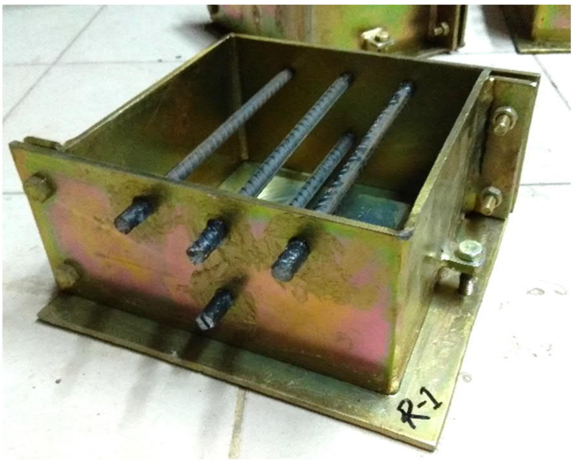
7.4.2 Accelerated corrosion testing

7.4.2.1 Sample preparation

A bespoke slab mould was manufactured with provision to place reinforcement bars at two different levels and 15 mm dyke feature on the ponding face of the concrete specimen as shown in Figure 10. The concrete slabs were cast in an inverted position (top bars towards the bottom) to reduce the influence of surface irregularities caused by hand finished surface and cracking caused by plastic shrinkage. Four 10mm diameter, 60 grade, deformed, mild steel bars were cast into the concrete slab specimens as shown in Figure 10. The reinforcement bars were positioned such that the top reinforcement bar has a cover of 20mm from the ponding surface and bottom three reinforcement bars are positioned at 70mm from the ponding face. The bottom three reinforcement bars are inter-connected by electrical wire to make them electrically continuous. When the concrete slabs are subjected to salt ponding, the closer positioning of the top reinforcement to the ponding face will preferentially corrode the steel and therefore the top reinforcement will act as anode in the electro chemical corrosion process and the bottom three bars will act as cathode. The corrosion current or the charge passed between anode and cathode, due to the corrosion of top reinforcement bar is monitored using a standard resistance of 10 ohm connected across top and bottom reinforcement



(a) Schematic of reinforced concrete slab specimen for accelerated corrosion testing



(b) Preparation of Slab mould fitted with rebar

(c) Demoulded concrete slab showing ponding reservoir on the top

(d) Epoxy painting of side faces and exposed length of rebar

(e) Top and bottom rebars connected with 100 Ω resistor

Figure 10 Different stages of sample preparation of reinforced concrete slab for accelerated corrosion testing bars as shown in Figure 10. Prior to the casting of concrete slabs, the weight of each reinforcement bar used in casting the concrete slab was measured so that at the end of the accelerated corrosion testing, the reinforcement bars are extracted from the slab and measured for weight loss caused by corrosion of steel. The side faces of the concrete slab samples along with exposed surfaces of the reinforcement bars were painted with two coats of epoxy paint to protect the exposed length of reinforcement and lateral faces of concrete from accidental spillage of salt water during the salt ponding tests.

7.4.2.2 Modified ASTM G109 Salt ponding test

The modification from the standard ASTM G109 salt ponding test is the dimensions of the test specimen and the reservoir at the top of the sample is replaced by cast-in dyke feature in the concrete slab sample. In addition, the diameter of the reinforcement bar was 10mm and three bottom reinforcement bars were used as compared to 16mm diameter bars and two bottom bars in the standard test. After attaining the age of 28 days, each concrete slab sample was subjected to cyclic salt ponding and atmospheric drying test. The reservoir formed by the cast-in dyke feature was filled with 15% Sodium Chloride solution for 2 days and then the salt water is removed to allow atmospheric dying in ambient conditions in the laboratory for 5 days. Each cycle represented by 2 days of wetting (salt ponding) and 5 days of drying in ambient conditions and when concrete is exposed to prolonged cycles of wetting and drying will accelerate the penetration of salts (chloride ions) in concrete and associated corrosion of reinforcement bar embedded in concrete.

The corrosion of reinforcement in concrete slab samples were monitored every week using Elcometer 331 half-cell potential meter with silver in silver chloride reference electrode in accordance with ASTM C876-09. The average of three measurements made on the surface of the exposed face of concrete, along the alignment of top reinforcement bar, during the drying phase of cyclic ponding test was monitored every week. The higher negative potential values as classified in Table 25 indicate the probability of corrosion in the top reinforcement bar. However, it should be noted that half-cell potential values only indicate the probability of corrosion of reinforcement on the day of measurement.

Table 25 Specification for corrosion of steel in concrete for half-cell testing of concrete

Silver/silver chloride/1.0M KCL	Corrosion condition
>-100 mV	Low (10% risk of corrosion)
-100 to -250 mV	Intermediate corrosion risk
<-250 mV	High (>90% risk of corrosion)
<-400 mV	Severe corrosion

The macro-cell corrosion current between the anodic top reinforcement bar and cathodic bottom reinforcement bar was measured using voltmeter, by measuring voltage across standard resistance of 100 Ω and then calculating the corrosion current using Ohms law "I = V/R", where I is the corrosion current in Amp, V is the potential measured across the resistance in Volt and R is equal to 100 Ω. It may be noted that the potential measured across the resistance from the test slabs will be in millivolt and the corrosion current will be in milliamp (mA).

7.5 Concrete mix details

Based on the factors and variables considered for phase II study as described in section 4.2, the experimental research matrix obtained by design of experiments methodology gives 45 different concrete mixes. Among the 45 different concrete mixes, first 15 mixes contained stone aggregates, second 15 mixes contained machine crushed brick aggregates and third 15 mixes contain coated brick aggregates. All these 45 concrete mixes vary in different levels of cement content, cement type, aggregate type, salt contamination levels and corrosion inhibitor type. The material proportions and water/cement (W/C) ratio for these mixes were calculated based on the preliminary trial mixes studied in phase I experiments. The final W/C ratio and the proportions for each mix was obtained for a target slump of 75-100mm.

The final mix details per m^3 of concrete along with slump and density testing results for stone aggregate concrete mixes, brick aggregate concrete mixes and coated brick aggregate concrete mixes are shown in Table 26, Table 27 and Table 28 respectively. All these 45 concrete mixes were subjected to durability testing as described in section 7.4.

Table 26 Concrete mix proportions containing stone aggregate

Mix Ref	Free w/c ratio	Cement Content (kg)	OPC (kg)	Flyash (kg)	Slag (kg)	Coarse Aggregate (60%) (kg)		Sand (kg)	NaCl (Salt)	Calcium Nitrate (3.5% of cement content)	Set Retarder (Sika 4101 NS) (kg)	Sika Ferro gaurd 901 (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
						20 mm (50% of CA)	10 mm (50% of CA)								
R-1	0.40	450	360	0	90	493.5	493.5	658	2.25	0	0	11.25	178	75	2387.9
R-2	0.42	550	440	110	0	453.3	453.3	604.4	0	0	0	0	231	75	2336.3
R-3	0.47	450	360	90	0	496	497	662	2.25	0	0	11.25	210	130	2350
R-4	0.45	450	270	0	180	495.2	495.2	660.3	2.25	0	0	11.25	203	70	2351.9
R-5	0.43	550	385	165	0	443	443	590.6	0	0	0	0	235	135	2316.1
R-6	0.43	450	315	135	0	480.8	480.8	641	2.25	0	0	11.25	195	90	2317.1
R-7	0.42	450	450	0	0	492	492	656	2.25	0	0	11.25	190	75	2409.7
R-8	0.43	550	330	0	220	456.2	456.2	608.3	0	0	0	0	234	82	2375.6
R-9	0.4	550	550	0	0	456.5	456.5	608.6	0	0	0	0	220	120	2392.1
R-10	0.43	350	210	0	140	529.8	529.8	706.4	3.5	12.25	4.2	0	152	75	2381.1
R-11	0.47	350	350	0	0	524.4	524.4	699.1	3.5	12.25	5.25	0	163	85	2372.9
R-12	0.43	350	280	70	0	525.1	525.1	700.2	3.5	12.25	4.2	0	150	95	2391.2
R-13	0.38	550	440	0	110	458.4	458.4	611.39	0	0	0	0	209	70	2377.2
R-14	0.45	350	280	0	70	528.5	528.5	704.6	3.5	12.25	4.2	0	157	80	2370
R-15	0.44	350	245	105	0	518.6	518.6	691.4	3.5	12.25	4.2	0	154	90	2364.5

Table 27 Concrete mix proportions containing machine crushed brick aggregates

Mix Ref	Free w/c ratio	Cement Content (kg)	OPC (kg)	Flyash (kg)	Slag (kg)	Brick Aggregate (kg)	Sand (kg)	NaCl (Salt)	Calcium Nitrate (3.5% of cement content)	Set Retarder (Sika 4101 NS) (kg)	Sika Ferro gaurd 901 (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
R-16	0.56	350	350	0	0	748.3	748.3	1.75	0	0	0	196	75	2147.2
R-17	0.41	450	270	0	180	709.1	709.1	0	15.75	5.4	0	185	95	2188.1
R-18	0.57	350	210	0	140	752.1	752.1	1.75	0	0	0	199	72	2137.7
R-19	0.38	550	440	110	0	647.5	647.5	5.5	0	0	13.75	209	80	2136.1
R-20	0.39	450	360	90	0	710.8	710.8	0	15.75	5.4	0	175	130	2165.4
R-21	0.42	450	360	0	90	706.6	706.6	0	15.75	5.4	0	187	80	2176.7
R-22	0.58	350	280	70	0	753.4	753.4	1.75	0	0	0	201	70	2126.4
R-23	0.38	550	440	0	110	667.7	667.7	5.5	0	0	13.75	209	80	2155.6
R-24	0.61	350	280	0	70	758.2	758.2	1.75	0	0	0	213	70	2119.9
R-25	0.38	550	385	165	0	638.9	638.9	5.5	0	0	13.75	211	90	2133.8
R-26	0.55	350	245	105	0	739.9	739.9	1.75	0	0	0	192	72	2113.1
R-27	0.35	550	330	0	220	664.4	664.4	5.5	0	0	13.75	193	87	2157.9
R-28	0.4	450	315	135	0	693.4	693.4	0	15.75	5.4	0	178	110	2155.3
R-29	0.37	550	550	0	0	652.1	652.1	5.5	0	0	13.75	205	100	2175.8
R-30	0.38	450	450	0	0	704.2	704.2	0	15.75	5.4	0	169	75	2191.4

Table 28 Concrete mix proportions containing cement coated brick aggregates

Mix Ref	Free w/c ratio	Cement Content (kg)	OPC (kg)	Flyash (kg)	Slag (kg)	Coated Brick Aggregate (kg)	Sand (kg)	NaCl (Salt)	Calcium Nitrate (3.5% of cement content)	Set Retarder (Sika 4101 NS) (kg)	Sika Ferro gaurd 901 (kg)	Water (kg)	Slump (mm)	Plastic Density (kg/m³)
R-31	0.32	550	550	0	0	652	652	2.75	19.25	6.6	0	177	75	2176.7
R-32	0.33	330	330	0	220	664.4	664.4	2.75	19.25	6.6	0	184	75	2176.7
R-33	0.47	360	360	0	90	706.6	706.6	4.5	0	0	0	211	70	2110.1
R-34	0.56	280	280	70	0	753.4	753.4	0	0	0	8.75	198	80	2051
R-35	0.44	315	315	135	0	694	693	4.5	0	0	0	198	85	2101.4
R-36	0.28	385	385	165	0	639	638	2.75	19.25	6.6	0	154	100	2138.1
R-37	0.37	450	450	0	0	704.2	704.2	4.5	0	0	0	167	85	2159.5
R-38	0.46	280	280	0	70	758.2	758.2	0	0	0	8.75	162	95	2080.9
R-39	0.28	440	440	110	0	647.5	647.5	2.75	19.25	6.6	0	154	85	2153
R-40	0.44	350	350	0	0	748.3	748.3	0	0	0	8.75	153	75	2084.2
R-41	0.36	350	210	0	140	752.1	752.1	0	0	0	8.75	126	80	2076
R-42	0.37	450	270	0	180	709.1	709.1	4.5	0	0	0	166	90	2128.3
R-43	0.25	550	440	0	110	667.7	667.7	2.75	19.25	6.6	0	139	85	2168.6
R-44	0.35	450	360	90	0	710.8	710.8	4.5	0	0	0	159	85	2118.6
R-45	0.37	350	210	140	0	752.1	752.1	0	0	0	8.75	130	80	2050

7.6 Results and Discussions

7.6.1 NT Build 492 – Migration coefficient of concrete

The results of NT Build 492 test for concrete mixes containing stone aggregates are presented in Table 29, the results for brick aggregate concrete mixes are presented in Table 30 and for coated brick aggregates are presented in Table 31. The results presented in these tables show the average depth of penetration of chloride ions (average of two samples tested) and corresponding chloride migration coefficient, which is calculated based on equation (1), for each concrete mix. It should be noted that some of the concrete mixes contain varied proportions of salt and corrosion inhibitor added to the mix, however based on the test results, it can be observed that the influence of internal salts and corrosion inhibitor was found to be negligible on the migration coefficient of the concrete. The internal salts added in the mix was low concentration of 0.5-1% cement content of concrete, whereas the NaCl concentration used in NT Build test is 10% by weight, which is many factors higher than the internal chlorides present in the concrete. On the other hand the corrosion inhibitors used in this study works by increasing the passivation of reinforcement bars in concrete. Thus, with increase in passivation, the threshold chloride level to break the passivation increases.

Table 29 NT Build 492 durability testing results for stone aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Flyash (%)	Slag (%)	Applied Voltage (V)	Average Temp (°C)	Chloride Penetration depth - x_d (mm)	Non-Steady-State Migration Coefficient, D_{nssm} (X 10 $^{-12}$m^2/s)
R-1	450	0.40	0	20	25	27.9	16.69	12.70
R-2	550	0.42	20	0	30	27.7	9.69	4.18
R-3	450	0.47	20	0	30	27.1	10.88	4.83
R-4	450	0.45	0	40	30	27.0	11.56	5.10
R-5	550	0.43	30	0	35	26.9	8.06	3.02
R-6	450	0.43	30	0	40	27.7	13.0	4.49
R-7	450	0.42	0	0	25	27.6	17.41	9.77
R-8	550	0.43	0	40	30	27.3	8.84	3.92
R-9	550	0.4	0	0	20	28.7	17.0	11.49
R-10	350	0.43	0	40	30	28.6	14.66	6.79
R-11	350	0.47	0	0	20, 25	28.5	22.80	14.70
R-12	350	0.43	20	0	30	28.6	16.07	7.71

Mix Ref	Cement Content (kg/m3)	W/C ratio	Flyash (%)	Slag (%)	Applied Voltage (V)	Average Temp (°C)	Chloride Penetration depth - x_d (mm)	Non-Steady-State Migration Coefficient, D_{nssm} (X 10 $^{-12}m^2/s$)
R-13	550	0.38	0	20	25	28.2	15.15	8.33
R-14	350	0.45	0	20	25	28.5	16.84	9.56
R-15	350	0.44	30	0	30, 35	28.4	20.41	8.97

Table 30 NT Build 492 durability testing results for brick aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Flyash (%)	Slag (%)	Applied Voltage (V)	Average Temp (°C)	Chloride Penetration depth - x_d (mm)	Non-Steady-State Migration Coefficient, D_{nssm} (X 10 $^{-12}m^2/s$)
R-16	350	0.56	0	0	15	29.8	28.44	28.76
R-17	450	0.41	0	40	25	29.9	19.75	11.58
R-18	350	0.57	0	40	20	29.8	26.69	19.91
R-19	550	0.38	20	0	20	30.4	24.38	17.86
R-20	450	0.39	20	0	25	30.4	20.50	11.96
R-21	450	0.42	0	20	15	30.0	23.13	22.28
R-22	350	0.58	20	0	20	29.3	26.50	19.06
R-23	550	0.38	0	20	15	29.3	18.28	16.82
R-24	350	0.61	0	20	10, 15	29.1	26.13	32.38
R-25	550	0.38	30	0	20, 25	27.6	21.31	13.91
R-26	350	0.55	30	0	15, 20	27.5	26.69	23.16
R-27	550	0.35	0	40	15	27.4	10.94	9.58
R-28	450	0.4	30	0	20	28.0	20.13	14.07
R-29	550	0.37	0	0	10	29.7	16.92	24.11
R-30	450	0.38	0	0	15	29.6	22.38	21.72

Table 31 NT Build 492 durability testing results for coated brick aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Flyash (%)	Slag (%)	Applied Voltage (V)	Average Temp (°C)	Chloride Penetration depth - x**d** (mm)	Non-Steady-State Migration Coefficient, Dnssm (X $10^{-12} m^2/s$)
R-31	550	0.32	0	0	15	29.4	12.06	10.75
R-32	550	0.33	0	40	25	29.3	13.31	7.18
R-33	450	0.47	0	20	20	29.03	21.13	15.23
R-34	350	0.56	20	0	15	30.03	36.31	36.10
R-35	450	0.44	30	0	20, 25	29.98	24.25	16.06
R-36	550	0.28	30	0	20, 25	29.73	15.69	9.54
R-37	450	0.37	0	0	10, 15	30.25	15.63	18.06
R-38	350	0.46	0	20	15	30.33	22.13	21.83
R-39	550	0.28	20	0	20	30.15	20.69	14.86
R-40	350	0.44	0	0	10	29.83	20.89	30.86
R-41	350	0.36	0	40	15, 20	29.88	19.69	15.91
R-42	450	0.37	0	40	25	29.75	21.44	12.00
R-43	550	0.25	0	20	20	29.33	20.89	14.95
R-44	450	0.35	20	0	25	29.33	23.5	13.32
R-45	350	0.37	30	0	20	29.2	33.63	24.77

In order to compare the performance of various concrete mixes with different aggregate types and cement types, the migration coefficient of these mixes are plotted on a chart as presented in Figure 11- Figure 13

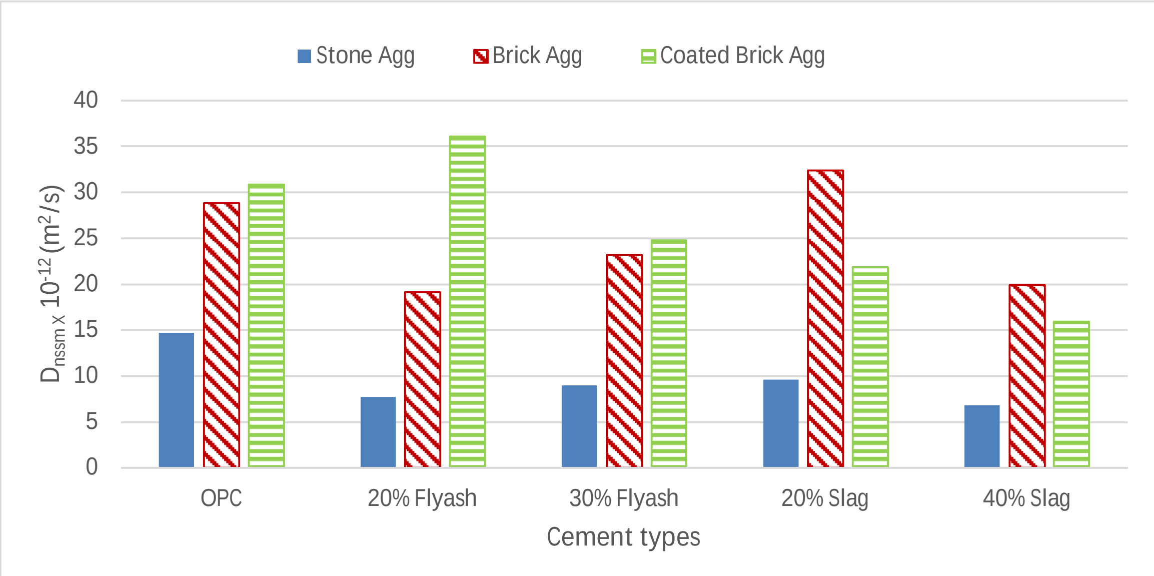


Figure 11 Comparison of Migration coefficient for different concrete mixes with 350 kg/m^3 cement content

The chloride migration test results for concrete mixes with 350 kg/m3 cement content as presented in Figure 11 suggests that stone aggregate concrete mixes performed much better as compared with brick aggregate and coated brick aggregate concrete. Comparison between different cement types used in these mixes suggest that flyash and slag additions in the mix reduced the migration coefficient values and improved the durability of the concrete. The benefit in use of coated brick aggregates on improving the durability of the concrete mix was not very well established in these low cement content concrete mixes. However, based on the test results it can be inferred that cement coated brick concrete mixes performed better with slag additions as compared with uncoated brick aggregates but performed worse with CEM I and Fly ash.

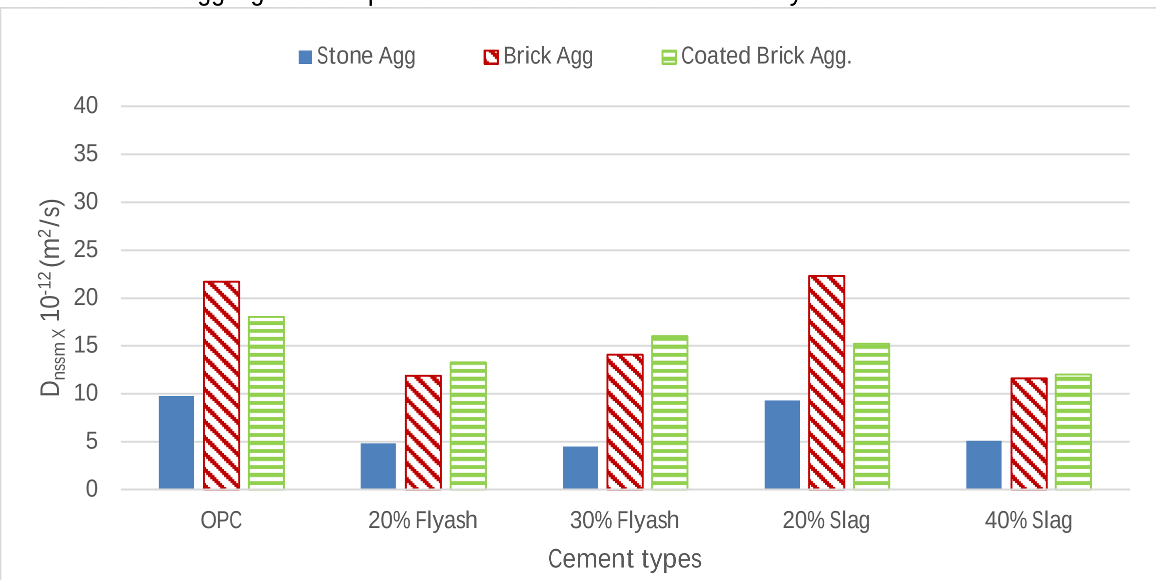


Figure 12 Comparison of Migration coefficient for different concrete mixes with 450 kg/m^3 cement content

The comparison of migration coefficient of concrete mixes with 450 kg/m3 cement content as presented in Figure 12 suggests that overall the migration coefficient values reduced with increase in cement content of the concrete. The comparison between different aggregate types used in the concrete clearly suggests that the stone aggregate concrete mixes have performed better with low migration coefficient values as compared with brick and coated brick aggregate concrete mixes. The comparison between different cement types suggest that the concrete mix with flyash addition has performed the best with very low values of chloride migration coefficient. The performance of coated brick aggregate concrete mixes varied with different cement types and no clear benefit in performance improvement was observed as compared with the brick aggregate concrete mixes.

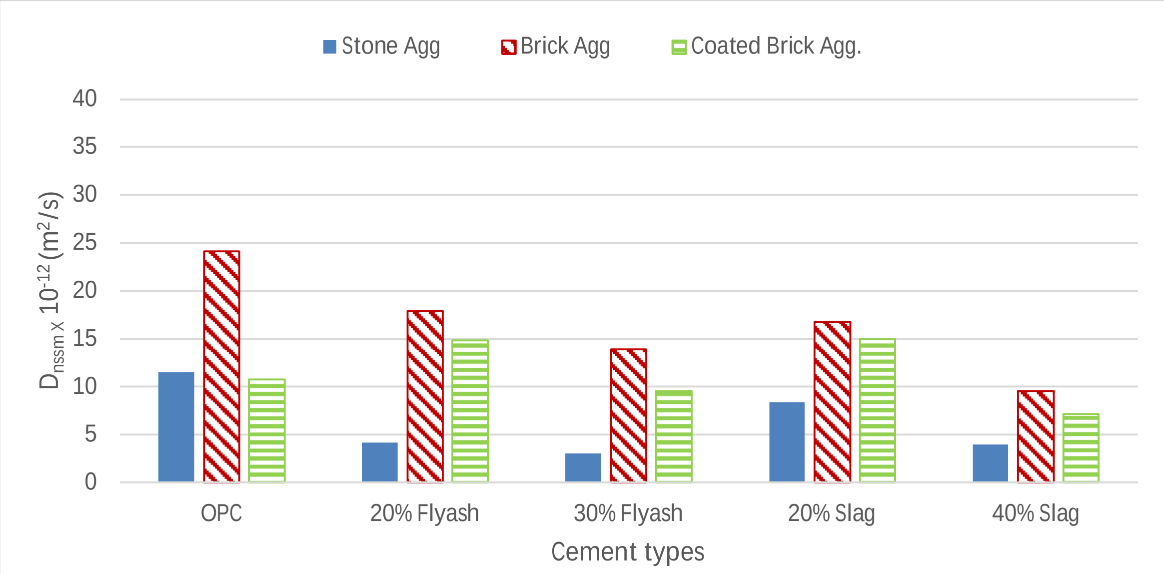


Figure 13 Comparison of Migration coefficient for different concrete mixes with 550 kg/m^3 cement content

The higher cement content of 550 kg/m3 in concrete has marginally improved the performance of concrete as presented in Figure 13. It is interesting to note that in the case of 100% OPC mixes, the migration coefficient values slightly increased at higher cement content for both stone aggregate and brick aggregate concrete mixes. However, the coated brick aggregate concrete has performed better at higher cement content especially with 100% OPC in the mix. The performance of coated cement aggregate mixes in blended cement mixes was observed to be better than the uncoated brick aggregate concrete mixes, however the stone aggregate concrete mixes performed the best among the three aggregate types tested. Moreover, stone aggregates mixes with blended cements performed better than the pure OPC mix and concrete with 30% flyash has performed the best in terms of lowest migration coefficient among all the concrete mixes tested.

7.6.2 Accelerated corrosion testing

Due to the limited time available for testing the concrete samples within the tenure of the project, the concrete samples were exposed to accelerated corrosion by wetting and drying cycles for 3-9 weeks depending on the sequence of casting the concrete slabs. In this limited period, only stone aggregate and brick aggregate concrete mixes were tested.

7.6.2.1 Macro-cell corrosion tests

The macro-cell corrosion measurements were made as described in section 7.4.2.2. The voltage across standard resistor of 100Ω connected between top and bottom reinforcement bars was measured on weekly basis prior to the start of the ponding cycle in each week. The weekly measurements made on all the sample up to the time of writing this report showed “zero” voltage between the top and bottom reinforcement bar, which suggests that the corrosion of the top reinforcement has not yet been initiated. Similar studies on accelerated corrosion of reinforcement using cyclic ponding tests suggest that, it takes around 4 months to 1 year depending on the quality of concrete to initiate corrosion of reinforcement in these tests. Therefore, further monitoring of these ponding slabs is needed to understand the performance of different concrete mixes in resisting the ingress of salts and associated corrosion of reinforcement.

7.6.2.2 Half-cell Potential testing

The half-cell potential testing of ponding slabs were done in accordance with ASTM C876-09. The half-cell potential values for different concrete samples varied between -60 mV to -330mV. Based on the classification, values more negative than -250 mV indicate high probability of reinforcement corrosion.

Figure 14 Half-cell potential testing on a concrete ponding slab

The analysis of concrete mixes showing high probability of corrosion do not provide any conclusive relationship between mix parameters such as salt content, blended cements, aggregate type or presence of corrosion inhibitor and the corrosion activity of reinforcement monitored by half-cell potential testing. It should be noted that the half-cell potential testing is influenced by various factors such as moisture condition of concrete, temperature, and ionic conductivity of concrete at the time of measurement. Moreover, the test technique only provides probability of reinforcement corrosion and does not confirm corrosion activity or rate of corrosion. Long-term monitoring of the ponding slabs is essential to understand the corrosion behaviour and performance of various concrete mixes.

Table 32 Half-cell potential values (mV) for concrete ponding slab samples

Mix Ref	Week3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
R-1	-	-	-	-64.67	-111.89	-118	-158
R-2	-	-	-	-256.67	-267.11	-235.11	-293.33
R-3	-	-	-	-170.67	-194.78	-172.33	-226
R-4	-	-	-	-125.33	-125	-111.56	-115.33
R-5	-	-	-	-52.33	-61.67	-58.56	-66
R-6	-	-	-	-124.33	-150.78	-155.56	-174
R-7	-	-	-	-113.67	-144.44	-140.67	-161.33
R-8	-	-	-	-120	-127.89	-128.11	-156
R-9	-	-	-	-34.67	-37.78	-13.56	-58
R-10	-	-	-	-163.67	-164.78	-170.67	-186
R-11	-	-	-	-202	-198.56	-166.11	-205.33
R-12	-	-	-	-167.67	-192.11	-196.44	-241.67

Mix Ref	Week3	Week 4	Week 5	Week 6	Week 7	Week 8	Week 9
R-13	-	-	-	-189.33	-195.44	-191.33	-230.33
R-14	-	-	-	-169.67	-195.67	-217.33	-240
R-15	-	-	-	-228.33	-243.11	-263.56	-255
R-16	-187.33	-276.67	-219.78	-231	-	-	-
R-17	-180.67	-201.44	-178.89	-265.67	-	-	-
R-18	-183.33	-202.78	-174.44	-238.33	-	-	-
R-19	-212	-231.89	-216.67	-245.67	-	-	-
R-20	-115.67	-165.22	-159.78	-223	-	-	-
R-21	-143.33	-194.67	-174.67	-228	-	-	-
R-22	-109.67	-110.89	-102.33	-121.33	-	-	-
R-23	-391.33	-241.78	-226.78	-267.33	-	-	-
R-24	-162.33	-177.44	-184.56	-209.67	-	-	-
R-25	-309.33	-323.11	-291.44	-327.33	-	-	-
R-26	-201.33	-161	-280.44	-180.67	-	-	-
R-27	-174.33	-182	-165.56	-171.33	-	-	-
R-28	-138.67	-148.22	-137.67	-155.67	-	-	-
R-29	-273.67	-286.56	-278.22	-303	-	-	-
R-30	-151.33	-154.89	-175.67	-185	-	-	-

7.7 Conclusions – Phase II study

The outcome of the durability testing of various concrete mixes studied in phase II laboratory testing gives the following conclusions:

- This study confirms the importance of durability testing (NT Build 492 test) in designing the concrete mix for coastal regions of Bangladesh.
- The durability of brick aggregate concrete mixes was significantly poorer than the stone aggregate concrete mixes
- The durability performance of concrete improved with increase in cement content of the concrete. However, in the case of 100% OPC concrete mix the no further improvement in durability performance was observed with increase in cement content from 450 kg/m^3 to 550kg/m^3.
- Concrete mixes with flyash addition showed better durability performance in comparison to slag based concrete mix. In general, among the different cement types, 100% OPC concrete mix showed poor durability performance as compared to blended cement based concrete mix.
- Among all the concrete mixes tested in the experimental programme, concrete mix with 30% flyash as cementitious addition and 550 kg/m^3 cement content showed the best durability performance to resist chloride induced corrosion.
- The study on accelerated corrosion of reinforced concrete samples was inconclusive due to the time limitations on the tenure of the project. This study will be useful in determining the performance of corrosion inhibitors in resisting corrosion of reinforcement in concrete and also helps in understanding the effects of chloride contaminated water on corrosion of reinforcement in concrete. Further monitoring of ponding slabs is needed to understand the influence of various study factors on the corrosion of reinforcement in concrete.

8 Final project report

The final project report will combine the information and discussions provided in all the previous reports and provide final recommendation to LGED on the specification of concrete mix for coastal districts of Bangladesh. The final report will take onboard the comments made by various stakeholders at the workshop event especially on the cost effectiveness of recommended solution in comparison to existing practices. The final report will also provide assessment on the service-life of different options studied in the Field and Laboratory testing phase and provide final recommendations based on best international construction practices.