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Climate Resilient Concrete Structures in Marine Environment of Bangladesh

Final Project Report

Mott MacDonald Ltd.

AsCAP Project Reference Number BAN2077A

February 2018

MOTT MACDONALD

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

Quality assurance and review table			
Version	Author(s)	Reviewer(s)	Date
Draft	Sudarshan Srinivasan Ian Gibb		16/10/17
1.0	Sudarshan Srinivasan Ian Gibb	M Abedin NV Leta	09/01/2018
2.0	Sudarshan Srinivasan	M Abedin	16/02/2018

ReCAP Database Details: Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh			
Reference No:	BAN2077A	**Location**	Bangladesh
Source of Proposal	N/A	**Procurement Method**	Full and Open
Theme	Infrastructure	**Sub-Theme**	Effective Whole Life Rural Asset Management
Lead Implementation Organisation	Mott MacDonald Ltd	**Partner Organisation**	Local Government Engineering Department (LGED) Bangladesh
Total Approved Budget	£222,258	**Total Used Budget**	£222,258
Start Date	10 June 2016	**End Date**	31 December 2017
Report Due Date	06 October 2017	**Date Received**	16 February 2018

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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 examines 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 Project Report

This final report combines the information and discussions provided in all the previous milestone reports viz., Inception report, Condition survey report and Final laboratory and field testing report and provides final recommendation to LGED on the specification of concrete mix for coastal districts of Bangladesh. This report addresses the comments made by various stakeholders at the workshop. This report further analyses the results obtained in field and laboratory study phase by using service-life models to evaluate the minimum durability cover required for a defined exposure condition. This report provides final recommendation in terms of limiting values for concrete mix based on the exposure classification in the coastal regions of Bangladesh.

Key words

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

Acknowledgements

The project team would like to greatly acknowledge the continuous support provided by LGED engineers throughout the tenure of the project.

The kind contribution of cement products supplied by Bashundhara cement, Bangladesh and corrosion inhibitor supplied by Yara Intl ASA, Norway are greatly acknowledged.

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

ASIA COMMUNITY ACCESS PARTNERSHIP (AsCAP)

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.

See www.research4cap.org

Executive Summary – Final Report

This project examines the major factors that contribute to premature deterioration of concrete structures, develops cost effective concrete mix design to enhance durability of future structures and makes recommendation on improvements in construction practice and workmanship considered necessary to improve service life. These factors are examined in various systematically planned stages viz., Inception stage, Condition survey stage, Laboratory and field testing stage and Stakeholder workshop.

The outcomes of the inception report highlight the gaps in the literature especially relating to durability testing of locally available materials in Bangladesh and benefits in the use of higher proportion of fly ash and slag in producing durable concrete mix. The observations made from the desk study also highlights the issues relating to workmanship, lack of good quality control practices and use of contaminated or low-quality materials in the production of concrete, which are prevalent in coastal districts of Bangladesh.

The condition survey report, which describes investigation of various concrete structures in four coastal districts viz., Gopalganj, Bagerhat, Noakhali and Cox's Bazar, suggests that workmanship issues, substandard materials and aggressive environmental conditions are some of the major reasons for premature deterioration of concrete structures in the coastal districts of Bangladesh.

During the laboratory testing stage, various key factors influencing the durability of concrete were assessed using international standard durability tests viz., NT Build 492 and modified AASHTHO salt ponding tests. The results of durability testing of concrete suggest that cement replacement with 30% fly ash in concrete showed better durability performance to resist deterioration caused by chloride induced corrosion. The results also indicate that durability of brick aggregate concrete mixes was significantly poorer than the equivalent stone aggregate concrete.

Based on the observations from the condition survey stage and analysis of results on the durability testing of various concrete mixes tested in laboratory testing phase, the final recommendations for producing durability concrete mix to withstand the marine environment in coastal districts of Bangladesh are below:

- Brick aggregates should not be used in reinforced concrete elements in coastal districts of Bangladesh
- The concrete mixes for reinforced elements in coastal districts should be classified based on the exposure class and specified in accordance to the limiting values given in Table 7-1
- All the concrete mixes used in coastal districts should be durable mix designed in the laboratory. Concrete mix design methodology should include chloride migration tests (NT Build 492)
- High range water reducing admixture shall be used in all the concrete mixes
- The chloride content of water used in concrete production shall be less than 1000ppm

Contents

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, particularly, excessive intrusion of seawater, air borne chlorides and the high humidity of the costal 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 in 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.

The outcome of the Project is to provide recommendations that will help to build and maintain cost-effective, resilient concrete structures exposed to harsh marine condition in the rural areas.

1.2 Methodology

On award of the contract Mott MacDonald Ltd (MML) mobilised their team, combining international specialists with local experience and expertise in Bangladesh. The international experts are highly experienced in designing, specifying and investigating concrete structures in a range of aggressive environments, with their local counterparts combining a wealth of academic and research professionals together with engineers experienced in testing and supervising construction works in the field.

The project plan involves the following key stages:

1.2.1 Inception stage

Understand the objectives of the Project and meet key contacts. Undertake a desk study and literature review of previous studies into the performance of concrete structures in the marine environment and identify potential solutions for customisation and use in Bangladesh. Identify key variables that could affect the durability of marine concrete structures such as the different levels of marine exposures and climate change variability along the coastal sections; availability of fresh water compared to saline water; availability of local sand and aggregate (salt free/contaminated); and the suitability of the available cements to marine conditions. Develop a research matrix of the key variables to be investigated.

1.2.2 Condition survey & site visits

Conduct condition surveys on concrete structures in different exposure conditions in the coastal regions to evaluate chloride levels and carbonation depths and quality of workmanship (e.g.. cover to reinforcement) and visit new construction sites to understand actual construction practices.

1.2.3 Laboratory Work

Building on the findings of the literature review, condition survey and site visits, potential opportunities to enhance the climate resilience of concrete structures are explored, with the aim to develop more robust mix designs able to withstand the aggressive climate and potentially to be more tolerant of poor quality materials.

1.2.4 Final Report

A stakeholder workshop was held to discuss the findings of the research work. This final project report is based on the information and conclusions arrived in Inception stage report, Condition survey report and final laboratory testing report, including the outcomes of the stakeholder workshop was prepared and provides recommendations on the mix design and construction methodology for making durable and sustainable concrete structures in the coastal area and/or recommendations for further research where field demonstrations, monitoring and evaluation of the suitability of the proposed solutions are required. The outcomes of the project will be published in conference paper at International conference on concrete durability to be held at Leeds in 18-20 July 2018.

1.3 Inception Stage

1.3.1 General

The project team as shown in Table 1-1 was mobilised for the project.

Table 1-1 Project team members

Position	Name	Company
Team Leader	Ian Gibb (IG)	Mott MacDonald
Deputy Team Leader/ Materials Engineer	Sudarshan Srinivasan (SS)	Mott MacDonald
Design/Project Manager	Richard Lebon (RL)	Mott MacDonald
Peer Review	Prof. Khan Amanat (KA)	BUET
Structural Engineer	Yasmin Dil Khan (Tina)	Mott MacDonald
Field Technician	Dipan Dhali (DD)	Mott MacDonald

The international team conducted an initial visit to Bangladesh to attend series of meetings aimed at developing background knowledge of the issues and available resources, establishing a network of useful contacts and exploring potential solutions. Some of the key meetings, contacts and information obtained are summarised in Appendix A1.

The local team focussed on the collection of local literature on concrete materials and durability of concrete in coastal regions of the country, conducting an extensive programme of meetings with clients, local contractors, material suppliers and collecting local testing related information.

1.3.2 Construction Practice

A detailed understanding of construction practice in the rural marine environments was developed during the condition survey stage of the Project. However, the contrasting standards of construction illustrated locally within Dhaka, through observation of extensive drainage works taking place in Banani (Locality in the district of Dhaka) and by a site visit to the Elevated Expressway Project which is currently under construction. At the Elevated Expressway, two state-of-the art on-site ready mix plants were in the process of being commissioned to supply the concrete to the project.

The local drainage works were extensively using hand-mixed concrete (see Figure 1-2) and occasionally mechanically mixed concrete. Coarse aggregates were manually crushed bricks, which appeared to receive no processing to remove fines. Concrete was placed in shuttering but there was no evidence of mechanical compaction taking place. Curing of the finished work was negligible with only very occasional spraying with water observed.

Figure 1-1 Concrete plants at the Elevated Expressway Project

Figure 1-2 Hand-mixed concrete at local drainage works in Dhaka city

Some of the significant factors to be addressed in this project are workmanship, material quality and quality control. However, it is recognised that in some regions, there may simply not be salt-free water or a ready supply of clean sand and therefore potential solutions exploring ways to mitigate or reduce the impact of these issues on the long-term durability of the concrete are explored.

One potential route is through the cement, which is a quality controlled product that will be used in each batch of concrete. While it is difficult to control the sources and properties of the sand and water, the cement could potentially be enhanced to improve the durability of the concrete. Initial thoughts that are further explored and developed during the laboratory testing phase include:

- Increasing/changing additions used in the cement
- Incorporating a water-reducing admixture in the cement (to reduce water demand and hence the level of embedded chlorides if the water is contaminated)
- Incorporating a corrosion inhibitor (to extend the time to initiation of corrosion or slow the propagation rate).

2 Literature Review

2.1 Concrete deterioration mechanisms

An introduction to the key deterioration mechanisms for concrete in a marine environment are discussed in the following section and are developed during the literature review. Durability issues for concrete structures relate to both direct attack/degradation of the concrete and corrosion of embedded reinforcement. The extent to which a concrete structure is at risk to either form of deterioration is dependent on many factors including the specific local environment, concrete mix, method of mixing, method of placement, workmanship, etc.

2.2 Reinforcement Corrosion

Corrosion is the electrochemical oxidation of steel. Reinforcement is normally protected from corrosion in concrete by a passive layer of iron oxide that forms around the steel. There is a period that the steel is in a passive state (the initiation period). Eventually, as a result of carbonation or chloride ingress, the steel de-passivates and the corrosion process can commence (propagation period). The corrosion products occupy a higher volume than the original steel, inducing stresses in the concrete, leading to cracking and spalling. The diagram in Figure 2-1 illustrates the two phase initiation/propagation model.

Temperature is an important factor in influencing the rate of corrosion and other chemical reactions (an increase in temperature of 10°C is generally responsible for increasing rate by a factor of between 1.6 and 2).

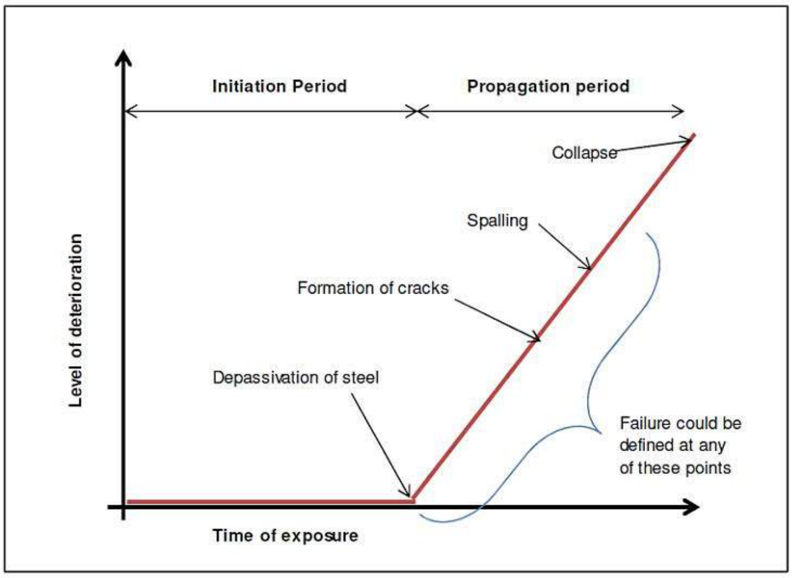


Figure 2-1 Two phase initiation/propagation model (Gibb 2014)

2.2.1 Influence of Chlorides

The presence of chlorides, either in the original mix (embedded) or entering the concrete from its surface, can allow the establishment and movement of chloride ions in the pore water within the concrete matrix. When the chloride ion in the concrete surrounding the reinforcement reaches a critical 'threshold level' the passive protection provided by the concrete is destroyed. In such circumstances electrical cells can develop on the surface of the reinforcement which can lead to reinforcement corrosion which, in turn, can lead to cracking and/or spalling of the surrounding concrete. Chloride-induced corrosion is characterized by pitting corrosion of the reinforcement which can lead to significant loss of cross-sectional area in a relatively short period of time.

2.2.2 Influence of Carbonation

Carbonation of concrete is the reaction of carbon dioxide, which enters the concrete from the air, with the cementitious matrix of the concrete. This leads to a reduction of the concrete's alkalinity progressively inwards from the surface. When the advancing carbonation front reaches the reinforcement the surrounding passive / protective, film is destroyed. If water and oxygen and water are present general corrosion of the steel can occur.

Carbonation will not progress in conditions where the pore structure of the concrete is either saturated with moisture or exposed to invariably high humidity (>80% relative humidity), so it is not an issue for permanently submerged surfaces. Also, it will not progress in very dry conditions, i.e. Carbonation is rapid in dry condition where there is less than 50% relative humidity, however corrosion of reinforcement will be slow due to less availability of water. The variable humidity conditions and exposure to occasional rainfall associated with the above-ground elements means that carbonation may proceed in sub-atmospherically exposed elements.

2.3 Alkali Aggregate Reaction (AAR)

Alkali-silica reaction (ASR) is the most common form of alkali-aggregate reaction (AAR). ASR occurs when active silica constituents of the aggregate react with alkalis originating from the cement or other sources to form calcium alkali silica gel. This gel imbibes water, producing a volume expansion, which can give rise to internal stress within the concrete and produce deleterious effects: Damaging ASR will, however, only occur when the following are present:

- A high moisture level within the concrete or an external source of water;
- Sufficient reactive silica within the aggregate;
- A high concentration of reactive alkalis within the concrete or from another source such as dissolved salts in groundwater.

In practice, the potential for AAR in the concrete elements can be minimized through careful selection and control of the concrete constituents, i.e. by restricting the aggregates used to those with a low risk of reactivity and placing limits on the total alkali content of the concrete mix.

2.4 Chemical and Physical Attack

2.4.1 External Sulfate Attack

Sulfate solutions within groundwater can react with the components of the hydrated cement; although the precise mechanisms remain uncertain, it seems that the internal stress generated by the growth of the reaction products leads to general disintegration of the affected concrete, for example by cracking and softening, increasing permeability and reducing strength.

Reactions occur between the salts in solution (which are in their ionized form) and the hydrated calcium aluminate phases and calcium hydroxide ('portlandite') in the cement paste. The potential severity of the attack is dependent on the sulfate ion concentration of the groundwater, which is controlled by the solubility of the salts; sodium and magnesium sulfates are highly soluble while calcium sulfate is not.

2.4.2 Internal Sulfate Attack

Internal sulfate attack typically occurs through a process known as Delayed Ettringite Formation (DEF) in which the ettringite (a calcium sulfoaluminate mineral) - which normally forms then decomposes during hydration - subsequently re-forms in the hardened concrete. The ettringite crystals exert an expansive force within the concrete as they grow. This causes the cement paste to expand, but the aggregate does not and so no longer contributes to concrete strength, since it is effectively detached from the cement paste. Often, the gaps between cement paste and aggregate become filled with needle-like ettringite crystals. Once established it can cause expansion and cracking of concrete members in a similar manner to ASR.

Conditions necessary for DEF to occur are:

- High temperature (>65-70°C approx.), usually during curing (steam curing or heat of hydration in large pours) but not necessarily;
- Intermittent or permanent water saturation of the concrete after curing;
- Iit is commonly associated with high sulfate and high alkali contents in the mix (and frequently occurs alongside alkali-silica reaction, ASR).

DEF usually occurs in concrete that has either been steam cured, or which reached a high temperature during curing as a result of the exothermic reaction of cement hydration (e.g. mass concrete foundations).

2.5 Physical Salt Attack

Where concrete elements are exposed at their base to saline ground water and above, capillary suction and evaporation may cause super saturation and crystallisation in the concrete above ground, resulting in both chemical attack, on the cement paste (sulfate attack), and physical salt attack, as well as aggravated corrosion of steel (chlorides). This is particularly the case where a portion of the structure/element is exposed to frequent temperature and humidity changes, which tends to drive the capillary process.

Concrete, saturated with salt solutions, particularly chlorides and sulfates, can suffer from crystallisation pressure damage during periods of drying. As water evaporates from the pore solutions, they become increasingly concentrated until saturation is reached. Crystals will then begin to grow within the pore space of the material. As the crystals grow, their expansion is impeded by the surrounding cement paste and the resulting internal stresses disrupt the matrix of the material, causing softening and shallow spalling. Crystallisation pressures in excess of 60 N/mm^2 have been measured for sodium chloride crystals.

2.6 Acid Attack

Acid solutions may be naturally present in groundwater, or the result of pollution. Many petroleum-based products on breakdown in the atmosphere result in the production of acidic compounds. Acidic gases may also be present in the environment from the waste products of industrial operations. The effect of these acids is to react with the alkaline compounds of the cement matrix of concrete, dissolving and removing them, weakening the cement paste and increasing its porosity (and, therefore, its susceptibility to other forms of deterioration).

2.7 Bangladesh Coastal Environment

Bangladesh has a large coastal area within the Bay of Bengal that covers 19 districts (148 sub districts), accounting for 32% of the land area (Dasgupta et al. 2014). The exposed and interior coastal zones of Bangladesh along with locations of different Upazilas and Pourashavas are shown in Figure 2-2.

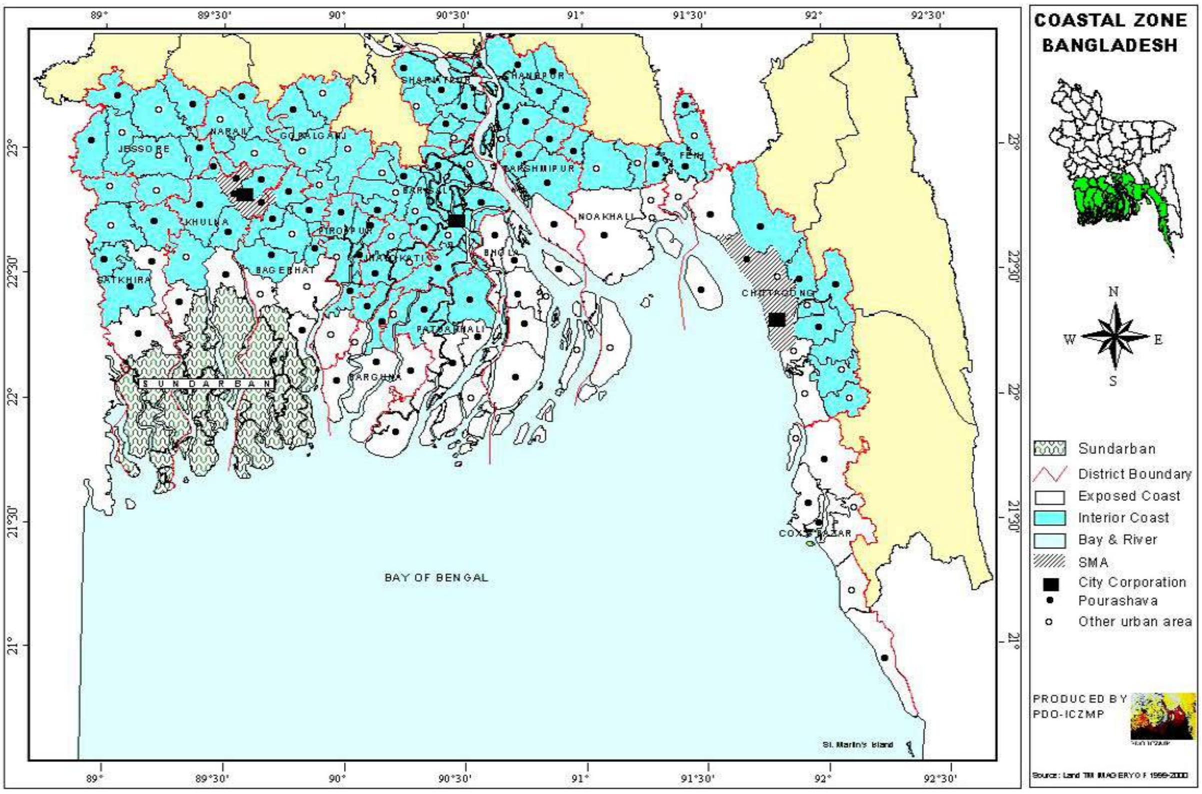


Figure 2-2 Coastal zone of Bangladesh (Ahmad, 2005)

2.7.1 General Climate

Bangladesh has tropical monsoon type climate with hot and rainy summers and dry winters. The climatic seasons in Bangladesh have been classified as winter (December-January), pre-monsoon (March-May), monsoon (June-September) and post-monsoon (October-November). The country experiences warm temperature from March-October, with peak in April - 33.5°C and a secondary peak in September – 31.6°C as shown in Figure 2-3. January is the coolest month with lowest minimum temperature averaging at 12.5°C.

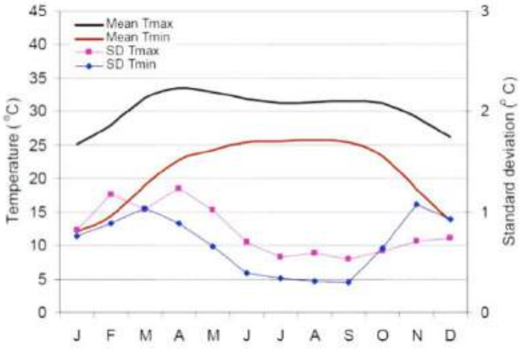


Figure 2-3 Annual distribution of average minimum and maximum temperature of Bangladesh based on 1948-2004 data (ADB, 2013)

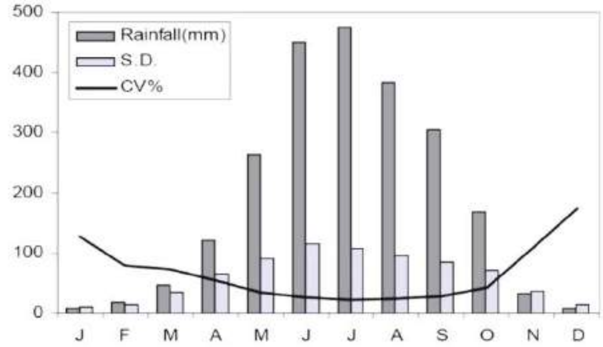


Figure 2-4 Annual distribution of mean rainfall of Bangladesh based on 1948-2004 data (ADB, 2013)

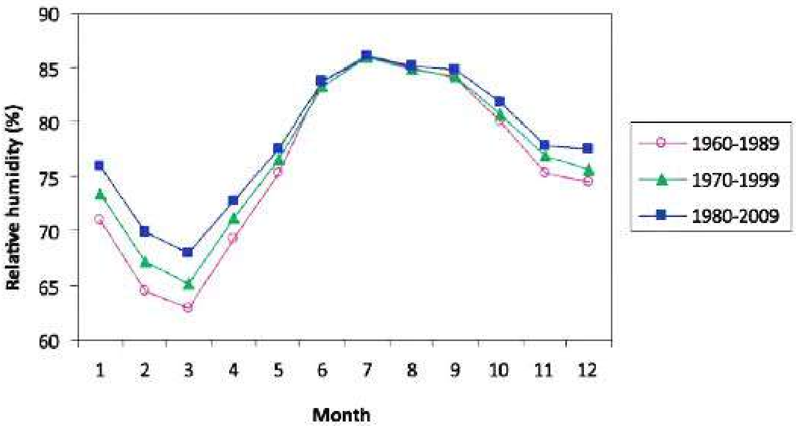


Figure 2-5 All Bangladesh monthly normal humidity variation (Mondal et al., 2013)

Bangladesh received average annual rainfall of 2286mm (ADB, 2013). The annual distributions of country's mean monthly rainfall is shown in Figure 2-4. It can be observed that most of the rainfall occurs in the monsoon period between June-September, which amounts to approximately 70% of the annual rainfall. Based on the historical data on the country's monthly normal variation in relative humidity shown in Figure 2-5, it can be observed that the normal humidity variation in a year is between 70-85% and high humidity levels are observed in the monsoon period (June-September) (Mondal et al. 2013).

2.7.2 Ground conditions

Soil formations of Bangladesh consist predominantly of medium to fine sands, silts and clays and a combination of these soil fractions. The typical soil stratification in the coastal region of Bangladesh is presented in Figure 2-6. In the south-west zone of the country, gravel is almost non-existent and organic matters in the form of peat, semi-decomposed and decomposed vegetable matter are frequently encountered in varying proportions in the soil fractions. In the south-east zone of the country fine sand and silt and a combination of the two are more frequently encountered than clay especially in the upper layers of the soil strata (Serajuddin, 1998).

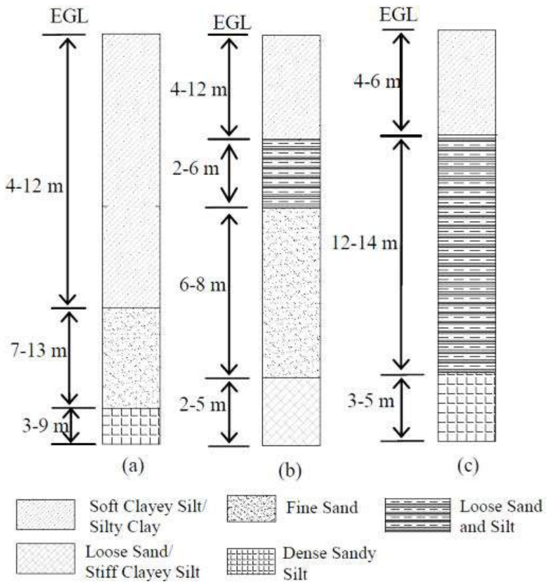


Figure 2-6 Typical sub-soil profile of coastal regions of Bangladesh: (a) Bhola region (b) Chittagong region and (c) Noakhali region (Anisuzzaman et al.., 2013)

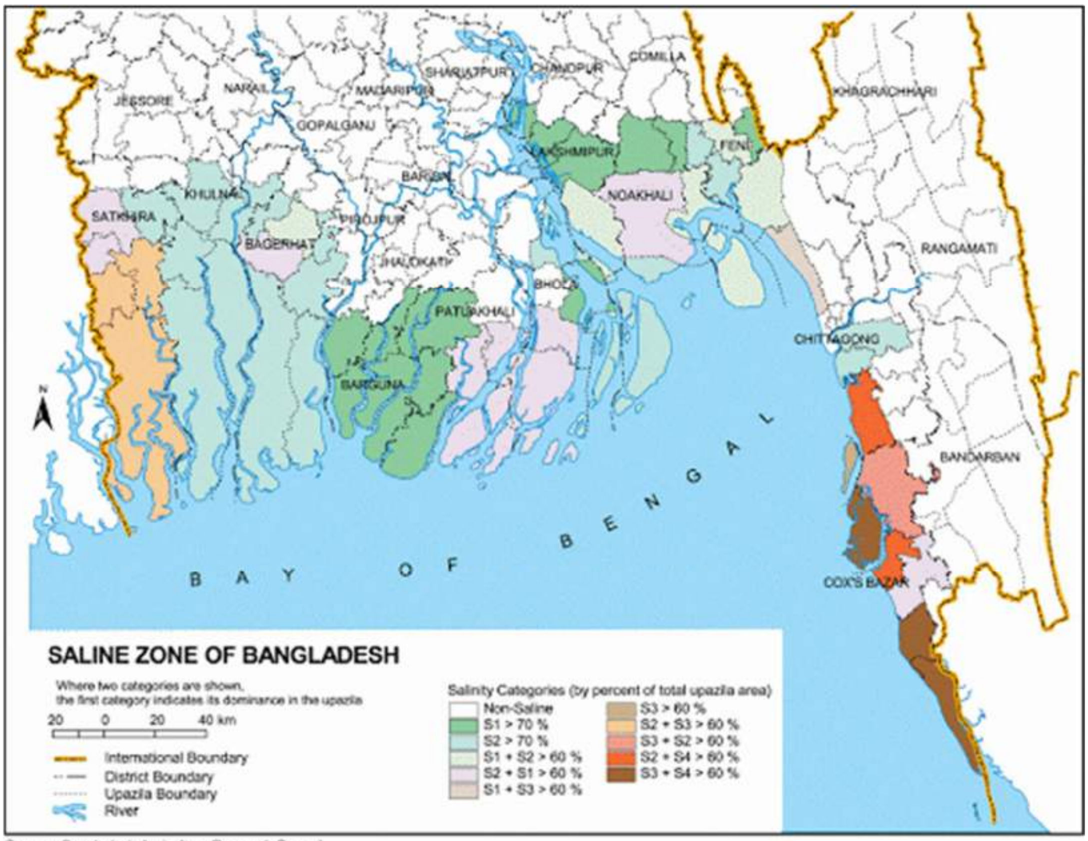
Durability of concrete exposed to ground are influenced by chloride and sulfate salts present in the soil. The concentration of these salts in ground in the coastal areas is generally high and therefore needs to be assessed so as to design durable concrete.

2.7.3 Salinity

Salinity of soil and ground water in the coastal regions of Bangladesh is a major issue affecting the livelihood of people in terms of reduction in agricultural output and lack of good drinking water in the region (Dasgupta et al. 2014). Chloride (Cl^-) is a common anion in soil and groundwater, in most cases present in the form of sodium chloride, which builds up salinity. High chloride concentrations in the ground increase the risk of corrosion of reinforcement in concrete since chloride ions may migrate into the concrete and lead to a loss of passivity at the rebar surface.
The salinity of soil in the coastal regions of Bangladesh are zoned as shown in Figure 2-7. A similar contour map on the salinity levels in ground water is shown in Figure 2-8 and Figure 2-9. Although the salinity data was produced for applications related to agriculture and sanitation, the spatial variation in the severity of the ground exposure conditions can be judged, which is useful for the design of concrete structures in the coastal regions.

2.7.4 Airborne salts

Marine aerosols not only affect the exposed coastal areas but also the inner coastal regions. The marine aerosols composed primarily of seawater along with pollutants in the atmosphere and principally constitutes of chlorides and sulfates. The deposition of these airborne salts on the surface of concrete structure causes disintegration of cover concrete due to crystallisation pressure of salts and subsequent corrosion related damage of structure. A study on influence of airborne salts on the coastal infrastructure of Bangladesh reports that the extent of chloride and sulfate deposition on mortar specimens has been observed to be up to a distance of 207 m from the shoreline (Hossain et al. 2009). Figure 2-9 presents the spatial variation of the maximum river salinity level during 2011–2012 in the southwest zone. The spatial variation in the deposition of marine salts measured using wet candle sensors from the shoreline of Bangladesh is shown in Figure 2-10.
Based on the literature review on the influence of marine salts on coastal infrastructure in Bangladesh, it can be observed that the exposed coastal zone can be extends up to 200m from the shoreline.



Source: *Bangladesh Agriculture Research Council*

Figure 2-7 Saline zone of Bangladesh (Source: Bangladesh Agriculture Research Council)

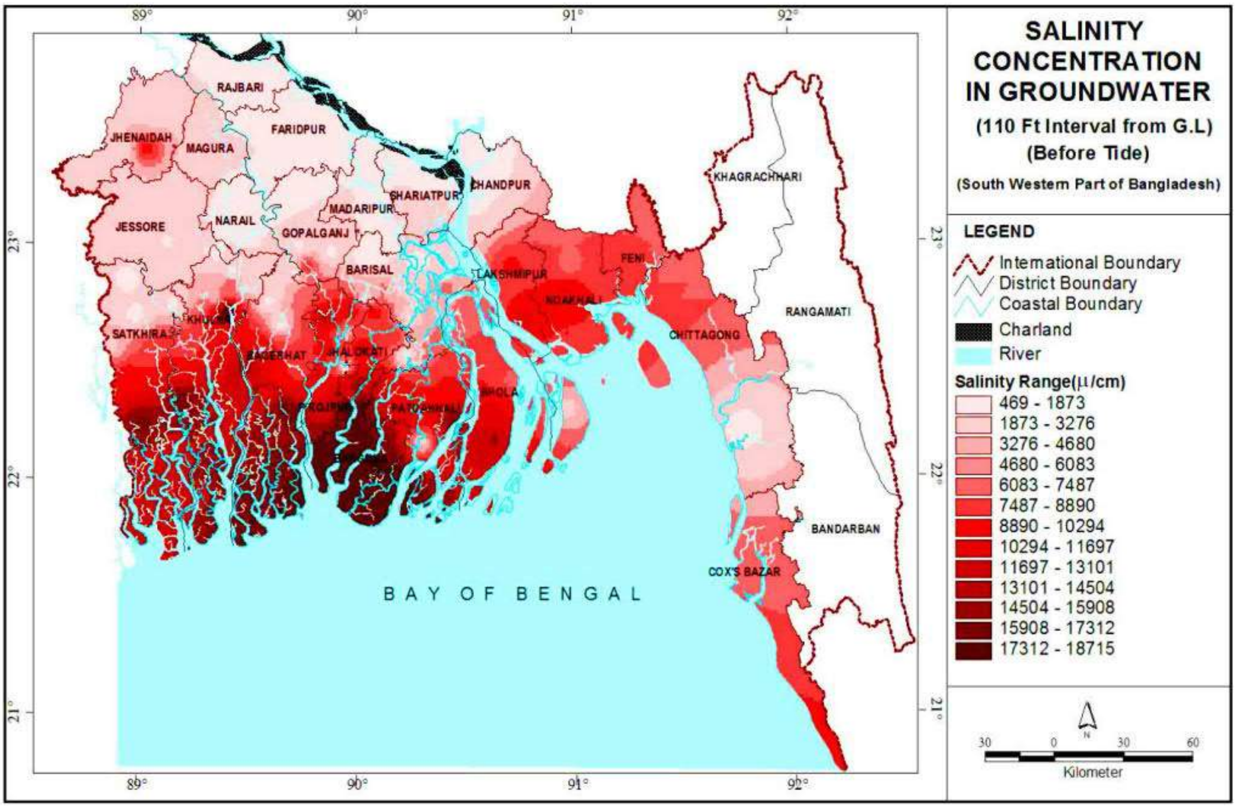


Figure 2-8 Salinity of ground water at a depth of 34m (BADC, 2011)

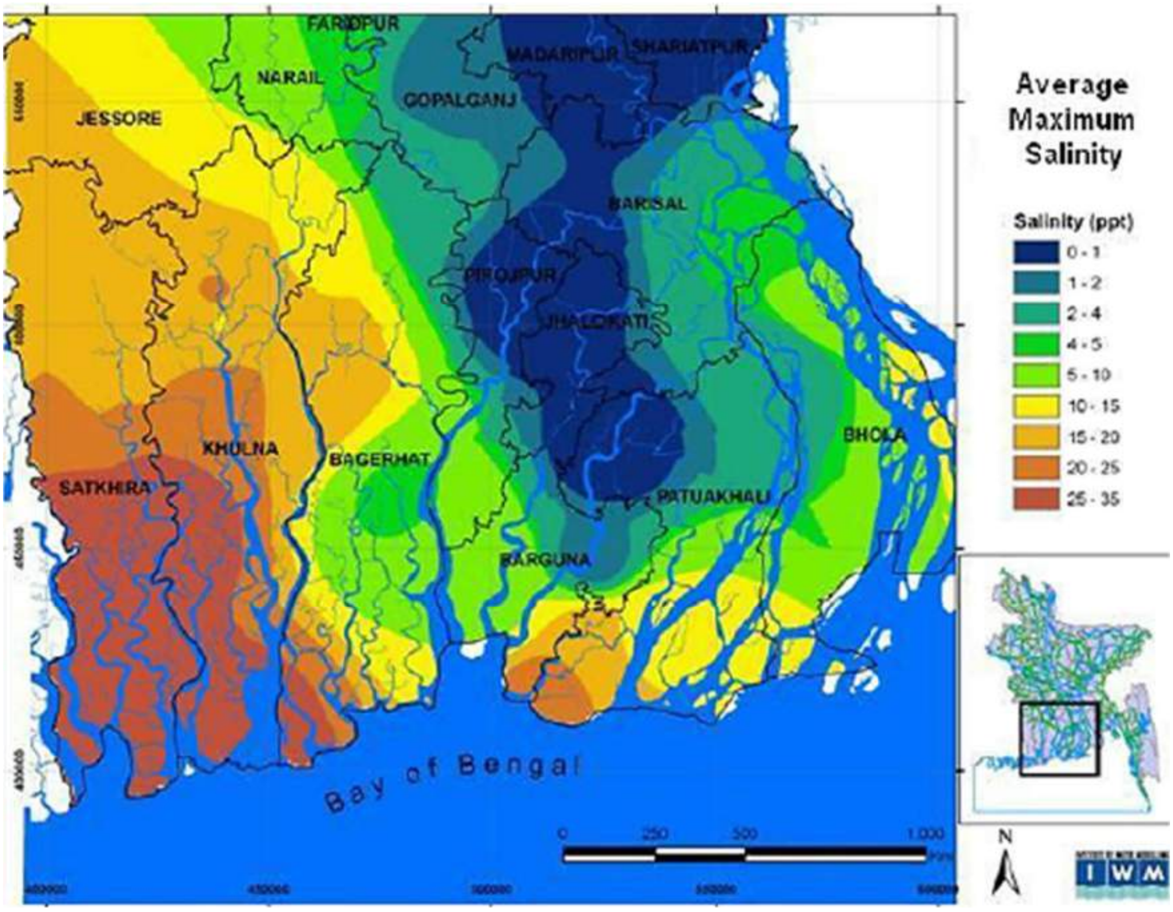


Figure 2-9 Map of average maximum salinity of river water in the southwest region of Bangladesh (Dasgupta et al., 2014)

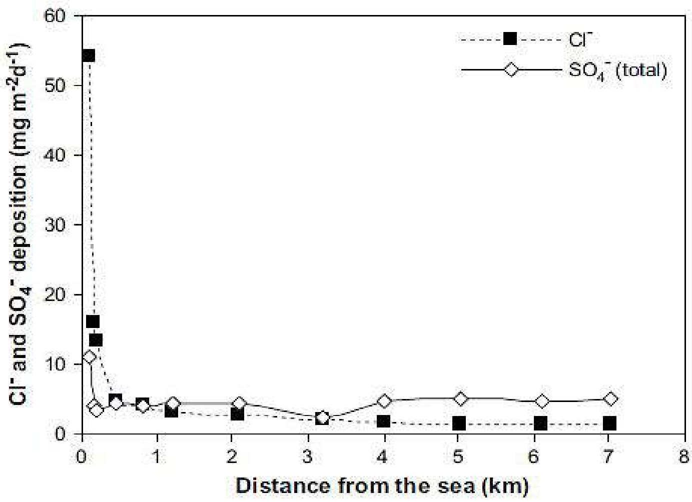


Figure 2-10 Variation of dry deposition of marine salts away from the shoreline (Hossain et al. 2009)

2.7.5 Sulfates in the ground

Concrete exposed to sulfates in the soil or groundwater are detrimental to the durability of concrete. Sulfate ions are transported from the ground into the concrete and react with cement hydrates to form destructively expansive minerals leading to deterioration of concrete. The physical signs of deterioration caused by sulfate attack include degradation caused by expansion (with or without cracks), surface erosion and softening of the cement matrix. BRE SD1 provides a guidance on the classification of soil conditions for sulfate attack and specifying durable concrete according to the chemical classification of the ground exposure conditions.

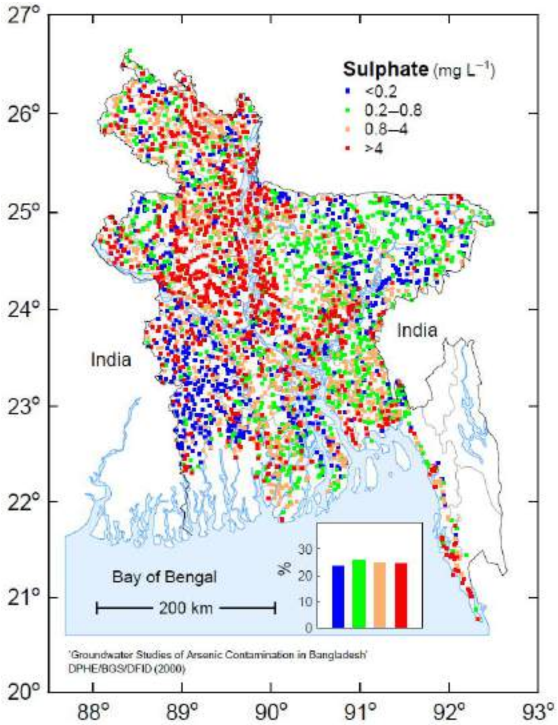


Figure 2-11 Spatial variation of sulfate in groundwaters from the National Hydrochemical Survey (BGS, 2001)

A previous study on the chemical contamination of groundwater in Bangladesh suggests that sulfate concentrations are in general very low across the country (BGS, 2001). This study highlights that lowest sulfate concentrations in groundwater was observed in the south-west and southern parts of Bangladesh (shown in Figure 2-11). The comparison of sulfate concentrations with the guidance in BRE SD1 suggests that the ground water has extremely low levels of sulfates especially in the coastal regions of the country.

2.7.6 Acidic ground

Studies on acid sulfate soils in Bangladesh suggest that around 0.7 M ha of land in different pockets of Cox's bazar and Khulna district, in the coastal region of the country, are affected with acid sulfate soils. The pH value of water tested in these areas varied between 3.7 and 7.0 depending on the time of sampling. Concrete structures exposed to this acidic environment suffer disintegration of cement matrix and associated damage of concrete elements.

2.8 Materials

2.8.1 Cement

Bangladesh imports most of the raw materials (Clinker, Gypsum, Fly ash, Limestone fines and Slag) required for cement production. The cement industry in Bangladesh holds an installed capacity of 33-35 Million MT, while it can supply 25-27 Million MT efficiently (IDLC 2015). Mainly two types of cement are currently available in the country, Portland Composite Cement (CEMII) constitute the bulk production and Ordinary Portland Cement (CEM I) constitute the rest (IDLC 2013; Uddin Mohammed, 2007). The widely used Portland Composite Cement conforms to EN 197-1:2003, CEM II/B-M type and is composed of Clinker: 70-79%, Gypsum up to 5% and up to 20% of Fly ash/Limestone/Slag. It should be noted that the 'M' designation in cement type means that any of the replacement materials can be used.

2.8.2 Fly ash and slag

Based on the discussions held with local cement manufacturers, most of the fly ash or slag used in the cement is imported from other countries. However, it is important to emphasise that local Thermal Power Plants in Bangladesh produce around 52000 MT of fly ash every year, which has a potential to be used in cement, but due to lack of government regulations most of the Fly ash produced is dumped in local landfills (Tammim et al. 2013).

2.8.3 Aggregates

Broken brick chips are widely used as coarse aggregates in concrete, especially in coastal districts due to the shortage in availability of stone aggregates. The brick aggregates are produced by crushing standard bricks either manually or by using crusher machines. First class picked Jhama brick chips are generally specified as preferred coarse aggregates in construction projects. Shingle gravel aggregates (round shaped stone), available in some parts of the country are used in concrete production due to their better workability characteristics. A comparison of engineering properties of stone aggregates collected from different sources in Bangladesh is presented in Table 2-1. Rahman et al. 2014, studied on wider scale on the spatial variability of coarse and fine aggregates in Bangladesh. In addition to fresh aggregates, recycled aggregates are available mainly in cities, where the aggregates are recycled from demolished concrete structures (Uddin et al. 2013) Natural sand from different sources in the country are used as fine aggregate in concrete. Figure 2-12 shows the soil texture map of Bangladesh and it can be observed that the coastal areas of the country mainly have silt or silty clay soil, which when used as fine aggregate is detrimental to the performance of concrete. Crushed stone dust available as a by-product from stone crushing industry in Sylhet has a great potential to be used as fine aggregate in concrete (Ahmed et al. 2010). The cost comparison of coarse aggregate types available in different regions of Bangladesh is shown in Figure 2-13.

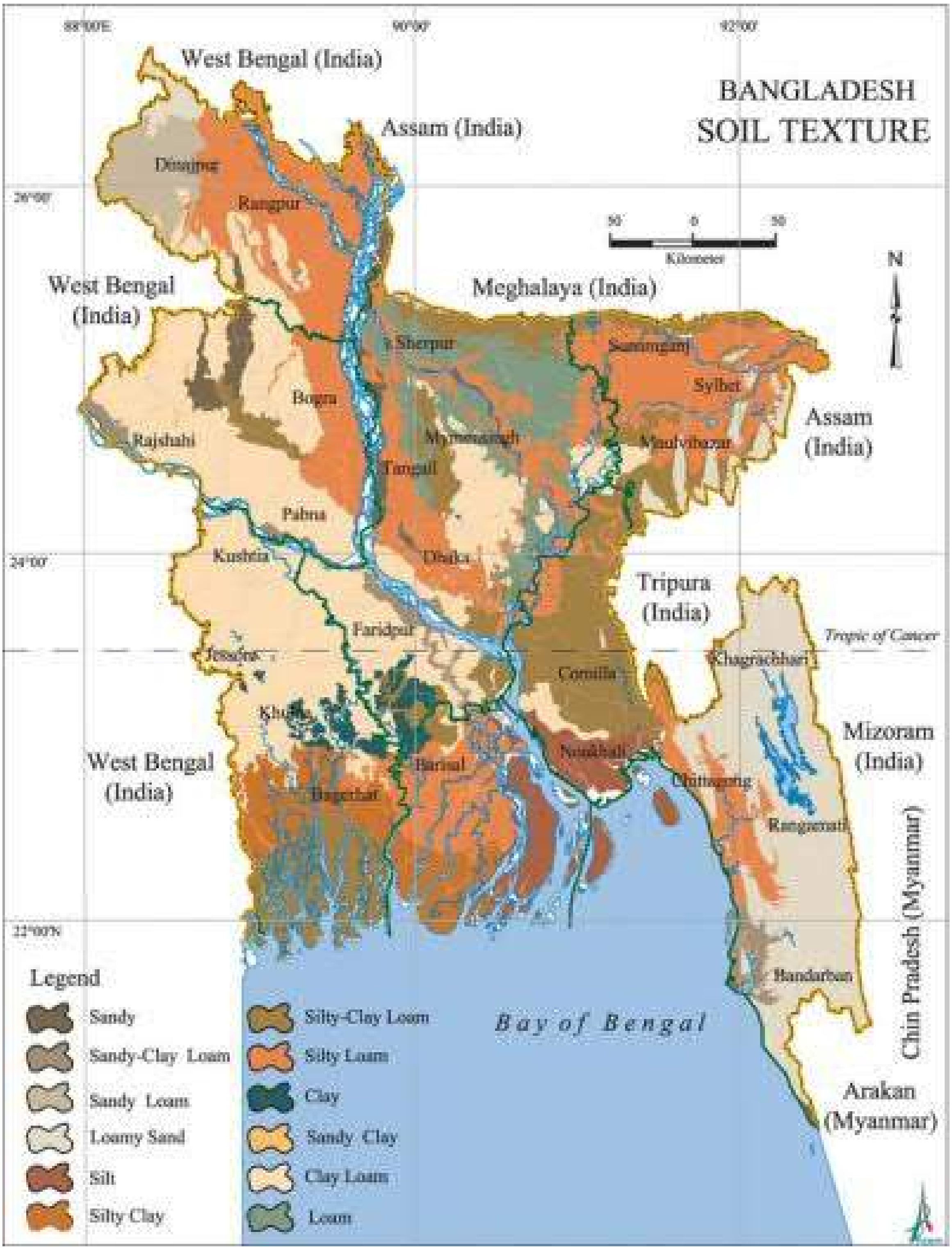


Figure 2-12 Bangladesh soil texture map

Table 2-1 Properties of different stone aggregates sourced in Bangladesh (Rahman et al. 2014, Alam et al 2014, Rasel et al 2011)

Properties	Stone aggregates				Other Aggregates		
	Zaflong in Sylhet	Volaganj in Sylhet	Vozonpur in Panchagarh	Boropukuria in Dinajpur	Brick Chips	Shingles	Jhama Brick chips
Specific Gravity	2.57	2.69	2.50	2.79	2.07	2.52	
Absorption Capacity (%)	1.4	1.32	1.93	0.95	11.5	2.0	12.2
Unit Weight (kg/m3)	1645	1695	1674	1732	1079	1209	1500
Aggregate Impact Value (%)	13.49	12.48	13.86	10.50	18		
Aggregate Crushing Value	18.72	17.50	18.53	15.06	30		
Ten Percent fines value (%)	13.86	14.14	13.93	14.0			
Flakiness Index (%)	18.95	18.55	18.45	17.95	17.0		
Elongation Index (%)	26.20	25.0	28.75	24.0			
Los Angles Abrasion Value (%)	29.0	28.3	28.5	26.4	38.0	20.78	37.16
Fineness Modulus	6.19	6.19	6.22	6.19	6.69	6.69	6.69

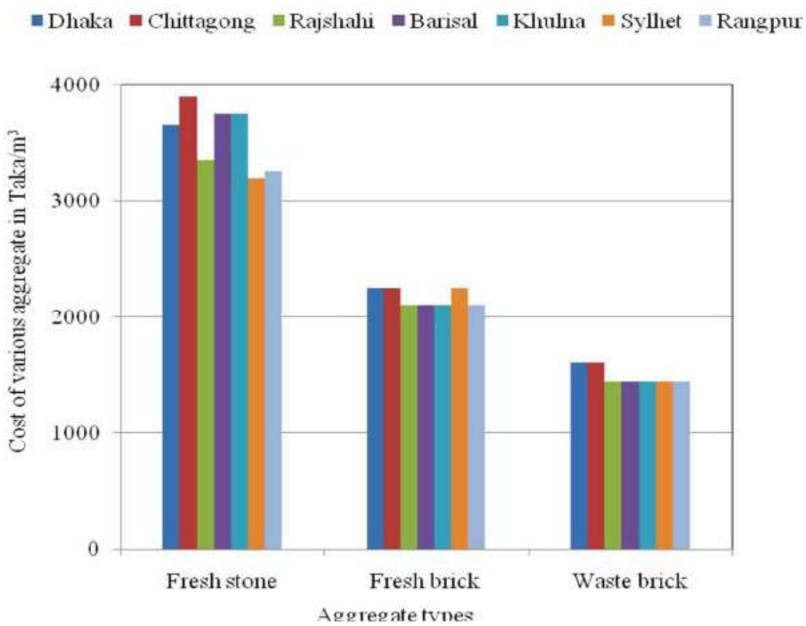


Figure 2-13 Comparison of cost per m^3 of coarse aggregate (Rasel et al. 2011)

2.8.4 Chemical admixtures

Different varieties of high range water-reducers and construction chemical are available in the country, however the use of these constituents are quite limited in coastal and rural construction projects.

2.8.5 Water

Salinity of water available in coastal areas is one of the major issues in Bangladesh. In most cases saline water available in the coastal areas has been used in concrete production, which increases risk of reinforcement corrosion in concrete and a major cause for early deterioration of concrete structures in coastal areas of Bangladesh (Bosunia and Choudhury, 2001).

2.9 Material problems

The use of unsuitable or contaminated materials has been a frequent cause of problems for reinforced concrete in Bangladesh. Problems may occur with all the raw materials used in the production of concrete, however, by careful specification and ensuring rigorous quality control procedures these may be significantly reduced. The literature review on some of the identified material related deficiencies associated with deterioration of concrete structures in coastal areas of Bangladesh are summarised below:

- Low strength cement
- Aggregate that is susceptible to alkali aggregate reaction
- Unburnt or low quality porous bricks used as coarse aggregates
- Use of fine sand with high silt content locally available from river deposits in alluvial plains of coastal areas reduce the strength and workability of concrete
- Variability in properties of steel reinforcement especially related to weight per unit length, cross-sectional area and surface deformations
- Contaminated mix constituents
- Contamination of steel surfaces (e.g. with salts)

2.10 Workmanship

It is recognised that workmanship is a major factor in obtaining good quality, durable concrete. In rural and coastal regions of Bangladesh, extreme cyclonic weather conditions are becoming more frequent contributing to the migration of the skilled workforce able to produce, place and cure concrete to the standards required to optimise its durability (Rahman and Rahman 2015).

A number of defects, which originate at the time of construction, are the result of poor workmanship. In concrete construction the two most common deficiencies which occur are:

- Porous concrete, with air pockets and honeycombing and lack of cover; air pockets or entrapped air are usually the result of insufficient compaction (vibration)
- Insufficient cover to reinforcement, caused by a poor standard of steel fixing, incorrect positioning or deformation of bars, the omission of spacers, movement of the steel during concrete placing, or irregularities in the formwork surfaces (or ground surface, where concrete is cast against the ground)

The literature review relating to the condition of concrete structures in the coastal districts of Bangladesh suggests serious issues relating to the poor workmanship at the time of construction (Uddin Mohammed 2007, Basunia and Choudhury 2001). Some of the identified workmanship issues that resulted in early deterioration of structures include:

- Use of contaminated materials
- Mistakes in or poor control over quantities/types of constituents in concrete mixes
- Use of un-sieved aggregates, un-washed aggregates and overly wet sand
- Lack of storage facilities for construction materials
- Excess water in the mix
- Use of incorrect concrete mixes
- Inadequate curing practices and period
- Distortion and displacement of formwork
- Placing of concrete from large height
- Improper compaction of concrete

Poor workmanship is a major contributory factor in increasing the rates of deterioration due to other forms of attack. It can generally be overcome by appropriate design to simplify construction details and using skilled and supervised workforce.

2.10.1 Climate change and its implications for coastal concrete structures

The future climate change scenario and its impacts on coastal concrete structures in Bangladesh is summarised in Table 2-2:

Table 2-2 Climate change impact on coastal concrete infrastructure

Climate element	Status of change (ADB 2013)	Impact on Infrastructure
Temperature	Current change: 0.4°C during last 50 years Future: 1.38-1.42°C by 2030 and 1.98-2.35°C by 2050	• accelerates deterioration processes • increases the water demand in concrete • increases shrinkage and thermal cracking in concrete • needs additional curing measures • increased thermal expansion of elements in existing structures
Rainfall	Current trend: 25 cm in last 50 years (wetter monsoon) Future scenarios: increase in rainfall 13.5-18.7% in 2030 22.3-24.7% in 2050 27% in 2060	• Increased flooding increases flood loading on structures • Wetter ground causes rising damp and related deterioration of concrete
Sea Level Rise (SLR)	Current SLR: 4-6mm/year Projection in 2030: 21 cm reference to land inside polders Projection in 2050: 39 cm reference to land inside polders	• SLR and increase in tidal levels increases the exposure to salts in seawater • Increased risk of corrosion in concrete structures

Climate element	Status of change (ADB 2013)	Impact on Infrastructure
	Tidal level will also increase with SLR	• Increase in biological deterioration of concrete
Tropical cyclones and surges	Tropical cyclone frequency and intensity will rise the destruction will be severe due to wind and surges The tropical cyclones may have wind up to 275 km/hr in the future	• Increases the wind loading and flooding loading on structures • Increases the contamination of construction materials
Salinity	The 5 ppt (5000 ppm) line will move further inland affecting the Pourashavas of Amtali and Galachipa in 2050 and the whole of these Pourashavas and Mathbaria will come under the 5 ppt (5000 ppm) line in 2100	• Increased salinity increases the risk of reinforcement corrosion and reduces the service-life of concrete structures • Increases the contamination of construction materials • More structures exposed to chlorides
CO_2 emission (Gunter and Rahman, 2012)	Baseline in 2005: CO_2 emission of 40 Mt Future emission in 2050 with no improvement in energy efficiency: 628 Mt (15 times to 2005 value) Future emission in 2050 with reaching EU's 2030 efficiency: 183 Mt (7 times to 2005 value)	• Increases the depth of carbonation in exposed concrete thereby increases the risk of reinforcement corrosion in concrete

2.11 Design standards and specifications

Construction of concrete structures in the coastal region of Bangladesh is governed by various LGED standards. The list of LGED standards relevant to the specification of concrete is listed below:

- Building Design Standard, Aug 2015 Amendment Notice
- Bridge Design Standards for LGED, June 2012, Amendment notice
- Road Structures Manual for Double Lane Bridges (RSM'08), Part A Design criteria, guidelines and design methods for RC/PC bridges, box culverts and slope protection works, Nov 2008
- Technical Specification for Buildings, LGED, First Edition, Jan 2005
- Technical Specification for Bridges on the Upazila & Union Roads, LGED, Mar 2004

2.11.1 Concrete specification for buildings

Review of various clauses in LGED technical manuals and standards (listed in section 3.7) related to concrete specification for buildings are collated in Table 2-3.

Table 2-3 Limiting values for concrete materials in LGED specification for buildings

Property	Standard	Type A		Type B		Type C	
		Stone	Brick	Stone	Brick	Stone	Brick
Application		Severe seismic zone ≤6 stories		Severe cyclone zone		Normal zone	
Compressive Strength		20		25		20	
Cement type	EN 197/ASTM C150	CEM I	CEM II	CEM I		CEM I	CEM II
w/c ratio		0.4-0.45		0.4		0.4-0.45	
WRA	ASTM C494 (Type A)	Optional		Required		Optional	
Admixtures (Chemical and Mineral)	Chloride content	<1% by weight of admixture					
Steel rebar (MPa)	ISO 6935, ASTM A615 & A706	400		400		400	
Sand FM	ASTM C33	2.2		2.2		2.2	
Grading	ASTM C33						
Absorption (%)		≤2%	≤15%	≤2%		≤2%	≤15%
LA		≤33	≤38	≤33		≤33	≤38
Mix proportions		1:2:4	1:1.5:3	Mix design required		1:2:4	1:1.5:3
Water	ASTM C 1602	Potable water, Chloride ions <3000ppm					
Formwork				Steel			
Durability of Concrete	LGED technical specification for Buildings, 2005 Clause 10.1.6	Special exposures: - Low permeability concrete when exposed to water W/C <0.5 - Marine and salt environment W/C <0.40 Sulfate exposure: - Sulfate resisting cement with W/C ratio given in the table below - Calcium chloride shall not be used as admixture in concrete exposed to severe or very severe sulfate environment					

Sulfate exposure	Water soluble sulfate (SO4) in soil (percent by weight)	Sulfate (SO4) in water	Cement type[1]	Maximum water cement ratio by weight
Negligible	0.00-0.10	0-150		
Moderate[2]	0.10-0.20	150-1500	II, IP(MS), IS(MS),	0.50

Property	Standard	Type A	Type B	Type C

			P(MS), I(PM)(MS), I(SM)(MS)	
Severe	0.20-2.00	1500-10000	V	0.45
Very Severe	Over 2.00	Over 10000	V plus pozzolan	0.45

1. For types of cement see ASTM C150 and C595
2. Sea water

Corrosion of reinforcement:
Maximum chloride ion content for corrosion protection

Type of member	Maximum water soluble chloride ion(C1)in concrete, percent by weight of cement
Reinforced concrete exposed to chloride in service	0.15
Reinforced concrete that will be dry or protected from moisture	1.00
Other reinforced concrete construction	0.30

2.11.2 Concrete specification for bridges

Review of concrete related clauses specified in Road Structures Manual (RSM'08) are given in Table 2-4.

Table 2-4 Limiting values for concrete materials in LGED specification for Bridges

Material	Property	Limiting value
Concrete	Strength	Minimum strength of PSC girder – 35 MPa Minimum Strength of RCC components of Bridge – 25 MPa Grades of concrete specified in RSM'08:

Grade	28 days cylinder strength	Application
Class 10	10 MPa	Plain concrete below foundation
Class 15	15 MPa	Plain concrete in other cases
Class 20*	20 MPa	Reinforced concrete components of superstructure, substructure and piles
Class 25*	25 MPa	
Class 30	30 MPa	Pre-stressed concrete
Class 35	35 MPa	

<table>
<tr><th>Material</th><th>Property</th><th>Limiting value</th></tr>
<tr><td></td><td></td><td>* For class 20 and 25 – minimum cement content 330 and 350 kg/m3 respectively and maximum W/C ratio: 0.5</td></tr>
<tr><td>Steel</td><td>Strength</td><td>Conforming to BDS 1313:1991
Minimum yield strength of steel – 415 MPa (Grade 60)</td></tr>
<tr><td>Cement</td><td>General</td><td>Conforming to EN197-1:2000 and BDS EN 197-1:2003</td></tr>
<tr><td>Aggregates</td><td>General</td><td>Fine aggregates: Conforming to AASHTO M6-87 or BS 882:1983
Coarse aggregates: Conforming to AASHTO M80-87 or BS 882:1983</td></tr>
<tr><td>Water</td><td>Quality</td><td>Water containing <2000ppm of total dissolved solids

Chemical limit of mixing water
<table>
<tr><th>Chemicals</th><th>Test method</th><th>Maximum Concentration (ppm)</th></tr>
<tr><td>Chlorides (Cl):
• Concrete in Bridge decks
• Other reinforced concrete in moist environments</td><td>ASTM D512</td><td>500
1000</td></tr>
<tr><td>Sulfate (SO_4)</td><td>ASTM D 516</td><td>3000</td></tr>
<tr><td>Alkalis ($Na_2O+0.658K_2O$)</td><td></td><td>600</td></tr>
<tr><td>Total solids</td><td>AASHTO T26</td><td>50000</td></tr>
</table>
</td></tr>
</table>

2.12 Strategy for Achieving Durability

2.12.1 Overview

Best practice for ensuring durability of reinforced concrete elements includes:

- 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.

2.12.2 Use of Supplementary Cementitious Materials (SCMs)

As discussed in section 3.4.1, there are mainly two type of cements produced in Bangladesh viz.,CEM I (Ordinary Portland Cement) and CEM II A-M (Portland Composite Cement). The later type contains supplementary cementitious materials such as Fly ash and slag along with limestone powder as inert filler at a combined dosage of up to 20%. The cement producers in Bangladesh generally vary the proportions of Fly ash, slag and limestone content in the Portland Composite Cement depending on the quality and availability of these materials. Therefore, in order to study the performance of one type of SCM, most of the research studies on optimising the use of SCMs have used manual blending techniques with CEM I in the laboratory.

One such study on the use of fly ash generated from Barapukeria power plant in Bangladesh suggests that around 5-10% of locally available fly ash can be used as cement replacement in concrete without compromising on the workability and 28 days strength of the concrete (Alam et al. 2006). However, the merits of later age (56 days and above) strength development of fly ash based concrete were not reported in this study. Another study on the use of Barapukeria fly ash blended cement in improving the durability characteristics of concrete suggests a replacement level of 30-50% based on the improvement in strength after 90 days and reduction in the permeability of concrete measured by water permeability and rapid chloride penetration resistance of concrete (Islam and Islam, 2014). A study on the long-term strength performance of cement mortars with fly ash as partial replacement of cement at different levels suggest an optimum dosage of 40% based on 90 days compressive and tensile strength development results (Islam and Islam, 2010).

Local research study on the use of slag as cement replacement in concrete suggests 30% slag as optimum cement replacement based on better long-term strength characteristics, ultrasonic testing on cube samples and resistance to physical deterioration caused by exposure to different concentrations of salt water (Moinul Islam et al. 2010). However, based on the discussions we had with the cement manufacturers, slag used in CEM II is largely imported from outside the country. At this stage of the report the source and quality of locally produced slag is unknown.

A study on commercially available CEM I and PCC cements in Bangladesh on the improvement of durability performance of concrete clearly suggests that PCC cements outperform based on the low permeability results obtained from rapid chloride penetration tests. However, contrary to this, based on the discussions we had with local cement manufacturers we understand that the general opinion of contractors and/or concrete manufacturers in the rural regions of the country is that CEM I based concrete is better in all aspects including durability as compared with CEM II due to the superior strength characteristics of CEM I based concrete.

It was also observed that one of the major impediments in use of higher additions of SCMs in the cement is the marketing competition between various cement suppliers in the country to produce high strength (28 days strength) cement and more often strength is used as primary criteria in choosing particular brand cement for a construction project. Moreover, the benefits of using blended cements on long-term strength and durability characteristics of concrete are not very well adapted in national standards, for example recent amendment to LGED Building Design Standard suggests only CEM I cement for Type B (severe cyclone) exposure condition, which is predominantly for coastal regions of the country (LGED, 2015).

Based on the review of available literature on the performance of locally available SCMs viz., fly ash and slag, it can be observed that the current levels of cement replacement in Portland Composite Cement (up to 20%) can potentially be increased to 30% or greater replacement by fly ash or slag to improve the long-term durability performance of the concrete.

2.12.3 Stone aggregates vs Brick aggregates

Scarcity of natural rock deposits in Bangladesh necessitates the use of brick aggregates in concrete. Moreover, brick aggregates are widely used in concrete production in the country especially in rural areas due to its ready availability, low cost and low unit weight (lesser transportation costs and low workmanship efforts) as compared with stone aggregates.

Extensive studies on the use of brick aggregates in concrete suggests that the brick aggregate concrete has lower strength, high water absorption and high permeability characteristics as compared with normal concrete. However, brick aggregate concrete provides adequate quality concrete for use in reinforced concrete construction.

Studies on strength characteristic of brick aggregate concrete suggests a 33% reduction in compressive strength and 28% reduction in elastic modulus compared with stone aggregate concrete (Abdur Rashid 2012). A partial replacement of stone aggregate with brick aggregate produced better strength characteristics compared to full replacement (Khaloo, 1994). Some of the studies on the use of high quality crushed bricks in concrete reported better compressive strength compared to crushed stone aggregates (Akhtaruzzaman and Hasnat, 1983; Khaloo, 1994; Mansur et al. 1999).

Durability performance of crushed brick aggregate concrete suggests greater water penetration and higher chloride ion permeability compared to crushed stone aggregate concrete (Anwar Hossain, 2011). In this study it was also reported that the water permeability of crushed brick aggregate concrete was found to be directly influenced by the crushing strength of brick, absorption capacity and LA abrasion value of brick.

Durability studies of brick aggregate concrete exposed to salt environment suggests, low resistance to chloride penetration and reduction in time to initiation of corrosion of reinforcement with increase in brick aggregate content (Adamson, 2015). However, due to high porosity of brick aggregates, the concrete with brick aggregates showed superior freeze-thaw resistance characteristics compared with 100% crushed stone coarse aggregate concrete. In addition to this, brick aggregate concrete had demonstrated better performance in high alkali content concrete and the low expansion caused by alkali-silica reaction (ASR) did not affect the engineering properties of brick aggregate concrete (Bektas, 2014)

Based on the above discussions on the review of available literature on the durability performance of brick aggregate concrete, it can be concluded that inclusion of crushed bricks as corase aggregate in concrete is detrimental to the long-term durability performance of concrete especially in aggressive exposure conditions experienced in the coastal regions of Bangladesh.

2.12.4 Use of Water Reducing Admixtures (WRAs)

A wide variety of high range water reducing admixture are available in the Bangladesh market, however the use of these chemical admixtures in rural and coastal regions of the country is very limited due to budget constraints and lack of knowledge on their proper use. The possibility of incorporation of water reducing admixture as powdered addition in cement bags can be explored through discussions with cement manufacturers and admixture suppliers in the country.

2.12.5 Cover to the reinforcement

In reinforced concrete structures, a minimum cover to reinforcement is necessary to protect the steel from corrosion and to provide resistance against fire. The minimum cover for durability protects the reinforcing steel from ingress of detrimental agents such as chlorides and carbon dioxide. The minimum concrete cover specified in Bangladesh National Building Code (BNBC) 2011 is as follows:

Clause 8.1.7.2 Minimum cover for cast-in-place concrete exposed to mild environment:

(a) Minimum concrete cover for concrete cast against and permanently exposed to earth shall be 75 mm.

(b) Concrete exposed to earth or weather:

Bar size:19mm dia to 57mm dia	50mm (minimum cover)
Bar size:16mm dia and smaller	40mm (minimum cover)

(c) The following minimum concrete cover may be provided for reinforcement for concrete surfaces not exposed to weather or in contact with ground:

	Minimum cover (mm)
Slabs, walls:	
40mm dia to 57mm dia	40
36mm dia bar and smaller	20
Beams, Columns:	
Primary reinforcement, ties, stirrups, spirals	40
Shells, folded plate members:	
19mm dia bar and larger	20
16mm dia bar and smaller	16

The BNBC also provides guidelines on nominal cover to all reinforcement, maximum free water cement ratio and minimum cement content required for various minimum concrete strengths used in different exposure conditions as given in Table 2-5. In addition clause 8.1.7.8 of BNBC specifies minimum cover required for corrosion protection in severe exposure conditions.

Table 2-5 Nominal concrete cover and other requirements (for MAS 20mm) for various exposure conditions (BNBC 2011)

Environment	Exposure Conditions	Cover (mm) required at strength (minimum f'_c N/mm^2)						
		20	25	30	35	40	45	50
Mild	Concrete surfaces protected against weather or aggressive conditions	30	25	20	20	20	20	20
Moderate	Concrete surface away from severe rain Concrete subject to condensation Concrete surfaces continuously under water Concrete in contact with non-aggressive soil	40	35	30	25	20	20	20
Severe	Concrete surfaces exposed to severe rain, alternate wetting and drying or severe condensation		45	40	30	25	25	20
Very severe	Concrete surfaces exposed to sea water spray, corrosive fumes			50	40	30	30	25
Extreme	Concrete surfaces exposed to abrasive action, e.g. sea water carrying solids or flowing water with pH < 4.5 or machinery or vehicles				60	50	40	30
Maximum water/cement ratio		0.65	0.65	0.60	0.55	0.50	0.45	0.42
Minimum cement content (kg/m^3)		315	325	350	375	400	410	420

Clause 8.1.7.4 For concrete cast against and permanently exposed to earth, minimum cover shall be 75 mm.
Clause 8.1.7.8 For corrosion protection, a specified concrete cover for reinforcement not less than 50 mm for walls and slabs and not less than 65 mm for other members may be used. For precast concrete members a specified concrete cover not less than 40 mm for walls and slabs and not less than 50 mm for other members may be used.

Based on the nominal and minimum cover requirement specified in BNBC and test results from the conditions survey of concrete structures in coastal environment of Bangladesh, the obtained data is used to populate the bespoke probabilistic corrosion model that will give the probability of each mix achieving defined service life in marine environment. The final matrix for trial mixes is based on the optimisation of each parameter in the probabilistic model.

2.12.6 Curing

Curing of concrete is crucial to maintain the moisture and temperature in concrete for early age strength development and to minimise shrinkage cracking in the concrete. BNBC 2011 clause 5.11 specifies that the concrete temperature shall be maintained above 10°C and shall be cured for at least 7 days after placement for normal concrete and 3 days for high early strength concrete.

Previous case studies on condition survey of concrete structures in coastal areas of Bangladesh identified inadequate curing to structural members viz., columns, beams and walls and use of contaminated water for curing resulted in early deterioration of concrete (Bosunia and Choudhury, 2001; Uddin Mohammed, 2007; LGED, 2015).

Research studies on the effect of sea water curing on concrete strength characteristics suggests a 10% drop in compressive strength of seawater cured concrete compared with plain water cured concrete (Moinul Islam et al. 2011). However, studies on variable curing conditions of brick aggregate concrete suggest lesser influence on strength development compared with stone aggregate concrete (Ahmed and Saiful Amin, 1998). This unique property of brick aggregate is caused by the higher absorption of porous brick aggregates, which provides internal moisture required for cement hydration and particularly in the case of inadequate curing at the surface.

2.12.7 Type of reinforcement bars

In Bangladesh typically three grades of reinforcement steel are available viz., 40 grade, 60 grade and Thermo-Mechanically treated (TMT) high strength steel. The 40 and 60 grade steel refers to 40,000 psi (276 MPa) and 60,000 psi (413 MPa) yield strength respectively, whereas high strength TMT bars have 72,500psi (500 MPa) yield strength. Among the three types it is believed that TMT bars have superior corrosion resistance characteristics. Study on corrosion behaviour of different sources of TMT steel bars available in Bangladesh suggest that the strength levels of TMT steel bars have no influence on the corrosion rate, whereas small amounts of alloying elements such as Chromium, Nickel and Copper improves the corrosion resistance of steel bars (Aminul Islam, 2015).

Another study on the strength characteristics of TMT bars suggest that excessive high levels of strength in TMT bars can cause poor ductility and shear type brittle fracture in reinforcing steel bars and recommends that for better tensile properties the heat treatment process of TMT bars should be closely controlled to the chemical compositions of the hot rolled steel bars (Kabir and Islam, 2014).

Based on the review of available grades of steel in Bangladesh, it was observed that grade 60 and TMT bars are popularly used in most of the construction projects. However, very little information is available on the comparison of corrosion behaviour of these two types of steel in concrete elements.

2.12.8 Use of Corrosion inhibitors

Corrosion inhibitors such as calcium nitrate and amino alcohols are widely used as cast-in corrosion inhibitors in reinforced concrete. These inhibitors do not actually stop the corrosion reaction, but delay the initiation of steel corrosion and lengthen the propagation period. Highways Agency UK guidance on the use of cast-in corrosion inhibitors suggests that corrosion inhibitors are more effective in low chloride environment (BA 57/01, 2001).

2.12.9 Performance based testing and specification

Traditional specifications for attaining durable concrete are prescriptive based such as limiting criteria for concrete strength, cement content and water-cement ratio. While standards are gradually moving towards performance based specifications, more information is needed to assist in designing concrete for service life. The complexity of various mechanisms as well as environmental factors involved in the deterioration of concrete demands an approach where performance criteria based on durability properties of concrete has to be suggested. The main advantage of this type of specifications is that the relationship between concrete performance and mix characteristics can be related with tests of concrete durability properties.

Based on the literature review and previous conditions surveys of structures in coastal regions of Bangladesh, it is observed that chloride induced corrosion of reinforcement and associated damage to concrete structural elements is one of the major reasons for early failure of concrete structures. The performance of concrete to resist chloride ingress and corrosion of reinforcement is generally investigated by studying the chloride migration in concrete by diffusion tests for example, NT Build 492 and also by means of corrosion studies where concrete samples with embedded reinforcement bars are subjected to accelerated corrosion environment and rate of corrosion of steel is measured.

The data collected from this laboratory testing for different concrete mixes along with information obtained from condition assessment of coastal structures and local exposure conditions, has been used to populate the predictive corrosion models that gives the probability of each mix achieving a defined service life. Through this methodology an optimum mix for a given exposure class can be specified. This methodology also helps in classifying the performance requirement of concrete for different exposure conditions experienced by concrete structures in the coastal regions of Bangladesh.

2.13 Summary of literature review

2.13.1 General

The literature review covers a wide range of available information as follows:

- Quality and variability of available local materials used in concrete production
- Local climatic conditions
- Aggressiveness of environment in coastal regions
- Material and workmanship related issues identified in coastal regions
- Research studies on optimisation of locally available materials to improve concrete strength
- Durability studies mainly focussing on strength development, water permeability and chloride ion permeability

2.13.2 Identified gaps in literature review

Although many papers on environment, materials and performance of concrete structures are available especially relating to coastal regions of Bangladesh, major gaps were identified, which need to be addressed. These are detailed below:

- 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 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 on the condition of concrete structures and in particular little information related to local exposure condition, 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 the 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 would be invaluable for the design and service life assessment of concrete structures in the region.

3 Condition Survey of Concrete Structures

3.1 Condition survey scope

The objective of the condition survey was to develop an understanding of the impact of the exposure conditions on the durability of concrete in Bangladesh's rural marine environment. Following discussions with LGED, four areas were identified for investigation; Bagerhat, Noakhali, Gopalganj and Cox's Bazar. The road infrastructure managed by LGED in each district consists of Upazilla roads, Union roads, village roads and all bridges along the road network. The road infrastructure details for each identified coastal district are presented in Table 3-1. The road infrastructure managed by LGED is classified as follows

- Upazilla roads – Roads connecting Upazilla headquarters with growth centers
- Union roads – Roads connecting Union headquarters with Upazilla headquarters, growth centers and local markets
- Village road
    - Category A (VA) - Roads connecting villages with Union Headquarters, growth centers or local markets
    - Category B (VB) – Roads within a village

The four identified districts provide a good representation of different levels of aggressiveness in the coastal regions of Bangladesh. Cox's Bazaar has some of the highest salinity levels in Bangladesh, Noakhali and Bagerhat are mid-level and the salinity in Gopalganj is low.

Table 3-1 Road infrastructure details in each identified coastal district

District	Area (km^2)	No of Upazila	No of Union	No of Pourashava	Upazilla Road (km)	Union Road (km)	Village Road (km)
Gopalganj	1484	5	68	4	618.41	336.17	1139.71 (VA) 899.4 (VB)
Bagerhat	3959	9	75	3	712.87	553.01	2893.85 (VA) 2137.19 (VB)
Cox's bazar	2492	8	71	4	402.36	521.11	1204.5 (VA) 2253.57 (VB)
Noakhali	4203	9	88	8	653.37	886.04	3456.99 (VA) 4437.1 (VB)

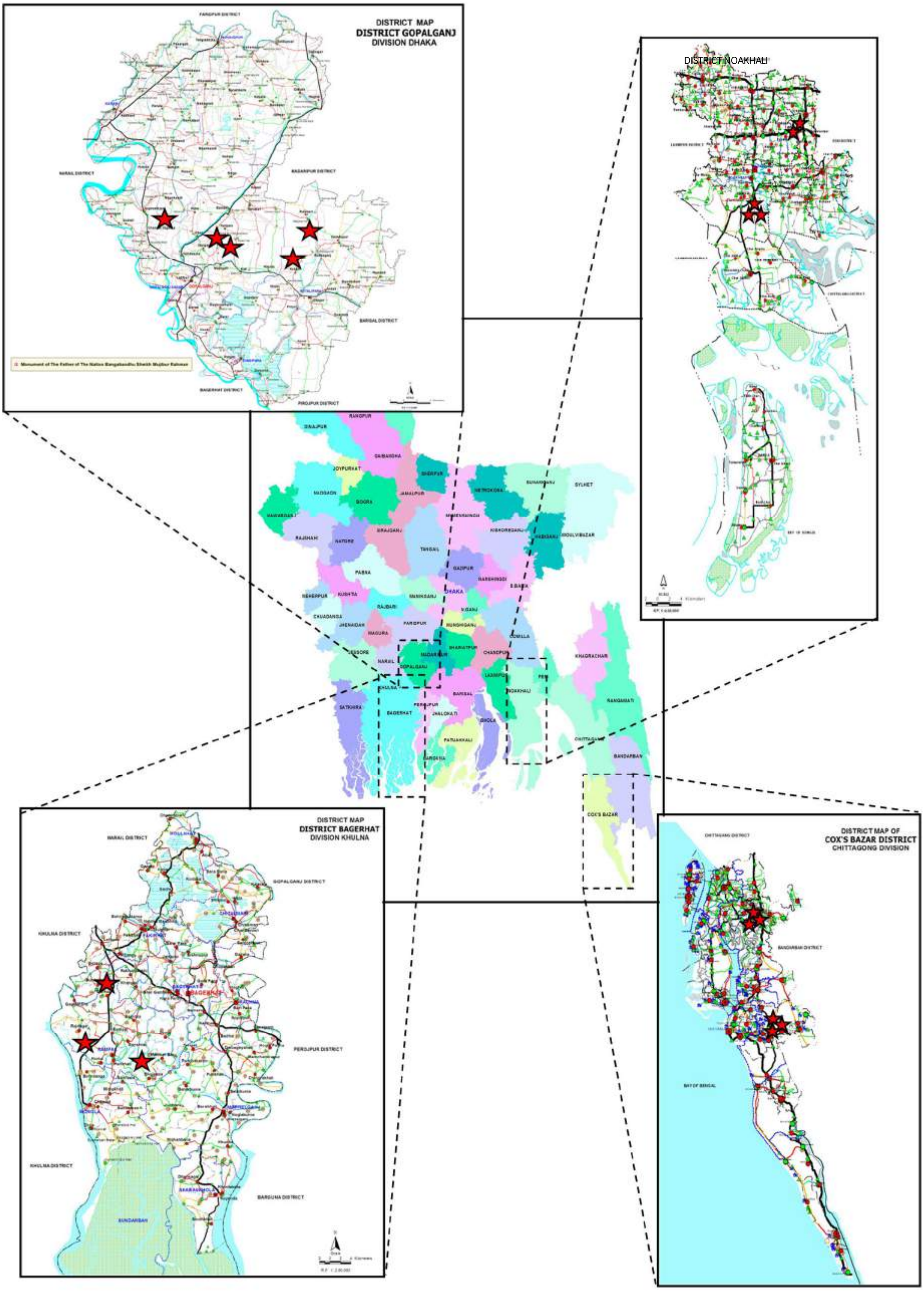


Figure 3-1 Identified coastal districts and location details for condition survey of concrete structures

3.2 Research Matrix

The scope for the condition survey of structures in the identified coastal districts of the country include intrusive testing and visual inspection of concrete structures that vary in type of structure, age, exposure conditions, method of concrete mixing and aggregate type (Brick/Stone aggregate) used in the concrete mix as presented in the research matrix in Table 3-2. Based on the testing variables given in Table 3-2, the site locations for concrete structures were identified as shown in Figure 3-1.

Table 3-2 Research matrix for condition survey of structures

Objective	Study	Variable
To analyse the main causes of deterioration of existing marine concrete structures	To study the condition of concrete structures in the different exposure conditions of coastal regions	<u>Exposed coast</u> Gopalganj – None Bagerhaat – Mongla Cox's Bazar – Cox's bazar sadar, Ukhia, Maheshkhali Noakhali – Subarnochar, Kobirhat <u>Inner coast</u> Gopalganj – Gopalganj Sadar, Kotalipara, Tongipara Bagerhaat – Rampal Cox's Bazar – None Noakhali – None
	To study the influence of local aggregates	Stone aggregates vs Brick Aggregates
	To study the condition of structure at different ages	>15 years old 5-15 years old 1-5 years old

Where safe access to highway structures was limited, findings were augmented by additional surveys on concrete elements in buildings as presented in Appendix B to provide greater information on workmanship issues, quality of local materials and chloride contamination of concrete structural elements.

3.3 Test techniques

3.3.1 Visual Inspection

Visual inspection is a valuable source of information recorded during the condition survey. The visual inspection survey records the observations including photos on features related to workmanship, structural serviceability, and material deterioration.

3.3.2 Non-destructive testing of concrete

3.3.2.1 Rebound hammer testing

Rebound hammer method is simple test that can rapidly take large number of readings at little expense. The guidelines on use of rebound hammer are covered in detail in BS EN 12504-2 and ASTM C805, which suggest that the rebound method should not be considered a substitute for strength determinations, but only as a useful preliminary or complementary method. The estimates of standard error in determining surface hardness/strength of concrete using this test method vary between 10% and 25%. This technique can be used to assess uniformity of concrete quality, to compare concrete with a reference in statistical terms and to indicate changes in characteristics of concrete with time. The factors that influence the surface hardness test depend on test orientation, type of surface, age and compaction of concrete, surface moisture conditions, type and content of cement, type of aggregate and surface carbonation of concrete. When selecting the test location, areas exhibiting honeycombing, scaling, irregular surface and high porosity must be avoided.

Rebound hammer testing was done using Elcometer 181 analogue test hammer as shown in Figure 3-2 on smooth or levelled concrete surfaces free from any dust or loose materials in accordance with BS EN 12504-2:2012.

Figure 3-2 Elcometer 181 rebound test hammer

3.3.2.2 Covermeter survey

A covermeter locates the embedded steel by measuring the intensity of the magnetic field it produces. The intensity of signal detected by the covermeter can be correlated to a depth of reinforcement from the concrete surface thus measuring the cover. Covermeters are predominantly used in scanning and identifying low cover regions in a structure and are frequently used as a quality control tool in construction sites. The accuracy of covermeters under normal site conditions is within ±5mm. However, in heavily reinforced members, the effect of secondary reinforcement reduces the accuracy measurements of cover. Apart from knowing the extent of low cover region, covermeters are also used to identify the exact location of reinforcement for coring or drilling tests and repair detailing. The factors influencing the test method include bar diameter, spacing of bars, aggregate with magnetic properties and other electromagnetic interferences at site. BS 1881: part 204 gives recommendations and describes the principles of their operation. The covermeter surveys were carried out using an Elcometer 331 with standard head as shown in Figure 3-3 in a grid of 500mm spacing and the lowest cover in the grid was recorded.

Figure 3-3 Elcometer 331 covermeter with standard head

3.3.2.3 Half-cell potential survey

The half-cell potential test estimates the potential corrosion activity of steel. The corrosion potentials of steel are measured against a reference consisting of electrode of a metal in an electrolyte. The commonly used reference half-cell are copper in copper sulphate or silver in silver chloride but other combinations are available. The corrosion potentials measured are based on reference electrodes and the criteria assessing corrosion condition for silver in silver chloride reference electrode is shown in Table 4-25. The variations in half-cell potentials are stable and reproducible in the range of ±25 mV. The detail guidelines on equipment and method are described in ASTM C 876 and there is no equivalent British standard, but BS 1881: part 201 gives a brief description on limitation and applications of the test method. Half-cell potential measurements are often carried out when reinforcement corrosion is suspected or evident in a structure. This method is widely used as a low cost test method that provides iso-potential contour maps used to easily identify zones of corrosion risk. However, it should be noted that the potentials obtained depends on the presence of moisture, therefore to counter for seasonal variations, an average of many readings taken during different weather conditions should be considered.

Half-cell potential survey was carried out using Elcometer 331 with silver in silver chloride reference electrode as shown in Figure 3-4 in a grid of 500mm spacing and the lowest half-cell potential (highest negative value) in the grid was recorded.

Figure 3-4 Elcometer 331 Half-cell meter with silver in silver chloride reference electrode

Table 3-3 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

3.3.3 Intrusive testing of concrete

3.3.3.1 Concrete core testing

Concrete core samples provide a direct means of testing the strength of in-situ concrete. Core samples can also be used for visually examining any voids, cracks in concrete, type and shape of aggregates. Compressive strength of concrete was measured by testing either 75mm diameter or 100mm diameter core samples in accordance with BS EN 12504-1:2009.

3.3.3.2 Chloride profile testing

The chlorides in concrete are present in two different forms, free chlorides and bound chlorides. The chlorides can be either physical or chemical binding of chlorides with cement hydration products. To initiate the corrosion process, the content of free chloride ions in the pore solution need to reach a critical chloride concentration. Chloride content in concrete is most widely reported as a percentage of cement content in concrete, which can be obtained by acid digestion of dust samples. To determine the chloride profile, dust samples were collected at 3 or 4 different depths (5-30mm, 30-55mm, 55-80mm and 80-105mm) depending on the cover of concrete and the chloride content of each dust sample was determined in accordance with BS 1881-124:2015.

3.3.3.3 Carbonation depth measurement

Carbonation depth in concrete is assessed using a solution of phenolphthalein indicator in ethyl alcohol that appears pink when it is in contact with uncarbonated concrete with pH values above 9 and colourless in contact with concrete which has lower pH. The test is most commonly carried out by spraying the indicator on freshly exposed surfaces of concrete broken from the structure, for example core holes or drilled holes or on split core samples. Care should be taken that dust from drilling, coring or cutting does not get on the treated surface, otherwise already carbonated zones can show up as alkaline.

3.3.3.4 Quantab strips

Quantab chloride test strips (Quantab High and Low range) supplied by Hach company as shown in Figure 3-5 provide an easy method for testing the chloride concentration in water by merely dipping a strip in water and waiting a few minutes for capillary action to saturate it. Following saturation, the strip is read and the corresponding chloride concentration is found using a chart printed on the bottle.

Figure 3-5 Quantab chloride test strips

3.4 Site visits

3.4.1 Gopalganj District:

3.4.1.1 Road bridge at Dilip Chattar village (Raghunanthapur – Teligati road route)

The concrete road bridge constructed in 1997 is around 18m in length and has three spans of 6m each. The bridge deck is supported by concrete piers on an open masonry foundation. The reinforced concrete elements consist of plain steel bars with natural coarse aggregate concrete. The visual observation on deteriorated areas indicate corrosion and associated delamination and spalling of cover concrete as shown in Figure 3-6(b). The deteriorated areas of concrete indicate poor grading of coarse aggregates (Shingles) and low quality of concrete. The results of concrete testing of bridge deck are presented in Table 3-4. The half-cell potential values measured on deck slab 3 indicate high probability of on-going corrosion of reinforcement in the deck slab. The tests for carbonation of concrete show that only the top wearing coarse layer of the deck slab has been carbonated. The visual inspection log is presented in Table 3-8 and the photo log in Appendix E.

(a) Road bridge – 20m length

(b) Concrete spalling, delamination and reinforcement corrosion in railings

Figure 3-6 Road bridge at Dilip Chattar village (Raghunanthapur – Teligati road route)

Table 3-4 Results of concrete testing of bridge deck at Dilip Chattar*

Rebound Hammer

Rebound Number:

	1	2	3	4	5	6	7	8	9	Avg
Deck slab 1	31	30	29	32	30	24	29	30	30	29
Deck slab 2	30	24	30	20	22	28	25	30	28	26
Deck slab 3	30	31	32	32	33	28	34	35	32	32

Cover meter

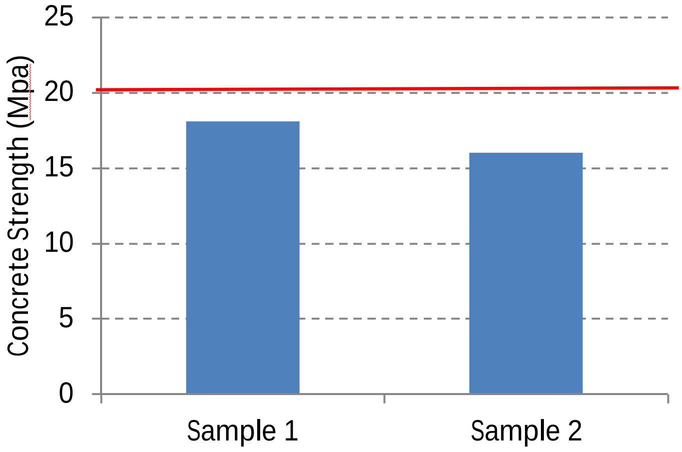
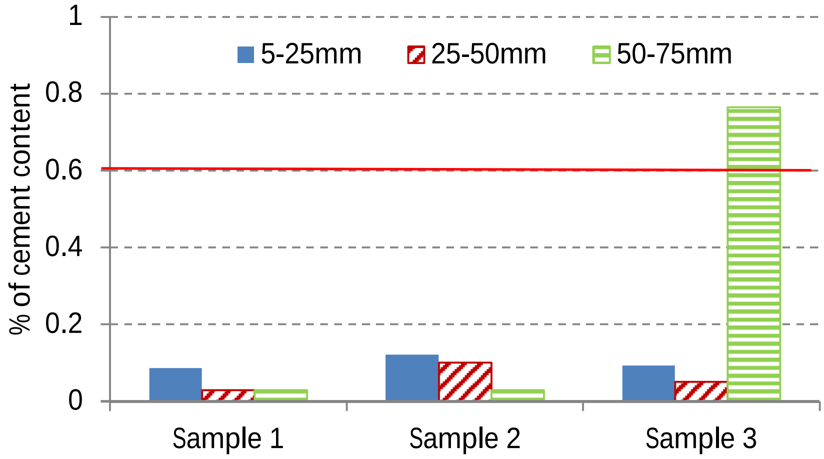
Cover varied between 65mm (min) to 75mm (max) on deck slab

Half-Cell Potentials

Deck slab 3 Potentials (mV)

South → North; East ↓ West

1	-335	-241	-244	-300
2	-318	-207	-228	-258
3	-268	-198	-220	-250
4	-250	-209	-278	-305
5	-235	-209	-350	-221
6	-255	-198	-270	-270
7	-269	-165	-310	-140
8	-231	-120	-233	-179
9	-191	-138	-119	-200

<table>
<tr><td>Carbonation</td><td>Deck slab concrete: 20-25mm carbonation on all three deck slabs</td></tr>
<tr><td>Concrete core – Strength testing</td><td>
</td></tr>
<tr><td>Concrete dust - Chloride profile testing</td><td>
</td></tr>
</table>

3.4.1.2 Silna river road bridge

This bridge constructed in 2000 is similar in design to the road bridge at Dilip Chattar, except that the concrete was made of broken brick aggregates. Two spans of the bridge collapsed approximately one year ago, possibly due to scouring and settlement of foundation. As shown in Figure 3-7 , the deck slab 1 was completely submerged in water and one end of deck slab 2 is still sitting on the pier cap, while the other end is sitting on the submerged deck slab 1. The concrete testing was conducted on undamaged deck slab 3 and the results are presented in Table 3-5. The measured half-cell potential values indicate high probability of on-going corrosion of reinforcement in deck slab 3. The visual observation of concrete in damaged locations indicate porous and low quality concrete with poorly graded brick aggregates. The visual inspection log is presented in Table 3-8 and the photo log in Appendix E.

(a) Silna river Road bridge – Collapsed

(b) Concrete spalling and reinforcement corrosion in railings

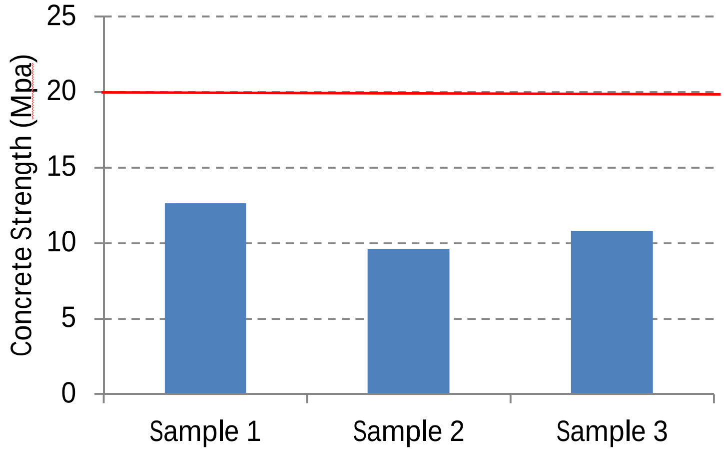
(c) Deterioration of concrete and rebar corrosion on railings

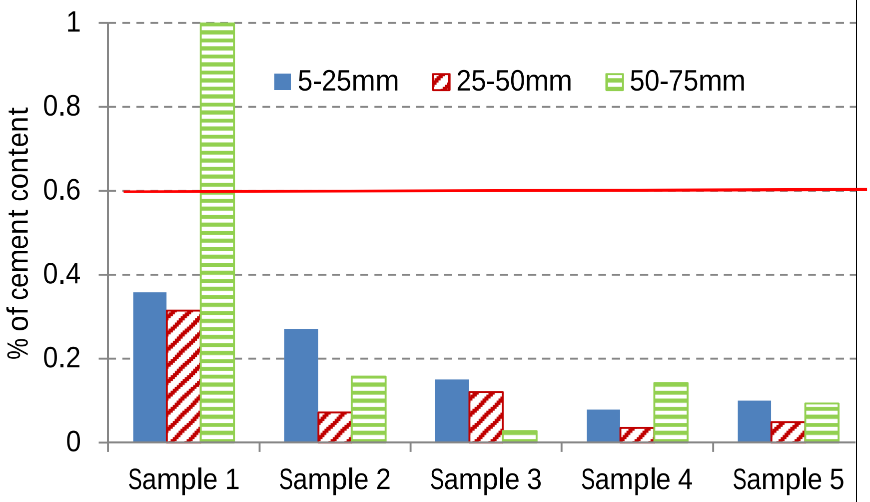
(d) Collapsed concrete deck in water

Figure 3-7 Collapsed Silna river road bridge

Table 3-5 Results of concrete testing of bridge deck at Silna river bridge*

Rebound Hammer	Rebound Number:										
		1	2	3	4	5	6	7	8	9	Avg
	Deck slab 3	30	32	36	38	38	38	30	30	36	34
	Deck slab 2	30	26	30	26	31	24	26	30	30	28
Cover meter	Cover varied between 45mm (min) to 55mm (max) on deck slab										

<table>
<tr><td>Half-Cell Potentials</td><td>
Deck slab 3 Potentials (mV)
South → North
East ↓ West
<table>
<tr><td>1</td><td>-262</td><td>-263</td><td>-292</td><td>-261</td></tr>
<tr><td>2</td><td>-220</td><td>-282</td><td>-262</td><td>-264</td></tr>
<tr><td>3</td><td>-245</td><td>-234</td><td>-234</td><td>-250</td></tr>
<tr><td>4</td><td>-251</td><td>-244</td><td>-248</td><td>-240</td></tr>
<tr><td>5</td><td>-248</td><td>-222</td><td>-231</td><td>-233</td></tr>
<tr><td>6</td><td>-190</td><td>-187</td><td>-121</td><td>-182</td></tr>
</table>
</td></tr>
<tr><td>Carbonation</td><td>Deck slab concrete:
Core hole 1 – 30mm
Core hole 2 – 60mm
Core hole 3 – 30mm
Core hole 4 – 60mm</td></tr>
<tr><td>Concrete core – Strength testing</td><td>


</td></tr>
<tr><td>Concrete dust - Chloride profile testing</td><td>


</td></tr>
</table>

3.4.1.3 Chapail Bridge on Modhumoti River

This is a newly constructed (built in 2015) concrete bridge, around 600m length over the Modhumoti river (see Figure 3-8(a)). The concrete used in the bridge is made of imported stone aggregates. As this is a newly constructed structure, testing was limited to only concrete dust samples taken on a pier to test the chloride content of concrete. The results of NDT testing of concrete are presented in Table 3-6. The concrete cover in the pier varied between 45mm to 66mm.

(a) Chapail road bridge on Modhumati river

(b) Location of concrete dust samples on pier-1

Figure 3-8 Chapail bridge and concrete dust sampling on pier 1

Table 3-6 Results of concrete testing of Pier at Chapail Bridge*

Rebound Hammer — Rebound Number:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	41	44	42	45	52	45	44	43	40	44
Location 2	42	42	42	44	43	42	40	41	39	42
Location 3	42	35	30	35	42	44	41	34	40	43

Cover meter — Cover to reinforcement (mm)

	1	2	3	4	5	6	7	8	9	10
Location 1	55	50	48	58	55	62	65	61	57	47
Location 2	49	49	45	52	63	63	66	65	59	56

Min cover: 45mm;

Max cover: 66mm

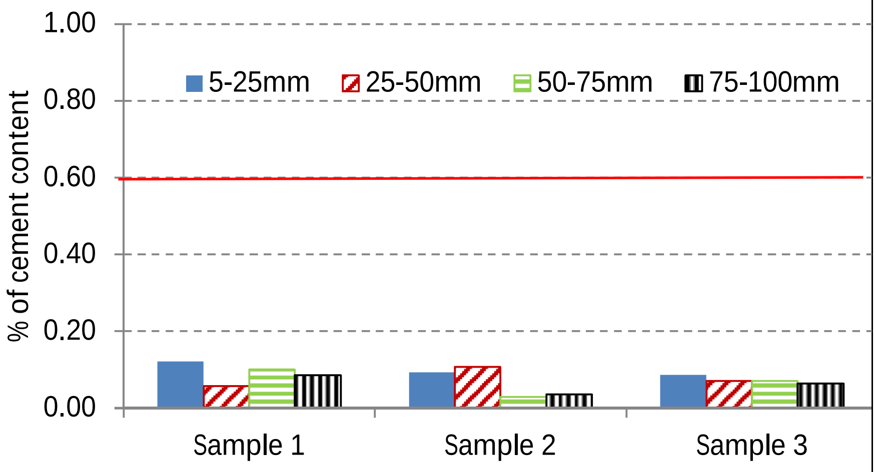
Concrete dust - Chloride profile testing	

Table 3-7 Chloride content of water in Gopalganj district

Sl No.	Location	Water Sample Type	% NaCl	ppm (mg/L) Cl^-
1	Silna Sadar, Silna River	River water	negligible	negligible
2	Silna Sadar	Tubewell water	0.068	414
3	Kotalipara, Ghagor Bazar	Pond water	negligible	negligible
4	Kotalipara, BAPARD Construction Site	Concrete mix water	negligible	negligible
5	Chapail River	River water	negligible	negligible

Table 3-8 Visual inspection photo log of concrete structures in Gopalganj district

Location	Observations	Photo Refs*
Gopalganj Sadar Upazilla Office, Gopalganj District		
Upazilla office Main gate & Fencing wall	RCC road and fencing wall with RCC columns constructed with brick aggregate concrete and plain steel bars	8168, 8169
Fencing – Fence posts	Concrete fence posts 165mm width X 275mm depth cross section The fence post concrete was severely damaged with exposed bars seen on the outer face of the fencing. Inner face of the fencing post concrete was found to be in good condition with an exception of one concrete post close to the main gate that shows severe deterioration with exposed corroded reinforcement	8170 8215-19
Reinforced concrete road	90-100mm thick concrete overlay on bituminous road constructed 3 years ago.	8220

Location	Observations	Photo Refs*
Dilip Chattar Road bridge at Raghunanthapur – Teligati road route, Gopalganj Sadar, Gopalganj District		
General	West facing view of the bridge General elevation view of the bridge (North facing)	4937 4955
Side rail and rail post (North side)	Severely deteriorated concrete at side rail and rail post with exposed reinforcement	4938
Deck slab	Abrasion related damage to the wearing course layer of deck slab concrete. No major cracks observed in deck slab concrete	4939
Side rail and rail post (South side)	Exposed reinforcement of side rail and rail post concrete caused by corrosion of reinforcement, predominantly seen in the south side rails of the bridge	4942-45
Silna Bridge (Broken bridge), Gopalganj Sadar, Gopalganj District		
General	General elevational view of the broken bridge General view from north west side General view from north east side	8293-96 8336 8341
Piers	The bridge is believed to be constructed on open foundation. Surface deterioration of pier concrete.	8297, 8298
Deck 3 (undamaged end)	West facing view of bridge showing Deck 3 Broken (missing) south end side rail Cracks observed on the north end side rail and rail post concrete Concrete deterioration caused by corrosion of reinforcement – showing exposed reinforcement	8321, 8322 8323 8324, 8327, 8328 8325
Deck 2	Various cracks observed in the side rail and rail post concrete, possibly caused at the time of bridge collapse	8326 -29
Deck 1	Collapsed and submerged deck possibly caused by settlement of pier.	8330, 8334
Damaged structure	Collapsed pier on the north side of the bridge, showing damaged concrete rails and rail posts with exposed reinforcement	8331-33
Chapail Bridge on Modhumoti River, Gopalganj District		

Location	Observations	Photo Refs*
General	General view of the bridge (Night view) Daylight view of the bridge	8344 100_9611-15
Old Upazilla Parizad Building, Kotalipara, Gopalganj District		
Corridor - Slab	Large areas of delaminated concrete in the roof slab soffit caused by corrosion of reinforcement. Photo showing large areas of exposed reinforcement in concrete elements	8222, 8224, 8226, 8229
Corridor – Beams	Large cracking (width 15-20mm) in roof slab beams with areas of exposed reinforcement	8223, 8225, 8227, 8228, 8235, 8236
Overhanging side wall / Drop wall	High level of reinforcement corrosion, delaminated concrete, and large areas of exposed reinforcement.	8227, 8228
Columns	Covermeter survey showed 75-80 mm of cover, however beak-out of column revealed it as brick column with no reinforcement. Covermeter scanning of local brick samples showed metallic signals in 2 of the 6 bricks. Possibility of metallic minerals in bricks.	8230-34

*Refer appendix E

3.4.2 Bagerhat District

3.4.2.1 Burridanga WFC road bridge, Mongla

This is a single span concrete bridge supported by masonry abutment and was believed to be constructed around 30 years ago. The concrete used in the deck slab and girders were observed to be poorly graded with higher proportions of >25mm aggregates. Large areas of concrete spalling caused by corrosion of reinforcement were observed as shown in Figure 3-9. Due to unsafe site conditions, it was not possible to access the girders and deck slab soffit, therefore only basic level of testing was done on the top surface of deck slab and the results are presented in Table 3-9. The visual inspection log is presented in Table 3-11 and the photo log in Appendix E.

(a) Burridanga WFC road bridge

(b) Deteriorated concrete girder and rebar corrosion at abutment

(c) Concrete spalling, exposed reinforcement at deck slab soffit

(d) Collection of concrete dust sample on side face of girder

Figure 3-9 Condition of concrete and dust sampling at Burridanga WFC road bridge

Table 3-9 Results of concrete testing at Burridanga road bridge deck slab*

<table>
<tr><td rowspan="5">Rebound Hammer</td><td colspan="11">Deck slab concrete
Rebound Number:</td></tr>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>Avg</td></tr>
<tr><td>Location 1</td><td>30</td><td>28</td><td>32</td><td>30</td><td>28</td><td>32</td><td>32</td><td>32</td><td>32</td><td>31</td></tr>
<tr><td>Location 2</td><td>28</td><td>24</td><td>26</td><td>27</td><td>28</td><td>30</td><td>27</td><td>28</td><td>26</td><td>27</td></tr>
<tr><td>Location 3</td><td>26</td><td>28</td><td>28</td><td>26</td><td>28</td><td>25</td><td>26</td><td>24</td><td>24</td><td>26</td></tr>
<tr><td>Cover meter</td><td colspan="11">Min cover: 75mm;
Max cover: 86mm</td></tr>
<tr><td>Carbonation</td><td colspan="11">Test showed only wearing course (40-45mm) depth carbonated</td></tr>
</table>

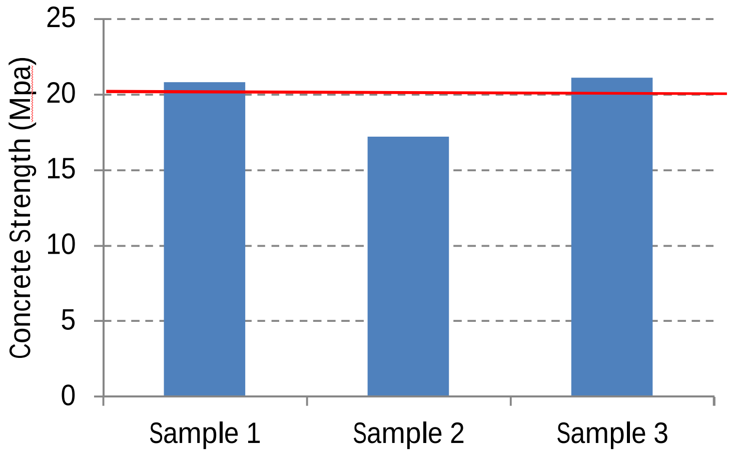
Concrete core – Strength testing	

Table 3-10 Chloride content of water in Bagerhat district

Sl No.	Location	Water Sample Type	% NaCl	ppm (mg/L) Cl-
1	Mongla, PWD Site	Concrete mix water	0.047	288
2	Mongla, Digraj Canal	Canal water	0.145	880
3	Mongla	Pond water	0.015	90
4	Rampal, Upazilla Complex, LGED	Pond water	0.035	213
5	Rampal, 48m Bridge in Gunabelai road, Bridge site	River water	0.074	446

Table 3-11: Visual inspection photo log of concrete structures in Bagerhat

Location	Observations	Photo Refs*
Dikraj College Road 2, Burridanga WFC road bridge, Mongla, Bagerhat District		
General	General view of the bridge Southern view of bridge	8350 8398-8400
Girder	Excessive spalling of concrete in Griders, showing exposed reinforcement Exposed aggregates in girder concrete showing larger size and poorly graded aggregates	8351 8392
Abutment	Spalling of concrete near to the abutment Brick abutment of bridge	8352 8391
Side rail	Broken south side rail of bridge with exposed reinforcement, showing corroded reinforcement North side rail post completely damaged and disappeared Closer view of exposed reinforcement in rail post	8354 8355 8358-60

Location	Observations	Photo Refs*
Deck slab	Bridge deck slab facing towards south-west	8356
Deck soffit	Concrete spalling at deck slab soffit, photo showing exposed reinforcement with greater than 25mm size aggregates in concrete	8395, 8396
Dikraj Government Primary School, Mongla, Bagerhat District		
General	General view of front of building	8362
Corridor	Columns	8365
Garden fence	Broken masonry column of garden fence	8366
Dikraj Government High School, Mongla, Bagerhat District		
General	General view of front of building	8390
Corridor	General view Longitudinal cracks in roof slab beams and columns	8388, 8382 8384, 8385, 8387
Mongla Upazilla office Guest house, Mongla, Bagerhat District		
Dining room	Corrosion related cracking and delamination of roof slab concrete beam in dining room	8410-8412
Fencing wall columns	Varied level of salt damage to fencing wall columns	8413-8423
Front corridor	Corrosion related cracking and delamination in inner face and bottom face of drop wall	8425-8427
Upazilla office complex building, Rampal, Bagerhat District		
General	General photos of upazilla complex building ground floor	8477-86
Upazilla Education office, Rampal, Bagerhat District		
General	General view of the building	8508
Columns	Salt damage to external columns of the building	8510-22
Roof slab	Cracks in roof slab concrete – Cantilever Severe salt damage to concrete column outcrop showing exposed brick aggregates	8524 8556-58

*Refer appendix E

3.4.3 Cox's Bazar District

3.4.3.1 RCC road in front of Nuniya Chara Primary School

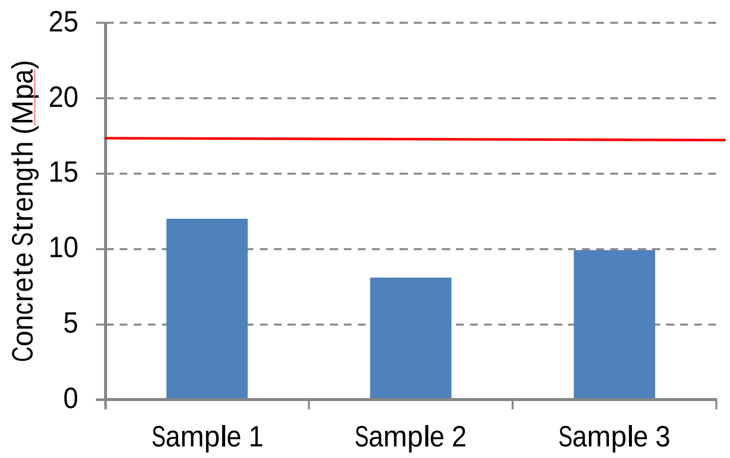
The RCC road was constructed in 2015 and stone chips was used as coarse aggregate in concrete. The results of rebound hammer and carbonation testing of concrete is presented in Table 3-12. The wearing coarse layer for road concrete was observed to be 20-25mm thick. The cover to the reinforcement was observed to be very high and out of range (>80mm) for the cover meter survey. Moreover, due to the high cover, half-cell potential values were observed to be low and further testing was abandoned.

Table 3-12 Results of concrete testing of RCC road

Rebound Hammer	Reinforced Concrete Road:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	24	19	24	24	25	26	23	26	21	24
Location 2	23	18	19	29	19	20	23	20	22	21
Location 3	30	22	28	19	22	28	30	32	30	27
Location 4	24	20	30	20	20	30	29	23	20	24
Location 5	28	30	22	28	29	21	28	29	30	27
Location 6	28	20	24	30	27	27	27	26	24	26
Location 7	25	24	22	26	40	28	29	30	30	28
Location 8	30	26	25	34	25	30	24	29	26	28
Location 9	22	24	34	23	30	30	29	22	24	26

Carbonation	Carbonation observed mostly in wearing course concrete layer. Core hole 1: 20mm Core hole-2: 18mm Core hole 3: 20mm



3.4.3.2 Horinmara Bridge, Modho Raja Palong

The bridge was constructed in 1972 and broken brick aggregates was used in the concrete. The visual inspection of the bridge suggests that the mid span of the bridge girders was deflected and associated cracks are observed in the girders. The abutment at one end of the bridge failed possibly due to over loading conditions as shown in Figure 3-10Figure 3-10 (a). Although it is not in our remit to make recommendations, the structural failures found in the bridge needs urgent attention by means of detailed structural inspection to determine the structural stability of the bridge. The rebound hammer testing of bridge deck concrete is presented in Table 3-13. The visual inspection log is presented in Table 3-17 and the photo log in Appendix E.

(a) Horinmara bridge – showing displacement cracking in abutments and corrosion of rebar in girders

(b) Concrete spalling and corrosion of exposed rebars in girder

(c) Top surface of bridge deck showing abrasion of wearing course

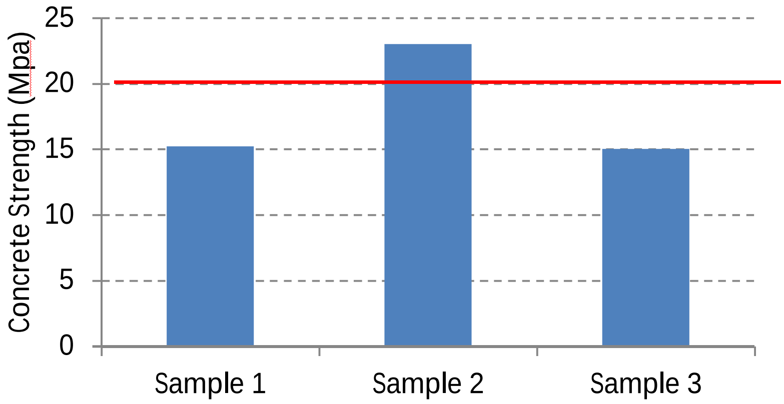
Figure 3-10 Condition of concrete at Horinmara Bridge, Modho Raja Palong

Table 3-13 Results of concrete testing of road deck at Horinmara bridge

Rebound Hammer

Ground floor external concrete columns:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	20	22	18	19	32	31	34	21	21	24
Location 2	18	14	13	16	14	18	24	20	14	17
Location 3	19	20	32	29	18	16	22	24	28	23
Location 4	26	23	29	19	20	22	29	29	30	25
Location 5	30	37	36	29	33	30	31	22	32	31
Location 6	32	30	28	30	30	40	31	30	25	34

Concrete core – Strength testing	

3.4.3.3 Concrete bridge opposite to Islampur Public Model School

The concrete bridge near Islampur public school was believed to be constructed around 25 years ago. The visual inspection of the deck slab of the bridge suggest that most of the wearing course concrete layer of the bridge has disappeared over time and the railings damaged due to corrosion of reinforcement as shown in Figure 3-11. The soffit of the bridge was not inspected as there was no safe access available. The results of concrete testing of deck slab is presented in Table 3-14. The visual inspection log is presented in Table 3-17 and the photo log in Appendix E.

(a) Overview of the bridge

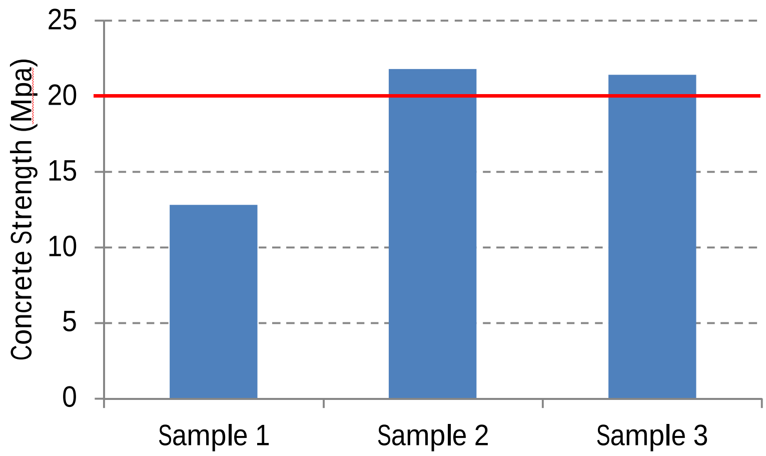
(b) Broken railings and exposed reinforcement

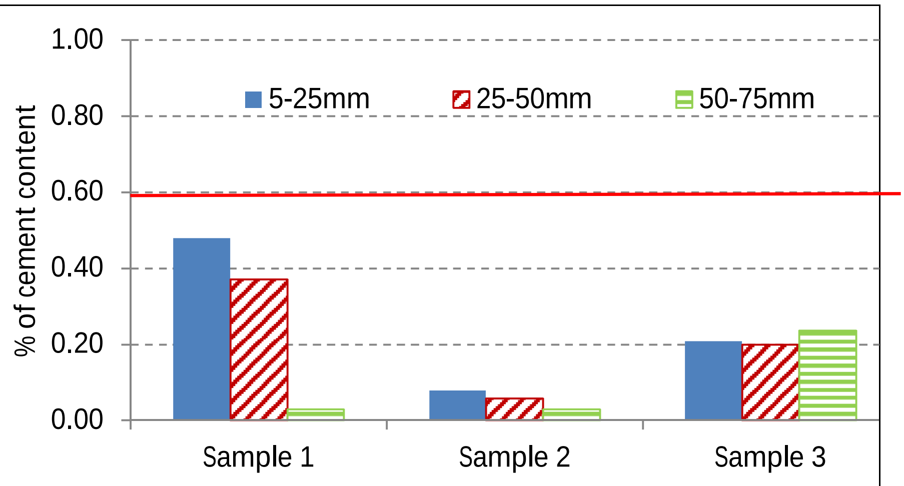
(c) Spalling of concrete, reinforcement corrosion in railings

(d) Carbonation test on railing concrete showing no carbonation

Figure 3-11 Condition of concrete bridge near Islampur Public Model School

Table 3-14 Results of concrete testing of bridge deck at Islampur*

<table>
<tr><td>Rebound Hammer</td><td>Ground floor external concrete columns:
<table>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>Avg</td></tr>
<tr><td>Column 1</td><td>28</td><td>35</td><td>38</td><td>25</td><td>22</td><td>25</td><td>24</td><td>28</td><td>32</td><td>29</td></tr>
<tr><td>Column 2</td><td>24</td><td>26</td><td>29</td><td>23</td><td>26</td><td>28</td><td>28</td><td>32</td><td>31</td><td>27</td></tr>
<tr><td>Column 3</td><td>42</td><td>34</td><td>39</td><td>26</td><td>32</td><td>34</td><td>28</td><td>34</td><td>25</td><td>33</td></tr>
<tr><td>Column 4</td><td>26</td><td>33</td><td>30</td><td>27</td><td>39</td><td>33</td><td>35</td><td>37</td><td>42</td><td>34</td></tr>
</table>
Average Strength:</td></tr>
<tr><td>Half-cell potentials</td><td>Potentials (mV)
<table>
<tr><td>Location 1</td><td>-140</td><td>-130</td><td>-125</td><td>-110</td></tr>
<tr><td>Location 2</td><td>-140</td><td>-123</td><td>-115</td><td>-100</td></tr>
<tr><td>Location 3</td><td>-142</td><td>-153</td><td>-160</td><td>-146</td></tr>
</table></td></tr>
<tr><td>Cover meter</td><td>Deck slab
Min cover: 65mm;
Max cover: 85mm
Rail post
Min cover: 65mm;
Max cover: 85mm</td></tr>
<tr><td>Carbonation</td><td>Deck slab
Core hole 1: 25mm
Core hole 2: 35mm
Core hole 3: 40mm</td></tr>
<tr><td>Concrete core – Strength testing</td><td>
</td></tr>
</table>

Concrete dust - Chloride profile testing	

3.4.3.4 Concrete culvert, Boakhali road, Islamabad Union

The concrete culvert (see Figure 3-12) was constructed in 2010. The visual inspection of concrete deck slab suggest stone chips aggregate was used in the concrete, however its grading was poor with an excess of particle >25mm. The results of rebound hammer testing on the deck slab concrete is presented in Table 3-15. The visual inspection log is presented in Table 3-17 and the photo log in Appendix E.

Figure 3-12 Concrete culvert at Boakhali road, Islamabad Union

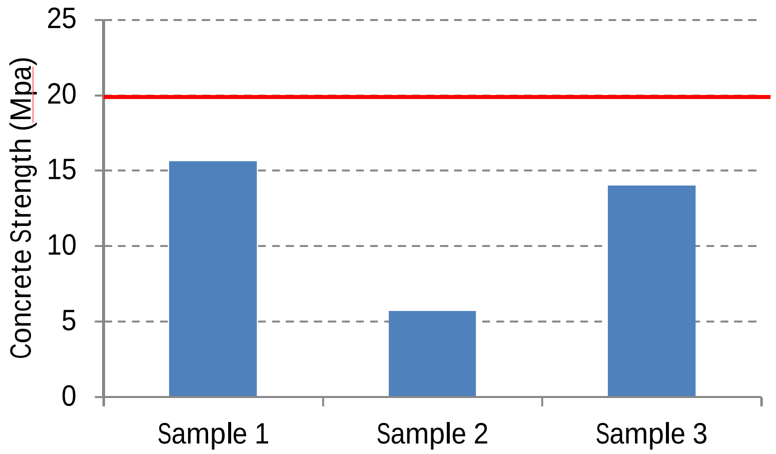
Table 3-15: Results of concrete testing of bridge deck at Boakhali road, Islamabad Union*

Rebound Hammer

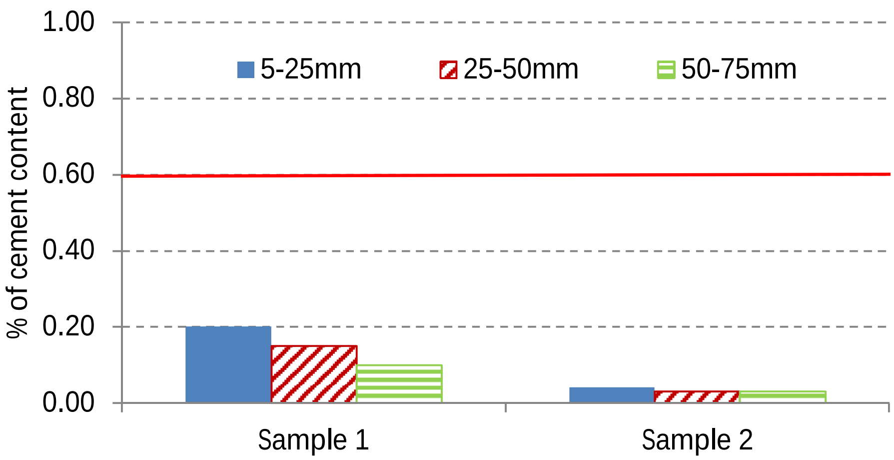
Bridge deck slab:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	28	23	18	22	30	32	43	32	27	29
Location 2	22	24	24	25	22	22	20	22	22	23
Location 3	25	23	28	27	29	20	26	30	23	26
Location 4	21	34	23	26	29	28	34	26	27	28
Location 5	29	32	26	32	35	36	35	39	30	33
Location 6	28	32	25	32	30	29	29	27	26	29
Location 7	21	23	20	31	22	34	22	19	20	24
Location 8	21	20	30	29	22	23	23	29	20	24
Location 9	27	20	21	22	21	20	23	25	27	23

Concrete core – Strength testing



Concrete dust - Chloride profile testing



*Concrete core testing and chloride testing results are pending

Table 3-16 Chloride content of water in Cox's Bazar district

Sl No.	Location	Water Sample Type	% NaCl	ppm (mg/L) Cl^-
1	North Naniachara Gov. Primary School, Cox's Bazar Sadar	Tubewell water	0.123	744
2		Pond water	0.236	1432
3	Moddho Raja Palang, Ukhiya	Canal water	negligible	negligible
4		Tubewell water	negligible	negligible
5	Bridge opposite of Islampur Public Model School, Islamabad, Cox's Bazar Sadar	Canal water	0.03	183
6		Tubewell water	negligible	negligible
7	Culvert, Boalkhali road, Cox's Bazar Sadar	Tubewell water	negligible	negligible
8		Irrigation Canal water	negligible	negligible
9	Adinath Mondir Jetty, Moheshkhali	River canal water	0.619	3755
10	GorokGhata - Shaplapur Janata Bazar road, Rashid Mia's Bridge, Boruna Canal, Moheshkhali	Boruna canal water	0.009	56
11	Model Gov. Primary School, Moheshkhali	Tubewell water	negligible	negligible
12	Upazilla Porishad, Moheshkhali	Large Pond water	negligible	negligible
13		Tubewell water	0.026	155
14	Gorok Ghata Gov. Primary School, Moheshkhali	Tubewell water	0.112	682

Table 3-17: Visual inspection photo log of concrete structures in Cox's Bazar

Location	Observations	Photo Refs*
Uttan Nania Chana Government Primary School, Cox's Bazar District		
General	Front and side view of the school Front view Side view	80087-89 80097-99 80100-101
Column – Ground floor	Crack in column concrete on the external face Concrete spalling and corrosion of reinforcement on the inner face of the column	80090 80112
Beam – Ground floor	Severe cracking of concrete in beam on external face, spalling of concrete caused by corrosion of reinforcement	80091, 80092

Location	Observations	Photo Refs*
Drop wall-1st Floor	Spalling of concrete, exposed reinforcement, and corrosion of reinforcement on the inner face (in classrooms)	80120-124
Column – 1st floor	Cracking in concrete column	80125
Classroom	General condition of classroom, spalling of concrete in roof slab beam, cracks in the columns and masonry walls, mould formation on the walls	80126-128
Staircase	Concrete spalling, delamination, and corrosion of reinforcement	80129-131
Classroom-2nd floor	Spalling of concrete in columns and window lintel beam, severe cracking of concrete in columns and delamination of concrete in roof slab beams	80132-80139
Md. Shofinbil Government Primary School, Cox's Bazar District		
General	Information board of Cyclone Shelter	90164
Column – 1st floor	Severely deteriorated concrete column- spalling of concrete caused by corrosion of reinforcement	90165
Class room – 1st floor	General view of class room	90167
Beam - 1st floor	Spalling and delamination of concrete in roof slab beam	90168-170
Column – 2nd floor	Longitudinal cracks and spalling of concrete in columns Spalling of concrete and corrosion of reinforcement in lintel beams Crack in Lintel beam	90171-172 90173-176 90184
Horinmara Bridge, Modho Raja Palong, Ukhiya, Cox's Bazar		
Bridge abutments, Girder and Piers	Longitudinal cracking, spalling of concrete and corrosion of reinforcement in girders Cracking and displacement of bridge abutment wall Cracking of concrete at Girder-pier joint	Horinmara bridge at Ukhiya (1)-(11)
Road view	Approach road view of the bridge	90212
Deck slab - Top view	Pot holes on the road deck	90213-214
Concrete bridge opposite to Islampur Public Model School, Napitkhali, Cox's Bazar Sadar		
General	General view of the bridge from road side General elevation and long view of the bridge	100247-248 100263

Location	Observations	Photo Refs*
Top surface	Wearing coarse layer of the bridge deck top has been totally disappeared over time	100249
Railing	Corrosion of reinforcement and associated spalling of concrete in rail post Longitudinal cracks in the concrete railing	100250-260 100261
Concrete culvert, Boalkhali road, Islamabad union, Cox's Bazar Sadar, Cox's Bazar District		
General	General view of the culvert. No major cracks or spalling of concrete observed on the top deck of the culvert.	100283-287

*Refer appendix E

3.4.4 Noakhali district

3.4.4.1 Box Culvert, Tamjapur, Punbochanbata, Subarnochar, Noakhali

(a) General view of the box-culvert

(b) Concrete spalling and rebar corrosion in railings

(c) Exposed rebar in outer face of south-west railing wall of the culvert

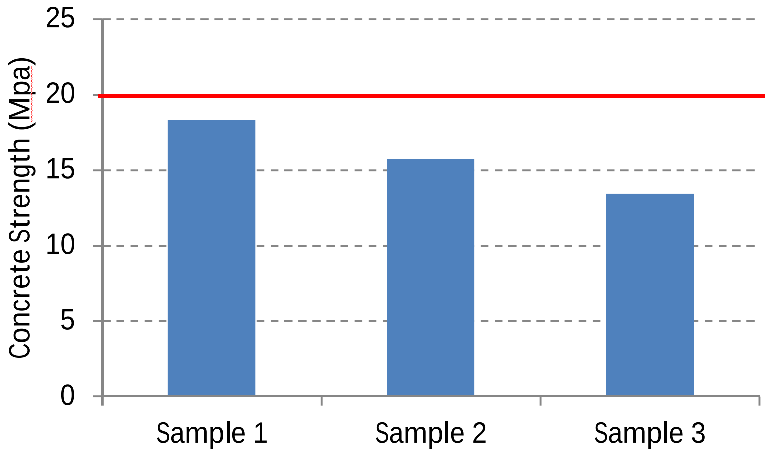
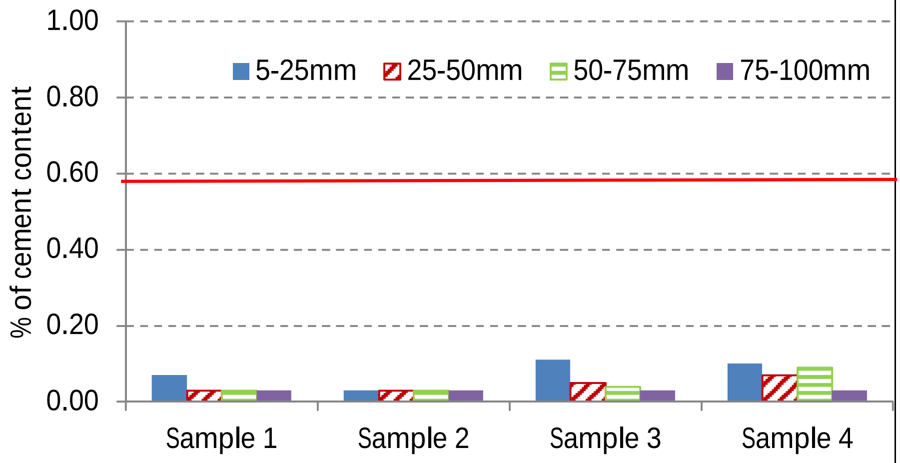
(d) Voiding at interface between wearing coarse and deck slab concrete

Figure 3-13 Condition survey of box culvert in Tamjapur, Subarnochar Upazilla

The box culvert as shown in Figure 3-13(a) is a 2 vent road structure with a length of 7.1m and width of 4m containing brick masonry abutment walls, deck slab with 40 grade plain reinforcement bars and concrete made of brick chips as coarse aggregates. The box culvert was believed to be constructed in 1996. The visual inspection survey identified severe delamination and spalling of concrete in railing walls and voiding of deck slab concrete as shown in Figure 3-13 (c) & (d). The results of the concrete testing are presented in Table 3-18. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

Table 3-18 Results of concrete testing of box culvert at Tamjapur*

<table>
<tr><td>Rebound Hammer</td><td>Wheel Guard/Railing wall:
<table>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>Avg</td></tr>
<tr><td>Location 1</td><td>20</td><td>22</td><td>17</td><td>24</td><td>29</td><td>28</td><td>27</td><td>25</td><td>19</td><td>23</td></tr>
<tr><td>Location 2</td><td>24</td><td>18</td><td>30</td><td>29</td><td>30</td><td>25</td><td>22</td><td>25</td><td>25</td><td>25</td></tr>
<tr><td>Location 3</td><td>28</td><td>22</td><td>20</td><td>17</td><td>23</td><td>22</td><td>25</td><td>17</td><td>26</td><td>22</td></tr>
<tr><td>Location 4</td><td>22</td><td>18</td><td>25</td><td>26</td><td>25</td><td>28</td><td>27</td><td>22</td><td>20</td><td>24</td></tr>
<tr><td>Location 5</td><td>25</td><td>17</td><td>28</td><td>30</td><td>30</td><td>24</td><td>23</td><td>26</td><td>28</td><td>26</td></tr>
<tr><td>Location 6</td><td>27</td><td>20</td><td>22</td><td>20</td><td>18</td><td>24</td><td>26</td><td>23</td><td>27</td><td>23</td></tr>
</table>
</td></tr>
<tr><td>Half-cell potentials</td><td>Potentials (mV) (on the road deck)
<table>
<tr><td>Location 1</td><td>-284</td><td>-282</td><td>-281</td><td>-292</td><td>-256</td></tr>
<tr><td>Location 2</td><td>-310</td><td>-305</td><td>-335</td><td>-318</td><td>-244</td></tr>
<tr><td>Location 3</td><td>-238</td><td>-246</td><td>-273</td><td>-241</td><td>-207</td></tr>
<tr><td>Location 4</td><td>-297</td><td>-342</td><td>-290</td><td>-240</td><td>-268</td></tr>
</table>
</td></tr>
<tr><td>Cover meter</td><td>Railing wall/Wheel Guard:
Min cover: 52mm;
Max cover: 68mm
Top covering of railing wall:
Min cover: 35mm;
Max cover: 65mm
Deck slab (top):
Min cover: 75mm;
Max cover: 85mm
(Road carpeting above deck slab concrete is more than 50-65mm thick)</td></tr>
</table>

Concrete core – Strength testing	
Concrete dust - Chloride profile testing	

*Concrete core testing and chloride testing results are presented in Appendix C &D

3.4.4.2 Box Culvert, Char Amanullah ward no 27, Punbochanbata, Subarnochar, Noakhali

The box culvert (see Figure 3-14(a)) was constructed in 2008 with concrete containing natural stone aggregates and reinforced with 40 grade deformed steel bars. The visual inspection of the structure identified corrosion activity and exposed reinforcement in railing walls. The results of concrete testing of deck slab are presented Figure 3-14. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

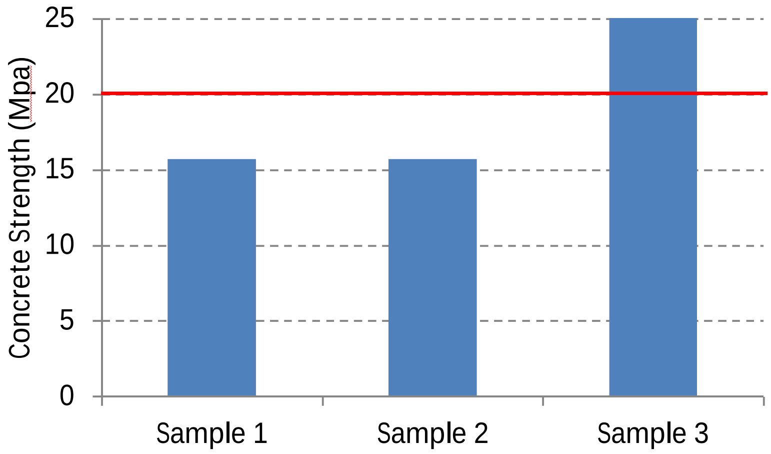
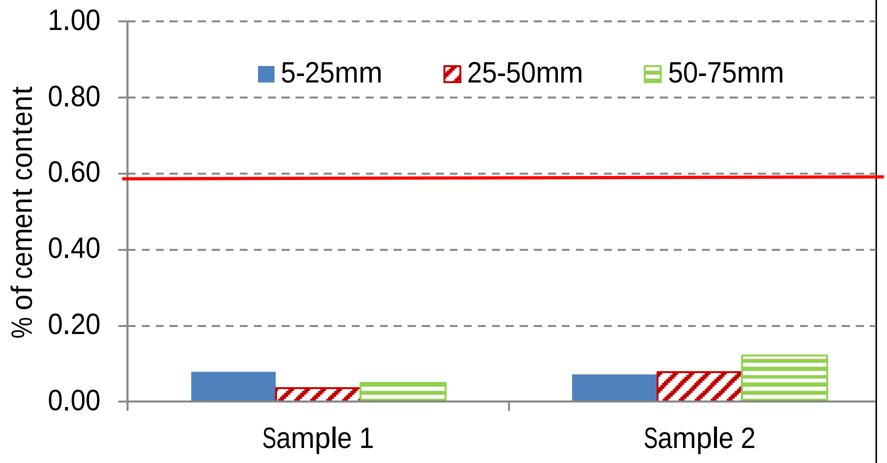
(a) General view of the box-culvert

(b) Core extraction from deck slab -north end

Figure 3-14 Box culvert at Char Amanullah, Punbochanbata, Subarnochar

Table 3-19 Results of concrete testing of box culvert deck slab at Char Amanullah, Punbochanbata, Subarnochar*

<table>
<tr><td>Rebound Hammer</td><td>Deck slab concrete:
<table>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>Avg</td></tr>
<tr><td>Location 1</td><td>28</td><td>29</td><td>30</td><td>29</td><td>26</td><td>28</td><td>30</td><td>28</td><td>29</td><td>29</td></tr>
<tr><td>Location 2</td><td>22</td><td>28</td><td>23</td><td>29</td><td>30</td><td>28</td><td>30</td><td>26</td><td>27</td><td>27</td></tr>
<tr><td>Location 3</td><td>30</td><td>24</td><td>22</td><td>23</td><td>23</td><td>27</td><td>20</td><td>26</td><td>25</td><td>24</td></tr>
</table></td></tr>
<tr><td>Half-cell potentials</td><td>Potentials (mV)
<table>
<tr><td>Location 1</td><td>-155</td><td>-170</td><td>-176</td></tr>
<tr><td>Location 2</td><td>-136</td><td>-124</td><td>-119</td></tr>
<tr><td>Location 3</td><td>-50</td><td>-110</td><td>-117</td></tr>
</table></td></tr>
<tr><td>Cover meter</td><td>Deck slab
Min cover: 43mm;
Max cover: 68mm
Top of wheel guard
Min cover: 30mm;
Max cover: 78mm</td></tr>
<tr><td>Carbonation</td><td>Deck slab
Core hole 1: 25mm
Core hole 2: 20mm
Core hole 3: 15mm</td></tr>
</table>

Concrete core – Strength testing	
Concrete dust - Chloride profile testing	

3.4.4.3 Burma Bridge, Chaprrashi canal, Kobirhat, Noakhali

The Burma bridge (see Figure 3-15(a)) was constructed on Chaprashi canal in the year 2000. The west abutment wall and the adjacent span of the bridge was collapsed possibly due to scouring and associated settlement of foundations. The bridge is currently connected by means of bamboo scaffolding and is restricted for pedestrian use only. The visual inspection of the bridge suggests that the rail posts of the bridge completely disappeared possibly due to corrosion activity and associated deterioration and spalling of concrete. The general observations on the concrete suggest poorly graded concrete, issues related to poor workmanship and an under designed deck slab (thickness of slab found to be only 70mm). The results of the concrete testing of the deck slab are presented in
Table 3-20. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

(a) General view of the Burma Bridge over Chaprashi canal

(b) Longitudinal cracking on wheel guard and disappeared rail posts

(c) Collapsed section of the bridge connected by bamboo scaffolding

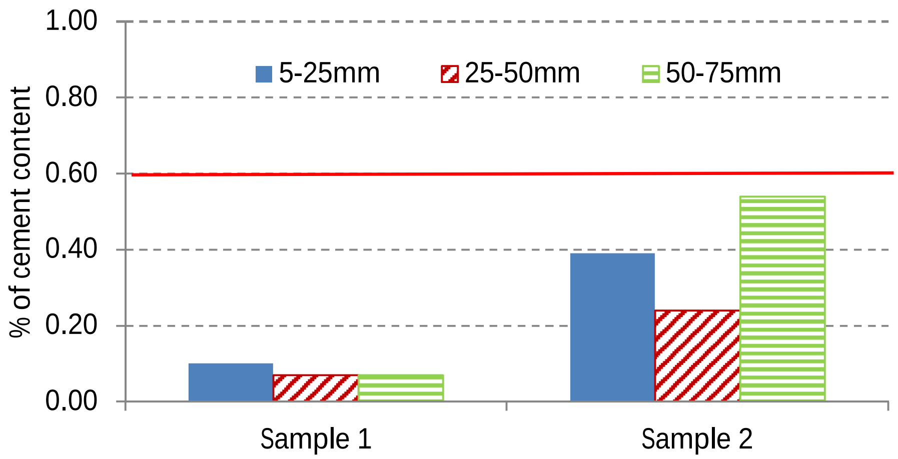
(d) Core hole showing large voiding in the deck slab concrete

Figure 3-15 Burma bridge at Chaprrashi canal, Kobirhat

Table 3-20 Results of concrete testing of Burma bridge deck slab at Chaprrashi canal, Kobirhat

Rebound Hammer — Deck slab:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	30	32	32	27	40	40	33	38	25	33
Location 2	21	19	22	18	20	21	22	22	22	21
Location 3	31	25	25	22	24	30	25	30	40	28
Location 4	40	32	40	48	30	46	35	40	37	39
Location 5	20	21	20	20	21	22	19	23	22	21
Location 6	38	33	33	29	32	30	31	30	39	33
Location 7	25	19	22	20	23	25	20	27	23	23
Location 8	23	28	22	21	30	28	25	19	30	25
Location 9	30	24	28	35	31	22	41	25	21	29

<table>
<tr><td></td><td>Average Strength:</td></tr>
<tr><td>Half-cell potentials</td><td>Potentials (mV)<table>
<tr><td>Location 1</td><td>-78</td><td>-42</td><td>-49</td></tr>
<tr><td>Location 2</td><td>-98</td><td>-100</td><td>-109</td></tr>
<tr><td>Location 3</td><td>-82</td><td>-40</td><td>-52</td></tr>
<tr><td>Location 4</td><td>-102</td><td>-62</td><td>-59</td></tr>
</table></td></tr>
<tr><td>Cover meter</td><td>The cover in the deck slab was out of range for the covermeter (>85mm)</td></tr>
<tr><td>Concrete core – Strength testing</td><td>Due to voiding in the deck slab, the length of core samples collected was not adequate to do a compressive strength test.</td></tr>
<tr><td>Concrete dust - Chloride profile testing</td><td>
</td></tr>
</table>

3.4.4.4 Box culvert Kolim Uddin pul, GEC road, Kobinhat, Noakhali

The box culvert (Figure 3-16(a)) was constructed in the year 2010 and the concrete used in the culvert contains natural stone aggregates. The visual inspection of the culvert suggests severely damaged rail posts as shown in Figure 3-16(b), which was caused due to truck collision. The results of the concrete testing of the deck slab are presented in Table 3-21. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

(a) General view of the box-culvert

(b) Severe damage to rail post

Figure 3-16 Condition survey of box culvert at Kolim Uddin pal, GEC road, Kobinhat

Table 3-21 Results of concrete testing of Box culvert slab at Kolim Uddin pal, GEC road, Kobinhat

Rebound Hammer

Deck slab:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	22	31	23	21	31	21	22	20	28	24
Location 2	18	20	20	22	19	21	22	30	21	21
Location 3	20	20	20	19	19	21	22	33	20	22
Location 4	26	30	20	29	25	30	32	23	31	27
Location 5	20	30	22	30	20	22	24	24	25	24
Location 6	32	20	22	27	18	28	20	29	22	24
Location 7	40	42	32	35	42	38	42	36	36	38
Location 8	30	29	30	20	32	22	24	30	29	27
Location 9	24	24	30	22	22	29	28	32	34	27

Half-cell potentials

Potentials (mV)

Location 1	-86	-56	-100
Location 2	-150	-99	-88

Cover meter

The cover in the deck slab was out of range for the covermeter (>85mm)

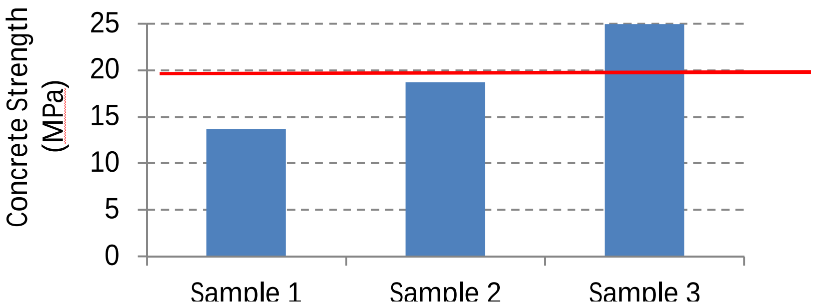


Table 3-22 Chloride content of water in Noakhali district

Sl No.	Location	Water Sample Type	% NaCl	ppm (mg/L) Cl^-
1	Charbata Jaipur School, Subarnochar	Deep Tubewell water - 915 ft	-	-
2		Shallow Tubewell water - 26 ft	0.015	90
3		Pond water	-	-
4	Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Shorhat, GC road, Purbocharbata, Subarnochar	Canal water	0.218	1321
5	Box Culvert, Char Amanullah, word no 27, Subarnochar	Canal water	0.007	42
6	Burma Bridge Chaprashi Canal, Char Gulakhali, Kabirhat	Canal water	0.033	198
7		Tubewell water	-	-
8	Char Mondolia Gov. Primary School, Kabirhat	Canal water	0.007	42
9	Two vent Box Culvert, Kolimuddinpul, Kabirhat	Canal water	-	-
10	LGED District office and guest house, Maizdi	Supply water	0.051	310
11		Deep Tubewell water	0.047	288
12		Shallow Tubewell water	0.055	333
13		Direct Supply water	0.011	64

Table 3-23 Visual inspection photo log of concrete structures in Noakhali

Location	Observations	Photo Refs*
Charbata Tajpur School, Subarnochar, Noakhali		
Classroom	Cracking of roof slab beam, delamination and spalling of concrete, exposed reinforcement	19-25
Column	Cracking and spalling of concrete in columns in front corridor of the building	26-33
General	Front elevation of the new school building	34
Box Culvert, Tamjapur, Punbochanbata, Subarnochar, Noakhali		
General	General view of the culvert from the road(Southeast to Northwest)	35-37
Railing	Northeast railing or wheel guard	38

Location	Observations	Photo Refs*
	- Complete spalling of cover concrete and exposed reinforcement on the outer side of the wheel guard or railing wall Southwest railing or wheel guard - Spalling of concrete and exposed reinforcement - Crack on wheel guard - Outer side of the wheel guard – Complete spalling of cover concrete and exposed reinforcement	45-49 39 40 41 42-44
Deck slab	Top layer of the deck slab showing wearing course layer and road carpeting layer	57-59
Box Culvert, Char Amanullah ward no 27, Punbochanbata, Subarnochar, Noakhali		
General	General view of canal under the box culvert General view from east side of the culvert	60-61 62
Railing wall / wheel guard	North side wheel guard / railing wall - Degraded concrete at the surface and exposed reinforcement - Exposed concrete stone aggregates and porous concrete South side railing wall/wheel guard	70-77 78 79-81
Burma Bridge, Chaprrashi canal, Kobirhat, Noakhali		
General	View of Chaprashi Canal from the bridge General view of the bridge	97-98 99-101, 106
Abutment	Cracking and displacement of abutment wall from the bridge span	102-105
Deck slab	General view of the deck slab Expansion joint of the bridge deck Abrasion of deck slab concrete	107 112, 114 113
Railing	Rail post failure and cracking on railing wall Spalling of concrete and exposed reinforcement of railing wall	108-111, 115 116
Collapsed span	Collapsed bridge span now connected by bamboo scaffolding	117-118
Char Mandolia Govt Primary School, Kobinhat, Noakhali		
General	Name board of the school Front view and side view of the school	121 122-125
Columns	Spalling of concrete and exposed reinforcement	126

Location	Observations	Photo Refs*
	Cracking in column Close-up view of exposed reinforcement and corrosion	127-130 131
Classroom	Spalling of concrete from columns inside the classroom Close-up view of columns showing exposed reinforcement and corrosion activity Longitudinal cracking on the roof slab beam General view of other classrooms Roof slab cracking	132-139 140-141 142 143, 144, 147, 151, 153 152, 155
Corridor	Roof slab	156
Box culvert Kolim Uddin pal, GEC road, Kobinhat, Noakhali		
General	General view of box culvert from the road	163
Railing	Exposed reinforcement in rail posts Cracking of concrete on railings	164-165, 167 166

*Refer appendix E

3.5 Discussion on condition survey test results

3.5.1 Comparison between Brick aggregate and stone aggregate concrete

The visual comparison of brick aggregate concrete and stone aggregate concrete used in the construction of road infrastructure elements clearly indicate that brick aggregate concrete structures displayed greater level of deterioration caused by chloride induced corrosion, abrasion related damage and salt attack related damage. The comparison of in-situ compressive strength tested for brick aggregate and stone aggregate concrete are presented in Table 3-24. It can be clearly inferred from the whole population of strength data obtained by core testing that the in-situ strength of brick aggregate concrete was lower than the stone aggregate concrete. The comparison of strength data for stone aggregate and brick aggregate also suggests that the maximum strength attained by brick aggregate concrete mixes are lower than the stone aggregate concrete, mainly caused due to the inferior quality and low strength value of brick aggregates.

3.5.2 Core testing – Compressive strength

Table 3-24 Comparison of in-situ strength of stone aggregate and brick aggregate concrete

Compressive strength (MPa)	Stone aggregate Concrete	Brick aggregate concrete
Average	18.13	15.85
Max	31.10	25.90
Min	5.70	9.60

The comparison of chloride testing data for brick aggregate and stone aggregate concrete are presented in Table 3-25. The chloride profile testing results suggest that the average data for chloride content at different depth was observed to be higher in the case of brick aggregate concrete as compared with stone aggregate concrete. It can be observed from Table 3-25 that the chloride content for brick aggregate concrete at the cover zone (50mm depth) was observed to be above the threshold chloride limit of 0.6%, which suggests that the reinforcement in these brick aggregate concrete elements are either de-passivated or undergoing active corrosion. Due to high porosity of brick aggregates, the concrete produced with brick aggregates provide less resistance to the penetration of external salts / chloride ions in concrete, which leads to corrosion related damage of concrete.

Table 3-25 Comparison of chloride profile in stone aggregate and brick aggregate concrete

Aggregate type	Chloride content (% of cement content)	5-25mm depth	25-50mm depth	50-75mm depth	75-100mm depth
Brick aggregate concrete	Average	0.66	0.57	0.51	0.80
	Max	2.90	2.76	2.83	2.57
	Min	0.03	0.03	0.03	0.03
Stone aggregate concrete	Average	0.18	0.15	0.19	0.05
	Max	0.56	0.73	1.20	0.09
	Min	0.03	0.00	0.00	0.03

3.5.3 Comparison between exposure – coastal districts

The comparison of chloride profile in concrete at different exposure conditions experienced in the four coastal districts studied are presented in Table 3-26. The results suggest that the chloride level in concrete at Cox's Bazar and Noakhali districts were observed to be higher as compared to Gopalganj and Bagerhat. Based on the collected data, the order of aggressively to marine conditions among these four districts are as given in Figure 3-17:

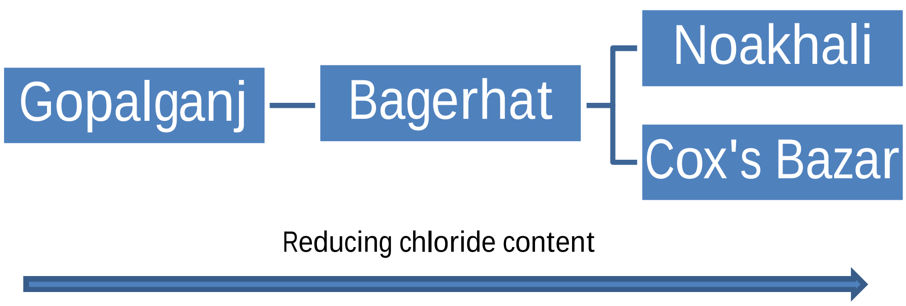


Figure 3-17 Hierarchy of regional chloride contents

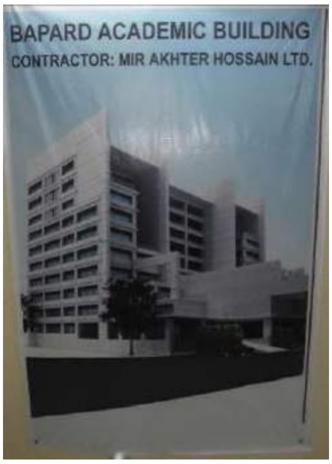
Table 3-26 Comparison of chloride profile in concrete between the selected four coastal districts

Coastal district	Chloride content (% of cement content)	5-25mm depth	25-50mm depth	50-75mm depth
Gopalganj	Average	0.28	0.25	0.36
	Max	2.90	2.73	2.83
	Min	0.03	0.03	0.03
Bagerhat	Average	0.48	0.35	0.32
	Max	2.70	2.63	1.65
	Min	0.07	0.00	0.00
Cox's Bazar	Average	0.43	0.43	0.37
	Max	2.66	2.73	2.60
	Min	0.03	0.03	0.03
Noakhali	Average	0.48	0.41	0.34
	Max	2.60	2.76	1.74
	Min	0.03	0.03	0.03

3.6 Inspection of new construction sites

3.6.1 BAPARD Academic Building

The academic building construction project as shown in Figure 3-18 is the biggest on-going project in Gopalganj district by LGED. The project involved building two 10 storey officer's accommodation building for Bangabandhu Poverty Alleviation and Rural Academy (BAPARD) in Kotalipara at an estimated cost of BDT 990 million each.



(a) Overview of BAPARD academic building

(b) Meeting with Contractor at site office

(c) Concrete batching plant at site

(d) Aggregate storage bins and cement silos

Figure 3-18 Inspection of concrete manufacturing facility at new construction site in Kotalipara

The inspection of concrete batching plant at BAPARD site suggested good quality control practices that includes proper storage of materials, regular testing of materials, fresh and hardened concrete in accordance with LGED standards and good maintenance of laboratory equipment. However, one interesting observation made at this site was the cement content in two strength grades of concrete used in the project. In the structural columns of the building a concrete mix of 35MPa strength was used, which consists of around 480 kg of CEM I cement, whereas for slabs and beams concrete mix of 28 MPa strength was used with around 435 kg of CEM I cement. The cement content in these two grades of concrete is observed to be high, which would cause early age thermal cracking in large sections, which in turn affects the long term durability of the structure.

3.6.2 PWD office site, Mongla

At this site concrete manufacturing and placement process was inspected as shown in Figure 3-19. The concrete materials were openly stored next to marine coast and adjacent pond water was used as mixing water as well as to wet the aggregates before mixing. The concrete used in the column was 1:1.5:3 mix that contains single graded broken brick aggregates. The gradation of aggregates was observed to be very poor and there were no quality control tests or moisture correction methods conducted at the time of mixing and placement of concrete.

(a) Machine crushed brick aggregates

(b) Concrete 10/7 mixer - manual addition of materials

(c) Manual transportation of concrete to building site

(d) Manual placement and compaction of concrete in a column

Figure 3-19 Concrete mixing and placement at PWD office site at Mongla

3.7 Concluding remarks

Based on the visual inspection notes and available testing information the findings on the condition survey of concrete structures are as follows:

- The condition of marine concrete structures greater than 15 years old in the exposed coastal Upazillas were found to be severely deteriorating. Some of the bridge structures, such as Silna river road bridge in Gopalganj and Burma bridge in Noakhali, have collapsed prematurely due to local factors such as dredging, associated scouring and settlement of foundations. Half-cell potential testing of most of the concrete structures at this age suggest high-severe risk of reinforcement corrosion. In some of the bridges the concrete railings were severely deteriorated and collapsed due to corrosion related failure. The visual observations on concrete cores extracted from these structures suggest workmanship issues related to use of poor graded aggregates, non-homogeneous concrete mix and voiding at the interface between deck slab concrete and wearing course layer.

- The visual observation of concrete core sample extracted from the culvert at Boalkhali road, Islamabad Union, Cox's Bazaar, under the 5-15 year age category, suggest that the stone aggregates used in the concrete were poorly graded with high proportion of >25mm particle size aggregates. The additional survey of buildings (presented in Appendix B) in this age category suggest that concrete with brick aggregates especially in exposed coastal Upazilla showed signs of early deterioration of concrete caused by salt scaling and corrosion of reinforcement.
- The newer concrete structures (1-5 years age category) predominantly had stone aggregates in concrete, which provides better durability compared with brick aggregate concrete. Access to only one concrete bridge structure - Chapail bridge in Gopalganj was provided by LGED in the age category of 1-5 years and intrusive inspection was limited to drilling dust sample. Additional information obtained from surveys carried out on concrete elements in buildings (presented in Appendix B) suggested that the cover to reinforcement was in compliance with LGED specification and no abnormal cracking or damage was observed in concrete elements. However, the inspection of new construction sites suggested that in the case of manual production of concrete workmanship issues related to use of poor graded aggregates, improper compaction of concrete, use of saline water for concrete mixing and lack of quality control testing were observed.
- The comparison on the use of stone aggregates vs brick aggregates suggest that greater absorption characteristics of brick aggregate concrete accelerates the deterioration process. The information obtained from LGED during the survey visit suggests their current practice is to use only stone aggregates in concrete production for bridge/road infrastructure projects.
- The comparison of salinity of local water samples obtained close to the road structures surveyed in each district (as presented in Table 3-7, Table 3-10, Table 3-16 and Table 3-22) suggest that the chloride content in ground water was observed to be low as compared with canal/river water in the exposed coastal Upazillas. The chloride content of water sourced from interior coastal Upazillas were observed to be very low/negligible. However, it should be noted that seasonal variations in chloride content of both river water and ground water were observed in previous studies. Therefore, as the water sampling was done during the rainy monsoon season (July-October), the chloride content of water is expected to be low compared to summer season.
- In-situ concrete strength for most of the structural elements were found to be much lower than the design strength of 20 MPa
- Chloride content in ground water was observed to be low compared with canal/river water in the exposed coastal Upazillas.
- The chloride content of water sourced from interior coastal Upazillas was observed to be very low/negligible.
- The observations on the variability of marine exposure on the condition of concrete clearly suggests that concrete structures in exposed coastal Upazillas have greater vulnerability to salt related damage. The deterioration process is rapidly accelerated in concrete structures containing brick aggregates especially in exposed coastal districts.

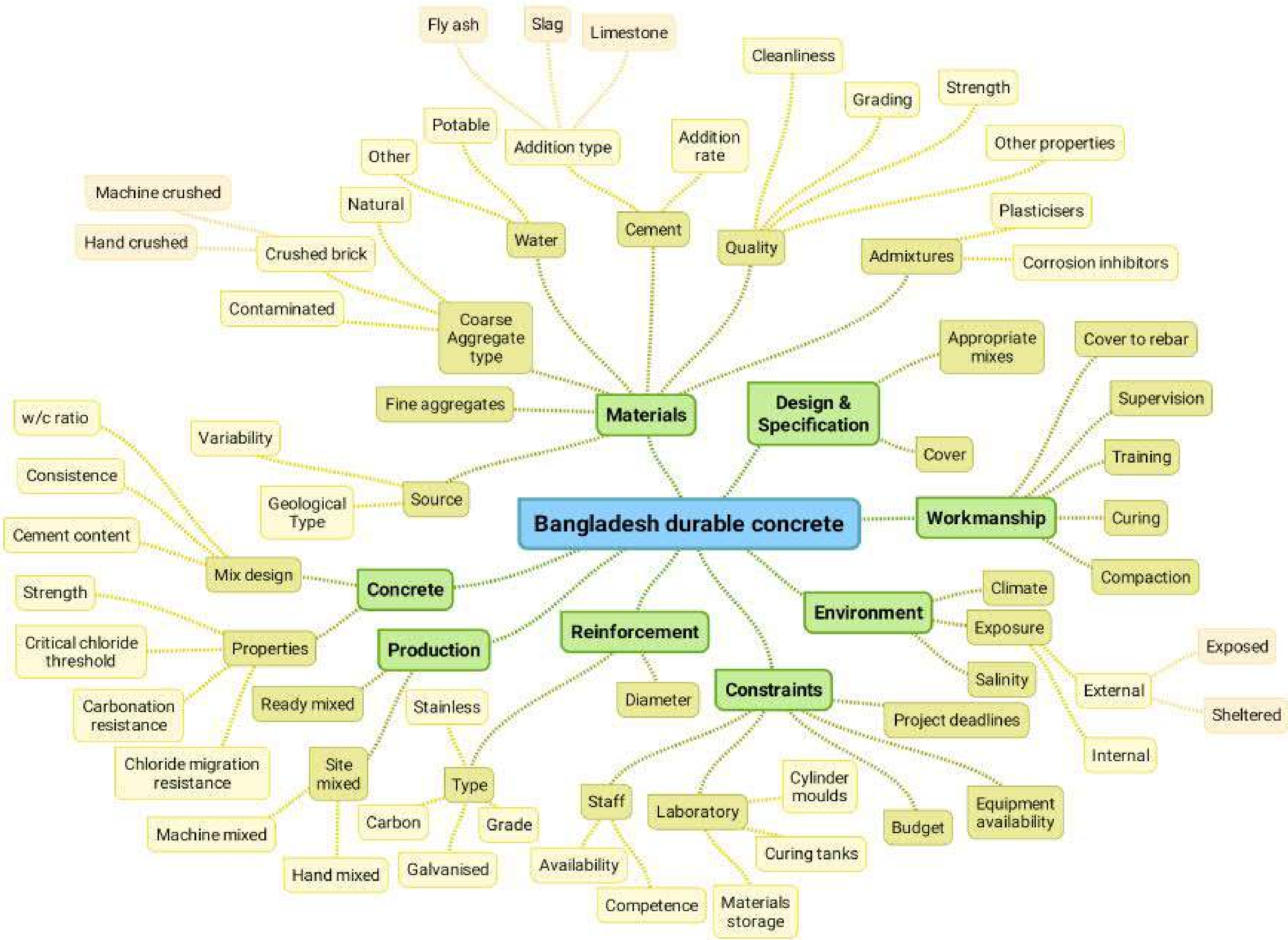


Figure 3-20 Inter-relationship between variables influencing durability of concrete

4 Field and Laboratory Testing

4.1 Introduction

Using the findings from the inception report and condition survey a laboratory testing programme was developed as discussed in this section.

Table 4-1 Categorisation of selected variables (critical variables highlighted in red)

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

4.2 Rationale behind variable selection

4.2.1 Selection of variables

There are many variables that could be considered as illustrated in Figure 3-20. 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.
In further research, 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 of concrete is 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 4-1 and among these variables critical variables as highlighted in red are selected for the mix design programme.

4.2.2 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 4-2.

Table 4-2 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

4.3 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; 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.

4.3.1 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 4-3, 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 helps to identify appropriate cement content for a given W/C ratio in the Phase-II testing of concrete.

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.

Table 4-3 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 Fly ash (30-40% cement replacement) Slag (30-50% cement replacement) Combination of Fly ash 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	<u>Preliminary Testing:</u> Specific Gravity Absorption Capacity (%) Unit Weight (kg/m3) Los Angles Abrasion (%) <u>Secondary Testing:</u> 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	<u>Cement Testing:</u> Setting time Normal consistency Compressive strength <u>Concrete testing:</u> Slump loss Compressive strength

4.3.2 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.

4.3.2.1 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 4-2, 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 4-4 based on a Taguchi L9 Orthogonal Array giving a total of 45 mixes required as presented in Table 4-5.

Table 4-4 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 are randomised and the following order has been created using Microsoft Excel RandBetween function.

Table 4-5 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

Run number	Cement type	w/c ratio	Coarse aggregate type	Contamination level	Cl dose
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
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

4.4 Material Selection and Testing

Materials were assessed for suitability in the trial mixes by testing in accordance with Table 4-6.

Table 4-6 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

4.4.1.1 Cement, Fly ash 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 presented in Table 4-7. The physical testing of the cement was conducted at LGED laboratory and the test results are presented in Table 4-8.

Table 4-7: Chemical characteristics of 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 (SO_3)	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 4-8: Physical characteristics of 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 Fly ash sample supplied by Bashundhara cement was imported from India, the physical and chemical characteristics of the Fly ash are given in Table 4-9.

Table 4-9 Chemical and Physical characteristics of Fly ash

Elements	Result (% mass)	BS EN 450-1: 2012 requirements
Calcium Oxide (CaO)	1.25	≤ 1.5%
Silicon dioxide (SiO_2)	59.60	$SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$
Aluminium oxide (Al_2O_3)	28.70	$SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$
Iron Oxide (Fe_2O_3)	6.64	$SiO_2+Al_2O_3+Fe_2O_3 \geq 70\%$
Magnesium Oxide (MgO)	0.97	≤ 4.0%
Sulphuric Anhydride (SO_3)	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 4-10. The test results show that the moisture content of the slag is higher than the limits specified in EN 15167-1:2006.

Table 4-10 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%

4.4.1.2 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.
The brick aggregates were also collected from Gaptoli, where a combination of first class bricks and picked Jhama brick were selected and machine crushed, such that the combined aggregates had a LA Abrasion value close to the 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 4-11 and Table 4-12.

Table 4-11 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	 1667

Test Parameter (units)	Result
10 mm	1472
LA Abrasion Combined aggregates (50% of 20 mm and 50% of 10 mm)	30.0
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 4-12 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

4.4.1.3 Fine Aggregate

The fine aggregate used in this study was Sylhet sand collected from Gaptoli. The physical properties of the fine aggregate are presented in Table 4-13.

Table 4-13 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

4.4.1.4 Water

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

4.4.1.5 Water-reducing admixture (HRWA)

Sikament 2002 NS, which is a high range water reducing admixture (HRWA) 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.

4.4.1.6 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 4-14.

Table 4-14 Chemical composition and density of Calcium Nitrate Corrosion Inhibitor

Test parameter	Result (%)
Total Nitrogen	2.57
Ammonium-N	1.28
Nitrate-N	15.87
Total CaO	29.8
Chlorine	0.0
Iron	0.03
Water insoluble >3µm	500 ppm
Bulk density	1.10 kg/l

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

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

This part of the phase-I study involved trial mixes to determine free W/C ratio and cement content for a constant slump, ensure mixes were cohesive and yielded 1.0m^3. The study focussed 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, concrete mixes with four different cement contents were tested. The free W/C ratio for each concrete mix 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 4-15.

Table 4-15 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)	Free Water (kg)	Slump (mm)	Plastic Density (kg/m³)
			20 mm (50% of CA)	10 mm (50% of CA)					
T-01	0.84	250	555	555	1111	741	211	90	2337
T-02	0.63	350	542	542	1084	722	219	80	2384
T-03	0.51	450	522	522	1044	696	231	90	2360
T-04	0.46	500	491	491	983	655	229	75	2389.
T-05	0.44	550	460	460	920	613	241	90	2375

In the case of concrete mixes with brick aggregates, the aggregates were pre-soaked for 1 hour such that the brick aggregates would not absorb significant additional water at the time of mixing and slump testing . 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 4-16.

Table 4-16 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

4.5.1.1 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 4-17.

Table 4-17 Mix proportions of concrete mixes with stone aggregates and HRWA

Mix Ref	w/c ratio	Cement (kg)	Coarse Aggregate (60%) (kg)		Sand (40%) (kg)	Sikaplast 2002NS (1%)	Free 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 HRWA as shown in Figure 4-1.

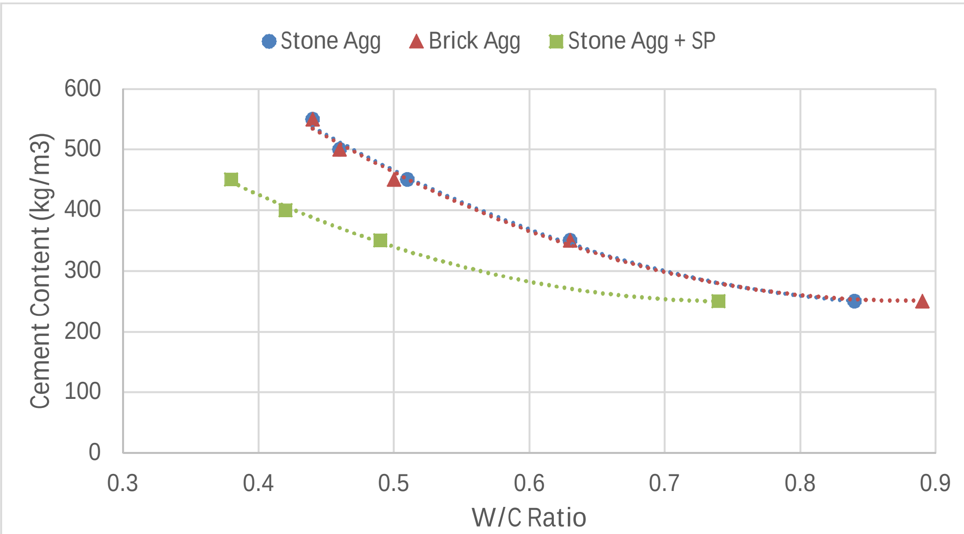


Figure 4-1 The relationship between W/C ratio and cement content of concrete

It can be observed from Figure 4-1 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 HRWA required less cement in the mix to produce similar workability. The relationship presented in Figure 4-1 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 4-18 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	42.3	47.5
T-07	0.93	250	Brick Aggregates	12.3	17.2
T-08	0.65	350	Brick Aggregates	20.8	26.8
T-09	0.52	450	Brick Aggregates	28.4	37.5
T-10	0.47	500	Brick Aggregates	30.1	37.8
T-11	0.45	550	Brick Aggregates	34.7	40.0
T-15	0.74	250	Stone Agg + SP	18.5	22.8
T-16	0.49	350	Stone Agg + SP	36.5	43.8
T-17	0.38	450	Stone Agg + SP	46.4	53.7
T-18	0.42	400	Stone Agg + SP	42.4	46.0

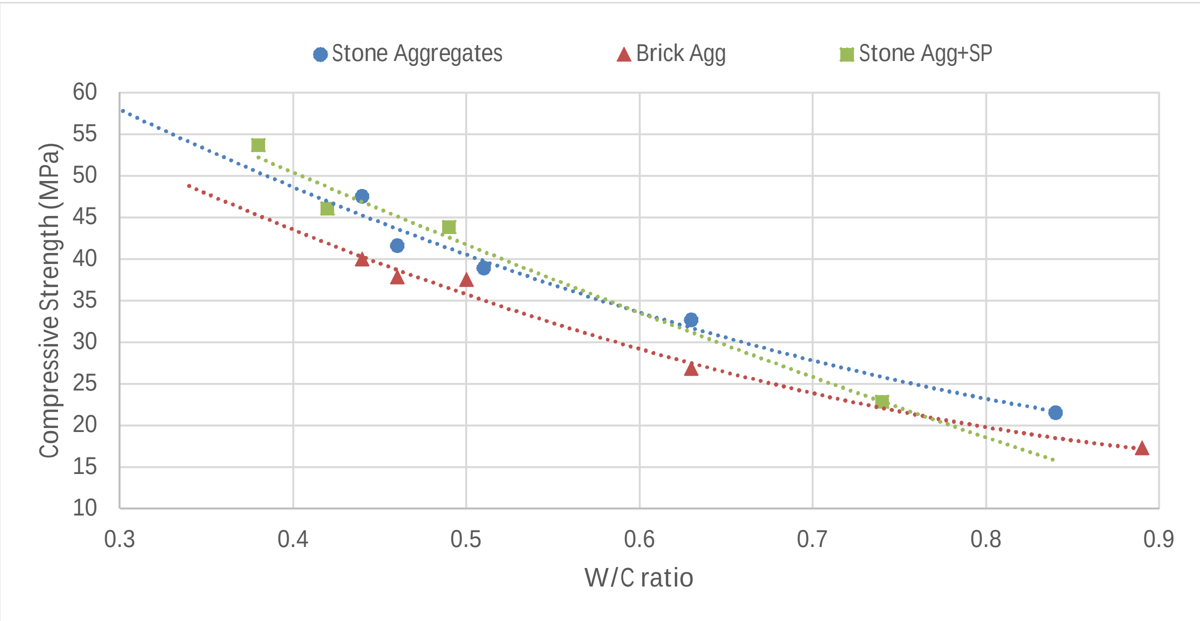


Figure 4-2 Relationship between W/C ratio and 28 days compressive strength of concrete

The 7-day and 28-day compressive strength results of the concrete mixes with stone and brick aggregates are presented in Table 4-18. A general trend in variation of 28 day strength of concrete at different W/C ratio can be observed in Figure 4-2 and presented in Table 4-18. 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 4-4, 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 4-2 that the concrete mixes with stone aggregates and stone aggregates+SP show a similar W/C ratio and strength relationship.

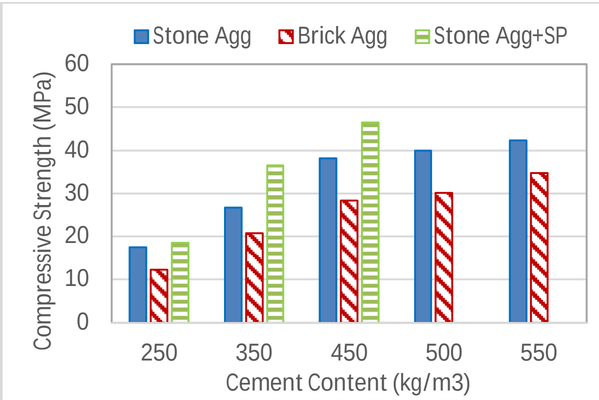


Figure 4-3 Comparison of 7 day compressive strength between brick and stone aggregate concrete

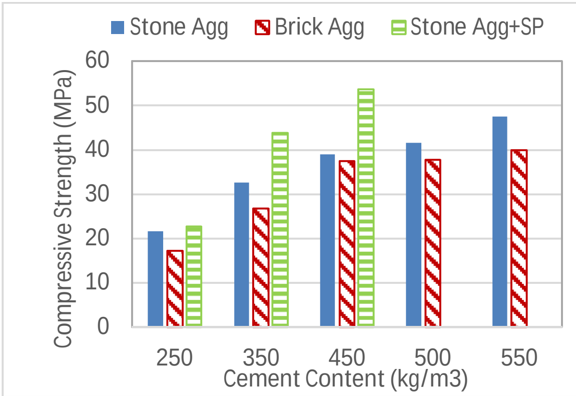


Figure 4-4 Comparison of 28 day compressive strength between brick and stone aggregate concrete

4.5.2 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 Table 4-19 and Table 4-20 respectively.

Table 4-19 Mix details of concrete with different proportions of Fly ash

Mix Ref	w/c ratio	CEM I (kg)	Fly ash (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% Fly ash)	0.50	315	135	489	489	652	225	100	2328
T-13 (75% CEM I & 25% Fly ash)	0.47	338	112.5	492	492	656	225	100	2341
T-14 (80% CEM I & 20% Fly ash)	0.47	360	90	494	494	659	225	70	2332

Table 4-20 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 varying replacement levels of Fly ash and slag are presented in Table 4-21 and shown in Figure 4-5. Based on the strength results it can be concluded that concrete mixes with slag additions produced slightly higher 28 days strength in comparison with 100% CEM I concrete mix. In the case of concrete mixes with Fly ash addition, although the strength results are lower than 100% CEM I concrete mix, the increase in strength after 28 days was observed to be higher than the slag concrete mixes.

Table 4-21 Compressive strength results of concrete mixes with different proportions of Fly ash 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% Fly ash	18.0	25.3	27.6
T-13	0.47	450	75% CEM I & 25% Fly ash	20.5	24.8	30.2
T-14	0.47	450	80% CEM I & 20% Fly ash	23.0	27.9	32.8
T-19	0.50	450	80% CEM I & 20% Slag	27.2	40.2	42.5
T-20	0.50	450	70% CEM I & 30% Slag	32.1	41.8	42.4
T-21	0.49	450	60% CEM I & 40% Slag	26.4	42.3	42.2
T-22	0.50	450	50% CEM I & 50% Slag	24.4	37.58	43.2

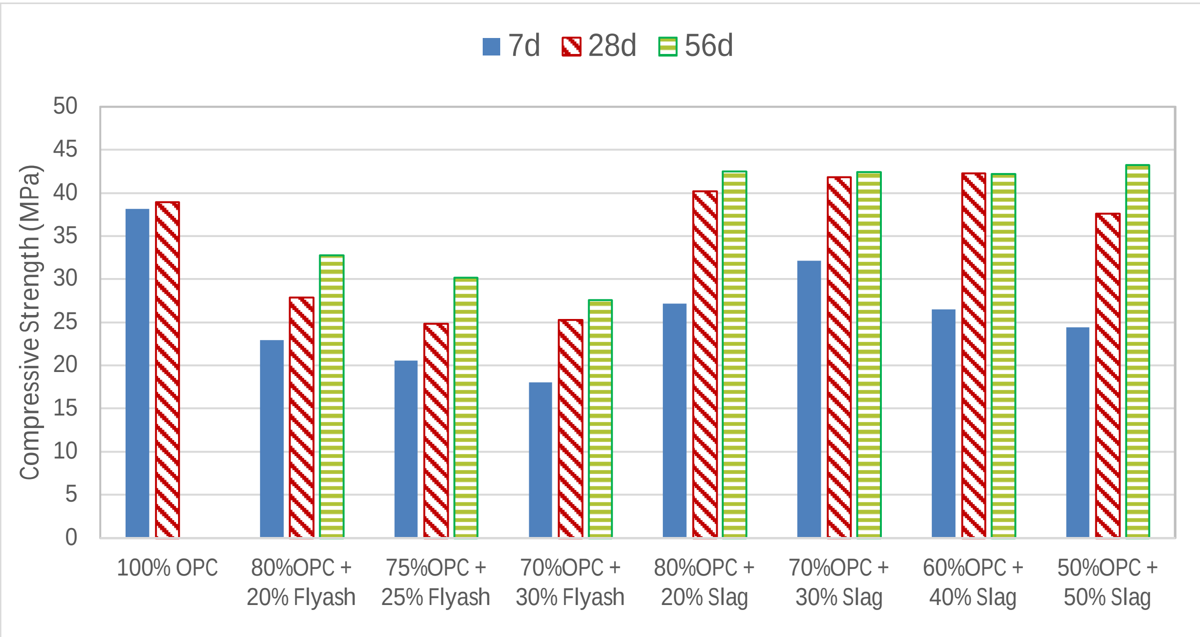


Figure 4-5 Comparison of strength development in concrete with different replacement levels of Fly ash and slag

4.5.3 Feasibility study on improving the properties of brick aggregates

Bangladesh has no good quality stone quarries, as most of the land is a flood plane of mud and sand. Most of the good quality stone aggregates used in concrete are imported from neighbouring countries (India, Bhutan, Vietnam etc). In the case of road infrastructure projects along the coastal districts of the country, the imported stone aggregates are largely transported by road, which adds cost in addition to the import costs. Therefore, the scarcity of stone along with transport costs combined makes the price of stone unusually high.

On the other hand, brick aggregates are locally produced and are priced at a fraction of the cost of the stone aggregates. The local production of bricks combined with low cost labour especially in coastal districts of the country keeps the cost of brick aggregates considerably low as compared with stone aggregates. Therefore, there is a cost benefit in the use of brick aggregates in the concrete, however the strength and durability performance of brick aggregate concrete need to be compared with stone aggregates to see the real benefit.

This feasibility study deals with improving the properties of brick aggregates by pre-coating with cementitious slurry and compare the performance of these coated brick aggregates with stone aggregate concrete. The preliminary testing involved coating the brick aggregates with cement slurry 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 Fly ash 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 4-22. The specific gravity and water absorption results presented in Table 4-22 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, one possible explanation is the presence of 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 4-22 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% CEM I	0.5	2.05	17.3
6%	100% CEM I	0.5	2.04	17.0
6%	100% CEM I	0.4	2.04	17.2
8%	100% CEM I	0.4	2.02	15.8
6%	60% CEM I + 40% Fly ash	0.5	2.01	16.3
6%	80% CEM I+20% Fly ash	0.5	2.00	16.6
8%	100% CEM I	0.5	2.01	17.3

Although a clear improvement in brick aggregate properties has not been observed with coated bricks, the 100% CEM I mixed coated bricks were further tested in a concrete mix at two different cement content and W/C ratios. The SSD mix proportions of concrete mix with three different coated brick aggregates are presented in Table 4-23.

Table 4-23 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%-CEM I), w/c-0.5	T-23	0.6	350	766	766	211	65	2097
	T-24	0.44	450	713	713	199	70	2117
6% CC (100%-CEM I), w/c-0.4	T-25	0.55	350	764	764	192	85	2110
	T-26	0.43	450	711	711	192	80	2131
8% CC (100%-CEM I), w/c-0.4	T-27	0.59	350	760	760	205	70	2095
	T-28	0.47	450	707	707	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 4-6.

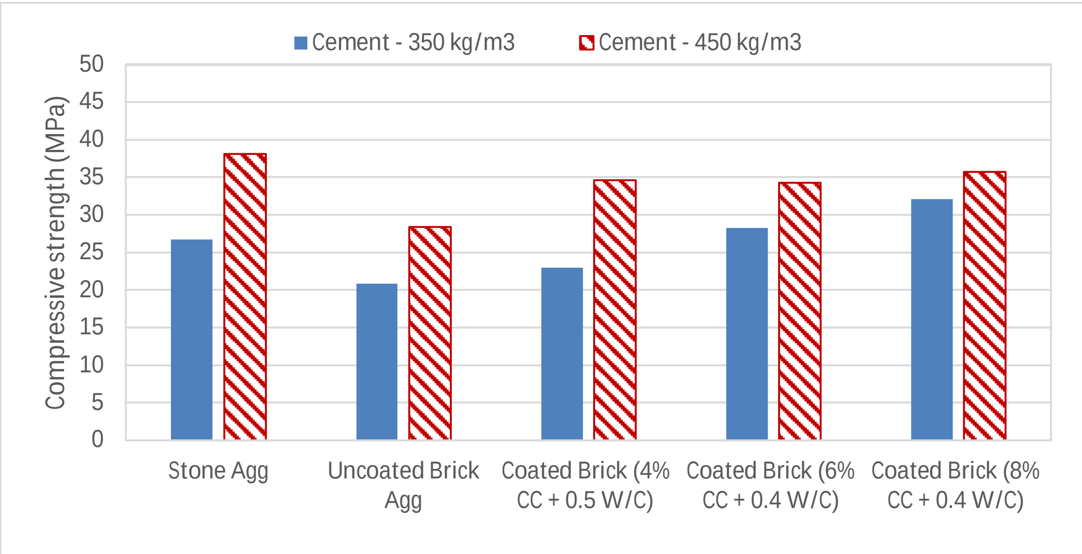


Figure 4-6 Compressive strength (7-day) of stone aggregate vs uncoated brick aggregate vs coated brick aggregate

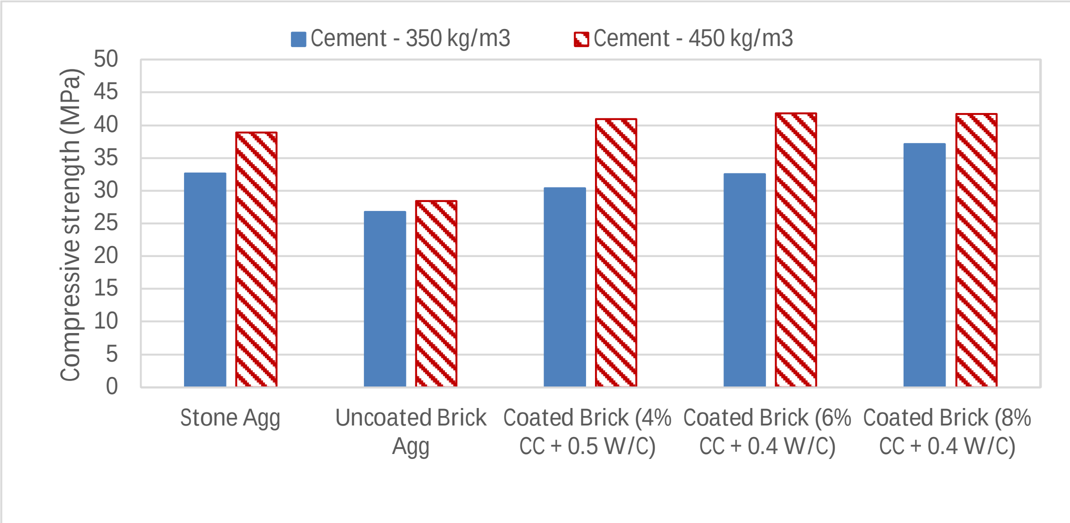


Figure 4-7 Compressive strength (28-day) of stone aggregate vs uncoated brick aggregate vs coated brick aggregate

The comparison of 7 day and 28 days strength results as shown in Figure 4-6 and Figure 4-7 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, which will be discussed in Phase II testing results.

4.5.4 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 4-24 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 4-24 Comparison of setting time of cement with different proportions of CI and retarder dosages

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

* High Air voids observed in the cement paste

4.5.5 Conclusions – Phase I study

The outcome of the various experimental studies pursued in phase-I testing gave 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 + HRWA 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 Fly ash and slag used in composite cements suggests that the concrete mixes produced with varied proportions of Fly ash and slag produced homogenous and cohesive concrete. The comparison of 100% CEM I concrete mix with Fly ash 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 reduces with increased Fly ash/slag levels. However, it is a well-established fact that due to slower pozzalanic and hydration reactions in Fly ash/slag based concretes, strength development , unlike in CEM I concrete, will continue after 28 days (>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 significantly and the water absorption of coated brick aggregates has slightly increased 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. Further testing is required to provide 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 can be counteracted. 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.

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

The purpose of the phase II testing was to study the durability performance of concrete by varying W/C ratio (or cement content), cement type, aggregate type, salt contamination and use of corrosion inhibitors. The impact of these factors on the durability of concrete has been studied using standard NT Build 492, which 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 using a modified ASTM G109 salt ponding test.

4.6.1 Materials

The materials used in the concrete mix for Phase II study is same as in Phase I study and as described in Section 4.4.

4.6.2 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, a moisture correction was applied to the aggregates and water content of the mix was 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 is compensated in the total water content. Liquid based chemical admixtures were measured volumetrically to the nearest millilitre.
All the constituents of the concrete were mixed in a 10/7 concrete mixer with a maximum capacity of 100 litres. Prior to each mixing, the concrete mixer was wetted using a damp 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 W/C 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.

4.6.3 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 were cured in separate curing drums to avoid contamination of the other concrete specimens. The slab moulds were 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.

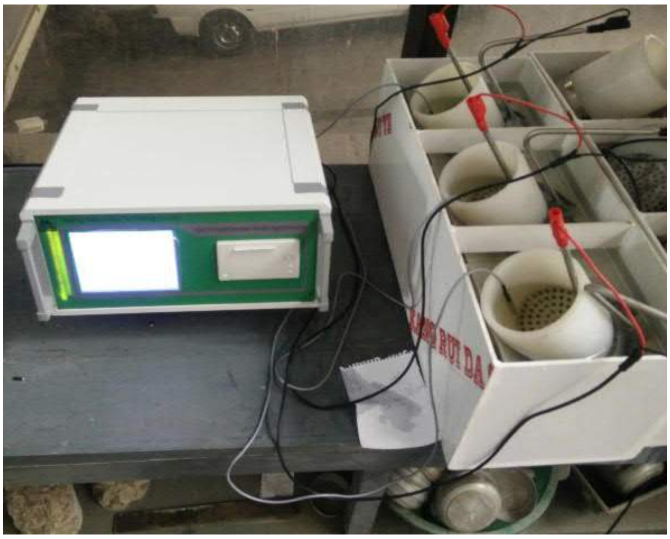
4.6.4 Durability Testing

4.6.4.1 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 4-8 The 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 4-8.

After subjecting the concrete specimens to chloride migration test for 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 taken as 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).

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

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

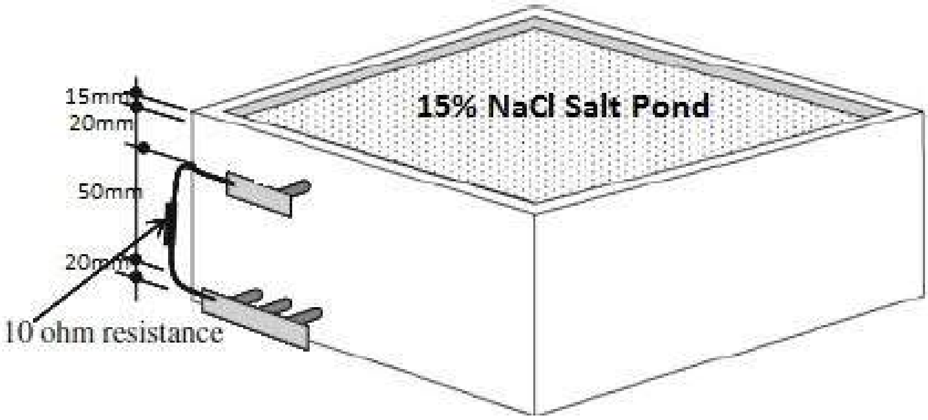
X_d : average value of the penetration depths, mm

T : test duration, hour

4.6.4.2 Accelerated corrosion testing

(A) Sample preparation

A bespoke slab mould was manufactured with provision to place reinforcement bars at two different levels and form a 15 mm dyke feature on the ponding face of the concrete specimen as shown in Figure 4-9. 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 4-9. 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 bars as shown in Figure 4-9. 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.



(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 4-9 Different stages of sample preparation of reinforced concrete slab for accelerated corrosion testing

(B) 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 28 days, each concrete slab sample was subjected to cyclic salt ponding and atmospheric drying. The reservoir formed by the cast-in dyke feature was filled with 15% Sodium Chloride solution for 2 days and then the salt water was removed to allow atmospheric dying in ambient conditions in the laboratory for 5 days. When concrete is exposed to prolonged cycles of wetting and drying, the penetration of salts (chloride ions) in concrete is accelerated 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 4-25 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 and does not provide accurate means of measuring on going corrosion of reinforcement bar in concrete.

Table 4-25 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).

4.6.5 Concrete mix details

Based on the factors and variables considered for phase II study as described in section 4.3.2, 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 SSD 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 4-26, Table 4-27 and Table 4-28 respectively. All 45 concrete mixes were subjected to durability testing as described in section 4.6.4.

Table 4-26 Concrete mix proportions containing stone aggregate

Mix Ref	Free w/c ratio	Cement Content (kg)	CEM I (kg)	Fly ash (kg)	Slag (kg)	Coarse Aggregate (SSD) (60%) (kg)		Sand (SSD) (kg)	NaCl (Salt)	Calcium Nitrate (3.5% of cement content)	Set Retarder (Sika 4101 NS) (kg)	Sika Ferro gaurd 901 (kg)	Free 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 4-27 Concrete mix proportions containing machine crushed brick aggregates

Mix Ref	Free w/c ratio	Cement Content (kg)	CEM I (kg)	Fly ash (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)	Free 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 4-28 Concrete mix proportions containing cement coated brick aggregates

Mix Ref	Free w/c ratio	Cement Content (kg)	CEM I (kg)	Fly ash (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)	Free 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

4.6.6 Results and Discussions

4.6.6.1 NT Build 492 – Migration coefficient of concrete

The results of NT Build 492 test for concrete mixes containing stone aggregates are presented in Table 4-29, the results for brick aggregate concrete mixes are presented in Table 4-30 and for coated brick aggregates are presented in Table 4-31. 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 salt added in the mix was a 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. 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 4-29 NT Build 492 durability testing results for stone aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Fly ash (%)	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
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 4-30 NT Build 492 durability testing results for brick aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Fly ash (%)	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 4-31 NT Build 492 durability testing results for coated brick aggregate concrete mixes

Mix Ref	Cement Content (kg/m3)	W/C ratio	Fly ash (%)	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 4-10- Figure 4-12

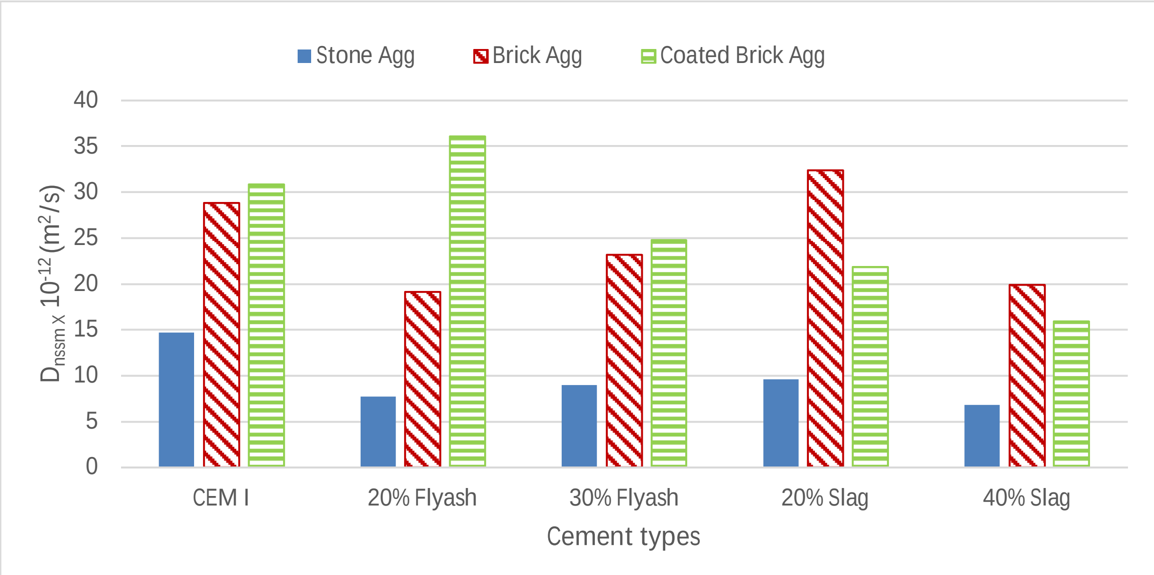


Figure 4-10 Comparison of Migration coefficient for different concrete mixes with 350 kg/m^3 cement content

The chloride migration test results for concrete mixes with 350 kg/m^3 cement content as presented in Figure 4-10 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 Fly ash 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.

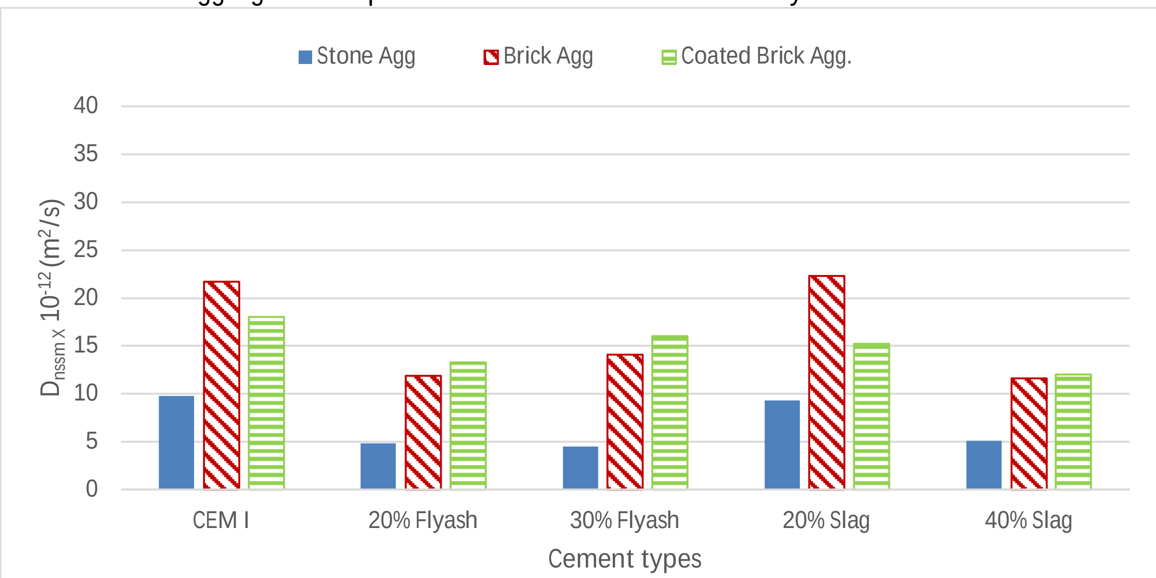


Figure 4-11 Comparison of Migration coefficient for different concrete mixes with 450 kg/m^3 cement content

The comparison of migration coefficient of concrete mixes with 450 kg/m^3 cement content (presented in Figure 4-11) 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 Fly ash 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 compared with the brick aggregate concrete mixes.

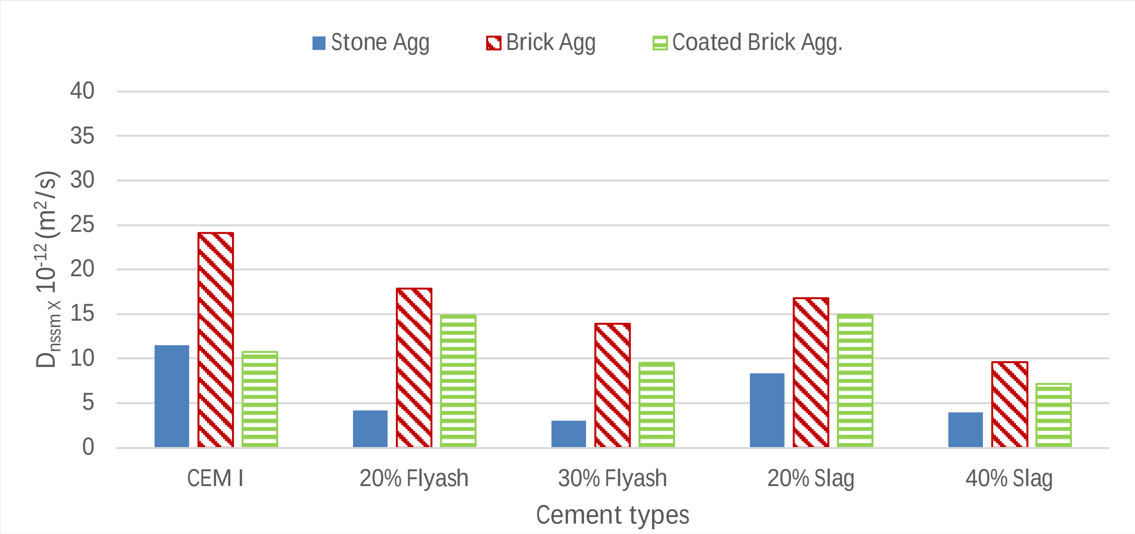


Figure 4-12 Comparison of Migration coefficient for different concrete mixes with 550 kg/m^3 cement content

The higher cement content of 550 kg/m3 in concrete has marginally improved the performance of concrete as presented in Figure 4-12. It is interesting to note that in the case of 100% CEM I 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% CEM I 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 CEM I mix and concrete with 30% Fly ash has performed the best in terms of lowest migration coefficient among all the concrete mixes tested.

4.6.6.2 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.

(A) Macro-cell corrosion tests

The macro-cell corrosion measurements were made as described in section 4.6.4.2(B). 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.

Figure 4-13 Measurement of macro-cell corrosion on ponding slabs

(B) 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 as presented in Table 4-32. Based on the classification, values more negative than -250 mV indicate high probability of reinforcement corrosion.

Figure 4-14 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 4-32 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
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	-	-	-

4.6.7 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
- In the case of concrete with blended cements, there was no relationship between strength and durability performance
- The durability performance of concrete improved with increase in cement content of the concrete. However, in the case of 100% CEM I concrete mix 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 Fly ash addition showed better durability performance in comparison to slag based concrete mix. In general, among the different cement types, 100% CEM I 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% Fly ash 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.

5 Stakeholder Workshop

The purpose of the workshop was to demonstrate the progress of the project provide technical training and capacity building through the content of the project presentation and response to technical questions; and obtain feedback for the ongoing development, uptake, and embedment of the project findings and recommendations.

Figure 5-1 Photo from stakeholder workshop held at LGED Head Office, Dhaka

5.1 Discussions and comments at the workshop

The Stakeholder Workshop was well attended, with a high level of engagement, interest, and experience brought to the table from the assembled floor of experts and practitioners. Where technical questions and comments were not directly answered in session (with reference to content in the presentation or existing circulated project reports), the comments raised typically focussed around the following key areas:

- Technical (and cost-related) questions around the relative proportions and benefits employed in different recommended mix designs;
- Requirement for piloting to test the recommended concrete mix designs;
- Cost of any new and recommended mix designs, and practical applicability to the context of rural roads projects, and where further research is needed into project and life cycle costing;
- Further work on the improvement of quality of locally available brick aggregates and their potential use in the production of durable concrete;
- Review and updating of LGED specifications and standards to incorporate the recommendations from the project study;
- Requests for ongoing training and capacity building of design and construction methodologies for ground improvement techniques for the rural roads network;

6 Further analysis and discussions

6.1 Service-life modelling

The translation of durability parameter such as chloride migration coefficient to real time performance values such as service life of concrete is very important for the implementation of durability design of concrete. In the case of concrete exposed to marine environment, the durability design will be based on predicting the time of initiation of reinforcement corrosion in concrete. Various service life models were developed to predict the time of initiation of corrosion using large amounts of empirical data on the chloride ion penetration in concrete, migration coefficient of concrete, threshold chloride content to initiate corrosion of concrete, concrete cover and influence of blended cements on corrosion of reinforcement.

There are two distinct approaches to model the deterioration mechanisms:

1) Deterministic approach, which assumes that an outcome is certain. A defined set of input parameters (e.g. cover, w/c ratio, relative humidity) when analysed will give a unique, non-varying output
2) Stochastic approach, which assumes that some of the input parameters will vary within defined distributions and a random element is generated so that defined input parameters will give different outputs for each run of the model. Multiple runs are used to estimate a probability distribution.

There are a range of deterministic models available, for example:

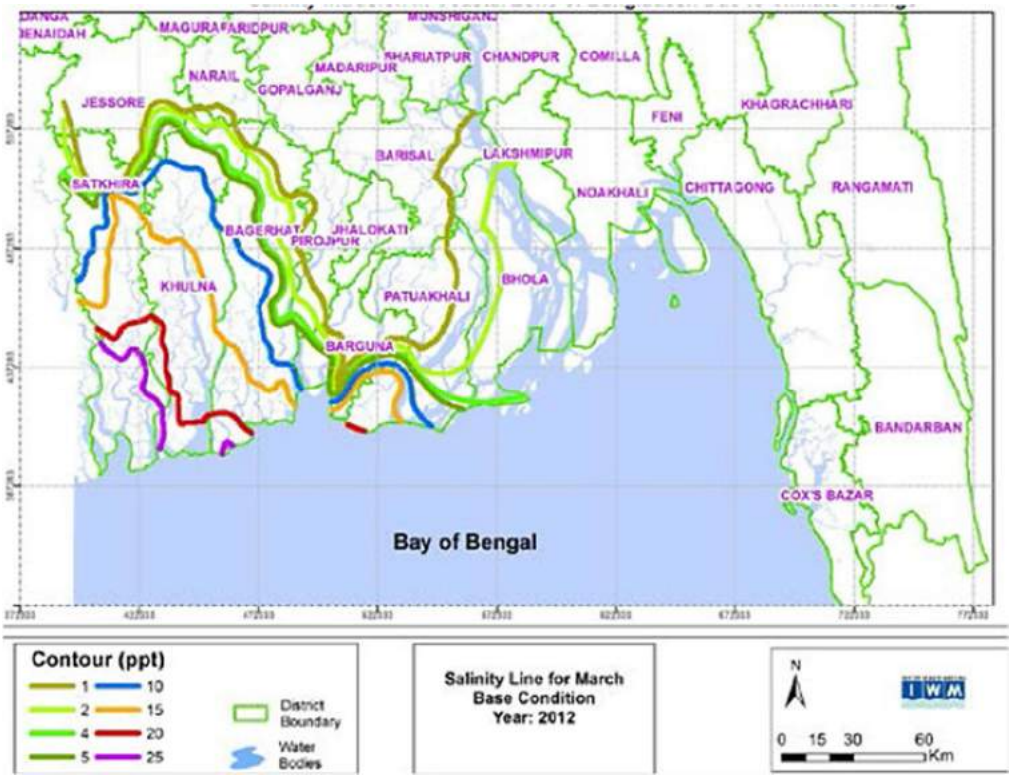
- CARBUFF (CSTR 61 carbonation model)
- AGEDDCA (CSTR 61 chloride model)
- Life365 (freely downloadable chloride model)

These deterministic models will give a definitive result for a set of input parameters.

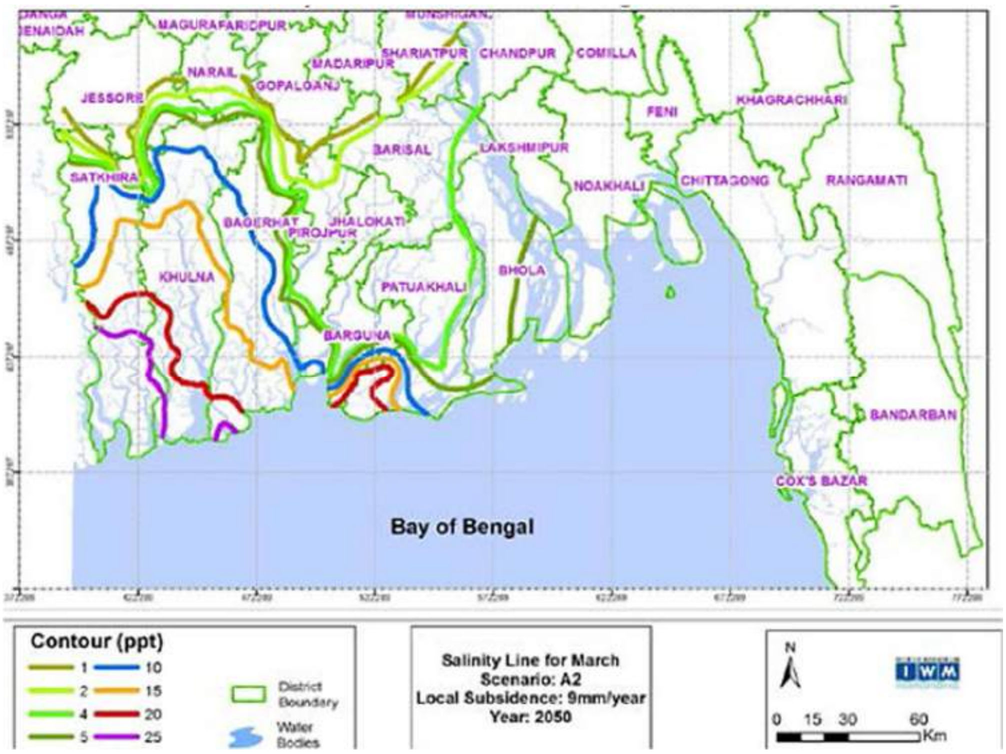
In this study a bespoke stochastic approach based deterioration model “CorrPredict” was used to evaluate different concrete mixes for predicting service-life of concrete structures in coastal environment. The details of the CorrPredict model and input values considered in the model are given in Appendix A2.

6.2 Influence of Climate change

The sea level rise due to climate change will increase the salinity levels in river water. Based on climate change modelling, the effects of future climate change on river salinity was observed to be more predominant in southwest coastal region of Bangladesh as shown in Figure 6-1 (a) & (b) (Dasgupta et al 2014).



(a) Baseline river salinity levels in 2012



(b) Worst future scenario of salinity intrusion levels due to climate change in 2050

Figure 6-1 Salinity intrusion in coastal zone of Bangladesh due to climate change (Dasgupta et al 2014)

It can be observed from Figure 6-1 (a) & (b) that in the worst case scenario, salinity intrusions cover the exposed coastal districts, for example the 5ppt line (5000ppm) moves further inland covering most of the Bagerhat district by 2050. Therefore, to design climate resilient concrete structures in coastal regions of Bangladesh, the concrete specifications should consider future salinity levels and design the concrete to resist the increased salinity and associated corrosion related deterioration. Based on the salinity levels of water, chloride content of concrete tested in the condition survey phase and future salinity levels estimated by climate change models, the exposure conditions in coastal regions of Bangladesh has been classified into four different classes as presented in Table 6-1. For each exposure class the design surface chloride content of concrete was assumed based on interpolation of empirical values established for similar exposure conditions in Europe and Middle-eastern countries. The assumed values of surface chloride content of concrete and chloride concentration of water was used as input values in CorrPredict service life model.

Table 6-1 Exposure classification in coastal regions of Bangladesh for chloride induced corrosion caused by external salts

Coastal region	Exposure class	Service-life model input values	
		Parameter	Value
<1 km from coastal line (exposed to sea water)	Extreme	Surface chloride (Cs) Cl concentration in water	4.5% of cement content 20,000 mg/l (seawater)
Exposed coastal districts	Severe	Surface chloride (Cs) Cl concentration in water	1.6% of cement content 5000 mg/l (Brackish water)
Inner coastal districts	Moderate	Surface chloride (Cs) Cl concentration in water	1.2% of cement content 2500 mg/l

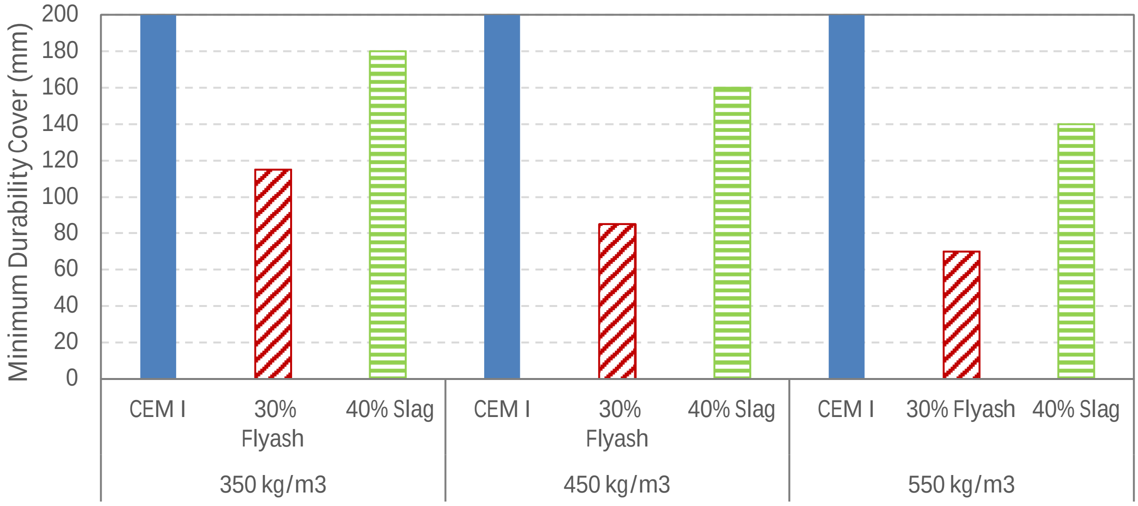
6.3 Service-life modelling results

Based on the input values for CorrPredict service life model as presented in Appendix A2 and exposure specific input values given in Table 6-1, the minimum durability cover for different variations in concrete mixes was assessed for design life of 75 years. The minimum durability cover required for different concrete mixes are presented in Table 6-2. The service life assessment of concrete mixes to calculate the minimum durability cover helps in identifying concrete mixes that can resist chloride ingress to reach reinforcement for design life of 75 years with realistic levels of cover. For example, the comparison of minimum cover value required for extreme exposure condition suggest that the best suitable concrete mix will be 70% CEM I + 30% Fly ash mix with stone aggregates and 550 kg/m^3 cement content at minimum cover of 70mm.

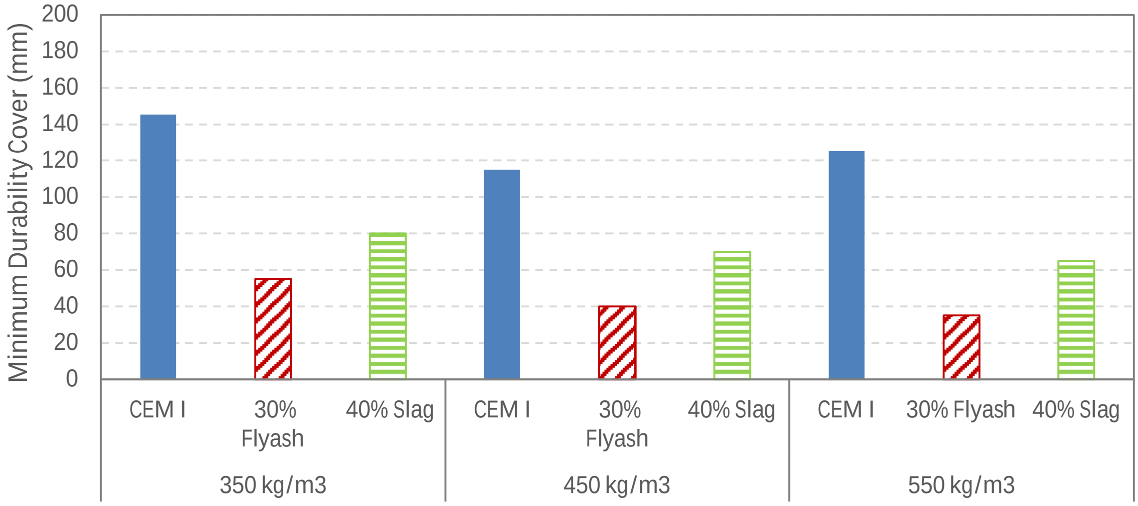
In general, for the three exposure conditions viz. Extreme, Severe and Moderate, the concrete mix with 30% Fly ash, stone aggregates and high cement content requires low minimum durability cover as compared with other concrete mixes. It can be observed from Table 6-2, concrete mix that contain 100% CEM I and/or brick aggregates require very high concrete cover, which will be impractical to implement and therefore cannot be recommended in all the three exposure conditions.

Table 6-2 Minimum durability cover for different concrete mixes for 75 year design life

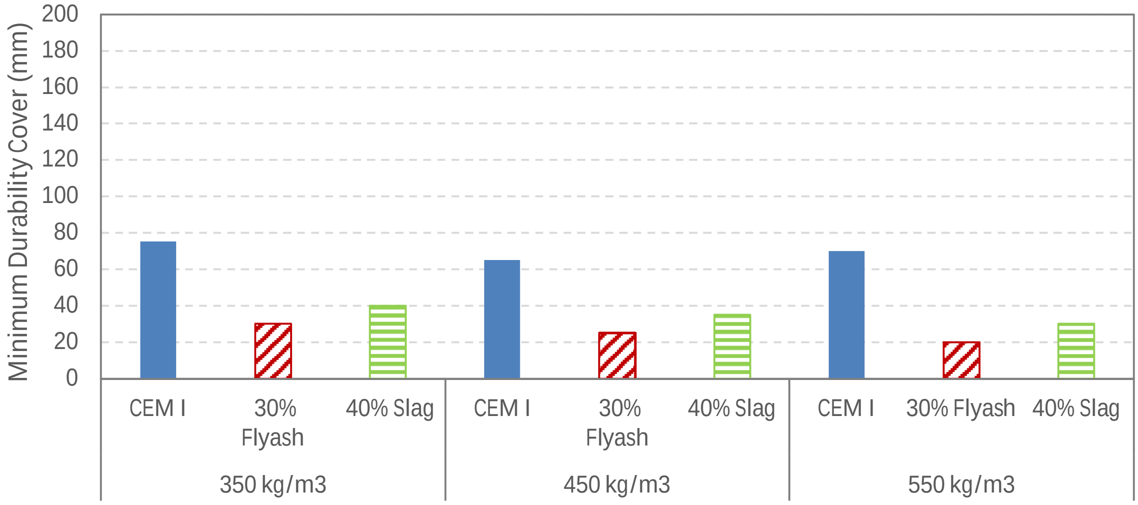
Cement content	Agg. type	Cement	Non-Steady-State Migration Coefficient, Dnssm (X 10 $^{-12}$m^2/s)	Extreme	Severe	Moderate
350 kg/m^3	Stone	CEM I	14.7	>200	145	75
	Stone	70% CEM I + 30% Fly ash	8.97	115	55	30
	Stone	60% CEM I + 40% Slag	6.79	180	80	40
	Brick	CEM I	28.8	>200	>200	110
	Brick	70% CEM I + 30% Fly ash	23.2	185	85	45
	Brick	60% CEM I + 40% Slag	19.9	>200	135	65
450 kg/m^3	Stone	CEM I	9.77	>200	115	65
	Stone	70% CEM I + 30% Fly ash	4.49	85	40	25
	Stone	60% CEM I + 40% Slag	5.07	160	70	35
	Brick	CEM I	21.7	>200	175	95
	Brick	70% CEM I + 30% Fly ash	14.1	150	70	35
	Brick	60% CEM I + 40% Slag	11.6	>200	105	55
550 kg/m^3	Stone	CEM I	11.5	>200	125	70
	Stone	70% CEM I + 30% Fly ash	3.02	70	35	20
	Stone	60% CEM I + 40% Slag	3.92	140	65	30
	Brick	CEM I	24.1	>200	180	95
	Brick	70% CEM I + 30% Fly ash	13.9	150	65	35
	Brick	60% CEM I + 40% Slag	9.58	>200	95	45



(a) Extreme exposure class



(b) Severe exposure class



(c) Moderate exposure class

Figure 6-2 Minimum durability cover required for concrete mix with stone aggregates for 75 year design life

The comparison of minimum durability cover required for different concrete mixes with stone aggregates in extreme exposure condition is presented in Figure 6-2(a). It can be observed that the cover required in extreme exposure condition for most of the concrete mixes are quite high and impractical to specify. The lowest minimum durability cover of 70mm can be provided by concrete mix with 30% Fly ash and 550 kg/m3 cement content. It should be noted that in situ nominal cover includes fixing tolerance depending on the construction technique. However, with the fixing tolerance the nominal cover for reinforced concrete element in extreme exposure can be very high and impractical to achieve. Therefore, in the case of extreme exposure conditions, the concrete mix have minimum durability cover with additional protection measures such as use of corrosion inhibitors in the concrete mix to achieve the 75 year design life.

The comparison of minimum durability cover required for concrete mixes in severe exposure condition as shown in Figure 6-2(b) suggest that both CEM I and slag based concrete require high levels of cover. The minimum durability cover required for 30% Fly ash mix was observed to be low compared with other concrete mixes and therefore can be specified for severe exposure conditions experienced in exposed coastal districts of Bangladesh.

The comparison of minimum durability cover for moderate exposure class as shown in Figure 6-2(c) suggest that 30% Fly ash and 40% slag mixes require cover lower than 40 mm and therefore can be specified for moderate exposure conditions experienced in inner coastal districts of Bangladesh.

6.4 Cost-effectiveness of concrete mix

The durability study on various concrete mixes with different proportions of mineral admixtures concludes that 30% Fly ash addition in the concrete with minimum cementitious content of 500 kg/m3 is the optimum composition to produce durable concrete exposed to marine environmental conditions experienced in the coastal districts of Bangladesh. In this section the cost effectiveness of this durable concrete mix is compared with standard concrete currently specified in LGED standards.

Table 6-3 Mix proportions for nominal mix and durable concrete mix

	LGED Standard	New Durable Concrete
Concrete mix	Nominal mix 1:1.5:3	Mix design at Laboratory
Water/Cement ratio	0.4	0.4
Cement content (kg)	410	500
Cement type	CEM I	CEM I + 30% Fly ash
Coarse Aggregate	= 0.856 m^3*1600 kg/m^3 = 1370 kg (stone aggregate) = 0.856 m^3*1200 kg/m^3 = 1027 kg (brick aggregate)	= 990 kg Stone aggregates
Sand	= 0.472 m^3 * 1600 kg/m^3 = 755 kg	= 660 kg
Water	164 Litres	200 Litres
High range water reducer	Appropriate amount to get target slump of 75-100mm = 4 kg (assumed 1% of cement content)	Appropriate amount to get target slump of 75-100mm = 5 kg (assumed 1% of cement content)

Table 6-4 Unit cost of materials

Sl. No.	Item	Unit Cost (BDT)	Unit
1	Cement (CEM I)	420	per bag (50 kg)
2	Fly ash	2800	per Ton
3	Slag	4000	per Ton
4	Stone Coarse Aggregate	6356	per m^3
5	Brick Aggregate (Machine broken)	3531	per m^3
6	Sylhet Sand	2825	per m^3
7	High range water reducer (HRWR)	150	Per kg

Table 6-5 Cost comparison between Nominal concrete mix and Durable concrete mix

	Nominal mix 1:1.5:3 (Stone aggregates)		Nominal mix 1:1.5:3 (Brick aggregates)		Durable concrete mix (Stone aggregate)	
Materials	Quantity (kg per m^3)	Cost (BDT)	Quantity (kg per m^3)	Cost (BDT)	Quantity (kg per m^3)	Cost (BDT)
Cement	400	3360	400	3360	350	2940
Fly ash	0	0	0	0	150	420
Water	164	Free	164	Free	200	Free
Coarse Agg	1370	5442	1027	3022	990	3933
Sand	755	1333	755	1333	660	1165
HRWR	4	600	4	600	5	750
Total Cost	10735 BDT/m^3		8315 BDT/m^3		9208 BDT/m^3	

The approximate mix proportions for nominal concrete mix and durable concrete mix is presented in Table 6-3. The unit cost of materials available at Dhaka is presented in Table 6-4. The cost comparison per cubic meter of concrete mix based on nominal mix and durable design mix is presented in Table 6-5. The cost comparison does not consider the transportation cost of materials to a construction site at coastal regions and the cost of good quality water to produce concrete at site. However, these costs will be similar for both nominal mix and durable concrete mix.

Based on the cost comparison provided in Table 6-5, the unit cost of durable concrete mix is observed to be lower than the nominal mix concrete when stone aggregates are used in the mix. The cost of brick aggregate nominal mix concrete is lower than the durable concrete mix, but the strength and durability of designed concrete mix will be far better than the brick aggregate nominal concrete mix. It should be noted that, in the case of durable concrete mix, there will be additional capital costs in performing the trial mixes and associated durability testing in the laboratory.

7 Final recommendations

The design of concrete mixes has two strands viz., design for durability and design for strength. This report provides limiting values for concrete mix for durability. It should be noted that the final concrete mix should fulfil the design strength requirements. Therefore, the final cement content or water/cement ratio for concrete mix should be sufficient to attain the minimum design strength, which may be greater than that is required for durability.

7.1 Concrete specification for coastal districts of Bangladesh

Based on the discussions and conclusions achieved in the condition survey phase and field and laboratory study phase optimum and cost-effective concrete mixes have been identified for different exposure classes in the coastal districts of Bangladesh. The final recommendation for concrete mix should be based on the limiting values specified based on the exposure class as shown in Table 7-1

Table 7-1 Limiting values of durable concrete mix designed for 75 year service life

Coastal region	Exposure class	Limiting values for concrete			
		Minimum cover (mm)	Minimum cement content (kg/m3)	Cement type permitted	Additional protection measures
<1 km from coastal line (exposed to sea water)	Extreme	70	500	70% CEM I + 30% Fly ash (CEM II/B-V)	+Use of High range water reducing admixture + Corrosion inhibitor
Exposed coastal districts	Severe	40	400	70% CEM I + 30% Fly ash (CEM II/B-V)	+Use of High range water reducing admixture
Inner coastal districts	Moderate	40	300	70% CEM I + 30% Fly ash (CEM II/B-V), 60% CEM I + 40% slag (CEM III A)	+Use of High range water reducing admixture

7.1.1 Amendments to concrete specification in LGED schedule of rates standard

In majority of tender based contracts executed by LGED, the specification for concrete mix has been referred to basic specification given in 2015 schedule of rates document published for each district (cover page shown in Figure 7-1). The specification for reinforced concrete mainly consists of four different mixes with limiting values for each mix, which is based on the 28 days compressive strength of concrete as shown in Table 7-2.

Figure 7-1 LGED standard schedule of rates document

Table 7-2 Concrete specification in accordance with LGED schedule of rates 2015 standard

Concrete mix	Specification for concrete mix
RCC-17BCCM	➢ Nominal mix 1:2:4 ➢ Max w/c - 0.45 ➢ 17 MPa strength ➢ CEM II/A-M (42.5N) ➢ Crushed picked brick chips
RCC-20SCCM	➢ Nominal mix 1:2:4 ➢ Max w/c - 0.40 ➢ 20 MPa strength ➢ CEM I (52,5 N) ➢ Well graded stone aggregates
RCC-25SCCM	➢ Nominal mix 1:1.5:3 ➢ Max w/c - 0.40 ➢ 25 MPa strength ➢ CEM I (52,5 N) ➢ Well graded stone aggregates ➢ Water reducing admixture
RCC-30SCBP	➢ Nominal mix 1:1.5:3 ➢ Max w/c - 0.40 ➢ 25 MPa strength ➢ CEM I (52,5 N) ➢ Well graded stone aggregates ➢ Water reducing admixture

Based on the conclusions arrived in this study, the concrete specification in the LGED schedule of rates should be amended as listed below:

- Brick aggregates should not be used in reinforced concrete elements in coastal districts of Bangladesh
- The concrete mixes for reinforced elements in coastal districts should be classified based on the exposure class and specified in accordance to the limiting values given in Table 7-1
- All the concrete mixes used in coastal districts should be durable mix designed in the laboratory. Concrete mix design methodology should include chloride migration tests (NT Build 492)
- High range water reducing admixture shall be used in all the concrete mixes
- The requirements for stone aggregates and sand shall remain the same
- The chloride content of water used in concrete production shall be less than 1000ppm

8 Proposed follow-on activities

In order to achieve the ongoing development, uptake and embedment of the recommended solutions identified under the project, the following activities were identified:

- Project Cost/Benefit Analysis: Whole lifecycle costing of concrete structures focussing on a detailed comparison for a selected project under a) existing guidelines and practices versus b) the recommended solutions identified under this research project;
- Review and Update of Standards & Guidelines: Standards, guidelines and established practice that require to be reviewed and updated in line with the recommendations in this report, in close partnership with LGED, to be assured that design practice will reflect realistic and implementable solutions
- Training of Trainers: Successful implementation of the recommendations in this report relies on the training of local LGED engineers. The training workshops will also help in updating the local engineers on selection of appropriate materials for concrete, durability concrete mix design and quality control of concrete at construction sites.
- Supervision and Support for Pilot Project: In close partnership with LGED, an appropriate existing LGED construction project should be selected for the piloting and demonstration of the recommendations and mix designs from the project;

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Appendix A1

Summary of key meetings and information during Inception stage visits

Meeting/Event	Action/Key Contacts	Issues/Information
AsCAP National Steering Committee meeting	IG and RL gave a presentation on the background to the Project and proposed plan.	Potential clash of project objectives with Coastal Climate Resilient Infrastructure Project (CCRIP) identified Consider solutions for regions defined as "Inner Coastal" and "Exposed Coastal"
Local Government Engineering Department (LGED) meetings	A number of separate meetings held including with: MD. Abul Kalam Azad (Additional Chief Engineer) MD. Abul Monzur Sadeque (Executive Engineer – Planning) MD Abul Bashar (Superintending Engineer – Training and QC) Tapas Chowdhury (Senior Assistant Engineer)	A list of the 8 exposed coastal areas and 11 inner coastal districts was provided. Some districts have Upazillas (sub-districts) in both exposed and inner coastal classes Exposed coastal: Bhola, Cox's Bazaar Inner coastal: Barisal, Chandpur, Gopalganj, Jessore, Jhalkathi, Narail, Sariatpur Both Inner and Exposed Upzillas: Bagerhat, Barguna, Chittagong, Feni, Khulna, Laxmipur, Noakhali, Patuakhali, Pirojpur, Saatkhira LGED advised that to get a representative assessment of the different exposure conditions, four coastal districts were selected: Bagerhat, Noakhali, Gopalganj and Cox's Bazar Contact details of local LGED engineers have been provided but initial contact should be made through Abul Bashar LGED Design manuals are freely available and can be found on the following link http://www.lged.gov.bd/UnitPublication.aspx?UnitID=4 Inspection of LGED Central laboratory suggested basic testing facility suitable for routine testing (compressive strength of concrete cylinders) and routine aggregate testing (grading, absorption etc) and mix design development Copy of the CCRIP report provided

Meeting/Event	Action/Key Contacts	Issues/Information
Bangladesh University of Engineering and Technology (BUET)	Prof. Khan Mahmud Amanat Tanveer	Visited laboratory and in addition to the routine testing at LGED, capability to provide chemical testing of concrete and aggregates Discussion on a similar project undertaken by BUET indicated that the outcome of the project will be limited.
Blue/Gold Programme	Meeting with Engineers	Useful background on concreting practice in rural areas including shortage of quality raw materials in some areas (clean water, silt and salt free sand), tendency to add water to keep concrete usable and poor curing practice.
Aditya Birla Cement	Meeting in Dhaka Office and visit to Cement works Gautam Chatterjee (Country Manager) Pronoy Kumar Paul (Manager – Technical Services) Shaikh Abdur Rahaman (Departmental Head – Technical) Tanvir Ahmed (Senior Officer – Marketing)	The company was keen to explore opportunities to develop products for the rural marine environment. Cement production has a grinding facility that processed imported constituents. Produced both CEM I and CEM II/B-M (S-V-L). Plant was fully automated and on-site laboratory to enable production control testing.
Bashundhara Group	Meeting in Dhaka Office Kh. Kingshuk Hossain (Head of Division – Sales) Engr Saroj Kumar Barua (Deputy General Manager – Technical Support)	The company was very supportive of the project and the idea of developing products for the rural marine environment.

Appendix A2 – CorrPredict corrosion model – Input values

The CorrPredict chloride model developed based on the stochastic approach incorporated in the Model Code for service life design detailed in fib Bulletin 34. The model is based on the limit-state equation (eq 2) in which the threshold chloride level (C_{crit}) is compared to the actual chloride concentration at the depth of the reinforcing steel at time t.

$$C_{crit} = C(x = a, t) = C_0 + (C_{s,\Delta x} - C_0)\left[1 - erf\frac{d_c - \Delta x}{2 \times \sqrt{\left(\left\{exp\left(b_e\left(\frac{1}{T_{ref}} - \frac{1}{T_{real}}\right)\right)\right\}D_{RCM,0}.k_t.\left[\frac{t_0}{t}\right]^a\right)t}}\right] \quad - \quad (2)$$

All variables in the limit state function are statistically quantified (mean, standard deviation, and type of distribution function). The input values used in the CorrPredict chloride model for predicting the service life of a concrete element in marine splash zone is shown in Table A2-1. A sample screen shot of the Corrpredict model used in this study is shown in Figure A2-1.

Table A2-1 Input values used in CorrPredict Chloride model for concrete element in marine splash zone

Variable	Description	Unit	Distribution	Mean value	Standard Deviation
d_c	Concrete cover	mm	Normal distribution	Target 50mm	6
Δx	Depth of convection zone (ingress not to Fick's Law)	mm	BetaD	8.9	3.6
C_{crit}	Critical chloride concentration	% by weight cement	BetaD: $0.2 \leq C_{crit} \leq 2$	0.60	0.15
$C_{s,\Delta x}$	Concentration of chloride at depth Δx	% by weight cement	Log Normal Distribution	2.94 (slag) 2.1 (CEM I) 2.88 (Fly ash)	1.0
C_0	Background chloride	% by weight cement	Deterministic	0.15	-
b_e	Regression variable	K	Normal	4800	700
T_{real}	Temperature of the structural element or ambient	K	Normal	299	10
T_{ref}	Standard test temperature	K	Constant	299	-

Variable	Description	Unit	Distribution	Mean value	Standard Deviation
$D_{RCM,0}$	Diffusion coefficient at time t_0	10^{-12} m^2/s	Normal distribution	Obtained from Table 4-29 to Table 4-31	
a	Aging factor		BetaD: $0.2 \leq a \leq 2$	0.6	0.15 (depending on cement)
t_0	Time	years	Deterministic	0.0767	-
T	Design life	years	Deterministic	75	-

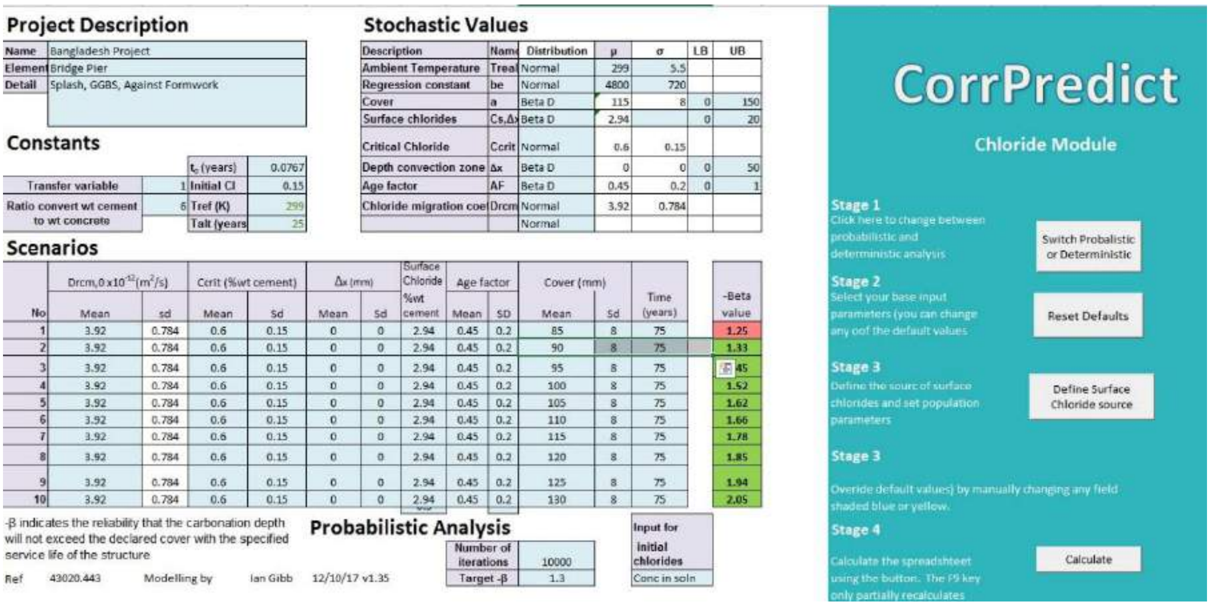


Figure A2-1 Screen shot of the CorrPredict Chloride induced corrosion deterioration model

Appendix B – Additional testing of concrete in Buildings

B.1 Gopalganj District

B.1.1 Gopalganj Sadar Upazilla Office

At Gopalganj Sadar Upazilla office, reinforced concrete columns in fencing wall and a reinforced concrete road were inspected. The fencing wall was around 25 years old and was constructed using brick aggregate concrete and plain steel bars. The reinforced concrete road was 3 years old and was constructed using brick aggregate concrete on an existing bituminous pavement. This site offered a good comparison of brick aggregate concrete of two different ages and therefore to investigate the quality of concrete, core samples were collected from the road to study the in-situ strength and concrete dust samples were collected from concrete columns in the fencing wall to study the chloride level in concrete. The concrete columns were also subjected to non-destructive testing using rebound hammer, cover meter and half-cell potential techniques as shown in Figure B1. The results of concrete testing are presented in Table B1. The visual inspection log is presented in Table 3-8 and the photo log in Appendix E.

(a) Concrete column in Upazilla office fence

(b) Concrete road in the Upazilla office

(c) NDT investigation of concrete columns

(d) Concrete core collection

Figure B1 Sample collection and testing of concrete at Gopalganj Sadar Upazilla Office

Table B1 Results of concrete testing of boundary wall columns at Gopalganj Sadar Upazilla office

Test	Result									
Rebound Hammer	Rebound Number:									
		1	2	3	4	5	6	7	8	9	Avg
	Col 1	32	33	36	35	32	30	29	36	32	33
	Col 2	30	29	25	25	24	28	28	24	28	27
	Col 3	22	26	26	26	24	32	32	30	29	27
	Concrete core testing result of road is pending.										
Cover meter	Cover varied between 40mm (min) to 50 mm (max)										
Half-Cell Potentials	Potentials (mV)										
	Top → Bottom										
	Col 1	-219	-189	-188	-290	-419					
	Col 2	-174	-176	-186	-255	-385					
	Col 3	-300	-286	-290	-328	-400					
Carbonation	<5mm carbonation on all three columns										

B.1.2 Old LGED Upazilla Parishad Building, Kotalipara

The Old LGED Upazilla office building in Kotalipara is a dilapidated structure that is believed to be constructed around 1970 and is now unoccupied and in a severely deteriorated state. The concrete used in different structural elements of the building was believed to be of 17MPa strength concrete using broken brick aggregates. As shown in Figure A2, the concrete elements are severely damaged by delamination, cracking and spalling in large areas due to corrosion of reinforcement. The high negative values of half-cell potentials and carbonation of concrete up to cover depth as presented in Table B2 indicate high levels of corrosion activity of reinforcement in the concrete elements. The visual inspection log is presented in Table 3-8 and the photo log in Appendix E.
An interesting observation made at this structure was that the cover meter survey of a masonry column indicated metallic presence in brick masonry. Following this, cover meter scanning of 6 different local bricks in Kotalipara showed that 2 of the 6 bricks triggered reinforcement presence, which was possibly due to metallic minerals in the bricks.

(a) Chapail road bridge on Modhumati river

(b) Location of concrete dust samples on pier-1

(c) Measurement of rebar spacing in roof slab concrete

(d) Concrete core extraction from first floor base slab

Figure B2 Dilapidated state of Old LGED office building in Kotalipara

Table B2 Results of concrete testing at old LGED Upazilla office at Kotalipara*

Rebound Hammer

1st floor - West beam (near stairs)

Rebound Number:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	28	27	28	39	30	30	28	30	31	30
Location 2	30	28	28	29	28	30	29	27	29	29

1st floor – East beam (near stairs)

Rebound Number:

	1	2	3	4	5	6	7	8	9	Avg
Location 1	36	35	33	34	36	34	29	24	38	33
Location 2	38	37	36	38	40	39	32	34	34	36

Cover meter

1st floor - West beam (near stairs)

Cover to reinforcement (mm)

	1	2	3	4	5	6
Inner face	47	48	49	51	46	39
Bottom face	28	34	37	43	45	54

Min cover: 28mm; Max cover: 54mm

1st floor - East beam (near stairs)

Cover to reinforcement (mm)

	1	2	3	4	5	6
Inner face	53	55	47	54	59	65
Bottom face	52	63	61	56	51	45

<table>
<tr><td></td><td>Min cover: 47mm; Max cover: 65mm</td></tr>
<tr><td>Half-cell Potentials</td><td>1st floor - West beam (near stairs)
Potentials (mV)
<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Inner face</td><td>-252</td><td>-240</td><td>-322</td><td>-297</td><td>-210</td><td>-144</td></tr>
<tr><td>Bottom face</td><td>-155</td><td>-148</td><td>-182</td><td>-296</td><td>-245</td><td>-218</td></tr>
</table>
1st floor - East beam (near stairs)
Potentials (mV)
<table>
<tr><th></th><th>1</th><th>2</th><th>3</th><th>4</th><th>5</th><th>6</th></tr>
<tr><td>Inner face</td><td>-240</td><td>-286</td><td>-193</td><td>-183</td><td>-168</td><td>-193</td></tr>
<tr><td>Bottom face</td><td>-292</td><td>-297</td><td>-270</td><td>-225</td><td>-224</td><td>-197</td></tr>
</table>
</td></tr>
<tr><td>Carbonation</td><td>Deck slab concrete:
Core hole 1 – 50mm
Core hole 2 – 45mm
Core hole 3 – 50mm</td></tr>
</table>

* chloride testing results are in Appendix D

B.2 Bagerhaat District

B.2.1 Dikraj Government Primary School building and High school building, Mongla

The primary school building was constructed in 2015 and broken brick chips were used in the concrete. At the time of the condition inspection, as the school was on term-time, only concrete columns in the corridor were inspected and concrete dust samples were collected to test the chloride content. The concrete columns were covered with 20-30mm mortar layer and all the external walls and columns were painted as shown in Figure B3(a). This additional layer of mortar and the painted surface provided additional layers of protection for the concrete and therefore the cover for reinforcement was observed to be high as given in Table B3.

The High school building was constructed by Public Works Department (PWD) of Bangladesh in 2001. It was believed that at the time of construction local water containing high level of chlorides might have been used in the concrete mix along with broken brick aggregates. The inspection of concrete elements in the main corridor of the building showed delaminated mortar layer along with longitudinal cracks in beams and columns. At the time of drilling of concrete for dust collections, it was observed that the concrete was porous/voided as the progression of drilling process went too fast and cracks appeared at the surface on the mortar layer. The visual inspection log for both primary school and High school is presented in Table 3-11 and the photo log in Appendix E.

(a) Dikraj Government Primary School building

(b) Collection of concrete dust samples in column

(c) Dikraj Government High School building

(d) School Corridor - Longitudinal cracks in columns and beams

Figure B3 Primary school and High school buildings in Mongla

Table B3 Results of concrete testing of column at Dikraj primary school building*

Rebound Hammer	Concrete column (in corridor) Rebound Number:									
		1	2	3	4	5	6	7	8	9	Avg
	Column 1	27	26	25	31	36	31	34	32	34	31
	Column 2	30	26	25	27	28	26	26	28	26	27
	Column 3	24	26	24	24	24	23	27	29	26	25
	Column 4	27	28	29	26	26	28	28	26	30	28
Cover meter	Min cover: 68mm; Max cover: 82mm									
Carbonation	No carbonation of concrete									

*Concrete chloride testing results are presented in Appendix D

B.2.2 Rampal LGED Upazilla office and Upazilla Education office

The LGED Upazilla office in Rampal is a recent construction built in 2014. The concrete used in columns and beams is 21 MPa design strength and imported stone aggregates were used in the concrete. The cover to the reinforcement in columns were found to be varying between 57-85mm, which includes 20mm mortar layer.

The Upazilla Education office in Rampal was constructed in 2008. The concrete used in columns, beams and roof slab of the building was believed to be around 20 MPa design strength and contains broken brick aggregates as coarse aggregates. As the Education office was closed, only external columns, lintels and cantilever edges of roof slab was inspected. It can be observed from Figure B4(c) & (d) that bottom portion of the columns and masonry walls were beginning to deteriorate due to capillary rise of moisture from the ground and associated salt attack. The level of deterioration of concrete observed in external columns varied around the building and the progression of deterioration is shown in Figure B5. The results of NDT covermeter testing of columns at LGED Upazilla office is presented in Table B4. The visual inspection log is presented in Table 3-11 and the photo log in Appendix E.

(a) LGED Upazilla Office, Rampal

(b) Testing chloride content of water using Quantab Strips at Rampal

(c) Rampal Upazilla Education office

(d) Salt damage on external faces of concrete columns and masonry walls

Figure B4 Condition survey of LGED Upazilla office building and Rampal Upazilla Education office building

Figure B5 Progression of concrete deterioration in columns of Rampal Upazilla Education Office

TableB4: Results of concrete testing of columns at Rampal*

Rebound Hammer	LGED Upazilla Office & Upazilla Education office: Due to thick external mortar layer on concrete columns, rebound hammer values were low
Cover meter	LGED Upazilla office - Concrete columns Min cover: 57mm; Max cover: 85mm Upazilla Education office – Concrete columns Min cover: 65mm; Max cover: 70mm
Carbonation	No carbonation of concrete

*Concrete chloride testing results are presented in Appendix D

B.3 Cox's Bazar District

B.3.1 Uttan Nuniya Chana Government Primary School

The primary school building was constructed in 1995 by LGED and broken brick aggregates were used as coarse aggregates in the concrete mix. The visual observation of concrete structural elements indicate that condition of concrete is severely deteriorated due to high corrosion activity of reinforcement as shown in Figure B6. The results of concrete testing are presented in Table B5. The half-cell potential testing in columns showed very low values due to delamination of concrete and therefore further testing for half-cell potentials was abandoned.
The scope of this condition survey is only to give a factual report on the condition of concrete elements and not to make any recommendation, however the condition of severe cracking and spalling of concrete observed in this building is found to be unsafe for occupation. It is therefore necessary that a detailed structural investigation of the school building and associated repair works are necessary before it can be used by local pupils. The visual inspection log is presented in Table 3-17 and the photo log in Appendix E.

(a) Govt. Primary School, Ukhiya

(b) Delamination and pattern cracking of concrete in column

(c) Cracking, delamination and spalling of concrete, mould growth on walls in class room

(d) Spalling of concrete and exposed reinforcement underneath staircase

Figure B6 Condition survey of government primary school building in Ukhiya

Table B5 Results of concrete testing of columns at Uttan Nania Chana primary school building*

<table>
<tr><td>Rebound Hammer</td><td>Ground floor external concrete columns:
<table>
<tr><td></td><td>1</td><td>2</td><td>3</td><td>4</td><td>5</td><td>6</td><td>7</td><td>8</td><td>9</td><td>Avg</td></tr>
<tr><td>Column 1</td><td>16</td><td>20</td><td>21</td><td>16</td><td>15</td><td>16</td><td>21</td><td>20</td><td>14</td><td>18</td></tr>
<tr><td>Column 2</td><td>34</td><td>31</td><td>29</td><td>31</td><td>29</td><td>28</td><td>24</td><td>37</td><td>34</td><td>31</td></tr>
<tr><td>Column 3</td><td>35</td><td>31</td><td>32</td><td>29</td><td>21</td><td>21</td><td>20</td><td>22</td><td>35</td><td>27</td></tr>
</table></td></tr>
<tr><td>Cover meter</td><td>External face - Concrete columns
Min cover: 65mm;
Max cover: 75mm</td></tr>
<tr><td>Carbonation</td><td>Column 1: <5mm
Column 2: 10mm
Column 3: <5mm</td></tr>
</table>

*Concrete chloride testing results are presented in Appendix D

B.3.2 Md. Shofinbil Government Primary School and Cyclone shelter

The primary school which is also used as emergency cyclone shelter was constructed in 1994. The concrete used in the structural elements was made of broken brick aggregates as coarse aggregates and marine sand as fine aggregates. The visual inspection of concrete elements of the building suggest that some of the concrete columns and beams in the structure are severely deteriorated and damaged as shown in Figure B7. The proximity of the building to sea coast makes it vulnerable to air borne chlorides and ingress of chlorides from ground. The quality of concrete was observed to be porous and poorly graded. Prolonged exposure of low quality concrete to marine conditions had resulted in corrosion of reinforcement and associated damage of cover concrete. The results of concrete testing of columns in ground floor of the building are presented in Table B6. Although it is not in our remit to make recommendations, the damaged condition of columns and beams in this building needs urgent attention as the on-going corrosion of reinforcement and spalling of concrete will pose imminent risk for pupils. The visual inspection log is presented in Table 3-17 and the photo log in Appendix E.

(a) Deteriorated concrete column

(b) Concrete spalling and rebar corrosion in lintel beams

(c) Cracking and, delamination of concrete in 1st floor columns

(d) Spalling of concrete and exposed reinforcement in 2nd floor

Figure B7 Condition of concrete at Md. Shofinbil Government Primary School

Table B6: Results of concrete testing of columns at Md. Shofinbil primary school*

Test	Results									
Rebound Hammer	Ground floor external concrete columns:									
		1	2	3	4	5	6	7	8	9	Avg
	Column 1	28	35	38	25	22	25	24	28	32	29
	Column 2	24	26	29	23	26	28	28	32	31	27
	Column 3	42	34	39	26	32	34	28	34	25	33
	Column 4	26	33	30	27	39	33	35	37	42	34
Cover meter	External face - Concrete columns Min cover: 65mm; Max cover: 85mm									
Carbonation	Column 1: 15mm Column 2: 20mm Column 3: 20mm									

*Concrete core testing and chloride testing results are presented in Appendix B and C

B.4 Noakhali District

B.4.1 Charbata Tajpur School, Subarnochar, Noakhali

The Charbata Tajpur school has North building that was constructed in 1994 and newer south building constructed in 2010. The visual inspection of the old school building suggests that the condition of concrete in the building is deteriorated as shown in Figure B8. The concrete in the building is observed to be of poor quality and contains poorly graded brick aggregates. Most of the concrete columns at the front corridor of the building as shown in Figure B8 were observed to be cracked, delaminated and spalled in the cover zone. The cracks and delamination of concrete in the classroom roof slab beams were observed to be critical and poses high risk for pupils. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

(a) General view of the new school building

(b) Longitudinal cracking in roof slab beam

(c) Cracking and, delamination of concrete in roof slab beam

(d) Cracking of concrete in column

Figure B8 Condition survey of school building at Subarnochar, Noakhali

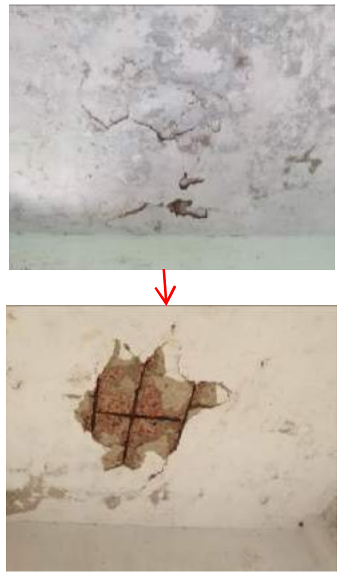
B.4.2 Char Mandolia Govt Primary School, Kobinhat, Noakhali

The Char Mandolia Government primary school was constructed in the year 2000 and the concrete in structural elements of the building contains brick chips as coarse aggregates. The visual inspection of the school building suggests severely damaged columns, delamination, and cracking of concrete beams in roof slab and dampness/water leaking in the roof slab as shown in Figure B9. The structural condition of the building is found to be poor and therefore needs urgent attention. The visual inspection log is presented in Table 3-23 and the photo log in Appendix E.

(a) General view of the Primary School building

(b) Concrete dust collection from the columns in the corridor

(c) Extensive corrosion induced damage of various columns in the school building



(d) Delamination and spalling of concrete in roof slab

Figure B9 Condition survey of concrete elements at Char Mandolia Govt Primary School, Kobinhat

Appendix C - List of concrete core samples and test results

Sl No.	District	Location	Name of the Core Sample	Date of sampling	No. of Core
1	Gopalganj	Gopalganj Sadar Upazilla road	GG 01	20/09/2016	1
2			GG 02		1
3			GG 03		1
4			GG 04		1
5			GG 05/01		1
6			GG 05/02		1
7			GG 05/03		1
8			GG 05/04		1
9			GG 05/05		1
10			GG 05/06		1
11		Kotalipara	Kot 01/01	21/09/2016	1
12			Kot 01/02		1
13			Kot 01/03		1
14			Kot 01/04		1
15			Kot 01/05		1
16	Bagerhat	Mongla	Mong 03/01	22/09/2016	1
17			Mong 03/02		1
18			Mong 03/03		1
19			Mong 04/01		1
20			Mong 04/02		1
21			Mong 04/03		1
22			Mong 04/04		1
23		Rampal	Rampal 03/01	23/09/2016	1
24			Rampal 03/02		1
25			Rampal 03/03		1
26	Cox's Bazar	Road infront of Nania Chara Primary School, Cox's Bazar Sadar	Sample 01	08/10/2016	1
27			Sample 02		1
28			Sample 03		1
29		Md. Shofirbil Gov. School/ Cyclone Centre, Ukhiya	Sample 04	09/10/2016	1
30			Sample 05		1
31			Sample 06		1

Sl No.	District	Location	Name of the Core Sample	Date of sampling	No. of Core
32		Bridge at Moddho Raja Palang, Ukhiya	Sample 07		1
33			Sample 08		1
34			Sample 09		1
35		Rubber Dam, Raja Palang, Ukhiya	Sample 10		1
36			Sample 11		1
37			Sample 12		1
38		Bridge opposite of Islampur Public Model School, Islamabad, Cox's Bazar Sadar	Sample 13	10/10/2016	1
39			Sample 14		1
40			Sample 15		1
41		Culvert, Boalkhali Road, Islampur, Cox's Bazar Sadar	Sample 16		1
42			Sample 17		1
43			Sample 18		1
44	Noakhali	Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Shorhat, GC road, Purbocharbata, Subarnochar	Sample 01	25/10/2016	1
45			Sample 02		1
46			Sample 03		1
47		Box Culvert, Char Amanullah, word no 27, Subarnochar	Sample 04		1
48			Sample 05		1
49			Sample 06		1
50		Two vent Box Culvert, Kolimuddinpul, Kabirhat	Sample 07	26/10/2016	1
51			Sample 08		1
52			Sample 09		1

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BRTC Bureau of Research, Testing & Consultation

CONCRETE LABORATORY

BRTC No.	: **1101-20589/16-17/CE; Dt: 9/10/2016**
Client	: M. Ben Witjes, Country Director, Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concele Stucture in the Marine Environment of Bangladesh
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 20/9/2016
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 20/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Mongla, Bagerhat	Mong 03/01	3.9	3.74	10.99	37,732	3020 psi (20.8 MPa)	Mortar (Stone Chips)
2	Mongla, Bagerhat	Mong 03/02	4.6	3.74	10.99	29,566	2490 psi (17.2 MPa)	Mortar (Stone Chips)
3	Mongla, Bagerhat	Mong 03/03	4.4	3.74	10.99	36,824	3060 psi (21.1 MPa)	Mortar (Stone Chips)
4	Mongla, Bagerhat	Mong 04/02	4.8	3.74	10.99	47,259	4020 psi (27.7 MPa)	Combined * (Stone Chips)
5	Mongla, Bagerhat	Mong 04/03	4.5	3.74	10.99	49,981	4180 psi (28.8 MPa)	Mortar (Stone Chips)
6	Mongla, Bagerhat	Mong 04/04	4.3	3.74	10.99	41,361	3410 psi (23.5 MPa)	Combined * (Stone Chips)

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

Countersigned by:

Dr. Abu Siddique
Professor
Department of Civil Engineering
BUET, Dhaka-1000, Bangladesh

Department of Civil Engineering, BUET, Dhaka-1000, Bangladesh

Test Performed by:

23/10/16

Snigdha Afsana
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BRTC Bureau of Research, Testing & Consultation

CONCRETE LABORATORY

BRTC No.	: **1101-20589/16-17/CE; Dt: 9/10/2016**
Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concele Stucture in the Marine Environment of Bangladesh
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 20/9/2016
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 20/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Gona Belai, Rampal Bagerhat	Rampal 03/01	3.5	2.72	5.81	17,913	2880 psi (19.9 MPa)	Mortar (Stone Chips)
2	Gona Belai, Rampal Bagerhat	Rampal 03/02	4.8	2.72	5.81	13,961	2400 psi (16.6 MPa)	Mortar (Stone Chips)
3	Gona Belai, Rampal Bagerhat	Rampal 03/03	4.5	2.72	5.81	11,765	1970 psi (13.6 MPa)	Mortar (Stone Chips)
-	-	-	-	-	-	---	-	-
-	-	-	-	-	-	---	-	-
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

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Countersigned by:

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Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 20/9/2016
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 20/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Gopalganj Sadar Upazila Road, Gopalgonj	GG 01	4.5	3.74	10.99	44,990	3760 psi (25.9 MPa)	Combined * (Brick Chips)
2	Gopalganj Sadar Upazila Road, Gopalgonj	GG 03	4.5	2.72	5.81	15,718	2630 psi (18.1 MPa)	Mortar (Stone Chips)
3	Gopalganj Sadar Upazila Road, Gopalgonj	GG 04	3.8	3.74	10.99	29,112	2320 psi (16 MPa)	Mortar (Stone Chips)
4	Gopalganj Sadar Upazila Road, Gopalgonj	GG 05/01	4.5	2.72	5.81	10,887	1820 psi (12.6 MPa)	Combined * (Brick Chips)
5	Gopalganj Sadar Upazila Road, Gopalgonj	GG 05/02	2.9	2.72	5.81	9,131	1390 psi (9.6 MPa)	Combined * (Brick Chips)
6	Gopalganj Sadar Upazila Road, Gopalgonj	GG 05/03	3.0	2.72	5.81	10,228	1570 psi (10.8 MPa)	Combined * (Brick Chips)

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

Countersigned *by*:

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Department of Civil Engineering
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CONCRETE LABORATORY

BRTC No. : **1101-20589/16-17/CE; Dt: 9/10/2016**

Client : M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald

Ref. No. : Letter; Dt: 6/10/2016

Project : Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh

Sample : **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]

Year of Construction : Not Mentioned   No. of Floors = Not Mentioned

Sample Collected by : **Client**   Date of Sample Collection: 20/9/2016

Test : **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**

Date of Test : 20/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Kotlipara, Gopalgonj	KOT 05/01	4.5	2.72	5.81	10,887	1820 psi (12.6 MPa)	Combined * (Brick Chips)
2	Kotlipara, Gopalgonj	KOT 05/02	3.0	2.72	5.81	9,131	1410 psi (9.7 MPa)	Combined * (Brick Chips)
-	-	-	-	-	-	---	-	-
-	-	-	-	-	-	---	-	-
-	-	-	-	-	-	---	-	-
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

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Countersigned by:

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CONCRETE LABORATORY

BRTC No.	: **110-122044/16-17/CE; Dt: 6/11/2016**
Client	: Mr. Ben Witjes, Country Director, Bangladesh, Mott MacDonald, Plot 77(Floor-6), Road 11, Block-M, Banani, Dhaka
Ref. No.	: letter; Dt: 2/11/2016
Project	: Study on Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh (Location:Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Shorhat, GC road, Purbocharbata, Subarna Char)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): 0, Aggregate Type: Brick Chips]
Date of Casting	: // Date of Sample Collection*: 25/10/2016
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 13/11/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Please see Project Location	Sample 01	5.1	3.70	10.75	30,244	2660 psi (18.3 MPa)	Combined **
2	Please see Project Location	Sample 02	4.8	3.70	10.75	26,195	2280 psi (15.7 MPa)	Combined **
3	Please see Project Location	Sample 03	4.3	3.70	10.75	23,046	1950 psi (13.4 MPa)	Combined **
4	-	-	-	-	-	-	-	-

* Samples were collected by Client.

** Combined = Mortar and Aggregate failure

* Samples were received in unsealed condition.

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

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Countersigned by:

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BRTC No.	: **110-122044/16-17/CE; Dt: 6/11/2016**
Client	: Mr. Ben Witjes, Country Director, Bangladesh, Mott MacDonald, Plot 77(Floor-6), Road 11, Block-M, Banani, Dhaka
Ref. No.	: letter; Dt: 2/11/2016
Project	: Study on Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh (Location:Box Culvert, Char Amanullah, word no 27, Subarna Char)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): 0, Aggregate Type: Stone Chips]
Date of Casting	: // Date of Sample Collection*: 25/10/2016
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 13/11/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Please see Project Location	Sample 04	3.7	2.72	5.81	13,961	2270 psi (15.7 MPa)	Combined **
2	Please see Project Location	Sample 05	3.7	2.72	5.81	13,961	2270 psi (15.7 MPa)	Combined **
3	Please see Project Location	Sample 06	3.7	2.72	5.81	27,794	4510 psi (31.1 MPa)	Combined **
4	-	-	-	-	-	-	-	-

* Samples were collected by Client.
** Combined = Mortar and Aggregate failure
* Samples were received in unsealed condition.

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

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Countersigned by:

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Professor
Department of Civil Engineering
BUET, Dhaka-1000, Bangladesh

Department of Civil Engineering * BUET, Dhaka-1000, Bangladesh *

Test Performed by:
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Dr. M. Habibur Rahman
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BRTC Bureau of Research, Testing & Consultation

Concrete Laboratory

BRTC No. : **110-122044/16-17/CE; Dt: 6/11/2016**
Client : Mr. Ben Witjes, Country Director, Bangladesh, Mott MacDonald, Plot 77(Floor-6), Road 11, Block-M, Banani, Dhaka
Ref. No. : letter; Dt: 2/11/2016
Project : Study on Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh (Location: Two vent Box Culvert, Kolimuddinpul, Kabirhat)
Sample : **Concrete Cylindrical Core** [Mix Proportion (as quoted): 0, Aggregate Type: Stone Chips]
Date of Casting : // Date of Sample Collection*: 26/10/2016
Test : **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test : 13/11/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Please see Project Location	Sample 07	5.0	3.70	10.75	22,596	1980 psi (13.7 MPa)	Mortar
2	Please see Project Location	Sample 08	4.3	3.70	10.75	32,044	2710 psi (18.7 MPa)	Combined **
3	Please see Project Location	Sample 09	3.7	3.70	10.75	44,641	3610 psi (24.9 MPa)	Combined **
4	-	-	-	-	-	-	-	-

* Samples were collected by Client. ** Combined = Mortar and Aggregate failure

* Samples were received in unsealed condition.

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

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Test Performed by:

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CONCRETE LABORATORY

BRTC No.	: **1101-21168/15-16/CE; Dt: 23/10/2016**
Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Road infront of Nania Chara Primary School, Cox's Bazar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 8/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Road	Sample- 01	5.4	3.70	10.75	19,611	1740 psi (12 MPa)	Mortar (Stone Chips)
2	Road	Sample- 02	4.4	3.70	10.75	13,781	1170 psi (8.1 MPa)	Mortar (Stone Chips)
3	Road	Sample- 03	5.4	3.70	10.75	16,248	1440 psi (9.9 MPa)	Mortar (Stone Chips)
-	-	-	-	-	-	---	-	-

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

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Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Md. Shofirbil Govt. School/ Cyclone Center, Ukhiya, Cox's Bazar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 8/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	--	Sample- 04	2.9	2.72	5.81	19,011	2900 psi (20 MPa)	Combined * (Stone Chips)
2	--	Sample- 05	3.4	2.72	5.81	16,816	2690 psi (18.6 MPa)	Combined * (Stone Chips)
3	--	Sample- 06	4.4	2.72	5.81	7,374	1230 psi (8.5 MPa)	Mortar (Stone Chips)
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

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Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Bridge at Moddho Raja Palang, Ukhiya, Cox's Bazar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned No. of Floors = Not Mentioned
Sample Collected by	: **Client** Date of Sample Collection: 9/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in	lb.		
1	Bridge	Sample- 07	3.1	2.72	5.81	14,181	2210 psi (15.2 MPa)	Combined * (Brick Chips)
2	Bridge	Sample- 08	3.9	2.72	5.81	20,329	3330 psi (23 MPa)	Combined * (Brick Chips)
3	Bridge	Sample- 09	3.6	2.72	5.81	13,522	2180 psi (15 MPa)	Combined * (Brick Chips)
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

Countersigned by:

Dr. Abu Siddique
Professor
Department of Civil Engineering
BUET, Dhaka-1000, Bangladesh

Department of Civil Engineering, BUET, Dhaka-1000, Bangladesh

Test Performed by:

29/10/16

Snigdha Afsana
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BRTC Bureau of Research, Testing & Consultation

CONCRETE LABORATORY

BRTC No.	: **1101-21168/15-16/CE; Dt: 23/10/2016**
Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Rubber Dam, Raja Palang, Ukhiya, Cox's Bazar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned; No. of Floors = Not Mentioned
Sample Collected by	: **Client**; Date of Sample Collection: 9/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Rubber Dam	Sample-10	4.7	2.72	5.81	16,816	2830 psi (19.5 MPa)	Combined * (Stone Chips)
2	Rubber Dam	Sample-11	4.5	2.72	5.81	25,379	4250 psi (29.3 MPa)	Combined * (Stone Chips)
3	Rubber Dam	Sample-12	4.3	2.72	5.81	19,231	3200 psi (22.1 MPa)	Combined * (Stone Chips)
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

Countersigned *by*:

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Professor
Department of Civil Engineering
BUET, Dhaka-1000, Bangladesh

Department of Civil Engineering * BUET, Dhaka-1000, Bangladesh *

Test Performed *by*:

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BRTC No.	: **1101-21168/15-16/CE; Dt: 23/10/2016**
Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Bridge opposite to Islampur Public Model School, Islamabad, Cox's Bazar Sadar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 10/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Bridge	Sample- 13	3.5	2.72	5.81	11,546	1860 psi (12.8 MPa)	Combined * (Brick Chips)
2	Bridge	Sample- 14	3.7	2.72	5.81	19,450	3160 psi (21.8 MPa)	Combined * (Brick Chips)
3	Bridge	Sample- 15	3.9	2.72	5.81	19,011	3110 psi (21.4 MPa)	Combined * (Brick Chips)
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

NOTE 3 — Among the supplied samples, sample no- 13 found to contain piece of reinforcement on the peripheral surface of the core

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

Countersigned *by*:

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BRTC Bureau of Research, Testing & Consultation

CONCRETE LABORATORY

BRTC No.	: **1101-21168/15-16/CE; Dt: 23/10/2016**
Client	: M. Ben Witjes, Country Director,Bangladesh, Mott Macdonald
Ref. No.	: Letter; Dt: 6/10/2016
Project	: Study on Climate Resilient Reinforced Concete Stucture in the Marine Environment of Bangladesh (Location- Culvert, Boalkhali Road, Islampur, Cox's Bazar sadar)
Sample	: **Concrete Cylindrical Core** [Mix Proportion (as quoted): Not Mentioned]
Year of Construction	: Not Mentioned — No. of Floors = Not Mentioned
Sample Collected by	: **Client** — Date of Sample Collection: 10/10/2015
Test	: **Compressive Strength of Concrete Cylindrical Core [ASTM C 42/C 42M]**
Date of Test	: 26/10/2016

TEST REPORT

Sl. No.	Location	Sample Identification Mark	Length of Sample	Diameter of Sample	Average Cross Sectional Area	Ultimate Load	Crushing Strength	Type of Failure
			in.	in.	sq. in.	lb.		
1	Culvert	Sample-16	5.4	3.70	10.75	25,440	2260 psi (15.6 MPa)	Combined * (Stone Chips)
2	Culvert	Sample-17	5.4	3.70	10.75	9,297	830 psi (5.7 MPa)	Mortar (Stone Chips)
3	Culvert	Sample-18	5.3	3.70	10.75	22,974	2030 psi (14 MPa)	Mortar (Stone Chips)
-	-	-	-	-	-	---	-	-

* Combined = Mortar and Aggregate failure

NOTE 1 — The diameter of core specimens for the determination of compressive strength in load bearing structural members shall be at least 3.70 in. [94 mm]. For non-load bearing structural members or when it is impossible to obtain cores with length-diameter ratio (L/D) greater than or equal to 1, core diameters less than 3.70 in. [94 mm] are not prohibited.

NOTE 2 — The compressive strengths of nominal 2-in. [50-mm] diameter cores are known to be somewhat lower and more variable than those of nominal 4-in. [100-mm] diameter cores. In addition, smaller diameter cores appear to be more sensitive to the effect of the length-diameter ratio.

COMMENT — Please compare the results with your corresponding design values and consult with your design engineer.

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Appendix D – List of concrete dust samples and test results

Sl No.	District	Location		Name of the Dust Sample	Date of sampling	No. of dust samples per hole
1	Gopalganj	Gopalganj Sadar		GG 01	20/09/2016	3
2				GG 02		3
3				GG 04/01		3
4				GG 04/02		3
5				GG 04/03		3
6				GG 05/01		3
7				GG 05/02		3
8				GG 05/03		3
9				GG 05/04		3
10				GG 05/05		3
11				GG 06/01		4
12				GG 06/02		4
13				GG 06/03		4
14		Kotalipara		Kot 01/01	21/09/2016	3
15				Kot 01/02		3
16				Kot 01/03		3
17				Kot 01/04		3
18	Bagerhat	Mongla		Mong 01/01	22/09/2016	3
19				Mong 01/02		3
20				Mong 01/03		3
21				Mong 02/01		3
22				Mong 03/01		3
23				Mong 03/02		1
24		Rampal		Rampal 01/01	23/09/2016	3
25				Rampal 01/02		3
26				Rampal 01/03		3
27				Rampal 01/04		3
28				Rampal 01/05		3
29				Rampal 01/06		3
30				Rampal 02/01		3

Sl No.	District	Location		Name of the Dust Sample	Date of sampling	No. of dust samples per hole
31				Rampal 02/02		3
32				Rampal 02/03		3
33				Rampal 03/01		3
34				Rampal 03/02		3
35				Rampal 03/03		3
36	Cox's Bazar	North Naniachara Primary Gov. School, Cox's Bazar Sadar	Column -1	Sample 01/01 ~ 03	08/10/2016	3
37			Column - 2	Sample 02/01 ~ 03		3
38			Column - 3	Sample 03/01 ~ 03		3
39			Drop Wall - 1	Sample 04/01 ~ 03		3
40			Drop Wall - 2	Sample 05/01 ~ 03		3
41		Md. Shofirbil Gov. School/ Cyclone Centre, Ukhiya	Column - 1	Sample 06/01 ~ 03	09/10/2016	3
42			Column - 2	Sample 07/01 ~ 03		3
43			Column - 3	Sample 08/01 ~ 03		3
44			Column - 4	Sample 09/01 ~ 03		3
45			Beam - 1	Sample 10/01 ~ 03		3
46			Beam - 2	Sample 11/01 ~ 03		3
47		Raja Palang, Ukhiya	Rubber Dam, Abutment / Wingwall	Sample 12/01 ~ 03	10/10/2016	3
48				Sample 13/01 ~ 03		3
49				Sample 14/01 ~ 03		3
50		Bridge opposite of Islampur	Bridge Rail -Post - 1	Sample 15/01 ~ 03		3

Sl No.	District	Location		Name of the Dust Sample	Date of sampling	No. of dust samples per hole
51		Public Model School, Islamabad, Cox's Bazar Sadar	Bridge Rail -Post - 2	Sample 16/01 ~ 03		3
52			Bridge Rail -Post - 3	Sample 17/01 ~ 03		3
53		Eidgah, Islamabad, Cox's Bazar Sadar	Sluice Gate - Top	Sample 18/01 ~ 04		4
54			Sluice Gate - Bottom	Sample 19/01 ~ 04		4
55		Culvert, Boalkhali Road, Islampur, Cox's Bazar Sadar	Rail - 1 (one side of culvert)	Sample 20/01 ~ 03		3
56			Rail - 2 (opposite side of culvert)	Sample 21/01 ~ 03		3
57	Noakhali	Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Shorhat, GC road, Purbocharbata, Subarnocharr	West - South Rail/ Wheel Guard	Sample 01/01 ~ 04	25/10/2016	4
58				Sample 02/01 ~ 04		4
59			North - East Rail/ Wheel Guard	Sample 03/01 ~ 04		4
60				Sample 04/01 ~ 04		4
61		Box Culvert, Char Amanullah, word no 27, Subarnochar	South Rail/ Wheel Guard	Sample 05/01 ~ 03		3
62			North Rail/ Wheel Guard	Sample 06/01 ~ 03		3
63		Burma Bridge Chaprashi Canal, Char Gulakhali, Kabirhat	North Rail/ Wheel Guard	Sample 07/01 ~ 03	26/10/2016	3
64			South Rail/ Wheel Guard	Sample 08/01 ~ 03		3
65		Char Mondolia Gov. Primary School, Kabirhat	Front Column - 1	Sample 09/01 ~ 03		3
66			Front Column - 2	Sample 10/01 ~ 03		3

Sl No.	District	Location		Name of the Dust Sample	Date of sampling	No. of dust samples per hole
67			Front Column - 3	Sample 11/01 ~ 03		3
68		Two vent Box Culvert, Kolimuddinpul, Kabirhat	North Rail/ Wheel Guard	Sample 12/01 ~ 04		4
69			South Rail/ Wheel Guard	Sample 13/01 ~ 04		4

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NICHOLLS COLTON ANALYTICAL

TEST REPORT

BS1881 CHLORIDE CONTENT

Chloride Content

Report no. L16/2679/MMD/001 – Amendment A	
Order reference: 373654CS01	Date of testing: 22 to 25/11/2016
Date of receipt: 21/11/2016	Date of issue: 01/12/2016

NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Gopalganj						
1	GG 01	Gopalganj Sadar	Concrete Dust	5-25	**0.023**	**0.17**
2	GG 01	Gopalganj Sadar	Concrete Dust	25-50	**0.017**	**0.12**
3	GG 01	Gopalganj Sadar	Concrete Dust	50-75	**0.020**	**0.14**
4	GG 02	Gopalganj Sadar	Concrete Dust	5-25	**0.007**	**0.05**
5	GG 02	Gopalganj Sadar	Concrete Dust	25-50	**0.009**	**0.06**
6	GG 02	Gopalganj Sadar	Concrete Dust	50-75	**0.019**	**0.14**
7	GG 04/01	Gopalganj Sadar	Concrete Dust	5-25	**0.012**	**0.09**
8	GG 04/01	Gopalganj Sadar	Concrete Dust	25-50	**< 0.004**	**<0.03**
9	GG 04/01	Gopalganj Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
10	GG 04/02	Gopalganj Sadar	Concrete Dust	5-25	**0.017**	**0.12**
11	GG 04/02	Gopalganj Sadar	Concrete Dust	25-50	**0.014**	**0.10**
12	GG 04/02	Gopalganj Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
13	GG 04/03	Gopalganj Sadar	Concrete Dust	5-25	**0.013**	**0.09**
14	GG 04/03	Gopalganj Sadar	Concrete Dust	25-50	**0.007**	**0.05**
15	GG 04/03	Gopalganj Sadar	Concrete Dust	50-75	**0.107**	**0.77**
16	GG 05/01	Gopalganj Sadar	Concrete Dust	5-25	**0.050**	**0.36**
17	GG 05/01	Gopalganj Sadar	Concrete Dust	25-50	**0.044**	**0.31**
18	GG 05/01	Gopalganj Sadar	Concrete Dust	50-75	**0.144**	**1.03**

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0320

L16/2679/MMD/001

NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	**Chloride Ion Content (% by mass of concrete)**	**Chloride Ion Content (% by mass of cement)**
Gopalganj						
19	GG 05/02	Gopalganj Sadar	Concrete Dust	5-25	**0.038**	**0.27**
20			Concrete Dust	25-50	**0.010**	**0.07**
21			Concrete Dust	50-75	**0.022**	**0.16**
22	GG 05/03		Concrete Dust	5-25	**0.021**	**0.15**
23			Concrete Dust	25-50	**0.017**	**0.12**
24			Concrete Dust	50-75	**< 0.004**	**<0.03**
25	GG 05/04		Concrete Dust	5-25	**0.011**	**0.08**
26			Concrete Dust	25-50	**0.005**	**0.03**
27			Concrete Dust	50-75	**0.020**	**0.15**
28	GG 05/05		Concrete Dust	5-25	**0.014**	**0.10**
29			Concrete Dust	25-50	**0.007**	**0.05**
30			Concrete Dust	50-75	**0.013**	**0.09**
31	GG 06/01		Concrete Dust	5-25	**0.017**	**0.12**
32			Concrete Dust	25-50	**0.008**	**0.06**
33			Concrete Dust	50-75	**0.014**	**0.10**
34			Concrete Dust	75-100	**0.012**	**0.08**
35	GG 06/02		Concrete Dust	5-25	**0.013**	**0.09**
36			Concrete Dust	25-50	**0.015**	**0.11**
37			Concrete Dust	50-75	**0.004**	**0.03**
38			Concrete Dust	75-100	**0.005**	**0.04**
39	GG 06/03		Concrete Dust	5-25	**0.012**	**0.08**
40			Concrete Dust	25-50	**0.010**	**0.07**
41			Concrete Dust	50-75	**0.010**	**0.07**
42			Concrete Dust	75-100	**0.009**	**0.06**
43	Kot 01/01	Kotalipara	Concrete Dust	5-25	**0.004**	**0.03**
44			Concrete Dust	25-50	**0.006**	**0.04**
45			Concrete Dust	50-75	**0.041**	**0.30**

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0320

L16/2679/MMD/001

NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	**Chloride Ion Content (% by mass of concrete)**	**Chloride Ion Content (% by mass of cement)**
			Gopalganj			
46	Kot 01/02	Kotalipara	Concrete Dust	5-25	**0.406**	**2.90**
47			Concrete Dust	25-50	**0.382**	**2.73**
48			Concrete Dust	50-75	**0.396**	**2.83**
49	Kot 01/03		Concrete Dust	5-25	**0.010**	**0.07**
50			Concrete Dust	25-50	**0.015**	**0.11**
51			Concrete Dust	50-75	**0.009**	**0.06**
52	Kot 01/04		Concrete Dust	5-25	**0.009**	**0.07**
53			Concrete Dust	25-50	**0.022**	**0.16**
54			Concrete Dust	50-75	**0.021**	**0.15**
			Bagerhat			
55	Mong 01/01	Mongla	Concrete Dust	5-25	**0.032**	**0.23**
56			Concrete Dust	25-50	**0.009**	**0.07**
57			Concrete Dust	50-75	**0.011**	**0.08**
58	Mong 01/02		Concrete Dust	5-25	**0.036**	**0.26**
59			Concrete Dust	25-50	**0.015**	**0.11**
60			Concrete Dust	50-75	**0.006**	**0.04**
61	Mong 01/03		Concrete Dust	5-25	**0.037**	**0.26**
62			Concrete Dust	25-50	**0.019**	**0.14**
63			Concrete Dust	50-75	**0.008**	**0.06**
64	Mong 02/01		Concrete Dust	5-25	**0.378**	**2.70**
65			Concrete Dust	25-50	**0.368**	**2.63**
66			Concrete Dust	50-75	**0.231**	**1.65**
67	Mong 03/01		Concrete Dust	5-25	**0.010**	**0.07**
68			Concrete Dust	25-50	**0.006**	**0.04**
69			Concrete Dust	50-75	**< 0.004**	**<0.03**
70	Mong 03/02		Concrete Dust	5-25	**0.076**	**0.54**

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0320

L16/2679/MMD/001

NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Bagerhat						
71	Rampal 01/01	Rampal	Concrete Dust	5-25	**0.063**	**0.45**
72			Concrete Dust	25-50	**0.053**	**0.38**
73			Concrete Dust	50-75	**0.065**	**0.46**
74	Rampal 01/02		Concrete Dust	5-25	**0.055**	**0.39**
75			Concrete Dust	25-50	**0.044**	**0.31**
76			Concrete Dust	50-75	**0.071**	**0.51**
77	Rampal 01/03		Concrete Dust	5-25	**0.079**	**0.56**
78			Concrete Dust	25-50	**0.061**	**0.44**
79			Concrete Dust	50-75	**0.040**	**0.28**
80	Rampal 01/04		Concrete Dust	5-25	**0.041**	**0.30**
81			Concrete Dust	25-50	**0.024**	**0.17**
82			Concrete Dust	50-75	**0.019**	**0.14**
83	Rampal 01/05		Concrete Dust	5-25	**0.023**	**0.17**
84			Concrete Dust	25-50	**0.077**	**0.55**
85			Concrete Dust	50-75	**0.023**	**0.16**
86	Rampal 01/06		Concrete Dust	5-25	**0.020**	**0.14**
87			Concrete Dust	25-50	**0.016**	**0.11**
88			Concrete Dust	50-75	**0.018**	**0.13**
89	Rampal 02/01		Concrete Dust	5-25	**0.194**	**1.38**
90			Concrete Dust	25-50	**0.079**	**0.56**
91			Concrete Dust	50-75	**0.079**	**0.57**
92	Rampal 02/02		Concrete Dust	5-25	**0.069**	**0.49**
93			Concrete Dust	25-50	**0.024**	**0.17**
94			Concrete Dust	50-75	**0.162**	**1.15**
95	Rampal 02/03		Concrete Dust	5-25	**0.054**	**0.38**
96			Concrete Dust	25-50	**0.054**	**0.39**
97			Concrete Dust	50-75	**0.039**	**0.28**

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NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Bagerhat						
98	Rampal 03/01	Rampal	Concrete Dust	5-25	**0.012**	**0.09**
99	Rampal 03/01	Rampal	Concrete Dust	25-50	**0.014**	**0.10**
100	Rampal 03/01	Rampal	Concrete Dust	50-75	**0.011**	**0.08**
101	Rampal 03/02	Rampal	Concrete Dust	5-25	**0.017**	**0.12**
102	Rampal 03/02	Rampal	Concrete Dust	25-50	**0.011**	**0.08**
103	Rampal 03/02	Rampal	Concrete Dust	50-75	**0.012**	**0.08**
104	Rampal 03/03	Rampal	Concrete Dust	5-25	**0.014**	**0.10**
105	Rampal 03/03	Rampal	Concrete Dust	25-50	**0.009**	**0.06**
106	Rampal 03/03	Rampal	Concrete Dust	50-75	**0.012**	**0.09**
Cox's Bazar						
107	Column-1, 01/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.021**	**0.15**
108	Column-1, 01/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	25-50	**< 0.004**	**<0.03**
109	Column-1, 01/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
110	Column-2, 02/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.012**	**0.09**
111	Column-2, 02/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	25-50	**0.004**	**0.03**
112	Column-2, 02/01~3	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
113	Column-3, 03/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.030**	**0.21**
114	Column-3, 03/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	25-50	**0.021**	**0.15**
115	Column-3, 03/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
116	Drop Wall-1, 04/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.102**	**0.73**
117	Drop Wall-1, 04/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	25-50	**0.102**	**0.73**
118	Drop Wall-1, 04/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	50-75	**0.053**	**0.38**
119	Drop Wall-2, 05/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.012**	**0.09**
120	Drop Wall-2, 05/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	25-50	**0.007**	**0.05**
121	Drop Wall-2, 05/01~03	North Naniachara Primary Gov. School, Cox's Bazar, Sadar	Concrete Dust	50-75	**< 0.004**	**<0.03**
122	Column-1, 06/01~03	Md. Shofirbil Gov. School/Cyclone Centre, Ukhiya	Concrete Dust	5-25	**0.018**	**0.13**
123	Column-1, 06/01~03	Md. Shofirbil Gov. School/Cyclone Centre, Ukhiya	Concrete Dust	25-50	**0.017**	**0.12**
124	Column-1, 06/01~03	Md. Shofirbil Gov. School/Cyclone Centre, Ukhiya	Concrete Dust	50-75	**0.067**	**0.48**

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NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Cox's Bazar						
125	Column-2, 07/01~03	Md. Shofirbil Gov. School/Cyclone Centre, Ukhiya	Concrete Dust	5-25	**0.030**	**0.22**
126			Concrete Dust	25-50	**0.018**	**0.13**
127			Concrete Dust	50-75	**0.027**	**0.19**
128	Column-3, 08/01~03		Concrete Dust	5-25	**0.075**	**0.54**
129			Concrete Dust	25-50	**0.089**	**0.64**
130			Concrete Dust	50-75	**0.168**	**1.20**
131	Column-4, 09/01~03		Concrete Dust	5-25	**0.033**	**0.23**
132			Concrete Dust	25-50	**0.102**	**0.73**
133			Concrete Dust	50-75	**0.089**	**0.64**
134	Beam-1, Sample 10/1~3		Concrete Dust	5-25	**0.012**	**0.09**
135			Concrete Dust	25-50	**0.009**	**0.06**
136			Concrete Dust	50-75	**0.007**	**0.05**
137	Beam-2, Sample 11/1~3		Concrete Dust	5-25	**0.012**	**0.09**
138			Concrete Dust	25-50	**0.012**	**0.09**
139			Concrete Dust	50-75	**0.007**	**0.05**
140	Rubber Dam, Abutment / Wingwall, 12/01~03	Raja Palang, Ukiya	Concrete Dust	5-25	**0.007**	**0.05**
141			Concrete Dust	25-50	**< 0.004**	**<0.03**
142			Concrete Dust	50-75	**< 0.004**	**<0.03**
143	Rubber Dam, Abutment / Wingwall, 13/01~03		Concrete Dust	5-25	**0.008**	**0.06**
144			Concrete Dust	25-50	**< 0.004**	**<0.03**
145			Concrete Dust	50-75	**< 0.004**	**<0.03**
146	Rubber Dam, Abutment / Wingwall, 14/01~03		Concrete Dust	5-25	**0.004**	**0.03**
147			Concrete Dust	25-50	**< 0.004**	**<0.03**
148			Concrete Dust	50-75	**< 0.004**	**<0.03**
149	Bridge Rail-Post-1, 15/01~03	Bridge Opp. Islanpur Public Model School, Islamabad, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.067**	**0.48**
150			Concrete Dust	25-50	**0.052**	**0.37**
151			Concrete Dust	50-75	**< 0.004**	**<0.03**

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NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Cox's Bazar						
152	Bridge Rail-Post-2, 16/01~03	Bridge Opp. Islanpur Public Model School, Islamabad, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.011**	**0.08**
153			Concrete Dust	25-50	**0.008**	**0.06**
154			Concrete Dust	50-75	**< 0.004**	**<0.03**
155	Bridge Rail-Post-3, 17/01~03		Concrete Dust	5-25	**0.029**	**0.20**
156			Concrete Dust	25-50	**0.028**	**0.20**
157			Concrete Dust	50-75	**0.033**	**0.23**
159	Sluice Gate-Top, 18/01~04	Eidgah, Islamabad, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.373**	**2.67**
159			Concrete Dust	25-50	**0.361**	**2.58**
160			Concrete Dust	50-75	**0.209**	**1.50**
161			Concrete Dust	75-100	**0.190**	**1.36**
162	Sluice Gate-Bottom, 19/01~04		Concrete Dust	5-25	**0.360**	**2.57**
163			Concrete Dust	25-50	**0.382**	**2.73**
164			Concrete Dust	50-75	**0.364**	**2.60**
165			Concrete Dust	75-100	**0.360**	**2.57**
166	Rail-1 (one side of culvert) 20/01~03	Culvert, Boalkhali Road, Islampur, Cox's Bazar, Sadar	Concrete Dust	5-25	**0.028**	**0.20**
167			Concrete Dust	25-50	**0.021**	**0.15**
168			Concrete Dust	50-75	**0.015**	**0.10**
169	Rail-1 (opposite side of culvert) 21/01~03		Concrete Dust	5-25	**0.006**	**0.04**
170			Concrete Dust	25-50	**< 0.004**	**<0.03**
171			Concrete Dust	50-75	**< 0.004**	**<0.03**
Noakhali						
172	West-South Rail/Wheel Guard, 01/01~04	Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Sorhat, GC Road, Purbocharbata, Subarnocharr	Concrete Dust	5-25	**0.010**	**0.07**
173			Concrete Dust	25-50	**< 0.004**	**<0.03**
174			Concrete Dust	50-75	**< 0.004**	**<0.03**
175			Concrete Dust	75-100	**< 0.004**	**<0.03**

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NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	Chloride Ion Content (% by mass of concrete)	Chloride Ion Content (% by mass of cement)
Noakhali						
176	West-South Rail/Wheel Guard, 02/01~04	Box Culvert, Terijapul, RHD Bhuiya Hat, Ansar Miahat, Sorhat, GC Road, Purbocharbata, Subarnocharr	Concrete Dust	5-25	**0.004**	**0.03**
177			Concrete Dust	25-50	**< 0.004**	**<0.03**
178			Concrete Dust	50-75	**< 0.004**	**<0.03**
179			Concrete Dust	75-100	**< 0.004**	**<0.03**
180	North-East Rail/Wheel Guard, 03/01~04		Concrete Dust	5-25	**0.015**	**0.11**
181			Concrete Dust	25-50	**0.007**	**0.05**
182			Concrete Dust	50-75	**0.006**	**0.04**
183			Concrete Dust	75-100	**< 0.004**	**<0.03**
184	North-East Rail/Wheel Guard, 04/01~04		Concrete Dust	5-25	**0.014**	**0.10**
185			Concrete Dust	25-50	**0.010**	**0.07**
186			Concrete Dust	50-75	**0.013**	**0.09**
187			Concrete Dust	75-100	**< 0.004**	**<0.03**
188	South Rail/Wheel Guard, 05/01~03	Box Culvert, Char Amanullah, word no.27, Subarnochar	Concrete Dust	5-25	**0.011**	**0.08**
189			Concrete Dust	25-50	**0.005**	**0.04**
190			Concrete Dust	50-75	**0.007**	**0.05**
191	North Rail/Wheel Guard, 06/01~03		Concrete Dust	5-25	**0.010**	**0.07**
192			Concrete Dust	25-50	**0.011**	**0.08**
193			Concrete Dust	50-75	**0.017**	**0.12**
194	North Rail/Wheel Guard, 07/01~03	Burma Bridge, Chaprashi Canal, Char Gulakhali, Kabirhat	Concrete Dust	5-25	**0.013**	**0.10**
195			Concrete Dust	25-50	**0.010**	**0.07**
196			Concrete Dust	50-75	**0.010**	**0.07**
197	South Rail/Wheel Guard, 08/01~03		Concrete Dust	5-25	**0.055**	**0.39**
198			Concrete Dust	25-50	**0.034**	**0.24**
199			Concrete Dust	50-75	**0.076**	**0.54**
200	Front Column-1, 09/01~03	Char Mondolia Gov. Primary School, Kabirhat	Concrete Dust	5-25	**0.234**	**1.67**
201			Concrete Dust	25-50	**0.153**	**1.09**
202			Concrete Dust	50-75	**0.159**	**1.14**

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NCA sample reference:	Client sample identification:	Client sample Location:	Sample type	Depth (mm)	**Chloride Ion Content (% by mass of concrete)**	**Chloride Ion Content (% by mass of cement)**
			Noakhali			
203	Front Column-2, 10/01~03	Char Mondolia Gov. Primary School, Kabirhat	Concrete Dust	5-25	**0.364**	**2.60**
204			Concrete Dust	25-50	**0.387**	**2.77**
205			Concrete Dust	50-75	**0.243**	**1.73**
206	Front Column-3, 11/01~03	Char Mondolia Gov. Primary School, Kabirhat	Concrete Dust	5-25	**0.122**	**0.87**
207			Concrete Dust	25-50	**0.109**	**0.78**
208			Concrete Dust	50-75	**0.069**	**0.49**
209	North Rail/Wheel Guard, 12/01~04	Two Vent Box Culvert, Kolimuddinpul, Kabirhat	Concrete Dust	5-25	**0.0.15**	**0.11**
210			Concrete Dust	25-50	**0.013**	**0.09**
211			Concrete Dust	50-75	**0.011**	**0.08**
212			Concrete Dust	75-100	**< 0.004**	**<0.03**
213	South Rail/Wheel Guard, 13/01~04		Concrete Dust	5-25	**0.015**	**0.11**
214			Concrete Dust	25-50	**0.007**	**0.05**
215			Concrete Dust	50-75	**0.006**	**0.04**
216			Concrete Dust	75-100	**< 0.004**	**<0.03**

NOTES:
1. Testing was in accordance with BS 1881: Part 124: 1988 Clause 10.2 using potentiometric titration.
2. A cement content of 14.0% was used in the calculation of chloride ion content.
3. Samples received were smaller than required by Clause 3.2 BS 1881 : Part 124 : 1988.
4. Samples were not passed over the 150micron BS Test Sieve before testing.
5. Quality control samples are tested with each batch of samples.

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Appendix E - Photos

Photos can be downloaded at the below link:

https://www.dropbox.com/sh/v9cjhu8brhs5xhe/AAD7kR92T-gN6hVIM3mAOflIa?dl=0

Appendix F – Stakeholder Workshop report

AsCAP
Asia Community Access Partnership

UKaid
from the British people

Climate Resilient Reinforced Concrete in the Marine Environment of Bangladesh

Stakeholder Workshop Report

Mott MacDonald

AsCAP Project Reference Number. BAN2077A

November 2017

MOTT MACDONALD

Quality assurance and review table			
Version	Author(s)	Reviewer(s)	Date
2.0	Sudarshan Srinivasan	Les Sampson	10/11/2017
	Ian Gibb	Maysam Abedin	
	Richard Lebon		
	Dil Yasmin Khan Tina		

ReCAP Database Details: Climate Resilient Reinforced Concrete for the Marine Environment			
Reference No:	BAN2077A	**Location**	Bangladesh
Source of Proposal		**Procurement Method**	Tender/Bidding
Theme		**Sub-Theme**	
Lead Implementation Organisation	Mott MacDonald Ltd	**Partner Organisation**	Local Government Engineering Department (LGED) Bangladesh
Total Approved Budget	£222,258	**Total Used Budget**	£222,258
Start Date	10 June 2016	**End Date**	31 December 2017
Report Due Date	05 September 2017	**Date Received**	

ReCAP Project Management Unit
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Cardno
Shaping the Future

Abstract

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.

This project has examined 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.

Under the key principles of research, uptake and embedment, a Stakeholder Workshop was conducted in partnership with the Local Government Engineering Department, in order to present and consult upon the findings of the project as presented in the Draft Final Report. This Report summarises the activities undertaken and recommendations discussed and agreed at the Stakeholder Workshop held on 21st September 2017.

Key words

Bangladesh, Coastal, Marine, Rural roads, Concrete, Deterioration, Corrosion, Lifecycle, Failure, Infrastructure research, Transport services research

Acknowledgements

The project team would like to greatly acknowledge the continuous support provided by LGED engineers and support staff throughout the tenure of the project and in hosting and providing logistical support to the Stakeholder Workshop held on 21st September 2017

ASIA COMMUNITY ACCESS PARTNERSHIP (AsCAP)

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.

See www.research4cap.org

Contents

1 Introduction

1.1 Project Background

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.

1.2 Project Aim

The overall aim is to provide durable, cost-effective concrete structures that can better withstand the effects of the harsh environments experienced in the coastal regions of Bangladesh.

1.3 Project Objectives

- To assess the difficulties in constructing concrete structures in the marine environment due to a lack of fresh water, and good quality sand and aggregates; and to evaluate the impact of this on the durability of concrete.
- To analyse the main causes of deterioration of existing marine concrete structures.
- To understand the rate of deterioration of marine concrete structures with the change of different parameters such as water quality and the effect on the water-cement ratio; cement type and content; types of sand and aggregate
- To develop guidelines and specifications for the durability of reinforced concrete used in concrete structures in the coastal areas of Bangladesh.

1.4 Workshop Purpose

The purpose of the workshop was to demonstrate the progress of the project against the above stated aims; present the technical conclusions of the project; and obtain feedback for the ongoing development, uptake, and embedment of the project findings and recommendations. The technical feedback and recommendations from the workshop will be incorporated in the revised Final Report and subsequent phases of the project, for which this Stakeholder Report acts as a supporting document.

2 Agenda

The workshop was scheduled from 09:30 – 17:00 and followed the agenda below:

09:30 – 10:00	Walk-in and registration (MM)
10:00 – 10:40	Inaugural Session chaired by **Mr. Md. Abdul Kalam Azad,** Additional Chief Engineer (Implementation) and Chairperson, ReCAP-ASCAP Steering Committee Welcome address by **Mr. Abdul Bashar,** Superintending Engineer, LGED; Speech by **Les Sampson,** Infrastructure Manager, ReCAP; Speech **Mr. Md. Abdul Kalam Azad,** Additional Chief Engineer, LGED; Speech and Inauguration of working session, **Mr. Shyama Prosad Adhikari,** Chief Engineer, LGED.
10:40 – 11:00	Tea Break
11:00 – 13:00	Working Session chaired by **Mr. Md. Abul Kalam Azad** Additional Chief Engineer (Implementation)
11:00 – 11:30	Presentation on "Condition Survey of Concrete Structures in Coastal Districts" (MM)
11:30 – 12:30	Presentation on "Design of Durable Concrete Mix for Coastal Environment" (MM)
12:30 – 13:00	Open Discussion
13:00 – 13:30	Summary Session, chaired by **Md. Abdul Kalam Azad,** Additional Chief Engineer (Implementation)
13:30 – 14:00	Lunch
14:00 – 17:00	Expert Panel Discussions

3 Attendees

Workshop attendees represented a wide range of organisations and interests, ranging from the Local Government Engineering Department to implementing agencies, research organisations, and the cement industry. A summary table of attendees is provided below, with a full list of attendees provided in Appendix A.

Table 1: Summary of Workshop Attendees

#	Organisation	Number of Participants
1	Local Government Engineering Department	53
2	Research for Community Access Partnership (ReCAP)	3
3	Road Research Laboratory, Roads and Highways Department	1
4	Roads and Highways Department	1

#	Organisation	Number of Participants
5	Dhaka Water Supply and Sewerage Authority	1
5	UltraTech Cement	1
6	Basundhara Cement	3
7	Sika Group	1
8	Five rings Cement	1
9	Mott MacDonald	18
	Total	**83**

The 60 LGED attendees represented the full spectrum of seniority and experience, ranging from junior engineers to mid-level and senior management, and covering departments including design; maintenance; research & development; education; and quality control. A wide range of projects were also represented at senior level, along with representatives from locations including Noakhali, Subarnachar, and Patuakhali; and technical departments such as Bridges and Roads & Highways. The breakdown of these LGED attendees is summarised in Table 2 below.

Table 2: Summary of LGED Attendees

#	LGED Department/Category	Number of Participants
1	Senior Management	6
2	Design	5
3	Maintenance	1
4	Research & Development	2
5	Planning	3
6	Training/Education	2
7	Quality Control	6
8	Roads & Highways	1
9	Regional	3
10	Project	20
11	Other	4
	Total	**53**

4 Discussions

The key issues and comments arising in the open floor discussion are summarised below. In inaugurating the working session, Mr. Shyama Prosad Adhikari, Chief Engineer, LGED, highlighted the effects of climate change and flood damage on many kilometres of rural roads, and requested continued support in developing cost-effective technical solutions. Mr Adhikari emphasised that the output of the research should be ready to put in practice. Highlighting the role of LGED's rural roads research fund, Mr. Adhikari emphasised the importance of bridging the gap between research and field-level implementation, and of applied research, where infrastructure investments are more cost-effective if research is applied.

Mr. Abul Kalam Azad, additional Chief Engineer, LGED chaired the working session and in his welcome address he appreciated the collaborative efforts of the consultant and LGED laboratory staff in producing sustainable solution for their coastal structures and emphasised the importance of implementing the outcomes of the research work. He mentioned that further work by training LGED engineers and updating their standard documents will help in implementing the final outcomes produced in the project.

Mr Les Sampson, Infrastructure manager, ReCAP spoke about Asia Community Access Partnership (AsCAP) programme for the rural transport sectors of Asia, which includes research on design standards and maintenance of low traffic rural roads and on transport services in rural areas. Mr Sampson emphasised that the focus of this programme is to stimulate the effective uptake of research outputs in policy and practice.

Mr. Bashar, Superintending Engineer, LGED in his welcome address briefly described the work undertaken by his team of engineers along with the consultant. Mr.Bashar appreciated the efforts of the consultant in training their Engineers in the conditions survey phase and laboratory testing phase. He highlighted that the large scale concrete trial mixes undertaken in the laboratory testing phase has resulted in studying 88 different concrete mixes and in total around 843 no of cylinders were tested.

For each comment or topic arising during this working session, a summary of the response provided either during the floor discussion or by inclusion and/or recommendations in the Final report is provided:

- Cost-effectiveness of durable concrete mix

  It was considered from the floor that the durable concrete mix solution recommended under this project should be cost-effective as compared with the existing concrete mixes. In response to this it was discussed that the cost effectiveness of durable concrete mix should be evaluated by looking at whole-life costing of the structure, which takes into account the cost of construction, durable service life of the structure and maintenance costs during the design life of the structure. It was agreed that a basic comparison of cost of durable concrete mix and existing concrete will be provided in the final report and the whole life costing for a sample project will be undertaken as part of further work.

- Use of Brick aggregates in concrete

  It was commented that brick aggregates are widely used in the coastal districts and how brick aggregates can be used to produce durable concrete mix. In response to this, the study concludes that use of brick aggregates produces less durable concrete, which results in early

deterioration of structures. Based on the condition survey of structures, it was observed that concrete structures containing brick aggregates showed early signs of deterioration within 8 years of construction. Moreover, the insitu strength of brick aggregate concrete was observed to be lower than equivalent stone aggregate concrete.
Brick aggregates can be used in plain concrete or un-reinforced concrete applications

- Concrete mix usually specified based on strength

  The final outcomes of the study specify concrete mix based on exposure conditions. Therefore, the LGED standards should move from strength based specification to durability based specification, which depends on the exposure condition of concrete. This is in line with other international standards, for example in British/European standards the durability specification of concrete mix is based on the various exposure classes. Similar to this, the exposure class for deterioration of concrete caused by chloride induced corrosion in coastal districts of Bangladesh has been classified into Extreme (<1 km from coast); Severe - Exposed districts and Moderate – Interior exposed districts. Based on these exposure classes the minimum cement content and minimum cover to the reinforcement is specified.

- Use of saline water in concrete

  Saline water is not recommended to be used in concrete as this caused corrosion of reinforcement and associated deterioration of concrete. However, saline water can be considered in un-reinforced concrete application.

- List of references to the information given in the presentation

  The list of references to all the information discussed in the workshop is given in references section in the final report.

- Further research to use more bricks in field level?

  The research study explored the use of cement coated brick aggregates in concrete. Although the initial results on this showed better strength as compared with equivalent stone aggregate concrete mix, a clear conclusion on the benefit in durability performance of the coated brick aggregates could not be arrived within the scope of the present study.
  There are advanced manufacturing techniques available in the UK that produce light weight clay aggregates, which can produce durable concrete mix. There is potential benefit in exploring these advanced manufacturing techniques in producing better quality aggregates. This can be explored in future projects by working closely with local SME's.

5 Photos

A selection of photos from the Stakeholder workshop are shown below.

6 Feedback

In addition to the discourse outlined above, a comments sheet was distributed to all participants, focussing on four key questions surrounding the project aims, objectives and presented results. The questions, comments and responses to these comments are copied below:

Question 1	**Comments and Responses** Submitted comments are shown in plain text, authors' responses in *italics*.
Did the project sufficiently cover the different aspects of issues related to performance of concrete structures in coastal regions? Any comments on additional aspect that needs to be covered?	What measures should be taken for using saline water? *Use of saline water is detrimental to the durability of reinforced concrete. However, saline water can be used in plain concrete elements where steel reinforcement is not used. The outcome of the project presented in final report recommends use of drinking water containing less than 1000 mg/l chloride content.*
	In coastal zone, reinforcement is attacked by corrosion. Need some measures to protect corrosion. *The outcome of the project as presented in the final report suggests minimum cement content and concrete cover for exposure condition to resist corrosion of reinforcement in concrete within the service life of the structure.*
	The project is being conducted within its scope. Other aspects of durable concrete structures e.g. coastal reinforcement etc. are not covered in scope but may require investigation in future. *The study on reinforcement corrosion has been undertaken by means of accelerated corrosion tests by subjecting reinforced concrete slab moulds to salt ponding tests and monitor the corrosion of reinforcement. Due to the limited time available within the scope of the project, performance of different concrete mixes to resist corrosion of reinforcement could not be concluded in the final report.*
	Which mixture is good for interior/ exterior? *The outcome of the project as presented in the final report suggests minimum cement content and concrete cover for exposed coastal districts and interior coastal districts. In general the final conclusion of the project recommends use of 30% flyash as cement replacement in concrete to enhance the durability of concrete in coastal environments.*
	Is the proposed concrete mix expensive or not? *The basic cost comparison of the suggested concrete mix with existing concrete is presented in section 6.4 of the final report.*

Question 2	**Comments and Responses** Submitted comments are shown in plain text, authors' responses in *italics*.
Do you agree with the finding of the project presented in the workshop? Are there any constraints affecting the implementation of our findings?	Agree with the findings
	Quality of CEM-II/BV cements must be strictly monitored. *Based on the observations made in the condition survey phase and experimental study phase of the project, obtaining good quality materials for concrete is one of the major issue that cause premature deterioration of concrete in the coastal districts. Further work is needed to address this issue, by working closely with cement suppliers to produce good quality CEM-II/B-C cements*
	Findings must be incorporated in the specifications of LGED and other government organizations. *The final report provides a simple specification for durable concrete mix based on the exposure conditions in the coastal regions of Bangladesh. This specification can easily be incorporated into LGED standards. Further work should include modification of LGED standards by working closely with different departments of LGED to incorporate the final outcomes of this project.*

Question 3	**Comments and Responses** Submitted comments are shown in plain text, authors' responses in *italics*.
Are the local engineers sufficiently trained on the topics covered in this workshop? What additional training is needed for the implementation of our findings?	Dissemination of the findings is needed. This can be done by training a group of core trainers who will, in turn train the field engineers and technicians. *Dissemination through training is crucial for the successful implementation of the project outcomes. Further training of LGED engineers is recommended for future work.*

Question 4	**Comments and Responses** Submitted comments are shown in plain text, authors' responses in *italics*.
What further work would you like to see undertaken to ensure findings of this project implemented successfully?	The proposal mix design should be investigated for other concrete properties e.g shrinkage. *Drying shrinkage of concrete is one of the deterioration process that can affect the durability of concrete. Further work in the implementation of the suggested concrete mixes should investigate the shrinkage of concrete mixes.*
	More study needed.
	A design chart/graph to design concrete in marine environment. *The final recommendation of concrete mix for different exposure conditions in the coastal regions are presented in a simple table, which is easy to refer to identify the cement content and concrete cover required for the structure.*

Question 5	**Comments and Responses** Submitted comments are shown in plain text, authors' responses in *italics*.
Additional comments, feedback and questions	Sand is a fine aggregate and very important. Sand from saline area, is also saline. Saline sand has negative effect on concrete quality. Think about sand. *Based on the condition survey visit and discussions with local LGED engineers in coastal districts, majority of the LGED projects use Sylhet sand. Availability of local sand in coastal districts is scarce and use of saline sand should be avoided. Moreover, local saline sand may not comply with the gradation, silt content and water absorption limitations specified in the LGED standards.*
	A detailed and comparative life cycle cost analysis can be made for a few specific projects. *Whole life costing for a specific project that compares use of durable concrete mix and existing concrete practice will clearly identify the benefits in increased service life of durable concrete design. This has been recommended for further work in future project.*
	What will be the proportion of aggregate? Finally need good quality. *Due to scarcity of stone aggregates, most of the aggregates used in LGED projects are imported from neighbouring countries. The quality of stone aggregates is crucial for the durability of concrete mix. The specification of aggregates in current LGED standards in general complies with the requirements for durable concrete mix.*
	Could you recommend any combination of making brick chips and stone chips and fly ash? *Based on the observations in the condition survey study and experimental study of various concrete mixes, it has been concluded that use of brick aggregates in concrete mix is detrimental to the durability of concrete in marine environment. The high porosity and absorption of brick aggregate provide an easy path for salts to penetrate into the concrete and thereby cause corrosion of reinforcement and early deterioration of reinforced concrete structures. In the final report, it has been recommended not to use brick aggregates in reinforced concrete elements in coastal districts of Bangladesh.*

7 Evaluation

Workshop participants were also requested to complete a workshop evaluation form to ensure feedback on the workshop organisation, delivery methods and content could be analysed and improved in delivery of future workshops.

The evaluation found that the key learnings from the workshop were considered to be:

- Understanding of the deterioration mechanisms for concrete in the marine environment;
- The poor performance of Ordinary Portland Cement (OPC) in high chloride (marine) environments;
- The benefits of fly ash in high chloride (marine) environments;
- The problems associated with the use of brick aggregates for concrete in the marine environment;
- Cement coating for brick aggregates;
- Testing mechanisms and methods for concrete;

The second part of the evaluation invited participants to score the workshop against criteria of usefulness; participation; timekeeping; logistics; and outcomes vs. expectations. On a scoring from 5 ("Very Useful") to 0 ("Absent"), the average score across all criteria was 4 ("Very Good"). The workshop scored highly on "overall usefulness", "logistical organisation" and the "summary of key points arising". An area of future improvement is identified in the ability of participants to contribute to the workshop, which is likely to have arisen from the high number of participants, coupled with time constraints that prevented the use of participative tools such as breakaway/group activities.

8 Conclusions

The Stakeholder Workshop was well attended, with a high level of engagement, interest, and experience brought to the table from the assembled floor of experts and practitioners. Where technical questions and comments were not directly answered in session (with reference to content in the presentation or existing circulated project reports), the comments raised typically focussed around the following key areas:

- Technical (and cost-related) questions around the relative proportions and benefits employed in different recommended mix designs;
- Requirement for piloting to test the recommended concrete mix designs;
- Cost of any new and recommended mix designs, and practical applicability to the context of rural roads projects, and where further research is needed into project and life cycle costing;
- Further work on the improvement of quality of locally available brick aggregates and their potential use in the production of durable concrete;
- Review and updating of LGED specifications and standards to incorporate the recommendations from the project study;
- Requests for ongoing training and capacity building of design and construction methodologies for ground improvement techniques for the rural roads network;

All received comments have been carefully analysed and addressed in the project Final Report, and where the key themes identified above have been incorporated in the recommendations for ongoing work for the embedment and uptake of the project findings.

Appendix A: Workshop Attendance List

#	Name	Organisation & Designation
1	Md. Abul Kalam Azad	Local Government Engineering Department, Additional Chief Engineer (Implementation)
2	Md. Mohsin	Local Government Engineering Department, Additional Chief Engineer (IWRM)
3	Md Joynal Abedin	Local Government Engineering Department, Additional Chief Engineer (Maintenance)
4	Mohammad Anwar Hossain	Local Government Engineering Department, Additional Chief Engineer (Urban Management)
5	Md. Khalilur Rahman	Local Government Engineering Department, Additional Chief Engineer (Design)
6	Les Sampson	Deputy Team Leader - Infrastructure, Research for Community Access Partnership (ReCAP/AsCAP)
7	Jasper Cook	Team Leader, Research for Community Access Partnership (ReCAP/AsCAP)
8	Maysam Abedin	Regional Technical Manager, Asia, Research for Community Access Partnership (ReCAP/AsCAP)
9	Ian Gibb	Mott MacDonald, Team Leader - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
10	Sudarshan Srinivasan	Mott MacDonald, Material Engineer - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
11	Md. Mosleh Uddin	Local Government Engineering Department, Senior Engineer (Admin)
12	AK Azad	Local Government Engineering Department, SE (Education)
13	AKM Sahadat Hossain	Local Government Engineering Department, Senior Engineer, Integrated Water Resources Management (IWRM)
14	Md. Abul Basar	Local Government Engineering Department, Senior Engineer, Integrated Water Resources Management (IWRM)
15	Noor Mohammad	Local Government Engineering Department
16	Abdur Rashid Khan	Local Government Engineering Department, Senior Engineer (Training)
17	Khondakar Ali Noor	Local Government Engineering Department, Senior Engineer (Design)
18	MD. Ali Akhtar Hossain	Local Government Engineering Department, Project Director, Sustainable Rural Infrastructure Improvement Programme (SRIIP)
19	Md. Abdus Salam Mandal	Local Government Engineering Department, Project Director, Large Bridges Construction

#	Name	Organisation & Designation
20	Gopal Debnath	Local Government Engineering Department, Project Director, Small Scale Water Resources Development Project (SSWRDP)
21	Md. AKM Lutfur Rahman	Local Government Engineering Department, Project Director, Coastal Climate Resilient Infrastructure Project (CCRIP)
22	Md. Tofazzal Ahmed	Local Government Engineering Department, Project Director, Union Connecting Road & Infrastructure Development Project, Greater Chittagong & Cox's Bazaar (GCCP)
23	Md. Zahidul Islam	Local Government Engineering Department, Executive Engineer (Design)
24	Md. Azherul Islam	Local Government Engineering Department, Executive Engineer (Design)
25	Md. Abadat Ali	Local Government Engineering Department, Executive Engineer (Design)
26	Md. Wahidur Rahman	Local Government Engineering Department, Executive Engineer, PEDP III
27	JM Azad Hossain	Local Government Engineering Department, Executive Engineer, PEDP III
28	Md. Abdur Rahim	Local Government Engineering Department, Executive Engineer, Quality Control
29	Syed Abdur Rahim	Local Government Engineering Department, Executive Engineer (Maintainence)
30	Abdul Monzur Md. Sadeque	Local Government Engineering Department, Executive Engineer (Planning)
31	Mahbub Alam	Local Government Engineering Department, Executive Engineer, Third Primary Education Development Programme (PEDP III)
32	Mahbub Imam Morshed	Local Government Engineering Department, Assistant Chief Engineer
33	Md. Enamul Hoque Khan	Local Government Engineering Department, Sr. AE (Quality Control)
34	Hosne Ara	Local Government Engineering Department, Sr. AE (Quality Control)
35	Ripon Hore	Local Government Engineering Department, AE R&D
36	Manos Mondal	Local Government Engineering Department
37	Ripon Hore	Local Government Engineering Department, AE R&D
38	AKM Mostofa Morshed	Local Government Engineering Department, AE, Planning
39	Md Faridul Islam	Local Government Engineering Department, AE, Planning
40	Sheikh Anisur Rahman	Local Government Engineering Department, Deputy Project Director, Emergency Cyclone Recovery and Restoration Project (ECRRP)

#	Name	Organisation & Designation
41	Abdul Baten Sarker	Local Government Engineering Department, SAE, Quality Control
42	Aftab Uddin	Local Government Engineering Department, SAE, Quality Control
43	Hosneara Begum	Local Government Engineering Department
44	Md. Yousuf Ali	Local Government Engineering Department, LT, Quality Control
45	Robiul Haque	Local Government Engineering Department
46	Abu Saleh Md. Hanif	Local Government Engineering Department, EE, Patuakhal
47	Md. Abdus Satter	Local Government Engineering Department, EE, Noakhali
48	Md. Hasan Ali	Local Government Engineering Department,
49	Md. Aminul Islam	Local Government Engineering Department, UE, Subarnachar
50	Mostadar Rahman	Local Government Engineering Department, Senior Consultant, Design
51	Ahmed Nawaz	Municipal Government and Services Project (MGSP), Deputy Team Leader
52	Jibon Krishna Saha	Local Government Engineering Department, DTL, Municipal Government and Services Project (MGSP)
53	Roby Jankar Chowdhury	Local Government Engineering Department, M&E Expert, Northern Integrated Development Project (NOBIDEP)
54	Dr Abdullah Al Mamun	Director, Road Research Laboratory
55	Jannat E Neeha	Local Government Engineering Department, AE, Roads & Highways Department
56	Md. Ahsan Habib, PEng.	Mott MacDonald, Deputy Team Leader - D&SC – SRIIP
57	Md. Abu Raihan	Mott MacDonald, System Management / Office Engineer - D&SC – SRIIP
58	Engr. Md. Mahmudul Islam	Superintending Engineer and Project Director, Dhaka Environmentally Sustainable Water Supply Project (DESWSP)
59	Md. Quaisarul Islam	Mott MacDonald, Deputy Team Leader, Management Design and Supervision Consultant, Dhaka Environmentally Sustainable Water Supply Project (DESWSP)
60	Pronoy Kumar Paul	UtraTech Cement, Sr.Manager-Technical Services
61	Kh. Kingshuk Hossain	Bashundhara Cement, Head of Division - Sales

#	Name	Organisation & Designation
62	Engr.Saroj Kumar Barua	Bashundhara Cement, Deputy General Manager - Technical Support
63	Md. Imam Al Kudrot E Elahi	Bashundhara Cement, Deputy Manager, Technical Support, Cement Sector
64	Md. Abul Khair	M/S. TECHNODEV, Sole Agent of Sika India Pvt. Ltd, General Manager
65	Aminul Islam	Fiverings Cement, Chief Engineer
66	Md. Anwarul Islam	Local Government Engineering Department, Municipal Government and Services Project (MGSP)
67	Mirza Md Iftekhar Ali	Local Government Engineering Department, XEN PME
68	Biswajit Kumar Kunda	Local Government Engineering Department, XEN PME
69	Vaskar Kanti Chowdhury	Local Government Engineering Department, XEN Design Unit
70	Khan Md Rabiul Alam	Local Government Engineering Department, Media Expert RTIP-II
71	Richard Samson Lebon	Mott MacDonald, Project Manager - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
72	Dr. Khan Mahmud Amanat	Mott MacDonald, Deputy Team Leader - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
73	Dil Yasmin Khan Tina	Mott MacDonald, Consultant, Structural Engineer - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
74	Dipan Dhali	Mott MacDonald, Research Associate - ReCAP Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh
75	Giasuddin Chowdhury	Mott MacDonald, Deputy Team Leader - Bangladesh Delta Plan 2100
76	Gazi Rahmani	Mott MacDonald, Senior Manager- Water Supply
77	Mosharraf Hossain	Mott MacDonald, Project Manager
78	Korban Ali	Mott MacDonald, Quality/ Material Engineer
79	Imran Mohammad	Mott MacDonald, Design & Construction Engineer
80	Mehedi Hassan	Mott MacDonald, Junior Engineer
81	Mahboob Hossain	Mott MacDonald, Bridge Engineer - Dhaka Elevated Expressway Project

#	Name	Organisation & Designation
82	Md. Sabbir Ahmed	Mott MacDonald, Researcher - Bangladesh Delta Plan 2100
83	Yeusuf Ahmed	Mott MacDonald, Junior Consultant, Integrated Water Resources Management (IWRM)

Appendix B: Workshop Evaluation

#	**Question 1.** Please list three things that you have learned during this workshop.		
1	Comparing cement use with OPC and PCC (slag and fly ash)		
2	Usefulness of fly ash		
3	OPC perform poorly in chloride environments	Flyash performs better than slag	Brick aggregates have significantly poor performance WRA beneficial
4	For marine environment we need to use CEBC-II(B-V) cement		
5	CEM-II type cement is useful for concrete work in coastal area	In all concrete work brick chips should be avoided for modern life	Always use WRA in concrete work
6	Carbonation deterioration mechanism	Coated brick aggregates	Chloride migration test and salt ponding test
7	Vulnerability and coastal marine concrete	Difference between OPC and PPC	Concrete test method and their reliability
8	How reinforced concrete structures in the marine environment.	We will be able to get durable and durable and economical concrete.	
9	Structure conditions in the coastal area of Bangladesh	How corrosion affects concrete	Mix design to overcome this situation
10	Durability performance tests	Cement coating brick aggregate	Outcomes of literature review
11	Concrete durability	Testing of concrete and aggregate	Best practice in concrete design

#	2. How would you rate the overall usefulness of this workshop?	3. To what extent did the workshop meet your expectations?	4. Were you, as a participant, able to effectively contribute to the different sessions of the workshop?	5. How do you rate the workshop schedule/ timetable ?	6. What was your impression of the logistical organisation and management of the workshop?	7. How would you rate the summary of key points arising from the workshop?
1	B	C	B	C	C	B
2	C	B	C	C	B	B
3	A	A	A	A	A	A
4	A	B	D	D	B	A
5	B	B	A	B	B	C
6	A	B	C	A	A	B
7	A	B	Z	A	A	A
8	A	A	B	B	A	B
9	A	B	A	A	A	A
10	B	C	C	C	C	B
11	B	B	C	B	B	B

#	8. What were the two best and most useful aspects of the workshop? A.	8. What were the two best and most useful aspects of the workshop? B.	9. How could the workshop have been improved?	10. Do you have any other comments or suggestions?
1	Laboratory testing comparison of OPC, flyash and slag	Final recommendations		
2	Inclusion and participants from outside organization	Time management and attentive participation of the stakeholders	Potential participants might be involved into this shortly.	
3	Durable concrete structures	Ingredient of cement	Materials from Bangladesh may be the 1st priority for research	
4	The study was useful but its main effectiveness will be in its implementation.	Mix design may look costly but it is cheap considering longer service life.	If the full results were shown	
5	Discussion on chloride Ion penetration test and its results	Literature review	A group work or brain storming session can be introduced	List of references should be incorporated in the documents.
6	Best presentation and materials			

Appendix C: Workshop Presentation

Climate Resilient Reinforced Concrete Structures in the Marine Environment of Bangladesh

Project Ref: BAN2077A

Outline of Presentation

Introduction

Background

Condition Survey of Structures

Recommendations

Laboratory Testing

Outline of Presentation

Introduction

Background

Recommendations

Condition Survey of Structures

Laboratory Testing

Project Details
Aims & Objectives

Aim

To provide durable, cost-effective concrete structures that can withstand effects of the harsh marine environments

Objectives

1. To assess difficulties in constructing concrete structures in the marine environment
2. To analyse main causes of deterioration of existing marine structures

Project Details
Aims & Objectives

Aim

To provide durable, cost-effective concrete structures that can withstand effects of the harsh marine environments

Objectives

3. To understand the rate of deterioration of marine concrete structures with the change of different controlling parameters
4. To develop guidelines and specifications for the durability of reinforced concrete in the coastal areas of Bangladesh

Project Details
Methodology

Desk study and research

- Literature review
- Desk study - Current practices, Material supply chain, quality etc.
- Research matrix
- **Deliverable**
  - Inception Report

Workshop

- Planning, Preparation and Organisation
- Inviting stake holders
- **Deliverable**
  - Workshop report

Condition survey

- Identifying structures
- Inspection and testing – Visual inspection, chloride profiles, Carbonation depth, Half-cell Potentials, Cover meter, Corrosion analyser, Strength, Chloride migration and Petrography
- **Deliverable**
  - Condition survey report

Final Report

- Guidelines and Specifications
- **Deliverable**
  - Final report

Laboratory testing

- Mix design development – material sourcing, testing, lab trials and mix optimisation
- Lab scale exposure trials and testing
- Durability testing
- **Deliverable**
  - Interim Report 1
  - Interim Report 2
  - Final Report

Outline of Presentation

Introduction

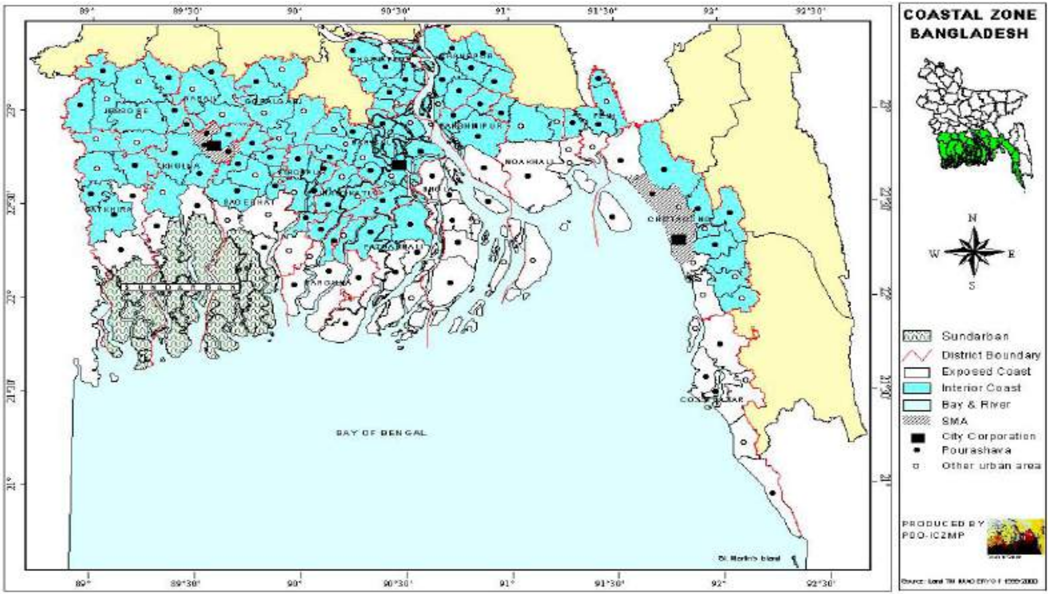
Background

Recommendations

Condition Survey of Structures

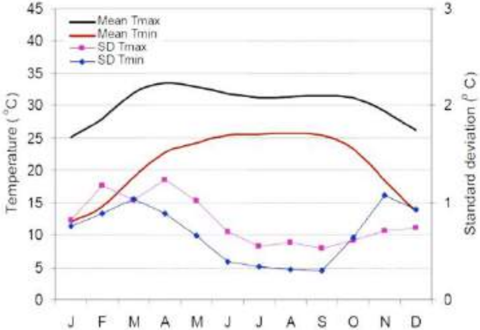
Laboratory Testing

Literature Review
Bangladesh Coastal Environment - Districts

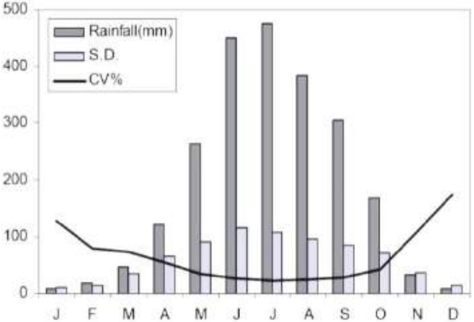


- 19 Districts
- 50 Upazillas in Exposed Coast (23935 sq. km)
- 91 Upazillas in Interior Coast (23266 sq. km)

Literature Review
Bangladesh Coastal Environment - Climate

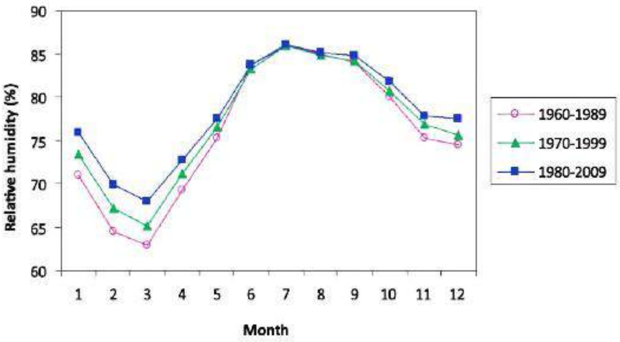


Temperature

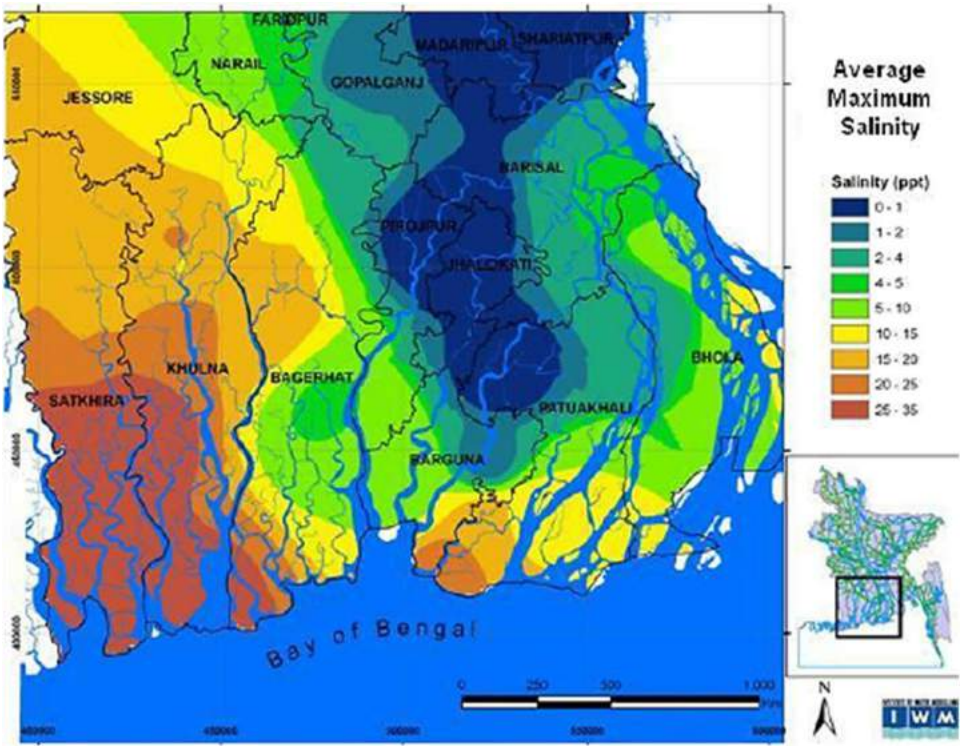


Rainfall

Relative Humidity



Literature Review
Bangladesh Coastal Environment - Salinity



Literature Review
Concrete Materials

Cement

- CEM I (OPC) & CEM II (PPC)
- 33-35 Million MT/year production capacity
- Flyash/Slag/Limestone is used as pozzolan at 21-30% replacement depending on availability
- Flyash and Slag are imported from neighboring countries

Local Flyash

- 52000 MT flyash produced at Barapukuria Power Plant every year
- Class F grade flyash
- Currently due to lack of regulations most of the flyash is disposed in dry embankments

Literature Review
Concrete Materials

Coarse Aggregate

- Broken brick aggregates, Stone aggregates and Shingles
- Brick aggregates – S, A, B and inferior grade
- Stone aggregates – Sylhet, Panchagarh, Dinajpur etc.

Fine aggregate

- Natural sand
- High silt and silty clay soil in the coastal regions
- Crushed stone dust available in Sylhet

Water

- Local drinking water
- Marine/contaminated water

Chemical Admixtures

- Wide range of admixtures
- Not normally used in rural/coastal regions

Literature Review
Workmanship issues in Construction

Identified workmanship issues in coastal districts

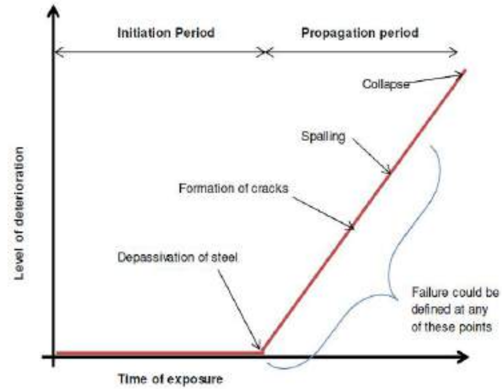
- use of contaminated materials;
- poor control over quantities/types of constituents in concrete mixes;
- lack of storage facilities for construction materials
- excess water in the mix
- Inadequate curing practices and period.
- distortion and displacement of formwork
- placing of concrete from large height
- Improper compaction of concrete

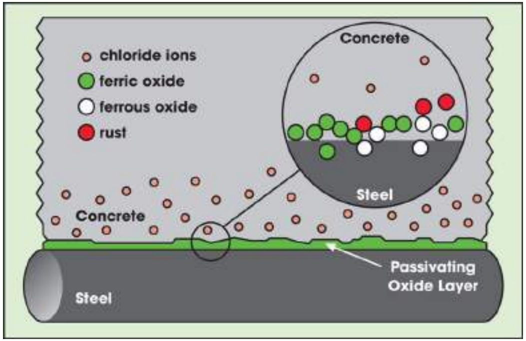
Literature Review
Concrete Deterioration Mechanisms

Chloride induced corrosion

Critical considerations include:

- Exposure environment
- Concrete quality
- Cover to reinforcement
- Construction quality
- Raw material quality





Literature Review
Concrete Deterioration Mechanisms

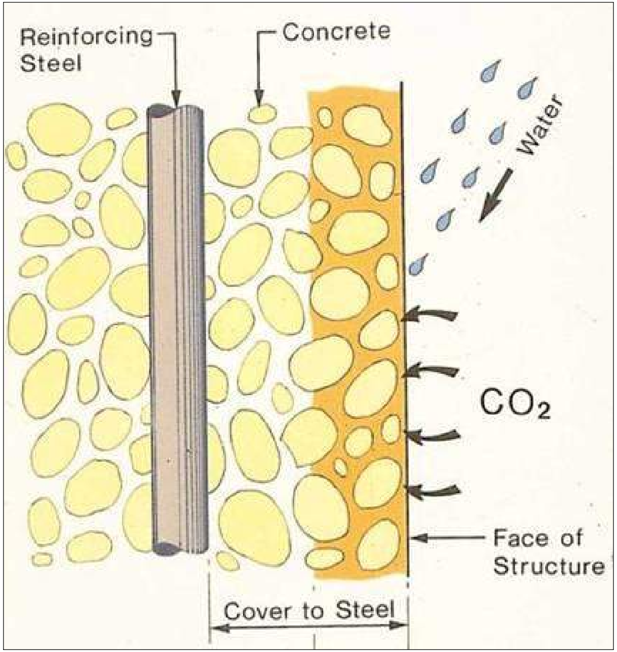
Other deterioration mechanisms

Carbonation

Sulfates

ASR

DEF



Literature Review
Durability issues in Construction

Identified durability issues in coastal districts

- Use of brick aggregates – porous concrete
- Insufficient cover to reinforcement
- Usage of deformed/corroded rebars
- Low usage of mineral additions (flyash/slag)
- Limited use of chemical admixtures

Literature Review
Workmanship & Durability Issues

Climate element	Status of change	Impact on Infrastructure
Temperature	**Current change**: 0.4°C during last 50 years **Future:** 1.38-1.42°C by 2030 and 1.98-2.35°C by 2050	• accelerates deterioration processes • increases the water demand in concrete • increases shrinkage and thermal cracking in concrete • needs additional curing measures • increased thermal expansion of elements in existing structures
Rainfall	**Current trend:** 25 cm in last 50 years (wetter monsoon) **Future scenarios**: increase in rainfall 13.5-18.7% in 2030 22.3-24.7% in 2050	• Increased flooding increases flood loading on structures • Wetter ground causes rising damp and related deterioration of concrete

Literature Review
Impact of Climate Change

Climate element	Status of change	Impact on Infrastructure
Sea Level Rise (SLR)	**Current SLR:** 4-6mm/year **Projection in 2030**: 21 cm reference to land inside polders **Projection in 2050**: 39 cm reference to land inside polders	• SLR and increase in tidal levels increases the exposure to salts in seawater • Increased risk of corrosion in concrete structures • Increase in biological deterioration of concrete
Salinity	The 5 ppt (5000 ppm) line will move further inland affecting the Pourashavas of Amtali and Galachipa in 2050	• Increased salinity increases the risk of reinforcement corrosion and reduces the service-life of concrete structures • Increases the contamination of construction materials • More structures exposed to chlorides

Literature Review
Impact of Climate Change

Climate element	Status of change	Impact on Infrastructure
CO_2 emission	**Baseline in 2005**: CO_2 emission of 40 Mt **Future emission in 2050 with no improvement in energy efficiency**: 628 Mt (15 times to 2005 value) **Future emission in 2050 with reaching EU's 2030 efficiency**: 183 Mt (7 times to 2005 value)	• Increases the depth of carbonation in exposed concrete thereby increases the risk of reinforcement corrosion in concrete

Inception Report
Gaps identified in Literature review

- Benefits of use of mineral additives in improving corrosion resistance of concrete
- Lack of testing information of chloride and carbonation levels, corrosion activity in existing concrete structures.
- Secondary measures to improve corrosion resistance
- Durability studies mainly focussed on strength improvement
- No modelling data on chloride induced corrosion of concrete structures

Outline of Presentation

Introduction

Inception Report

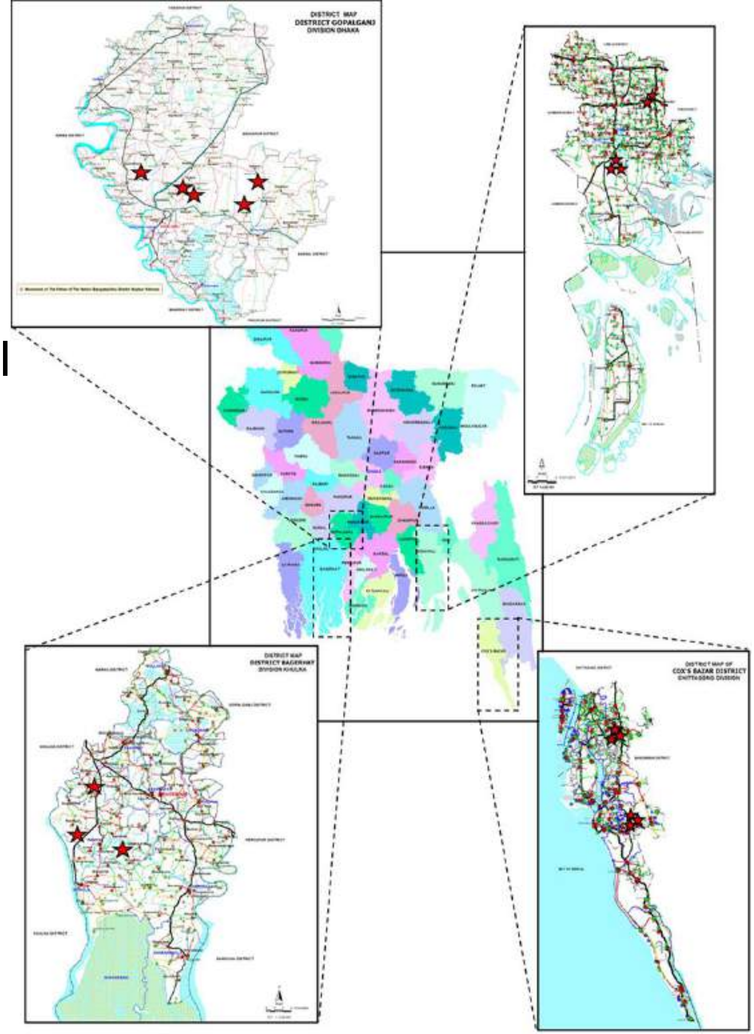
Condition Survey of Structures

Recommendations

Laboratory Testing

Condition Survey Phase

To develop an understanding of the impact of the exposure conditions on the durability of concrete in Bangladesh’s rural marine environment.



Selected districts –

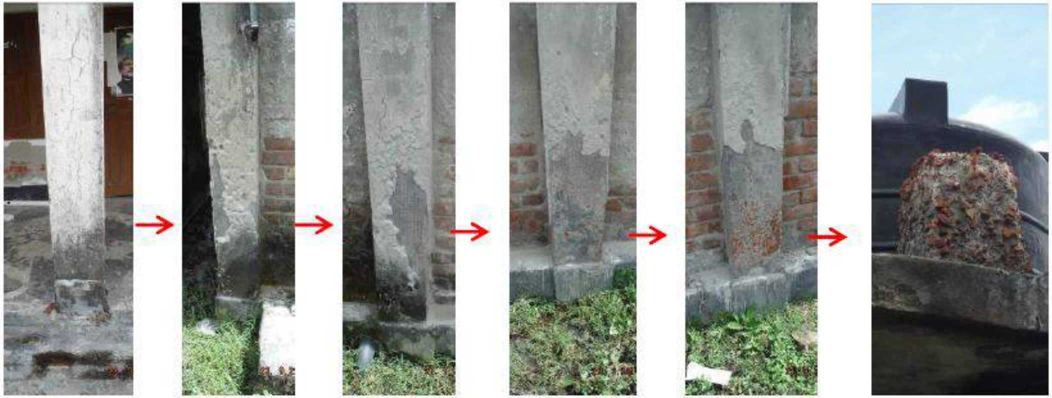
Following discussions with LGED, four areas were identified for investigation. These are –

- Gopalganj
- Bagerhat
- Cox’s Bazar and
- Noakhali

Bangladesh – Coastal Structures
Durability related damage

Condition Survey of Structures
Durability related damage

Condition Survey of Structures
Durability related damage



Condition Survey of Structures
Structural damage

Horinmara Bridge – Shear failure of Abutments

Condition Survey of Structures
Structural damage

Silna river road bridge

Mahmudpur Dulu Khan Bridge

Condition Survey of Structures
Workmanship issues

Condition Survey Phase – Test Techniques

- Visual Inspection
- Non-destructive testing of concrete
  - Rebound Hammer testing
  - Cover-meter test
  - Half-cell Potential survey
- Intrusive testing of concrete
  - Concrete core testing
  - Chloride profile testing
  - Carbonation depth measurement
  - Quantab strips

Figure 1 Elcometer 181 rebound test hammer

31 covermeter withstandardhead

1 Half-cell meter with silver in silver chloride referen

trips

Condition Survey of Structures

Water samples

Quantab strip – chloride content testing

Sl No.	Location	No of samples	Max. % NaCl	Max. ppm (mg/L) Cl^-
1	Gopalganj	5	0.068	414
2	Bagerhat	5	0.145	880
3	Cox's bazar	4	0.619	3755
4	Noakhali	3	0.218	1321

Condition Survey of Structures

Concrete testing

Sl No.	Location	No of Structures	No of Core samples	Concrete dust samples
1	Gopalganj	5	15	51
2	Bagerhat	5	10	54
3	Cox's bazar	5	18	63
4	Noakhali	6	9	39

- NDT testing at each structure – Rebound Hammer, Cover meter and Half-cell meter testing

Condition Survey of Structures
Concluding results

Stone Aggregates vs Brick Aggregates

Brick Aggregates – Chloride profile

	5-25mm	25-50mm	50-75mm	75-100mm
Average	0.66	0.57	0.51	0.80
Max	2.90	2.76	2.83	2.57
Min	0.03	0.03	0.03	0.03

Stone Aggregates – Chloride profile

	5-25mm	25-50mm	50-75mm	75-100mm
Average	0.18	0.15	0.19	0.05
Max	0.56	0.73	1.20	0.09
Min	0.03	0.00	0.00	0.03

Condition Survey of Structures
Concluding results

Stone Aggregates vs Brick Aggregates

Compressive strength (MPa)

	Stone	Brick
Average	18.13	15.85
Max	31.10	25.90
Min	5.70	9.60

Outline of Presentation

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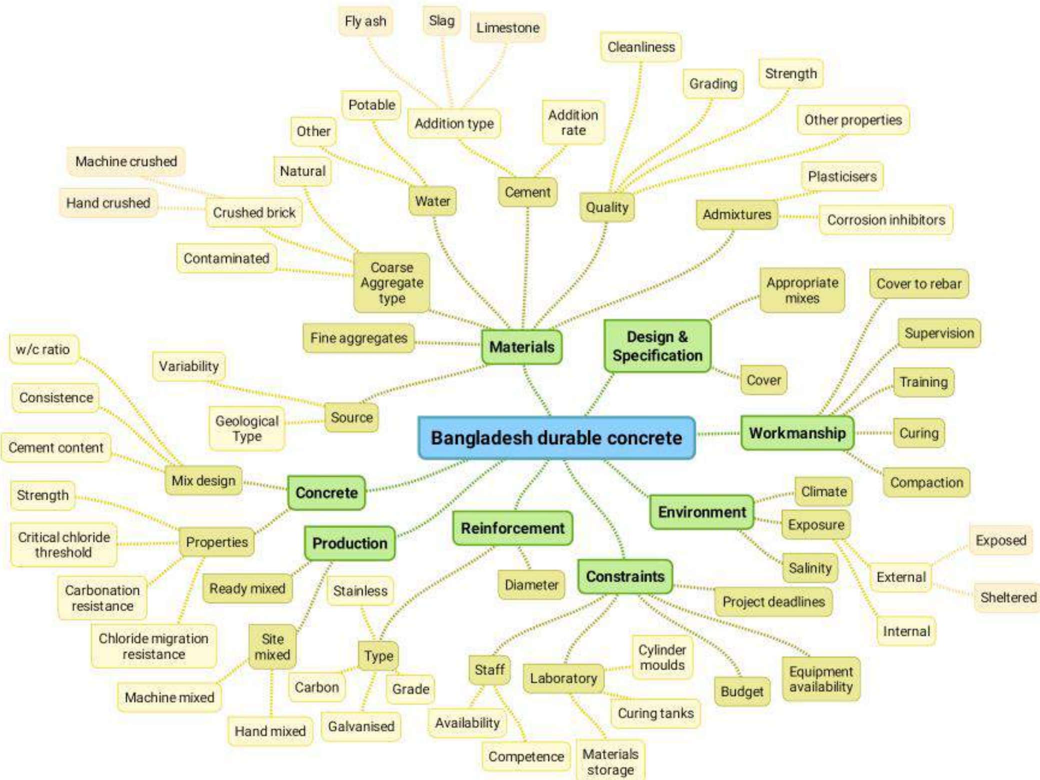
Condition Survey of Structures

Laboratory Testing

Laboratory Testing

Materials



Laboratory Testing

- Phase I testing
  - Establishing relationships between W/C ratio, Cement content and aggregate type
  - Optimising mineral additions in concrete mix
  - Influence of corrosion inhibitors on flow properties of concrete
- Phase II testing
  - Durability testing of concrete mixes
  - Service life modelling of concrete mixes

Laboratory Testing

Materials

Marerial	Source
Cementitious material	CEM I, Flyash and Slag supplied by Bashundhara Cement
Stone Aggregate	Local Aggregates (10 mm) Vietnam Aggregates (20 mm)
Brick Aggregatre	Combination of First Class bricks and Picked Jhama Bricks
Sand	Sylhet sand
Corrosion Inhibitor	(1) Calcium Nitrate (supplied by Yara Intl ASA, Norway) (2) Sika Ferroguard 901
Water reducing admixture	Sikament 2002 NS

Laboratory Testing – Phase I

Experimental Matrix

Study	Variables
To establish relationship between W/C ratio, Cement Content and Strength	Stone aggregates vs Brick Aggregates No Chemical Admixture vs Chemical Admixture
To increase the proportion of SCMs in concrete	Binder content and W/C ratio: Approximate binder content 350, and 400 corresponding to 0.6 and 0.5 W/C ratio Flyash (30-40% cement replacement) Slag (30-50% cement replacement) Combination of flyash and slag (>30% cement replacement)

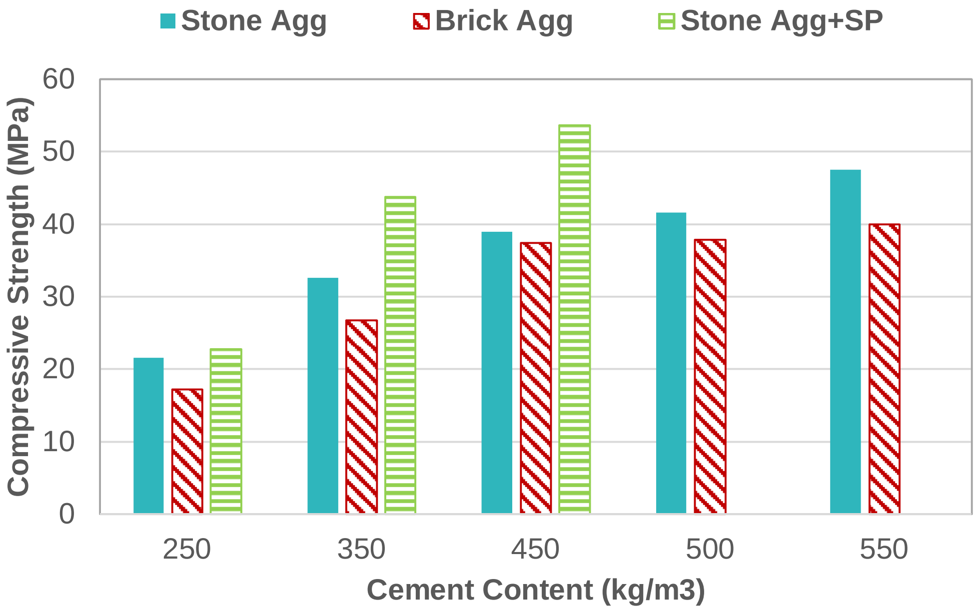
Laboratory Testing – Phase I

Experimental Matrix

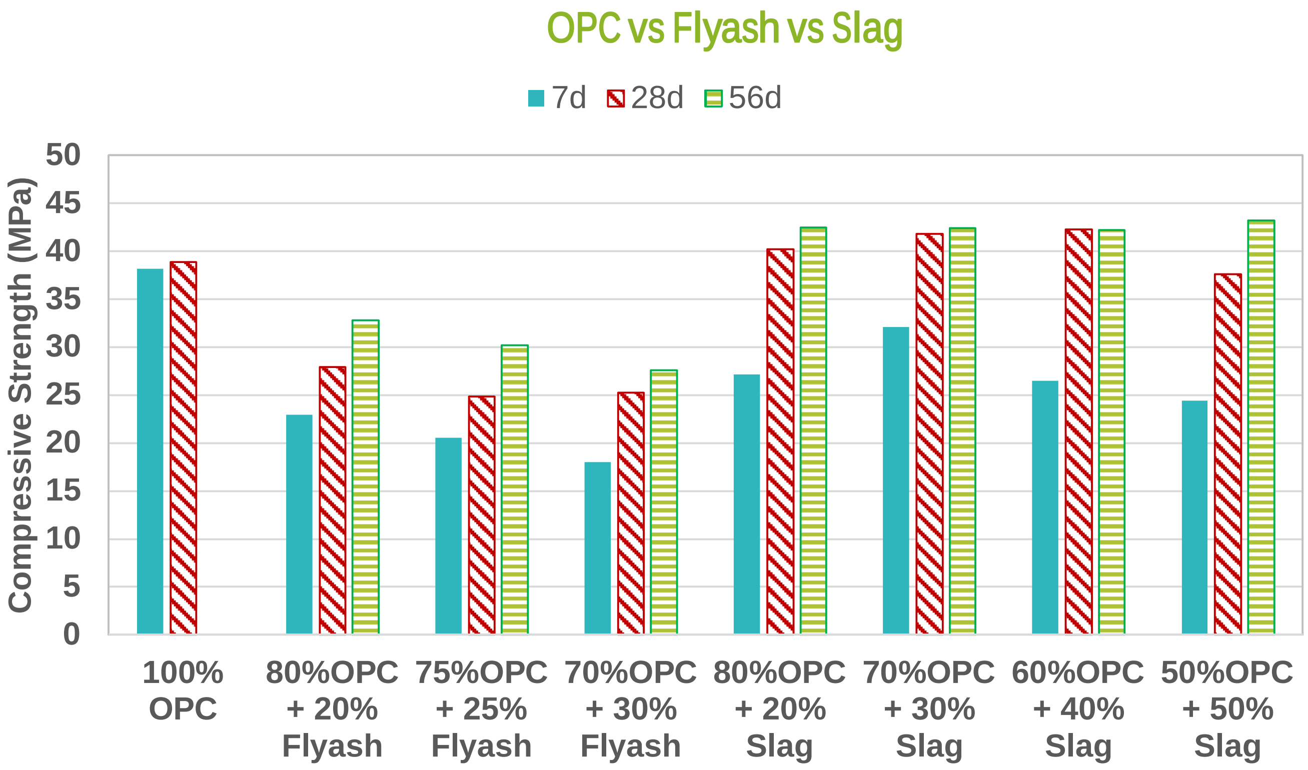
Study	Variables
Feasibility study on improving the properties of brick aggregates	Coated vs uncoated brick aggregates
To study the effect of Calcium Nitrate Corrosion inhibitor on fresh and hardened properties of concrete	Dosage of Corrosion Inhibitor: 3%, 3.5% and 4% W/C ratio: 0.4, 0.5 and 0.6

Laboratory Testing – Phase I

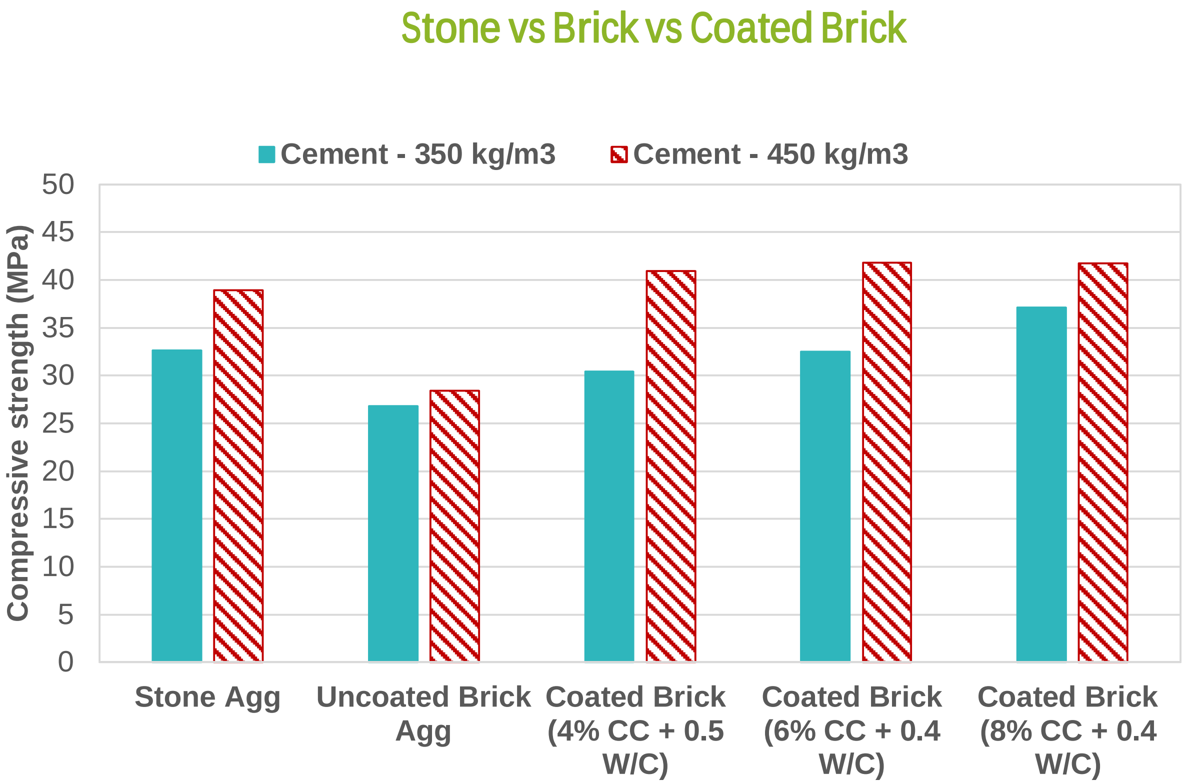
Stone Aggregates vs Brick Aggregates



Laboratory Testing – Phase I



Laboratory Testing – Phase I



Laboratory Testing – Phase II

Variables Matrix

Cement type	CEM I CEM IIA-V (20% FA) CEM IIB-V (30% FA) CEM IIB-S (20% slag) CEM IIIA (50% slag)	5
Cement content (free w/c ratio)	350 kg/m3 (0.6 w/c) 450 kg/m3 (0.5 w/c) 550 kg/m3 (0.4 w/c)	3
Coarse aggregate type	Natural aggregate (NA) Machine crushed Brick (MCB) Cement Coated Brick (CCB)	3
Water	Potable water 0.5% Chloride content 1.0% Chloride content	3
Corrosion Inhibitor	0 Calcium Nitrate Ferro Gaurd	3

Laboratory Testing – Phase II

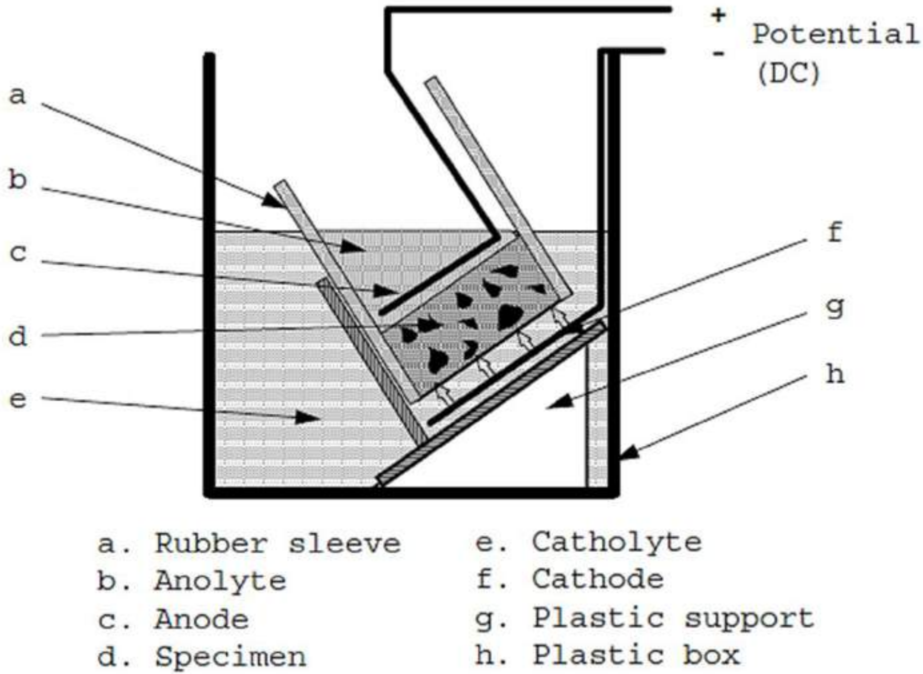
Experimental Matrix

- The full experimental matrix is designed using DOE factorial method (Design of Experiments)
- Various combination of factors resulted in 45 different concrete mixes
- Each concrete mix is tested for durability
    - NT Build 492 – Chloride migration test (Nordic standard)
    - Salt ponding test (accelerated field tests)
        - Modified ASTM G109
        - AASHTO T259 90-day ponding test

(15 mixes of coated brick aggregates are excluded)

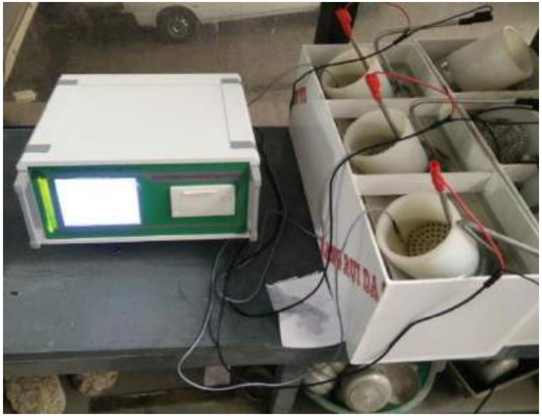
Laboratory Testing – Phase II

NT Build 492 – Chloride migration test



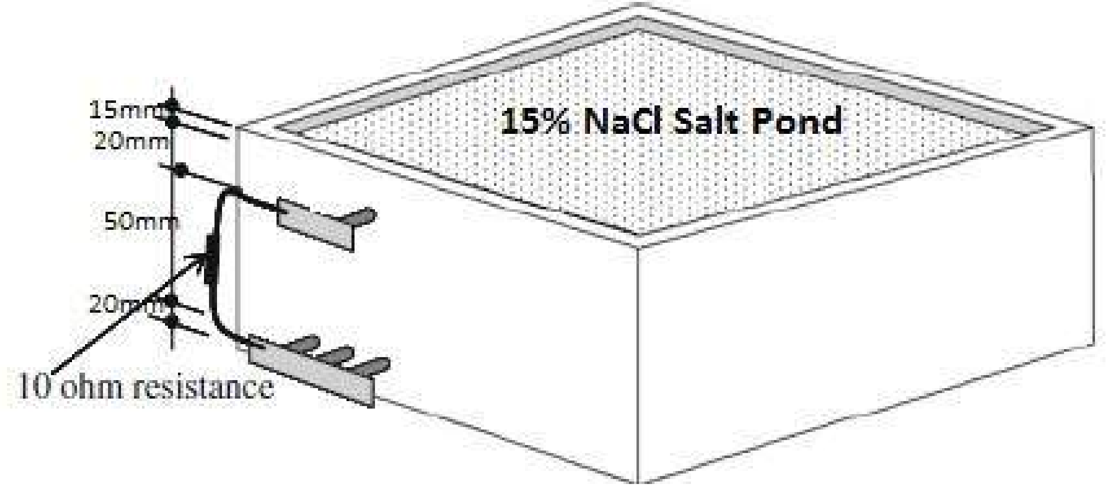
Laboratory Testing – Phase II

NT Build 492 – Chloride migration test (Durability test)



Laboratory Testing – Phase II

Salt Ponding test (Accelerated field exposure)
Modified ASTM G109 test



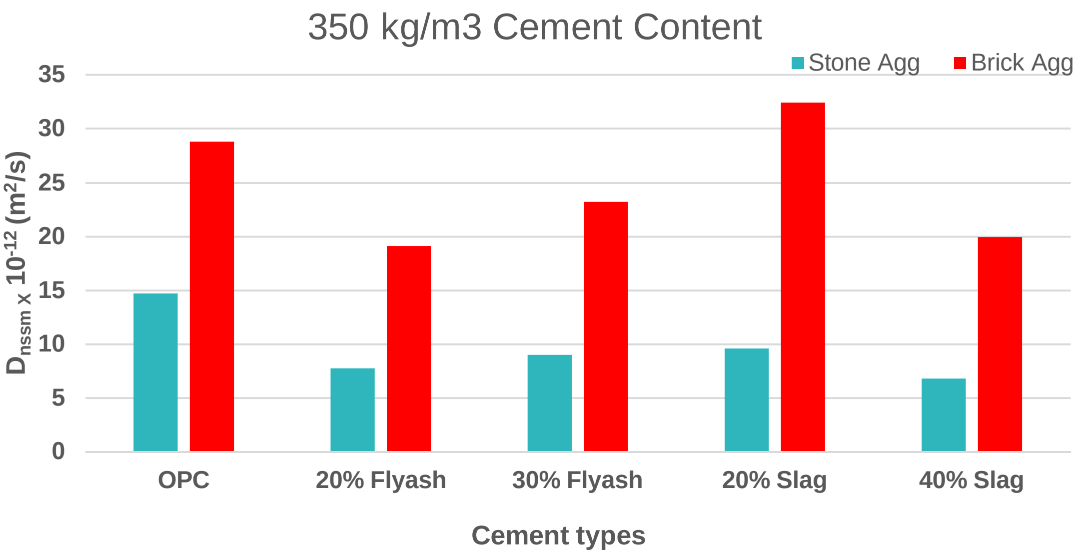
- 1 week cycle - 2 days salt ponding and 5 days drying
- Repeat cycles for up to 6 months

Laboratory Testing – Phase II

Salt Ponding test (Accelerated field exposure)

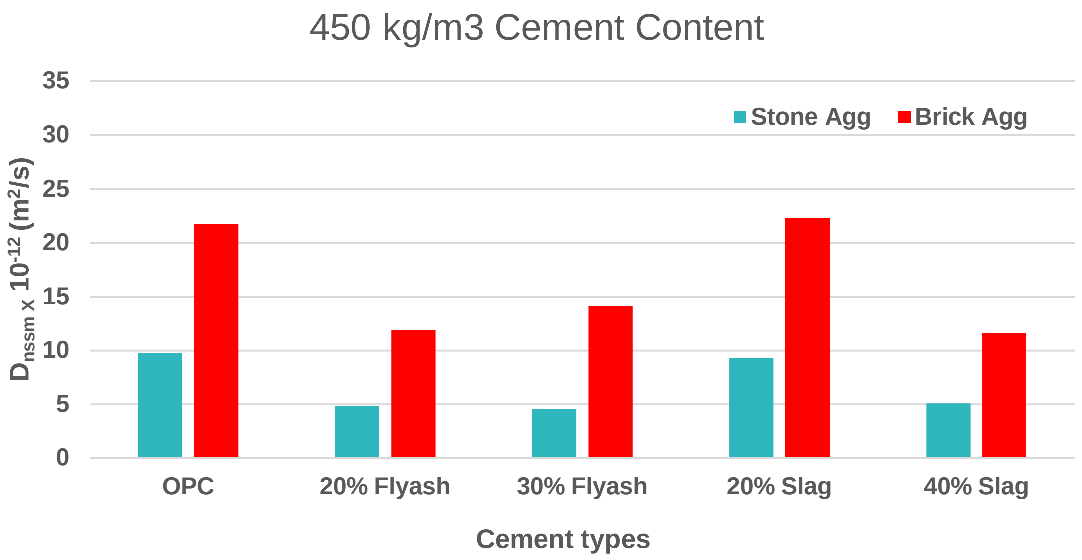
Laboratory Testing – Phase II

Chloride migration test - Results



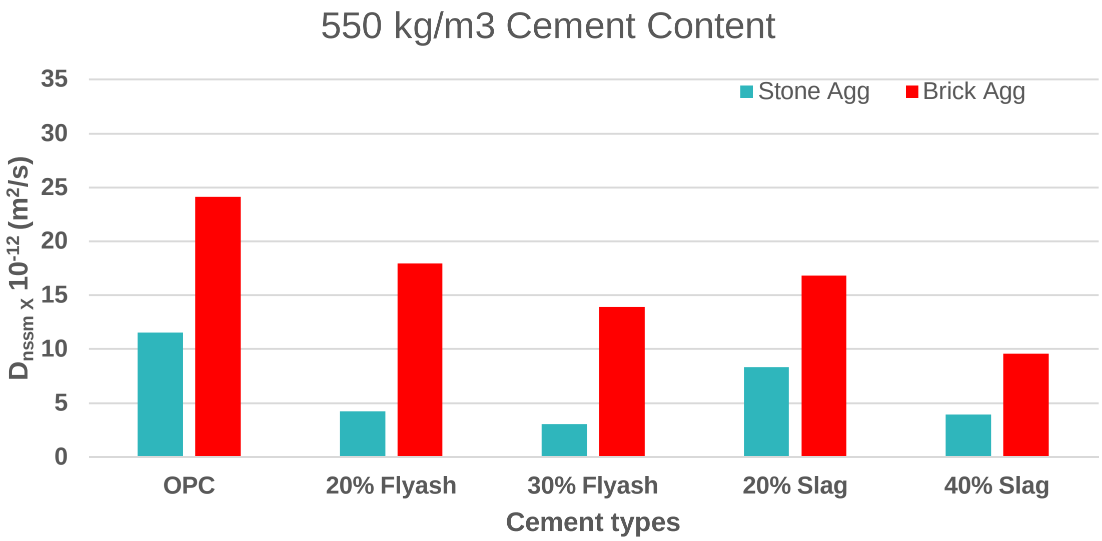
Laboratory Testing – Phase II

Chloride migration test - Results



Laboratory Testing – Phase II

Chloride migration test - Results



Laboratory Testing – Phase II

Salt ponding tests

- 3 months of salt ponding
- No conclusive results as active corrosion has not yet initiated
- Further testing is needed (up to 1 year) to get conclusive results
- Performance of corrosion inhibitors can be assessed using this test

Laboratory Testing – Phase II

Service-life modelling – CorrPredict Chloride model

- Results from laboratory testing used in CorrPredict (a bespoke probabilistic model based on FIB Bulletin 34)
- Determines cover required /service life for durability in marine environments

c

Key Input Parameters		
Cover	80	mm
Drcm,0	6E-12	m²/sec
Design Life	120	years

RELIABILITY I
Serviceability limit state
Onset of corrosion

Varying sceanrios for onset of corrosion limit

Reliability Index at fixed Drcm,0 and design life but var

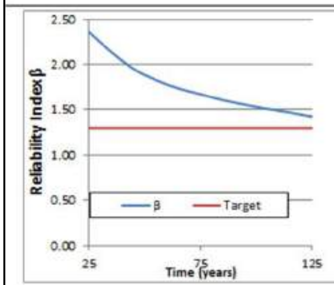
Drcm,0	6.00E-12	m²/sec				Design life	120	years				
Cover	0	10	20	30	40	50	60	70	80	90	100	110
β	-0.53	-0.36	-0.01	0.35	0.66	0.90	1.11	1.28	1.45	1.61	1.74	1.86

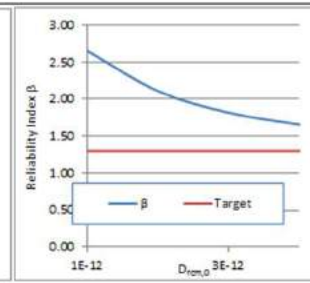
Reliability Index at fixed cover and design life but with vary

Cover	80 mm	Design life	120 years		
Drcm,0	1.2E-11	1E-11	8.00E-12	6.00E-12	4.00E-1
β	1.08	1.16	1.27	1.42	1.66

Reliability Index at fixed cover and Drcm,0 with varying

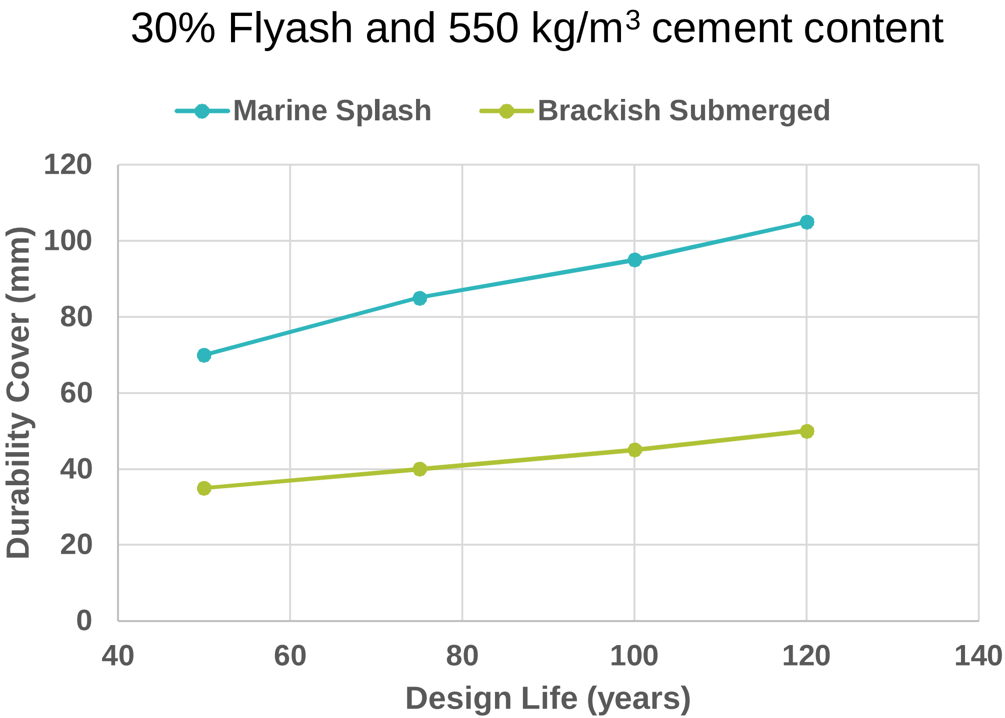
Drcm,0	6.00E-12				Cover	80							
Design life	25	35	45	55	65	75	85	95	105	115	125	135	145
β	2.36	2.14	1.95	1.83	1.74	1.67	1.61	1.56	1.51	1.47	1.43	1.39	1.37





Laboratory Testing – Phase II

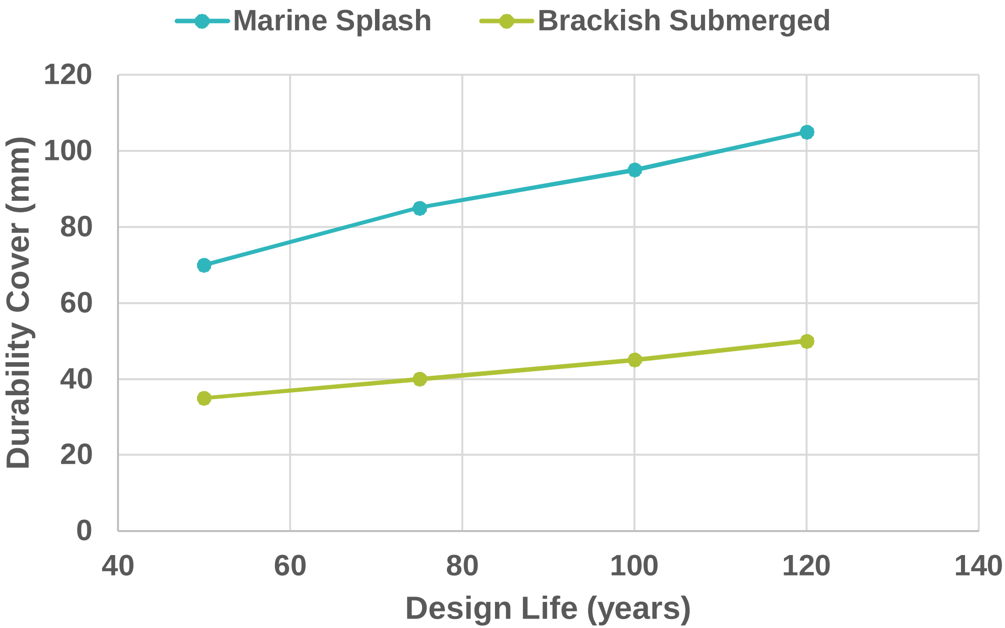
Service-life modelling – CorrPredict Chloride model



Laboratory Testing – Phase II

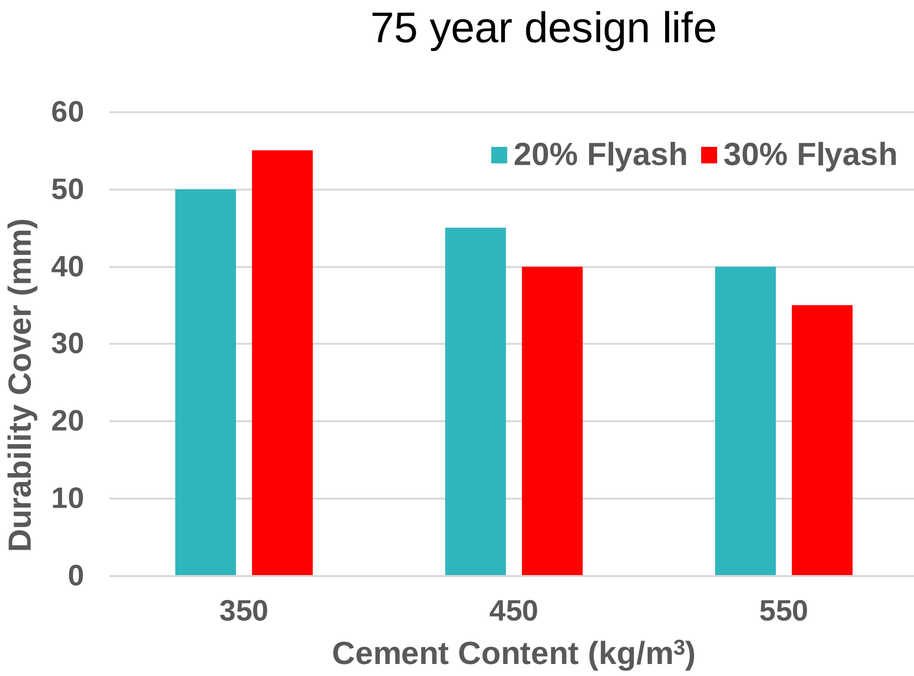
Service-life modelling – CorrPredict Chloride model

30% Flyash and 550 kg/m^3 cement content



Laboratory Testing – Phase II

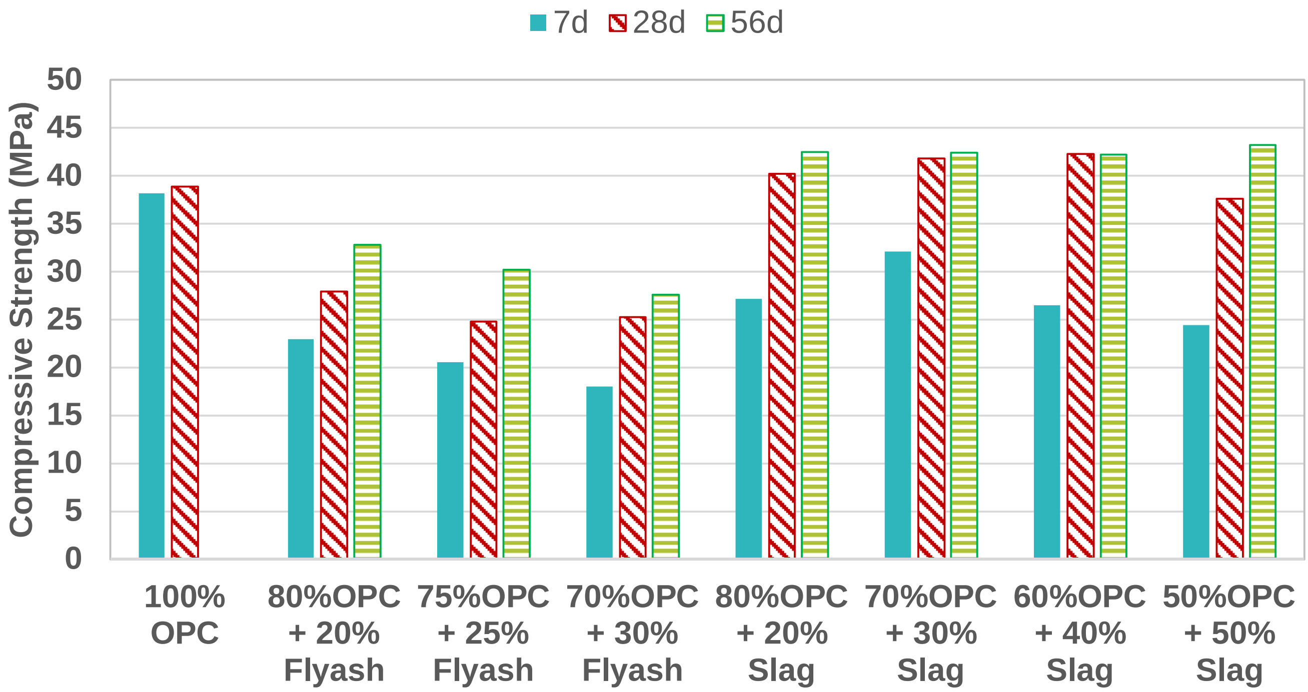
Service-life modelling – CorrPredict Chloride model



Laboratory Testing – Phase II

Service-life modelling – CorrPredict Chloride model

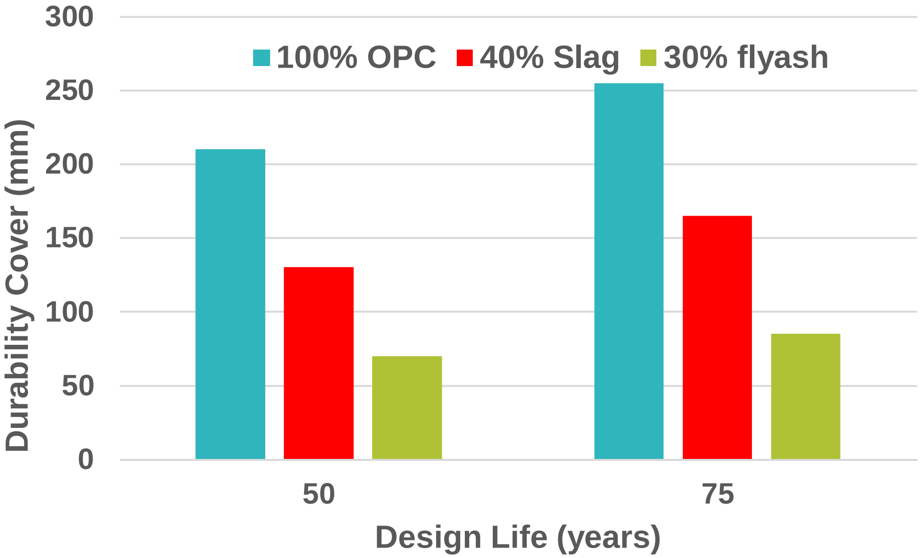
Strength vs Durability

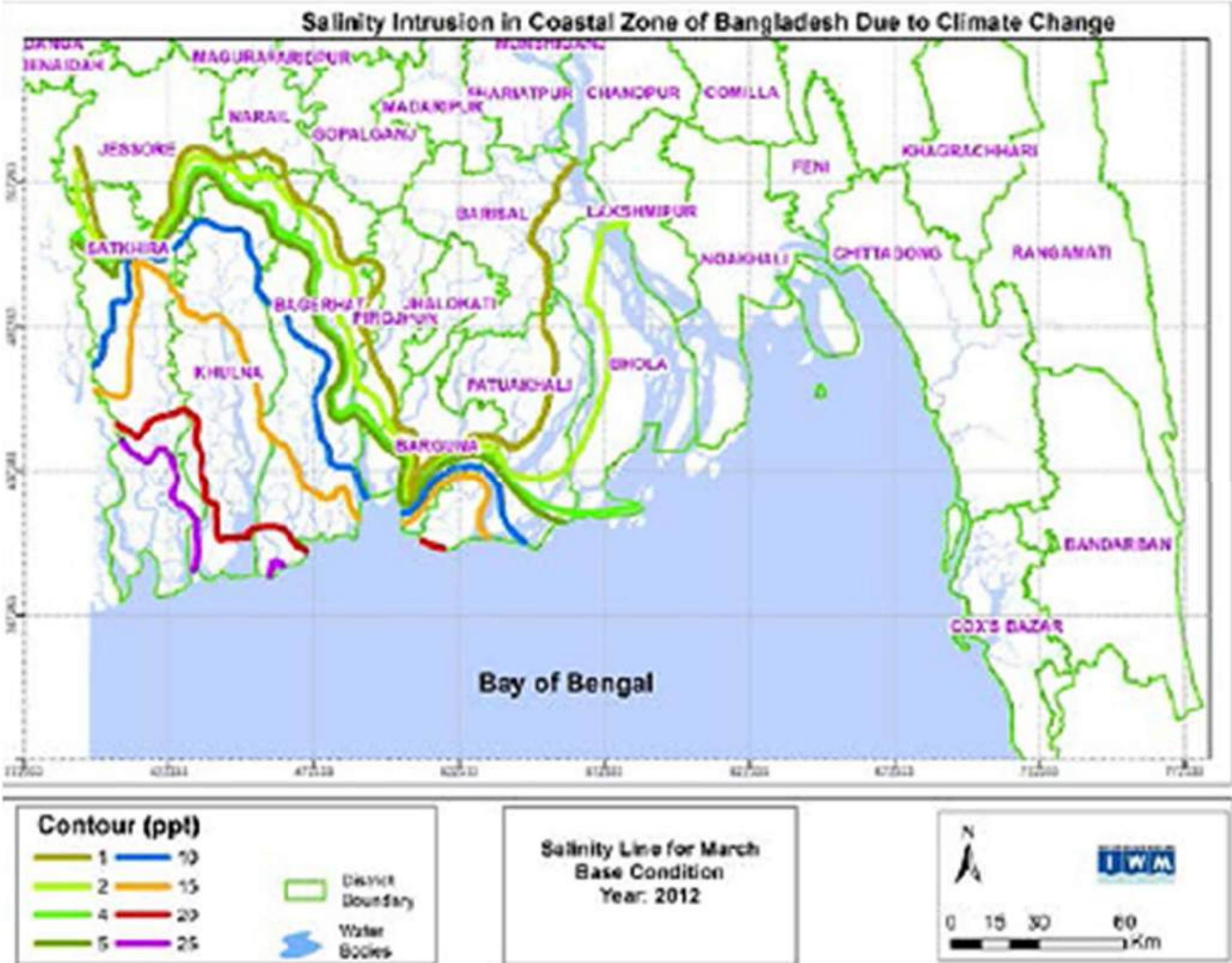


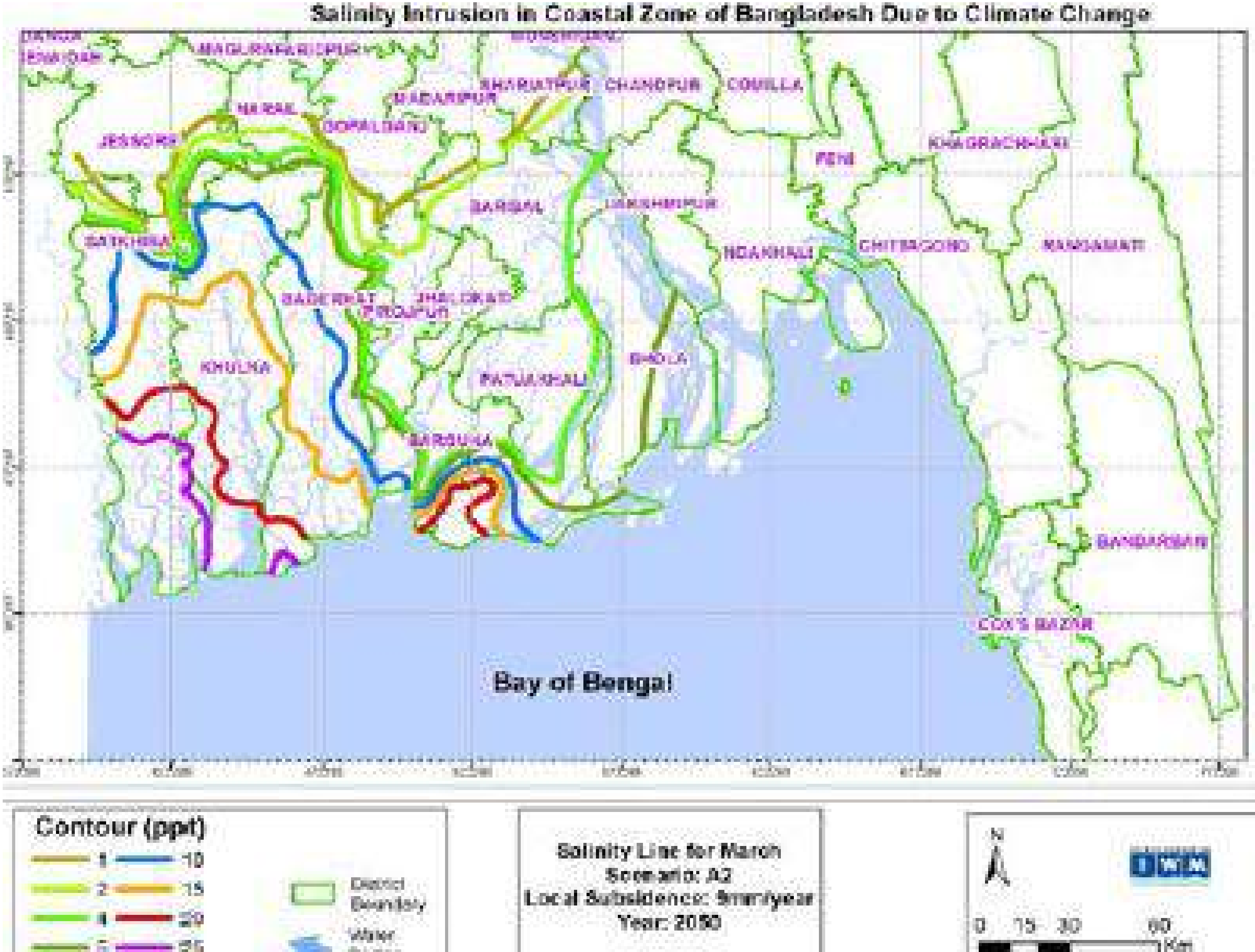
Laboratory Testing – Phase II

Service-life modelling – CorrPredict Chloride model

Strength vs Durability




Salinity Intrusion in Coastal Zone of Bangladesh Due to Climate Change
MAGURA FARIDPUR
SHARIATPUR
CHANDPUR
COMILLA
NARAIL
MADARIPUR
GOPALGANJ
JESSORE
KHAGRACHHARI
FENI
BARISAL
LAKSHMIPUR
SATKHIRA
NOAKHALI
CHITTAGONG
RANGAMATI
BAGERHAT
JHALOKATI
PIROJPUR
KHULNA
BHOLA
PATUAKHALI
BARGUNA
BANDARBAN
COX'S BAZAR
Bay of Bengal
Contour (ppt)
1
2
4
5
10
15
20
25
District Boundary
Water Bodies
Salinity Line for March
Base Condition
Year: 2012
N
0 15 30 60 Km
IWM



Salinity Intrusion in Coastal Zone of Bangladesh Due to Climate Change
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JHALOKATI
PIROJPUR
KHULNA
BHOLA
PATUAKHALI
BARGUNA
BANDARBAN
COX'S BAZAR
Bay of Bengal
Contour (ppt)
1
2
4
10
15
20
District Boundary
Salinity Line for March
Scenario: A2
Local Subsidence: 5mm/year
Year: 2050
N
0 15 30 60

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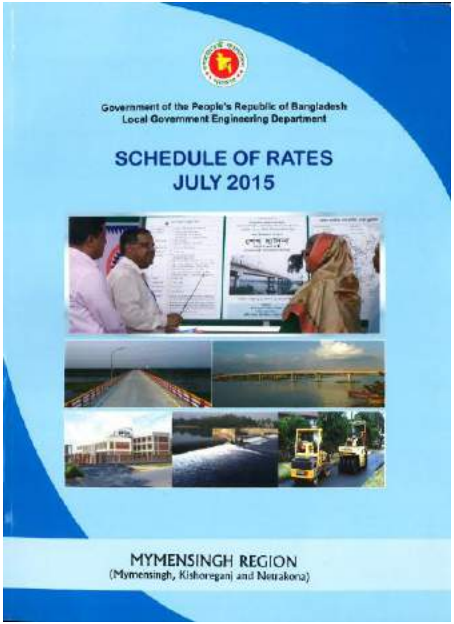
LGED Standards

Schedule of rates 2015 – Concrete specification

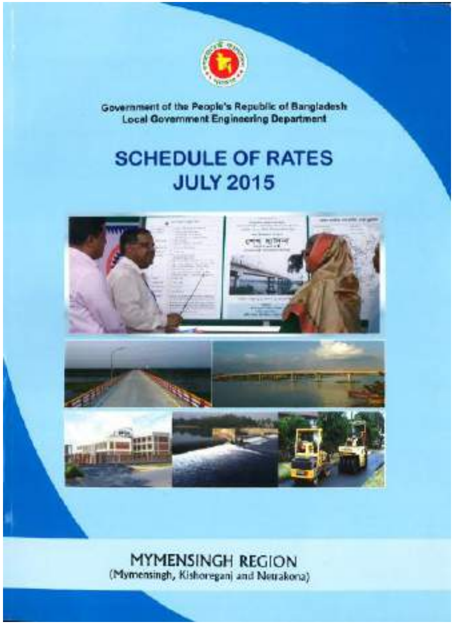
- RCC-17BCCM
  - Nominal mix 1:2:4
  - Max w/c - 0.45
  - 17 MPa strength
  - CEM II/A-M (42.5N)
  - Crushed picked brick chips
- RCC-20SCCM
  - Nominal mix 1:2:4
  - Max w/c - 0.40
  - 20 MPa strength
  - CEM I (52,5 N)
  - Well graded stone aggregates



LGED Standards

Schedule of rates 2015 – Concrete specification

- RCC-25SCCM
  - Nominal mix 1:1.5:3
  - Max w/c - 0.40
  - 25 MPa strength
  - CEM I (52,5 N)
  - Well graded stone aggregates
  - Water reducing admixture
- RCC-30SCBP
  - Laboratory mix design
  - 30 MPa strength
  - CEM I (52,5 N)
  - Well graded stone aggregates
  - Water reducing admixture



Conclusions from Laboratory testing

- OPC perform poorly in chloride environments
- Flyash performs better then slag
- Corrosion inhibitors not conclusive
- Brick aggregates have significantly poorer performance
- WRA's beneficial
- Concrete mix designs benefit from chloride diffusion tests (NT Build 492)

Final Recommendations

75 year design life ; 70%OPC+30% Flyash

	Splash		Submerged		Subaerial	
	Cover	**Min CC (kg/m^3)**	**Cover**	**Min CC (kg/m^3)**	**Cover**	**Min CC (kg/m^3)**
Marine	85	500	50	500	40	500
Brackish		400		400		400

Nominal Mix for 500 kg/m3 = 1:1:2 + WRA

Nominal Mix for 400 kg/m3 = 1:1.5:3 + WRA

Final Recommendations

- Training
  - Raise awareness on the benefits of mineral additions
  - Improve awareness on good construction practices e.g water addition in mix, proper compaction, proper curing etc.
- Mix designs
  - Brick aggregates should not be used in reinforced concrete structures
  - 30% flyash should be used in concrete in all aggressive chloride environments
  - Concrete mix design methodology should include chloride diffusion tests (NT Build 492)
  - Specifications should be updated to reflect latest best concreting practices

Final Recommendations

- Materials
  - Industry should move away from CEM II/A-M (20% of any addition) to CEM II/B-V (25-30% Flyash)

Acknowledgements

Thanks to

- LGED
- BUET
- Bashundhara Cement
- Yara Inc, Norway
- ReCAP

Future Work?

Asset Management of Structures

Thank You