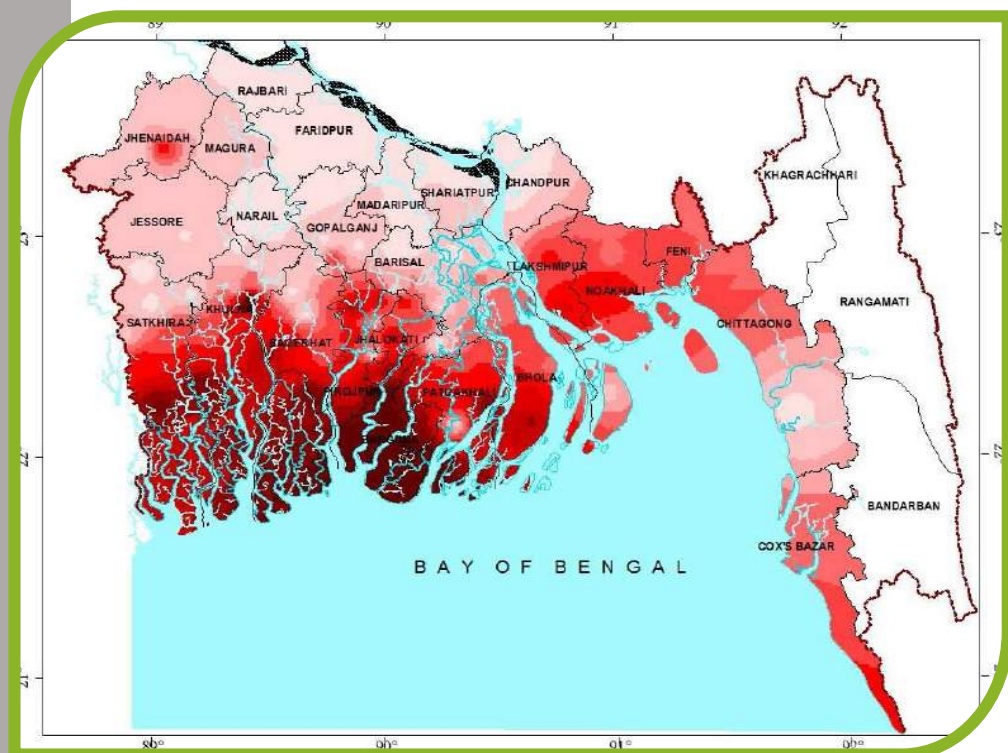




## Climate Resilient Concrete Structures in Marine Environment of Bangladesh

Inception Report



Mott MacDonald Ltd.

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August 2016



The views in this document are those of the authors and they do not necessarily reflect the views of the Research for Community Access Partnership (ReCAP), or Cardno Emerging Markets (UK) Ltd for whom the document was prepared

Cover Photo: Spatial variation of salinity in groundwater  
(Source: Bangladesh Agricultural Development Corporation)

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## 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.

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.

## Key words

Concrete durability, Corrosion, Carbonation, Bangladesh, Climate change, Coastal infrastructure, Condition survey, Chloride, Marine structures

## **RESEACH FOR COMMUNITY ACCESS PARTNERSHIP (ReCAP)** *Safe and sustainable transport for rural communities*

ReCAP is a research programme, funded by UK Aid, with the aim of promoting safe and sustainable transport for rural communities in Africa and Asia. ReCAP comprises the Africa Community Access Partnership (AfCAP) and the Asia Community Access Partnership (AsCAP). These partnerships support 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. The ReCAP programme is managed by Cardno Emerging Markets (UK) Ltd.

**See [www.afcap.org](http://www.afcap.org)**

## **Acknowledgements**

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

## **Acronyms, Units and Currencies**

£	British Pound
ADB	Asian Development Bank
AFCAP	Africa Community Access Partnership
ASCAP	Asia Community Access Partnership
GPS	Global positioning system
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.

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## **1 Introduction**

### **1.1 Background**

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

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

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

The outcome of the Project is to help 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 MML mobilised their team, combined international expertise with local experience and expertise in Bangladesh. The international experts have are highly experience 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.

A plan has been developed to deliver the Project within a year of the award of contract and 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/salted); 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 preliminary and detailed condition surveys on concrete structures in different exposure conditions of coastal regions to evaluate chloride levels and carbonation depths, quality of workmanship (eg. 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 and condition survey and site visits, potential opportunities to enhance the climate resilience of concrete structures will be 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 will be held to discuss the findings of the research work. A final project report based on the outcomes of the stakeholder workshop will be prepared providing 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 if field demonstrations, monitoring and evaluation of the suitability of the proposed solutions are required. A journal article(s) and/or conference paper(s) based on the outcomes of the research will also be written.

## **1.3 Concrete deterioration mechanisms**

An introduction to the key deterioration mechanisms for concrete in a marine environment are discussed in the following section and will be 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.

### **1.3.1 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 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 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).

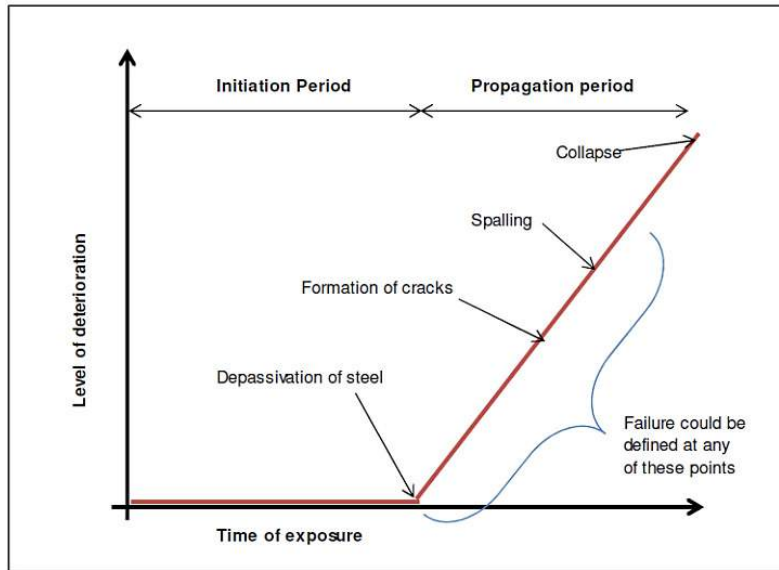


Figure 1 Two phase initiation/propagation model

### 1.3.2 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.

### 1.3.3 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. where there is less than 50% relative humidity. However, 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.

## 1.4 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.

## **1.5 Chemical and Physical Attack**

### *1.5.1 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.

### *1.5.2 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;
- It 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).

### *1.5.3 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<sup>2</sup> have been measured for sodium chloride crystals.

#### 1.5.4 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 Inception Stage

### 2.1 General

Following the signing of the contract a project team as shown in Table 1 was mobilised for the inception stage of the project.

**Table 1 Project team members involved in the Inception stage**

Staff	Designation
Farook Chowdhury (FC)	Project Director
Ian Gibb (IG)	Project Leader
Richard Lebon (RL)	Project Manager
Sudarshan Srinivasan (SS)	Materials Engineer
Dil Yasmin Dil Khan (DYK)	Deputy Team Leader
Khan Amanat (KA)	Peer Reviewer

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 gleaned are summarised Table 2.

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 meeting with clients, local contractors, material suppliers and collecting local testing related information.

### 2.2 Construction Practice

A detailed understanding of construction practice in the rural marine environments will be developed during the condition survey stage of the Project. However, the contrasting standards of construction was illustrated locally within Dhaka, through observation of extensive drainage works taking place in Banani (the district of Dhaka where the Mott MacDonald office is situated) 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 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 2 Concrete plants at the Elevated Expressway Project**



Pending further investigation, it is likely that some of the significant factors to be addressed will be 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 will also be 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 which will be further explored and developed during the laboratory research programme 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).

**Table 2 Summary of key meetings and information during Inception stage visits**

<b>Meeting/Event</b>	<b>Action/Key Contacts</b>	<b>Issues/Information</b>
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, up to four areas may need to be visited – the following were suggested: Bagerhat, Noakhali, Gopalganj and Cox’s Bazar Contact details of local LGED engineers will be provided but initial contact should be made through Abul Bashar LGED Design manuals are freely available and can be found on the following link <a href="http://www.lged.gov.bd/UnitPublication.aspx?UnitID=4">http://www.lged.gov.bd/UnitPublication.aspx?UnitID=4</a> Visited laboratory testing facilities – 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
Bangladesh University of Engineering and	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

Meeting/Event	Action/Key Contacts	Issues/Information
Technology (BUET)		Discussion o CCRIP project indicated that although large scope of project, budget is very small therefore output will be limited. Could provide some useful input into the Project
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)	Aditya Birla was keen to explore opportunities to develop products for the rural marine environment. Cement production was 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)	Constructive meeting held with largest cement producer in Bangladesh. Very supportive of idea of developing products for the rural marine environment.

### 3 Literature Review

#### 3.1 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 3.

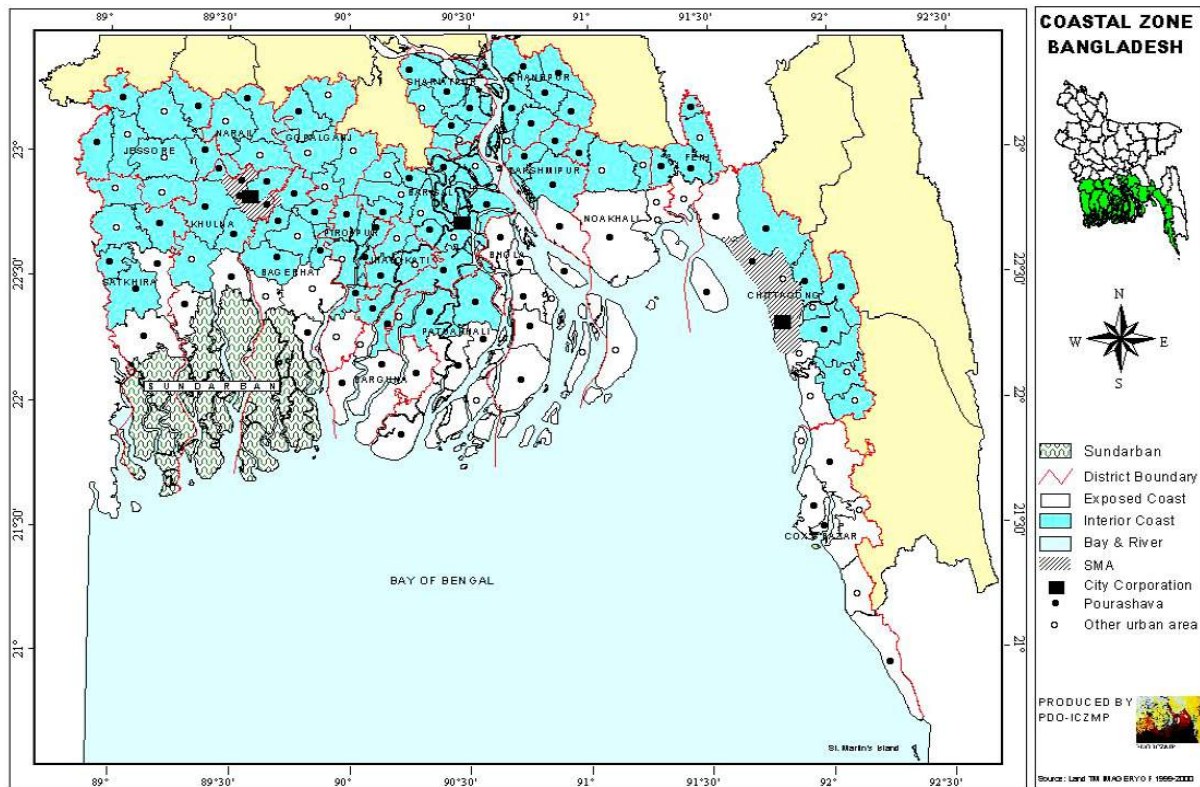


Figure 3 Coastal zone of Bangladesh (Ahmad, 2005)

#### 3.2 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 4. January is the coolest month with lowest minimum temperature averaging at 12.5°C.

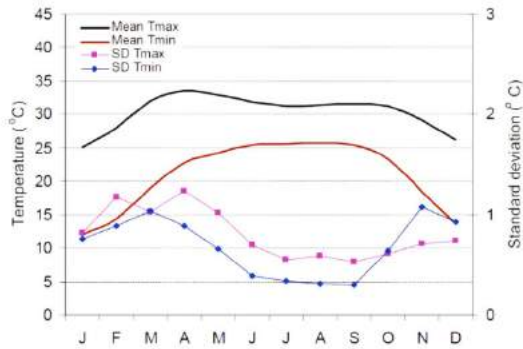


Figure 4 Annual distribution of average minimum and maximum temperature of Bangladesh based on 1948-2004 data (ADB, 2013)

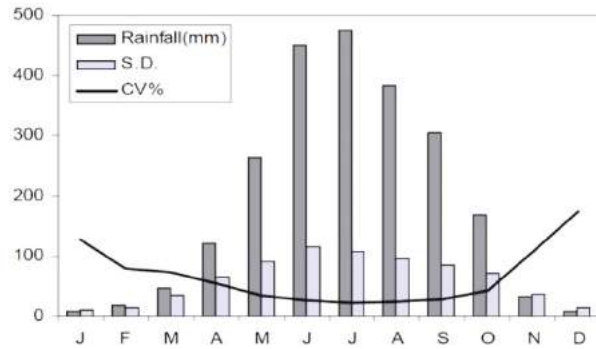


Figure 5 Annual distribution of mean rainfall of Bangladesh based on 1948-2004 data (ADB, 2013)

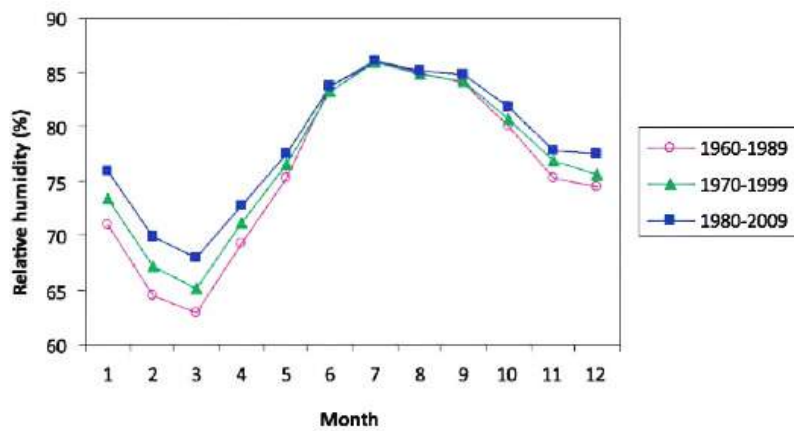
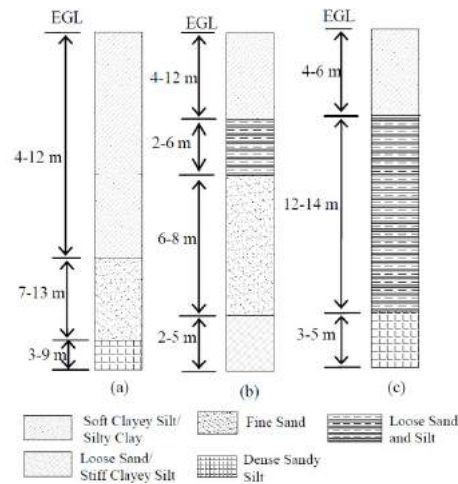


Figure 6 All Bangladesh monthly normal humidity variation (Mondal et al, 2013)

Bangladesh received average annual rainfall of 2286mm (ADB, 2013). The annual distributions of country’s mean monthly rainfall is shown in Figure 5. It can be observed from the Figure 5 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 6, 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).

### 3.3 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 7. 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 7 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.

### 3.3.1 Ground Salinity

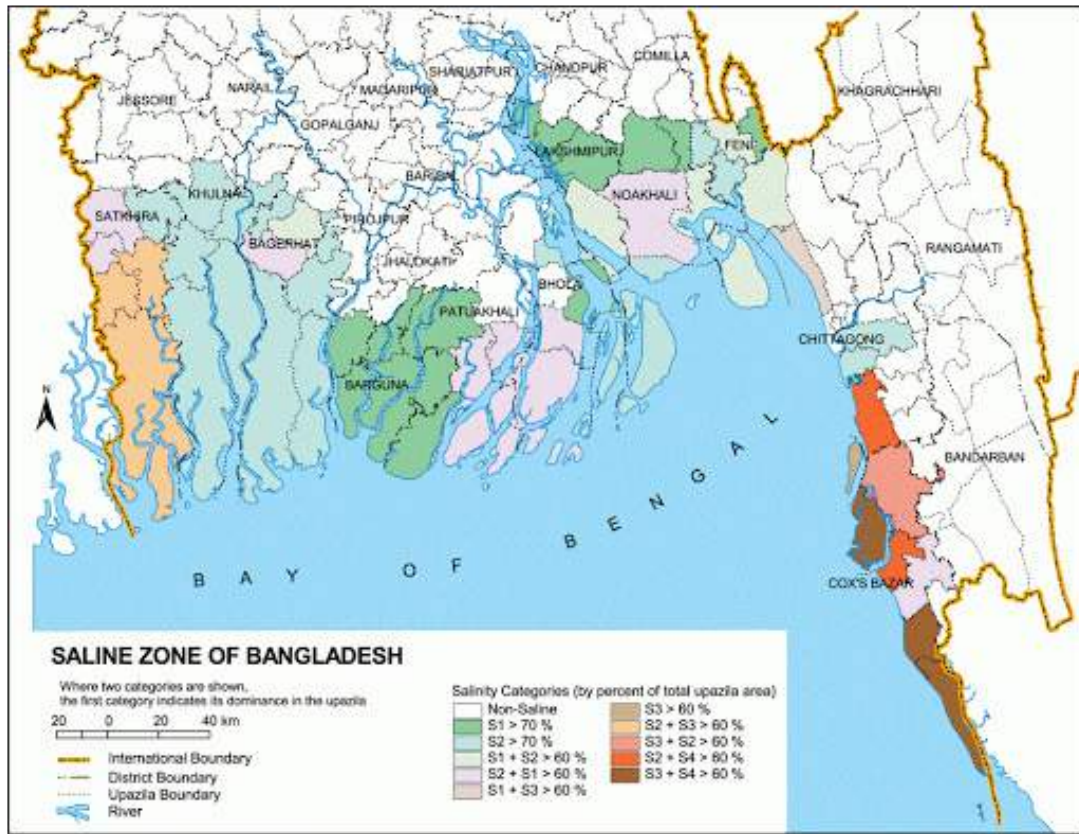
Salinity of soil and ground water in the coastal regions of Bangladesh is a major issue affecting the livelihood of people in terms of reduction in agricultural output and lack of good drinking water in the region (Dasgupta et al 2014). Chloride (Cl<sup>-</sup>) is a common anion in soil and groundwater, 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 reduction in passivity at the rebar surface.

The salinity of soil in the coastal regions of Bangladesh are zoned as shown in Figure 8, which shows the spatial variation in salinity levels in different coastal Upazilas. A similar contour map on the salinity levels in ground water is shown in Figure 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.

### 3.3.2 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). The spatial variation in the deposition of marine salts measured using wet candle sensors from the shoreline of Bangladesh is shown in Figure 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 extended up to 200m from the shoreline.



Source: Bangladesh Agriculture Research Council

Figure 8 Saline zone of Bangladesh (Source: Bangladesh Agriculture Research Council)

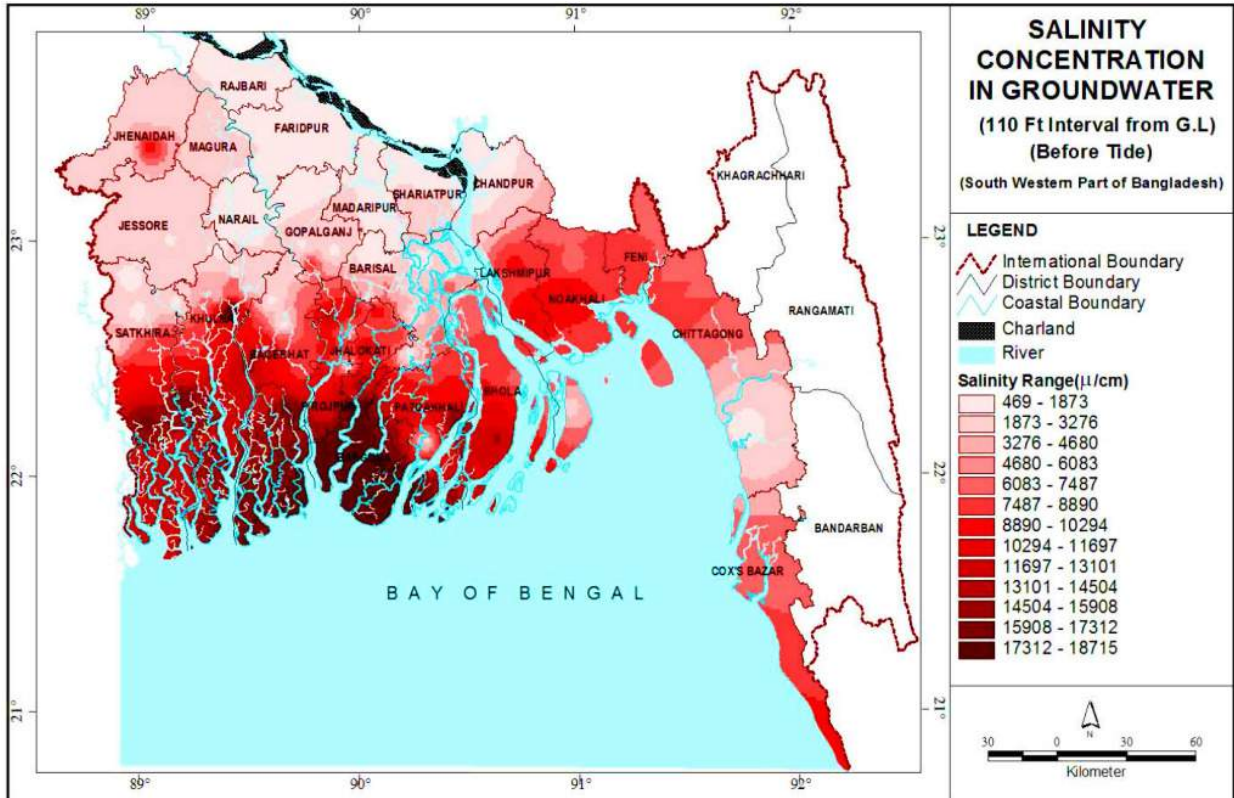


Figure 9 Salinity of ground water at a depth of 34m (BADC, 2011)

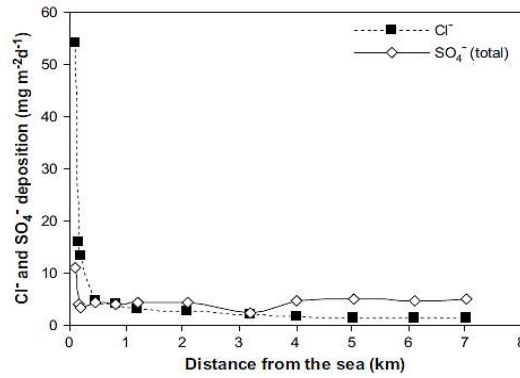


Figure 10 Variation of dry deposition of marine salts away from the shoreline (Hossain et al 2009)

### 3.3.3 Sulfates in 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.

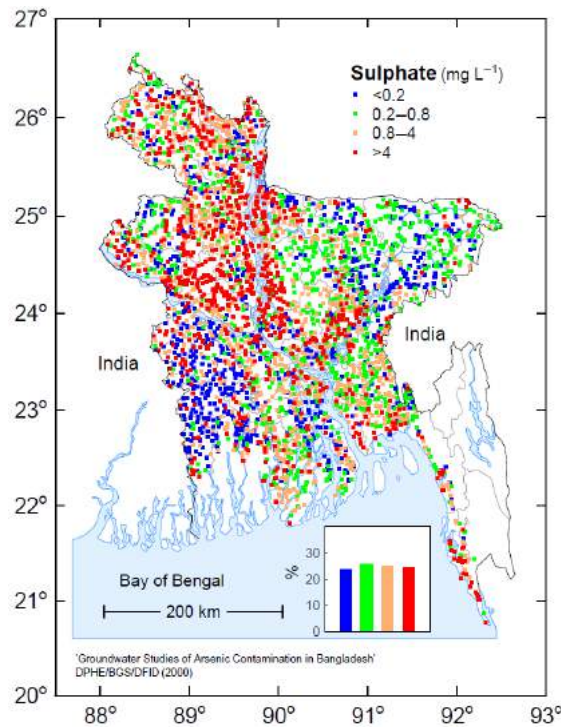


Figure 11 Spatial variation of sulfate in groundwaters from the National Hydrochemical Survey (BGS, 2001)

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 south-west and southern parts of Bangladesh as shown in Figure 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.

### **3.3.4 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 result in disintegration of cement matrix and associated damage of concrete elements.

## **3.4 Materials**

### **3.4.1 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 Flyash/Limestone/Slag: 21-30%.

### **3.4.2 Fly ash**

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, Thermal Power Plants in Bangladesh produce around 52000 MT of fly ash every year, which is largely disposed in dry embankments. Currently Fly ash is produced in only one thermal power plant and the qualitative analysis of fly ash sourced from Barapukuria Power Plant indicates it can be classed as Class F grade fly ash (Tammim et al 2013).

### **3.4.3 Aggregates**

Broken brick chips are widely used as coarse aggregates in concrete due to the shortage in availability of stone aggregates. 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 on engineering properties of stone aggregates collected from different sources in Bangladesh is presented in Table 3. 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 12 shows the soil texture map of Bangladesh and it can be observed that the coastal areas of the country mainly has 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 13.

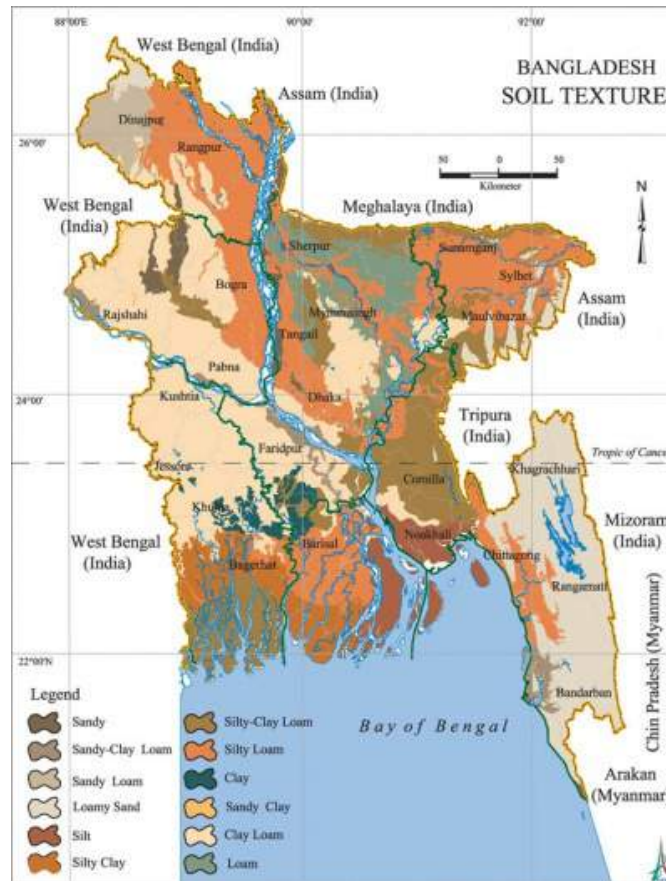


Figure 12 Bangladesh soil texture map

Table 3 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/m <sup>3</sup> )	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			

Properties	Stone aggregates				Other Aggregates		
	Zaflong in Sylhet	Volaganj in Sylhet	Vozonpur in Panchagarh	Boropukuria in Dinajpur	Brick Chips	Shingles	Jhama Brick chips
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

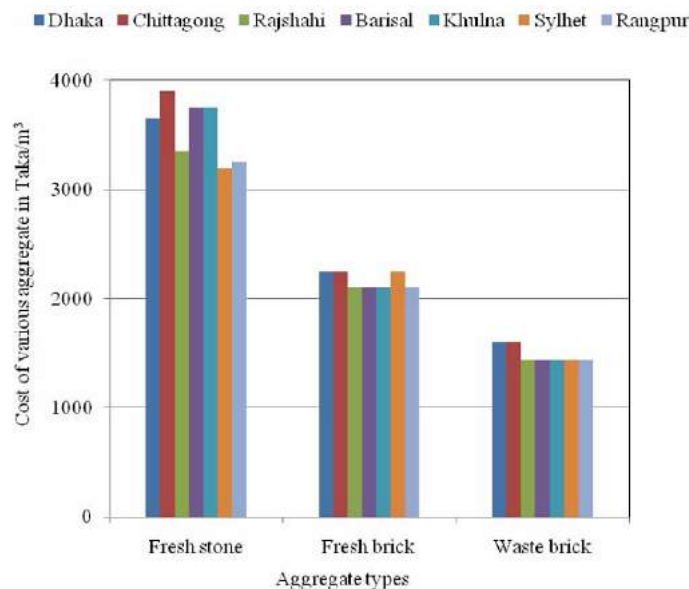


Figure 13 Comparison of cost per m<sup>3</sup> of coarse aggregate (Rasel et al 2011)

#### 3.4.4 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.

#### 3.4.5 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 have been used in concrete making, 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).

#### 3.4.6 Material problems

The use of unsuitable or contaminated materials has been a frequent cause of problems to 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 eliminated. 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 e.g. aggregates, water, cement, ggbs, pfa, etc;
- Contamination of steel surfaces (e.g. with salts).

### **3.5 Workmanship**

It is recognised that workmanship is a major factor in obtaining good quality, durable concrete, particularly in rural and coastal regions of Bangladesh where extreme cyclonic weather conditions are becoming more frequent contributing to the migration of skilled workforce able to produce, place and cure concrete to the standards required to optimize its durability in this aggressive environment.

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 on survey of condition of concrete structures in 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 attention during design to simplify construction details and using an appropriately skilled and supervised workforce.

### 3.6 Climate change and its implications on coastal concrete structures

The future climate change scenario and its impacts on coastal concrete structures in Bangladesh is summarised in Table 4:

**Table 4 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	<ul style="list-style-type: none"> <li>• accelerates deterioration processes</li> <li>• increases the water demand in concrete</li> <li>• increases shrinkage and thermal cracking in concrete</li> <li>• needs additional curing measures</li> <li>• increased thermal expansion of elements in existing structures</li> </ul>
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	<ul style="list-style-type: none"> <li>• Increased flooding increases flood loading on structures</li> <li>• Wetter ground causes rising damp and related deterioration of concrete</li> </ul>
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 Tidal level will also increase with SLR	<ul style="list-style-type: none"> <li>• SLR and increase in tidal levels increases the exposure to salts in seawater</li> <li>• Increased risk of corrosion in concrete structures</li> <li>• Increase in biological deterioration of concrete</li> </ul>
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	<ul style="list-style-type: none"> <li>• Increases the wind loading and flooding loading on structures</li> <li>• Increases the contamination of construction materials</li> </ul>
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	<ul style="list-style-type: none"> <li>• Increased salinity increases the risk of reinforcement corrosion and reduces the service-life of concrete structures</li> <li>• Increases the contamination of construction materials</li> <li>• More structures exposed to chlorides</li> </ul>
CO2 emission (Gunter and Rahman, 2012)	Baseline in 2005: CO2 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)	<ul style="list-style-type: none"> <li>• Increases the depth of carbonation in exposed concrete thereby increases the risk of reinforcement corrosion in concrete</li> </ul>

### 3.7 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

#### 3.7.1 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 5.

**Table 5 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	<p><b>Special exposures:</b></p> <ul style="list-style-type: none"> <li>- Low permeability concrete when exposed to water W/C &lt;0.5</li> <li>- Marine and salt environment W/C &lt;0.40</li> </ul> <p><b>Sulfate exposure:</b></p> <ul style="list-style-type: none"> <li>- Sulfate resisting cement with W/C ratio given in the table</li> </ul>					

Property	Standard	Type A	Type B	Type C																									
		below - Calcium chloride shall not be used as admixture in concrete exposed to severe or very severe sulfate environment																											
		<table border="1"> <thead> <tr> <th>Sulfate exposure</th> <th>Water soluble sulfate (SO<sub>4</sub>) in soil (percent by weight)</th> <th>Sulfate (SO<sub>4</sub>) in water</th> <th>Cement type<sup>1</sup></th> <th>Maximum water cement ratio by weight</th> </tr> </thead> <tbody> <tr> <td>Negligible</td> <td>0.00-0.10</td> <td>0-150</td> <td></td> <td></td> </tr> <tr> <td>Moderate<sup>2</sup></td> <td>0.10-0.20</td> <td>150-1500</td> <td>II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)</td> <td>0.50</td> </tr> <tr> <td>Severe</td> <td>0.20-2.00</td> <td>1500-10000</td> <td>V</td> <td>0.45</td> </tr> <tr> <td>Very Severe</td> <td>Over 2.00</td> <td>Over 10000</td> <td>V plus pozzolan</td> <td>0.45</td> </tr> </tbody> </table>	Sulfate exposure	Water soluble sulfate (SO <sub>4</sub> ) in soil (percent by weight)	Sulfate (SO <sub>4</sub> ) in water	Cement type <sup>1</sup>	Maximum water cement ratio by weight	Negligible	0.00-0.10	0-150			Moderate <sup>2</sup>	0.10-0.20	150-1500	II, IP(MS), IS(MS), P(MS), I(PM)(MS), I(SM)(MS)	0.50	Severe	0.20-2.00	1500-10000	V	0.45	Very Severe	Over 2.00	Over 10000	V plus pozzolan	0.45		
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		1. For types of cement see ASTM C150 and C595 2. Sea water																											
		<p><b>Corrosion of reinforcement:</b>                      Maximum chloride ion content for corrosion protection</p> <table border="1"> <thead> <tr> <th>Type of member</th> <th>Maximum water soluble chloride ion(C1)in concrete, percent by weight of cement</th> </tr> </thead> <tbody> <tr> <td>Reinforced concrete exposed to chloride in service</td> <td>0.15</td> </tr> <tr> <td>Reinforced concrete that will be dry or protected from moisture</td> <td>1.00</td> </tr> <tr> <td>Other reinforced concrete construction</td> <td>0.30</td> </tr> </tbody> </table>			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																	
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Other reinforced concrete construction	0.30																												

3.7.2 Concrete specification for bridges

Review of concrete related clauses specified in Road Structures Manual (RSM'08) are given in Table 6.

Table 6 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 <b>Grades of concrete specified in RSM'08:</b>																			
		<table border="1"> <thead> <tr> <th>Grade</th> <th>28 days cylinder strength</th> <th>Application</th> </tr> </thead> <tbody> <tr> <td>Class 10</td> <td>10 MPa</td> <td>Plain concrete below foundation</td> </tr> <tr> <td>Class 15</td> <td>15 MPa</td> <td>Plain concrete in other cases</td> </tr> <tr> <td>Class 20*</td> <td>20 MPa</td> <td rowspan="2">Reinforced concrete components of superstructure, substructure and piles</td> </tr> <tr> <td>Class 25*</td> <td>25 MPa</td> </tr> <tr> <td>Class 30</td> <td>30 MPa</td> <td rowspan="2">Pre-stressed concrete</td> </tr> <tr> <td>Class 35</td> <td>35 MPa</td> </tr> </tbody> </table>	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
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		Class 30	30 MPa	Pre-stressed concrete																	
Class 35	35 MPa																				
* For class 20 and 25 – minimum cement content 330 and 350 kg/m <sup>3</sup> respectively and maximum W/C ratio: 0.5																					
Steel	Strength	Conforming to BDS 1313:1991 Minimum yield strength of steel – 415 MPa (Grade 60)																			
Cement	General	Conforming to EN197-1:2000 and BDS EN 197-1:2003																			
Aggregates	General	Fine aggregates: Conforming to AASHTO M6-87 or BS 882:1983 Coarse aggregates: Conforming to AASHTO M80-87 or BS 882:1983																			
Water	Quality	Water containing <2000ppm of total dissolved solids  <b>Chemical limit of mixing water</b>																			
		<table border="1"> <thead> <tr> <th>Chemicals</th> <th>Test method</th> <th>Maximum Concentration (ppm)</th> </tr> </thead> <tbody> <tr> <td>Chlorides (Cl):                             <ul style="list-style-type: none"> <li>• Concrete in Bridge decks</li> <li>• Other reinforced concrete in moist environments</li> </ul> </td> <td>ASTM D512</td> <td>500 1000</td> </tr> <tr> <td>Sulfate (SO<sub>4</sub>)</td> <td>ASTM D 516</td> <td>3000</td> </tr> <tr> <td>Alkalis (Na<sub>2</sub>O+0.658K<sub>2</sub>O)</td> <td></td> <td>600</td> </tr> <tr> <td>Total solids</td> <td>AASHTO T26</td> <td>50000</td> </tr> </tbody> </table>	Chemicals	Test method	Maximum Concentration (ppm)	Chlorides (Cl): <ul style="list-style-type: none"> <li>• Concrete in Bridge decks</li> <li>• Other reinforced concrete in moist environments</li> </ul>	ASTM D512	500 1000	Sulfate (SO <sub>4</sub> )	ASTM D 516	3000	Alkalis (Na <sub>2</sub> O+0.658K <sub>2</sub> O)		600	Total solids	AASHTO T26	50000				
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Total solids	AASHTO T26	50000																			

## **4 Strategy for Achieving Durability**

### **4.1 Overview**

Best practice for ensuring durability of reinforced concrete elements are:

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

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

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

### **4.2 Primary Means of Protection**

The primary means of protection from deterioration should be the provision of innately durable concrete in the structures with an adequate cover depth to reinforcement. Concrete mix design is used to provide adequate structural performance together with sufficient resistance to deterioration from mechanisms including chloride induced corrosion, carbonation of concrete, sulfate attack, alkali-aggregate reaction etc. where required.

Difficult climatic conditions and scarcity of good quality materials are some of the major constraints faced at the coastal regions of Bangladesh. The performance of the concrete in structures is mainly controlled by the selection of appropriate quality of materials to produce low permeability and dense concrete to resist the ingress of contaminants in the cover zone of concrete.

The benefits of use of supplementary cementitious materials, aggregates types and water reducing admixture types in improving the strength and durability performance of concrete has been very well experimented and published in the last few decades. This section of the report reviews various case studies and published literature on the durability performance of concrete produced using locally available materials in Bangladesh.

#### *4.2.1 Selection of materials for provisional mix design*

##### **4.2.1.1 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 B-M (Portland Composite Cement). The later type contains supplementary cementitious materials such as flyash and slag along with limestone powder as inert filler at a combined dosage of 21-30%. The cement producers in Bangladesh generally vary the proportions of flyash, 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 an 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 (21-30%) can potentially be increased to  $\geq 30\%$  replacement by fly ash or slag or combination of both to improve the long-term durability performance of the concrete.

#### **4.2.1.2 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 33% reduction in compressive strength and 28% reduction in elastic modulus as 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 as compared with 100% crushed stone coarse aggregate concrete. In addition to this, brick aggregate concrete had demonstrated better performance in high alkali content in concrete and the low expansion caused by alkali-silica reaction (ASR) did not affect the engineering properties of 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 coarse aggregate in concrete is detrimental to the long-term durability performance of concrete especially in aggressive exposure conditions experienced in coastal regions of Bangladesh.

#### **4.2.1.3 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 are 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 will be explored through discussions with cement manufacturers and admixture suppliers in the country.

**4.2.1.4 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:*

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

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 7. In addition clause 8.1.7.8 of BNBC specifies minimum cover required for corrosion protection in severe exposure conditions.

**Table 7 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 <sup>2</sup> )						
		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		45	40	30	25	25	20

Environment	Exposure Conditions	Cover (mm) required at strength (minimum $f_c$ N/mm <sup>2</sup> )						
		20	25	30	35	40	45	50
	rain, alternate wetting and drying or severe condensation							
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 <sup>3</sup> )		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 will be 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 will be based on the optimisation of each parameter in the probabilistic model.

### Curing

Curing of concrete is crucial to maintain the moisture and temperature in concrete for early age strength development and to minimise thermal 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 such as columns, beams, walls etc 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 as 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 as 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 provide internal moisture required for cement hydration in the case of inadequate curing at the surface.

#### 4.2.1.5 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.

### **4.3 Secondary means of protection**

#### **4.3.1 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 lengthens 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).

Based on our initial discussions with cement manufacturers, corrosion inhibitors are currently not available in the country and need to be imported from outside. The local cement manufacturers have expressed their interest in closely working with us in this research project to explore the feasibility of incorporation of corrosion inhibitors in cement bags. Enquiries are being made with manufacturers of corrosion inhibitors in the UK and Europe for samples to be used in the research study for this project.

### **4.4 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, will be used

to populate the predictive corrosion models that will give 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.

## **5 Summary of literature review**

### **5.1 General**

As discussed in section 3 and section 4, 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

### **5.2 Identified gaps in literature review**

Although various information on environment, materials and performance of concrete structures are available especially relating to coastal regions of Bangladesh, however major gaps were identified, which needs to be addressed so as to get better information required for the design and assessment of concrete structures - as 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 proper condition survey of concrete structures that involves 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 marine environment. These models need crucial information on the durability properties such as chloride migration coefficient, maturity/strength development characteristics, surface chloride and climatic information of local environment. This information obtained at different exposure zones in the coastal regions of Bangladesh will be invaluable for the design and service life assessment of concrete structures in the region.

## 6 Test Programme

### 6.1 Introduction

Based on the information obtained in the literature survey and identified gaps in the available information, an extensive test programme is planned during the Project to assess the condition of existing structures and to develop the mix designs. The test programme will be carried out using a combination of the LGED and BUET laboratories.

### 6.2 Condition Survey & Site visits

The objective of the condition survey is to develop and 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.

At this early stage of the Project, it has not been possible to visit these areas and it is not clear how many or what type of structures will be available for inspection, their location or accessibility. The requirements of the condition survey will therefore be described in generic terms, outlining the objectives but realising that variations will need to be made depending on the nature of the structures being investigated.

From Figure 9 it can be seen that Cox's Bazaar has some of the highest salinity levels in Bangladesh, Noakhali and Bagerhat are mid-level and that salinity in Gopalganj is negligible. The exposure condition and level of salinity in ground water will undoubtedly have an impact on the aggressiveness of the environment, but to try and quantify the influence of salinity levels on service life with any degree of statistical confidence is beyond the scope of the project.

The number of variables impacting on service life (e.g. mix design, construction quality, cover, cement type, curing exposure etc) would mean that thousands of samples would need to be taken with a detailed knowledge of the structures tested (age, specifications, concrete mix designs, curing etc).

The condition survey will be used to gather some general information on the structures investigated. The testing and sampling of concrete at each structure shall be as specified in Annex C.

The testing schedule for testing involved in condition assessment of structures and availability of testing facility at BUET is shown in Table 8. The indicative costs for these tests are provided in Annex C.

**Table 8 Testing schedule for condition assessment of identified concrete structures in coastal regions**

Type of test	No of Locations	No of Areas	No of tests	Test availability in BUET
Covermeter survey	4 <sup>a</sup>	3 <sup>b</sup>	12 (4x3)	Available
Half-Cell Potential survey	4 <sup>a</sup>	3 <sup>b</sup>	12 (4x3)	Not Available
Rebound Hammer	4a	2b	12 (4x3)	Available
Core extraction (2 no 75mm dia core and 1 no 100mm dia core per area)	4 <sup>a</sup>	3 <sup>b</sup>	48 (4x3x4)	Available

Chloride analysis (chloride profile at four depths 5-30mm, 30-55mm, 55-80mm and 80-105mm per core)	4 <sup>a</sup>	3 <sup>b</sup>	48 (4x3x4)	Not available
Carbonation depth (phenolphthalein test)	4 <sup>a</sup>	3 <sup>b</sup>	12 (4x3)	Not available
Compressive strength ( Core testing)	4 <sup>a</sup>	3 <sup>b</sup>	24 (4x3x2)	Available

<sup>a</sup> Assumed one representative structure identified each at Bagerhat, Noakhali, Gopalganj and Cox’s Bazar regions

<sup>b</sup> At each structure two areas with visible signs of corrosion and one with no sign of external corrosion will be identified

### 6.2.1 Condition Survey report

This report will include outcome of the intrusive testing and visual inspection of different concrete structures based on visits to new construction sites that will be inspected as part of the condition survey phase of the project. The report will also provide comments on the current construction practices and guidelines for improvement based on international best practices. The outcome of the observations made in the condition survey of structures will be used to fine tune the variables and the research matrix for next phase - Mix design development and laboratory investigations.

### 6.3 Mix design development and Laboratory testing

At this inception stage of the project a range of variables have been proposed in the form of research matrix for phase-I and phase-II part of the laboratory investigations. The phase-I study deals with optimisation of the concrete mix to enhance its durability performance and phase-II part of the investigation focusses on studying the corrosion resistance characteristics and service-life assessment of reinforced concrete elements. However, the research matrix will be refined following the findings from the condition survey phase of the project, with the final research matrix to provide exact proportions/level of variables and a final schedule of trial mixes. In addition, at the start of experimental investigation studies a control concrete mix will be established for each study and baseline testing will be done along with other variables. The costing and schedule for laboratory tests will be submitted along with the condition survey report.

#### 6.3.1 Phase-I study

##### 6.3.1.1 Material sampling and testing

This part of the study involves collecting testing information (manufacturer’s latest test certificate or recent lab reports) on various sources of concrete materials available in the coastal region as shown in Table 9 and comparison of material properties in order to identify a representative sample for the study. Samples of the chosen representative material that will be used in the study shall be tested in accordance with the list of testing specified in Table 9.

**Table 9 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	<ul style="list-style-type: none"> <li>• Chemical analysis</li> <li>• Blaine fineness</li> <li>• Setting time (Initial &amp; Final)</li> <li>• Specific Gravity</li> <li>• Compressive Strength (3, 7 and 28 days)</li> </ul>
Fly ash	At least 3 no from most popular	<ul style="list-style-type: none"> <li>• Chemical analysis</li> </ul>

Material	Comparison of samples	Laboratory testing of chosen sample
	cement companies in coastal region	<ul style="list-style-type: none"> <li>• Blaine fineness</li> <li>• Specific Gravity</li> </ul>
Slag	At least 3 no from most popular cement companies in coastal region	<ul style="list-style-type: none"> <li>• Chemical analysis</li> <li>• Blaine fineness</li> <li>• Specific Gravity</li> </ul>
Aggregates	Locally available sand, brick chips, 'Machine Made' aggregates and stone aggregates should be sampled at Bagerhat, Noakhali, Gopalganj and Cox's Bazar	<ul style="list-style-type: none"> <li>• Specific Gravity</li> <li>• Absorption Capacity (%)</li> <li>• Unit Weight (kg/m<sup>3</sup>)</li> <li>• Los Angles Abrasion Value (%)</li> <li>• Ten Percent fines value (%)</li> <li>• Flakiness Index (%)</li> <li>• Elongation Index (%)</li> <li>• Fineness Modulus</li> <li>• Chloride content</li> </ul>
Water	Locally available drinking water and untreated water at Bagerhat, Noakhali, Gopalganj and Cox's Bazar	All the samples shall be tested to EN 1008 or ASTM equivalent

### 6.3.1.2 Concrete mix optimisation

This part of 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 10, which mainly focuses on 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 increase the proportion of SCMs in concrete mainly focusses on optimising the locally available fly ash and/or slag proportion in blended cement in the coastal regions of Bangladesh. The increased dosage of SCMs will reduce the permeability of concrete thereby improve better resistance to ingress of chloride ions and carbonation of concrete.

One of the novel features of phase-I study is feasibility trials on improving the properties of brick aggregates by various options such as pre-soaking, increased mixing times, use of 'machine made' brick aggregates and pre-treating them with thin cement slurry mix. A recent research study by Sarkar and Pal, 2016, suggests that addition of cement coating in over burnt brick aggregate has significantly reduced the impact value, LA Abrasion value, water absorption and increased the specific gravity of aggregates at an optimum 4% cement coating in bituminous concrete mixes.

This study shows a potential scope for improving the properties of brick aggregates, which can be tried in cement concrete mixes to check the improvement in durability properties of concrete. The feasibility study on brick aggregates involves preliminary testing of brick aggregates at 4% cement content (by weight of aggregate) in slurry at 0.45 W/C ratio will be compared with properties of uncoated brick aggregate. Based on the outcome of the preliminary testing, if the physical and mechanical properties of brick aggregates are significantly improved then study will be expanded to produce modified and cost effective brick aggregate concrete for use in aggressive salt environments in the coastal region.

Based on the literature survey, although brick aggregates are widely available in the coastal regions of Bangladesh, it was observed that due to high porosity of brick aggregates they are detrimental to the long-term durability of concrete. The study to compare different proportions of stone and brick aggregate in concrete aims to understand the optimum proportions of mixed stone and brick aggregates to improve the durability of concrete.

### 6.3.2 Phase-II study

The phase-II of the study builds on the outcome of phase-I and mainly focusses on improving 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 is given in Table 10, which involves tests to study chloride migration of concrete through NT Build 492 test method and corrosion rates of steel in reinforced concrete slabs subjected to accelerated corrosion environment.

To our knowledge, the NT Build 492 test is not available in Bangladesh. The test equipment is not complicated and could be replicated by a competent laboratory. Enquiries are also being made to explore purchasing a bespoke piece of equipment from the UK.

In addition to improving the corrosion resistance of reinforced concrete elements, the phase II study also looks into alternative concepts of corrosion free design of structures. In this part of the study, different examples of corrosion free concrete construction along with relative cost comparison between the design options.

**Table 10 Experimental Research Matrix**

Objective	Study	Variables	Techniques of analysis
Phase I - To optimise concrete mix constituents	To increase the proportion of SCMs in concrete	Binder content and W/C ratio: Approximate binder content 350, and 400 corresponding to 0.5 and 0.4 W/C ratio Flyash (30-40% cement replacement) Slag (30-50% cement replacement) Combination of flyash and slag (>30% cement replacement)	Fresh properties of concrete (slump, cohesion of mix, density and air content) Strength development (3, 7, 28, 56 and 90 days) Water penetration test DIN 1048 (28, 56 and 90 days)
	To study the feasibility of improving the properties of brick aggregates	Coated vs uncoated brick aggregates Handmade vs machine made brick aggregates Cement content in slurry Pre-soaking, Mixing time	<u>Preliminary Testing:</u> Specific Gravity Absorption Capacity (%) Unit Weight (kg/m <sup>3</sup> ) Los Angeles Abrasion (%) Ten Percent fines (%)  <u>Secondary Testing:</u> Fresh properties of concrete (slump, cohesion of mix, density and air content) Compressive Strength (7, 28 and 56 days) Water penetration test DIN 1048
	To optimise the proportion of	Stone : Brick 100:0	Combined gradation Unit Weight

Objective	Study	Variables	Techniques of analysis
	coarse aggregates (combination of stone aggregates and brick aggregates)	70:30 50:50 30:70 0:100 (0.5 W/C ratio and CEM I cement)	Fresh properties of concrete (slump, cohesion of mix, density and air content) Strength development (7, 28 days) Water penetration test DIN 1048
Phase II -To improve corrosion resistance of concrete structures	To study and improve corrosion resistance properties of concrete	Top two optimum cement combinations Top two optimum aggregate combinations Chloride content of concrete – 2%, 1% and 0.4% of cement content	Fresh properties of concrete (slump, cohesion of mix, density and air content) Strength development (3, 7, 28, 56 and 90 days) NTBuild 492 – Diffusion coefficient (28, 56 and 90 days) Corrosion rates and chloride ingress tests on reinforced concrete slabs subjected to accelerated corrosion environment.
	To improve corrosion resistance of steel	With and without corrosion inhibitor 60 grade steel, TMT steel bars (0.5 W/C ratio and CEM I cement)	Corrosion rates and chloride ingress tests on reinforced concrete slabs subjected to accelerated corrosion environment.
	Conceptualisation of corrosion free concrete structures	Steel free design concepts Corrosion free reinforcement	Comparison of design concepts

### 6.3.3 Laboratory investigation report

The outcome of the laboratory testing in phase-I and phase-II studies provide the basis for the specification of durable concrete mix for marine environment in Bangladesh. The report will also provide assessment on corrosion modelling and service-life improvement of reinforced concrete structures. The report will highlight the importance of performance based specification of concrete and also emphasise monitoring/testing durability of concrete at the design stage as well as during service-life.

### 6.4 Timetable of work

The proposed timetable of work includes the timing, sequence and duration of the proposed tasks, taking into account the below listed considerations is presented in Annexure A.

- Time taken for field and lab based tests given in the test programme
- Ready access to various concrete structures identified in the coastal districts
- Ready availability and access to laboratory testing equipment provided by LGED

The exact timetable is subject to amendment and possible delays due to the current security situation in Bangladesh and associated preparations needed to ensure staff safety.

## 7 Project outcomes

In addition to the objectives and deliverables provided in the terms of reference of the project, the condition survey and experimental investigation envisaged in this inception report will lead to the following output at the end of the project:

- Clear identification of typical issues during the construction of concrete structures in the rural regions of Bangladesh which affect the durability and provide guidelines based on international best practices for construction of concrete structures.
- Highlighting whole-life cost benefits of durable concrete mixes developed as an outcome of the project;
- Provision of simple guidance on the condition assessment of concrete structures based on international best practices;
- Highlighting and comparing the benefits of steel free or corrosion free design concepts;
- Dissemination of project outcomes in a national workshop in Bangladesh, peer-reviewed Journal papers, and international conferences where feasible.

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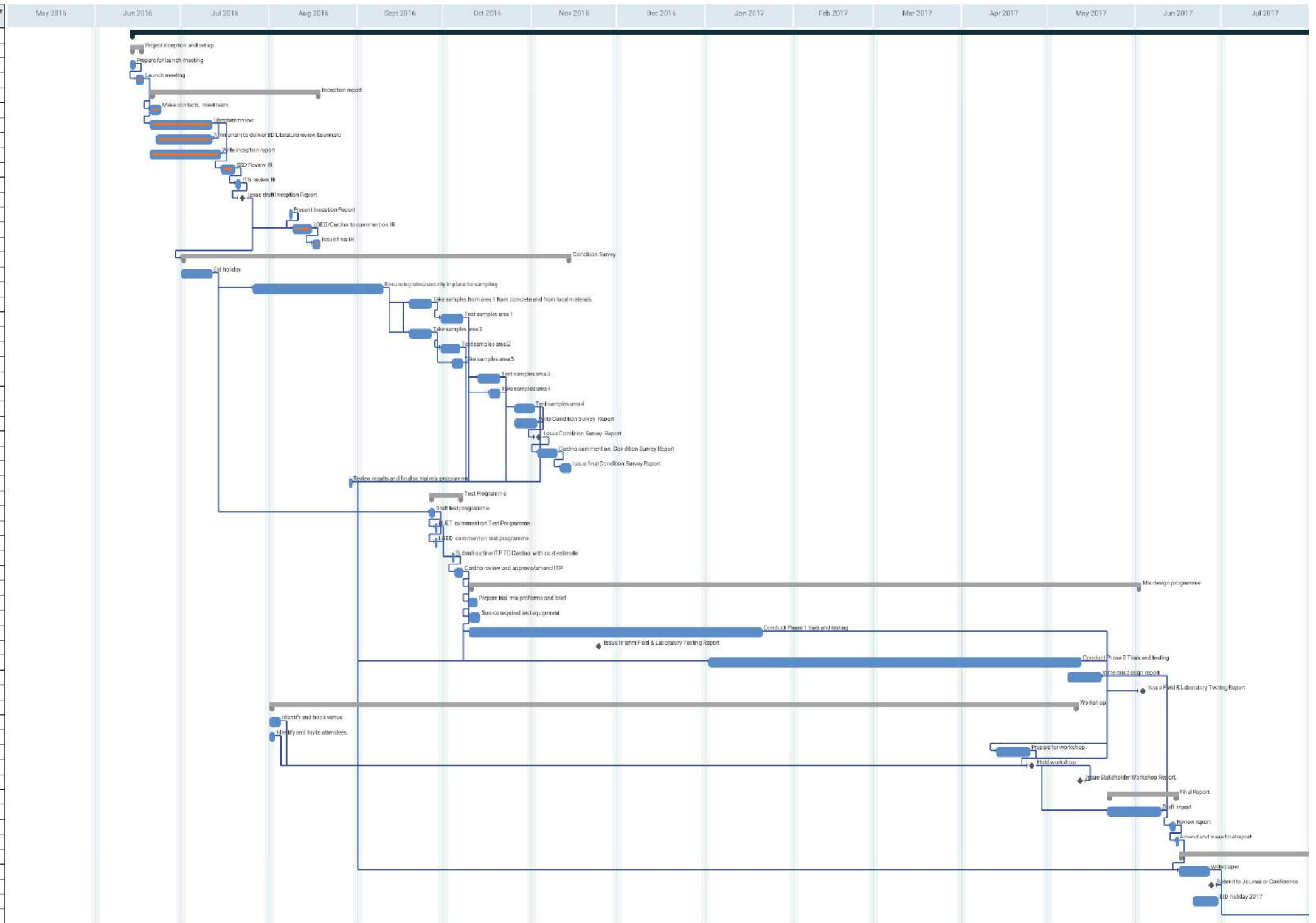
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Appendix A – Timetable of work

ID	Task Name	Duration	Start	Finish	Predecessors	Resource Name	% Complete
0	Bangladesh project	502d	13-Jun-2016	08-Aug-2017			17%
1	Project inception and set up	5d	13-Jun-2016	17-Jun-2016		IG	60%
2	Prepare for launch meeting	2d	13-Jun-2016	14-Jun-2016		IG	100%
3	Launch meeting	3d	15-Jun-2016	17-Jun-2016	2d	IG	100%
4	Inception report	44d	20-Jun-2016	18-Aug-2016			100%
5	Make contacts, meet team	4d	20-Jun-2016	23-Jun-2016	3d	IG	100%
6	Literature review	16d	20-Jun-2016	11-Jul-2016	3d	SS,IG	100%
7	Ammanant to deliver BD Literature	14d	22-Jun-2016	11-Jul-2016	6d		100%
8	Write inception report	19d	20-Jun-2016	14-Jul-2016	6d+3.0d	SS	100%
9	SSD Review IR	3d	15-Jul-2016	19-Jul-2016	8d	IG	100%
10	ITG review IR	2d	20-Jul-2016	21-Jul-2016	9d		100%
11	Issue draft Inception Report	0d	21-Jul-2016	21-Jul-2016	10d	SS	0%
12	Present Inception Report	1d	08-Aug-2016	08-Aug-2016			100%
13	LGED/Cardno to comment on IR	5d	09-Aug-2016	15-Aug-2016	11d+2.0d,12d		100%
14	Issue final IR	3d	16-Aug-2016	18-Aug-2016	11d	SS	100%
15	Condition Survey	97d	01-Jul-2016	14-Nov-2016	11d+2.0d	SS	0%
16	Eid holiday	7d	01-Jul-2016	11-Jul-2016			0%
17	Ensure logistics/security in place for	34d	26-Jul-2016	09-Sep-2016	16d		0%
18	Take samples from area 1 from concrete	6d	19-Sep-2016	26-Sep-2016	17d+5.0d	SS	0%
19	Test samples area 1	6d	30-Sep-2016	07-Oct-2016	18d+3.0d		0%
20	Take samples area 2	6d	19-Sep-2016	26-Sep-2016	18d,1.7d+5.0d		0%
21	Test samples area 2	5d	30-Sep-2016	06-Oct-2016	20d+3.0d		0%
22	Take samples area 3	4d	04-Oct-2016	07-Oct-2016	20d+5.0d		0%
23	Test samples area 3	6d	13-Oct-2016	20-Oct-2016	21d+3.0d		0%
24	Take samples area 4	4d	17-Oct-2016	20-Oct-2016	22d+5.0d		0%
25	Test samples area 4	5d	26-Oct-2016	01-Nov-2016	24d+3.0d		0%
26	Write Condition Survey Report	6d	26-Oct-2016	02-Nov-2016	25d+1.0d		0%
27	Issue Condition Survey Report	0d	02-Nov-2016	02-Nov-2016	26d		0%
28	Cardno comment on Condition Survey	5d	03-Nov-2016	09-Nov-2016	27d		0%
29	Issue final Condition Survey Report	2d	11-Nov-2016	14-Nov-2016	28d+1.0d		0%
30	Review results and finalise trial mix	1d	29-Aug-2016	29-Aug-2016	19d+2.0d,21d+2.0		0%
31	Test Programme	10d	26-Sep-2016	07-Oct-2016			0%
32	Draft test programme	2d	26-Sep-2016	27-Sep-2016	16d+2.0d		0%
33	BUET comment on Test Programme	1d	28-Sep-2016	28-Sep-2016	31d		0%
34	LGED comment on test programme	1d	28-Sep-2016	28-Sep-2016	31d		0%
35	Submit online ITP TO Cardno with cost	1d	04-Oct-2016	04-Oct-2016	33d+3.0d,34d+3.0		0%
36	Cardno review and approval/ITP	3d	05-Oct-2016	07-Oct-2016	35d		0%
37	Mix design programme	170d	10-Oct-2016	02-Jan-2017	36d		0%
38	Prepare trial mix proportions and brief	3d	10-Oct-2016	12-Oct-2016	36d		0%
39	Source required test equipment	4d	10-Oct-2016	13-Oct-2016	36d		0%
40	Conduct Phase 1 trials and testing	75d	10-Oct-2016	20-Jan-2017	36d		0%
41	Issue Interim Field & Laboratory Testing	0d	23-Nov-2016	23-Nov-2016			0%
42	Conduct Phase 2 Trials and testing	95d	02-Jan-2017	12-May-2017	30d,40d+60.0d		0%
43	Write mix design report	10d	08-May-2017	19-May-2017	40d+5.0d,42d+5.0		0%
44	Issue Field & Laboratory Testing Report	0d	02-Jun-2017	02-Jun-2017	43d		0%
45	Workshop	204d	01-Aug-2016	11-May-2017			0%
46	Identify and book venue	4d	01-Aug-2016	04-Aug-2016			0%
47	Identify and invite attendees	2d	01-Aug-2016	02-Aug-2016			0%
48	Prepare for workshop	8d	13-Apr-2017	24-Apr-2017	43d		0%
49	Hold workshop	0d	24-Apr-2017	24-Apr-2017	47d+120.0d,45d,4		0%
50	Issue Stakeholder Workshop Report	0d	11-May-2017	11-May-2017	49d+2.0d		0%
51	Final Report	19d	22-May-2017	15-Jun-2017			0%
52	Draft report	15d	22-May-2017	09-Jun-2017	45d+5.0d,49d		0%
53	Review report	2d	13-Jun-2017	14-Jun-2017	52d+1.0d		0%
54	Amend and issue final report	1d	15-Jun-2017	15-Jun-2017	53d		0%
55	Paper	38d	16-Jun-2017	08-Aug-2017			0%
56	Write paper	7d	16-Jun-2017	26-Jun-2017	30d,54d	SS,IG	0%
57	Submit to Journal or Conference	0d	26-Jun-2017	26-Jun-2017	56d		0%
58	Eid holiday 2017	7d	21-Jun-2017	29-Jun-2017			0%
59	Present paper	1d	08-Aug-2017	08-Aug-2017	57d+30.0d		0%



★ Denotes major milestones (as given in Terms of Reference)

## Appendix B: Site visit programme for condition survey

The site visit schedule for condition survey of structures in coastal districts are as given in the table below. The planned dates for the site visit are tentative at this stage of the project and subject to changes due to current security situation for travel to rural regions of the country and moreover depending on the availability of LGED Engineers.

Date & time	Structures	District (included Upazillas)	Testing
04/09/2016 to 06/09/2016	Local structures in each Upazillas identified by LGED (Total Number of structures surveyed in each district depends on safe access, logistics, power supply and time for sampling)	Gopalganj (Moksedpur, Tungipara, Kotalipara)	core extraction, covermeter survey, half-cell potential survey, Rebound hammer testing and concrete dust sampling
07/09/2016 to 09/09/2016		Bagerhat (Mongla, Rampal)	
18/09/2016 to 20/09/2016		Cox's Bazar (Coxs Bazar, Teknaf, Moheskhali)	
21/09/2016 to 23/09/2016		Noakhali (Noakhali, Companyganj, Subornachar)	