Climate resilient concrete structures in marine environment of Bangladesh

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ABSTRACT

Bangladesh has a vast coastal infrastructure seriously affected by climate change and associated extreme environmental conditions. The rural construction sector in Bangladesh will be undergoing rapid growth in the next 10 years through rural infrastructure development programmes funded by the Asian Development Bank and the World Bank. The Local Government Engineering Department (LGED in Bangladesh), owns the rural concrete infrastructure, maintains around 380, 000 linear metres of concrete bridges or 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 design and 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 paper reports on the findings of a research programme, funded by DfID, to identify the major factors that contribute to premature deterioration of concrete structures, consider future climate change and identify solutions to improve the durability of coastal concrete structures in Bangladesh. A condition survey undertaken for the project of bridges in the coastal districts indicated that the concrete structures were deteriorating 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. The paper also reports on the outcome of an experimental investigation on the performance of local materials aimed at developing concrete mixes which will provide enhanced durability in future concrete structures.

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

1.0 INTRODUCTION

Climate change is one of the major challenges faced by human kind in the 21st century. The global climate projections for the future is affected by past, present and future greenhouse gas emissions. Although, in recent years majority of countries agreed to the Paris climate agreement, which deals with mitigation of greenhouse gas emissions, however alongside efforts to reduce emissions we need to adapt for climate change that cannot be avoided. Climate change in the form of sea level rise, rise in temperature, rainfall and increase in frequency and intensity of extreme climatic events can directly impact the performance of civil structures.

Reinforced concrete structures when exposed to environmental actions will deteriorate over time, thereby affecting the structural performance and serviceability. The deterioration rate of reinforced concrete structures depends on the quality of materials, construction process, current and past environmental exposure conditions. Concrete deterioration in structures are most commonly caused by physical and or chemical processes in conjunction with variations in surrounding environmental factors. The chemical form of deterioration especially in coastal concrete structures are mainly contributed by corrosion of reinforcement by chlorides in seawater and/or interaction of carbon dioxide in atmosphere with cover concrete causing carbonation induced corrosion. When climate change alters the future environmental conditions, the concentration of carbon dioxide in atmosphere and salinity of seawater increases, which in turn will increase the deterioration rate and thereby reduce the service life of concrete structures. In the case of existing concrete structures which were designed without considering the effects of climate change, will incur increased maintenance costs to maintain the service life of the structure. Therefore, understanding the factors and impact of climate change on concrete structures is crucial not just only for the design of new structures but also helps in asset management strategies for the serviceability of existing structures.

Bangladesh is one of the countries that is prone to natural calamities and climatic hazards. Coastal areas of Bangladesh are made of low lying flood plane of mud and sand, which is at an average elevation of 1.0 -1.5m from the sea level. Due to its low-lying planes, the costal regions are frequently subjected to tidal floods, cyclonic storms and associated hazards such as landslides, increased salinity and erosion. A recent collapse of road bridge

Table 1. Climate change impact on coastal concrete infrastructure

Climate element	Status of change (ADB 2013)	Impact on Infrastructure
Temperature	Current change: 0.4°C during last 50 years Future: 1.38-1.42°C by 2030 and 1.98-2.35°C by 2050	• accelerates deterioration processes • increases the water demand in concrete • increases shrinkage and thermal cracking in concrete • needs additional curing measures • increased thermal expansion of elements in existing structures
Rainfall	Current trend: 25 cm in last 50 years (wetter monsoon) Future scenarios: increase in rainfall 13.5-18.7% in 2030 22.3-24.7% in 2050 27% in 2060	• Increased flooding increases flood loading on structures • Wetter ground causes rising damp and related deterioration of concrete
Sea Level Rise (SLR)	Current SLR: 4-6mm/year Projection in 2030: 21 cm reference to land inside polders Projection in 2050: 39 cm reference to land inside polders Tidal level will also increase with SLR	• SLR and increase in tidal levels increases the exposure to salts in seawater • Increased risk of corrosion in concrete structures • Increase in biological deterioration of concrete
Tropical cyclones and surges	Tropical cyclone frequency and intensity will rise the destruction due to wind and surges The tropical cyclones may have wind up to 275 km/hr in the future	• Increases the wind loading and flooding loading on structures • Increases the contamination of construction materials
Salinity	The 5 ppt (5000 ppm) line will move further inland affecting the Pourashavas of Amtali and Galachipa in 2050 and the whole of these Pourashavas and Mathbaria will come under the 5 ppt (5000 ppm) line in 2100	• Increased salinity increases the risk of reinforcement corrosion • Increases the contamination of construction materials • More structures exposed to chlorides
CO_2 emission (Gunter and Rahman, 2012)	Baseline in 2005: CO_2 emission of 40 Mt Future emission in 2050 with no improvement in energy efficiency: 628 Mt (15 times to 2005 value) and with reaching EU's 2030 efficiency: 183 Mt (7 times to 2005 value)	• Increases the depth of carbonation in exposed concrete thereby increases the risk of reinforcement corrosion in concrete

across Silna river in Gopalganj district caused by erosion of river bed is shown in Fig. 1.

The future climate change scenario and its impacts on coastal concrete structures in Bangladesh is summarised in Table 1. Understanding the implications of climate change on concrete structures is crucial in the design of new structures as well as effective maintenance of existing structures. The paper mainly reports on the outcome of an experimental investigation on the performance of local materials aimed at developing concrete mixes which will provide enhanced durability and climate resilient concrete structures.

2.0 BACKGROUND - COASTAL REGION OF BANGLADESH

2.1 Geography and climate

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). Majority of land close to the coasts is a flood plane of mud and sand at an average elevation of 1.0 – 1.5m from the sea level. Soil formations of Bangladesh consist predominantly of medium to fine sands, silts and clays and a combination of these soil fractions. In the south-east zone of the country fine

Fig. 1. Silna river road bridge collapse caused by erosion of river bed

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).

Bangladesh has tropical monsoon type climate with hot and rainy summers and dry winters. The country experiences warm temperature from March-October, with peak in April - 33.5°C and a secondary peak in September – 31.6°C. January is the coolest month with lowest minimum temperature averaging at 12.5°C. Bangladesh receives average annual rainfall of 2286mm (ADB, 2013). Most of the rainfall occurs in the monsoon period between June-September, which amounts to approximately 70% of the annual rainfall. The normal humidity variation in a year is between 70-85% and high humidity levels are observed in the monsoon period (June-September) (Mondal *et al.* 2013).

2.2 Local construction materials

Bangladesh imports most of the raw materials (Clinker, Gypsum, Fly ash, Limestone fines and Slag) required for cement production. 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 Portland Composite Cement conforms to EN 197-1:2003, CEM II/B-M type and is composed of Clinker: 70-79%, Gypsum up to 5% and up to 20% of Fly ash/Limestone/Slag. It should be noted that the 'M' designation in cement type means that any of the replacement materials can be used. Due to lack of government regulations to use waste materials or by-products that has potential benefits in concrete (Tammim *et al.* 2013), most of the mineral additions such as fly ash, slag and limestone powder are imported from neighbouring countries.

Based on the discussions during site inspection, 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.

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. The brick aggregates are produced by crushing standard bricks either manually or by using crusher machines. First class picked Jhama brick chips are generally specified as preferred coarse aggregates in construction projects. Shingle gravel aggregates (round shaped stone), available in northern parts of the country are used in concrete production due to their better workability characteristics. 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 available in the coastal regions may contain high silt or clayey silt content, 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), but due to lack of awareness and regulations, stone dust is generally not accepted in the rural infrastructure projects.

2.3 Material and workmanship issues

Use of unsuitable or contaminated materials and lack of quality workmanship are the major contributors to the premature deterioration of concrete especially in coastal regions of Bangladesh (Basunia and Choudhury 2001). Moreover, in rural and coastal regions of Bangladesh, extreme cyclonic weather conditions are becoming more frequent contributing to the migration of the skilled workforce able to produce, place and cure concrete to optimise its durability (Rahman and Rahman 2015).

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

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

Previous studies on concrete structures in coastal environment suggest 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

2.4 Review of local research on concrete performance

<u>Use of Supplementary Cementitious Materials (SCMs)</u>

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

Local research on the use of slag as cement replacement in concrete suggests 30% slag as optimum cement replacement based on better 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).

<u>Stone aggregates vs Brick aggregates</u>

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

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

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

<u>Curing</u>

Curing of concrete is crucial to maintain the moisture and temperature in concrete for early age strength development and to minimise shrinkage cracking in the concrete. Local standards 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 (LGED 2015).

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

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

2.5 Rationale of the study

Although majority of local research studies focused on wide range of topics related to environment, materials and performance of concrete structures in coastal regions of Bangladesh, some gaps were identified, which need to be addressed to understand and develop climate resilient and durable concrete structures for coastal regions of Bangladesh. Some of the identified gaps in the literature are as follows:

- Very little information on the benefits higher replacement levels of locally available fly ash and slag on long-term strength development and corrosion resistance of concrete.
- Numerous studies on the comparison of stone aggregates vs brick aggregates mainly focussed on the strength characteristics, however limited information was available on the variability in quality of brick aggregates, measures to improve quality of brick aggregates and corrosion resistance of brick aggregate concrete.
- Some of the previous surveys of concrete structures in coastal regions identified that corrosion of reinforcement and workmanship issues are the major reasons for deterioration of concrete structures based on visual observations. However, no testing data is available on the condition of concrete structures and in particular little information related to local exposure condition, extent of chloride and carbonation levels in concrete, extent of corrosion activity by half-cell surveys and in-situ strength and condition of concrete.
- Most of the available literature on durability studies of concrete using locally available materials focussed on influence of strength, very little on permeation properties of concrete and no information/data on corrosion resistance of concrete and steel type.
- Chloride induced corrosion models are widely used as a tool to predict the service life of concrete structures in the marine environment. These models need crucial information on the durability properties such as chloride migration coefficient, maturity/strength development characteristics, surface chloride and climatic information of local environment. This information obtained at different exposure zones in the coastal regions of Bangladesh would be invaluable for the design and service life assessment of concrete structures in the region.

The full scope of this research project covers all the above identified gaps, however this paper mainly focusses on the experimental investigation of various concrete mixes using different combinations of locally available materials on durability performance and service-life assessment of concrete exposed to coastal environmental conditions by taking into account climate change and associated increase in environmental loading.

3.0 EXPERIMENTAL METHODOLOGY

3.1 Selection of variables and levels

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

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

Three free water cement ratios was considered which will reflect the range of mixes used and act as a proxy for the effect of adding a water-reducing plasticiser.
Mixes are prepared with potable water and contaminated water at two different concentrations, which mainly helps to study the influence of use of contaminated water caused by issues related to poor workmanship on the durability performance of concrete. It is anticipated that using contaminated water will reduce the binding capacity of the concrete, accelerating the ingress of external chlorides. The selected concentration of contaminated water is based on the concentration level of local water tested in the four coastal districts.

Mixes are also prepared with two levels of corrosion inhibitor (CI) and without any CI as a control. While corrosion inhibitors are unlikely to be added on site in rural projects, consideration is being given to incorporating them into the bagged cement products.

Table 2. Experimental variables matrix

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

While calcium nitrite (commonly used CI) is an expensive constituent, which would preclude it from widespread application, there is evidence (Baghabra *et al.*, 2003) that the significantly cheaper calcium nitrate can also be effective at extending the propagation period of the housing process.

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

Based on the above discussions, the final variable matrix for the experimental study is presented in Table 2.

3.2 Material selection and testing

Cement:
Ordinary Portland Cement (OPC) or CEM I cement conforming to BS EN 197-1:2011 and BDS 197-1

Fly ash:
Fly ash used in the study was sourced from India and conforms to BS EN 450-1: 2012 requirements.

Table 3. Physical characteristics of stone aggregates

Test Parameter (units)	Result
Specific Gravity	
20 mm	2.74
10mm	2.65
Water Absorption (%)	
20 mm	0.40
10 mm	0.73
Unit weight (kg/m^3)	
20 mm	1667
10 mm	1472
LA Abrasion	
Combined aggregates (50% of 20 mm and 50% of 10 mm)	30.0
Ten percent fines (%)	
Combined aggregates	9.96
Flakiness Index (%)	
20 mm	14.84
10 mm	36.22
Elongation Index (%)	
20 mm	33.33
10 mm	41.22

Slag:
The slag used in the study was sourced from Japan and conforms to limits specified in EN 15167-1:2006.

Coarse Aggregates:
Most of the stone aggregates used in rural infrastructure projects in Bangladesh are imported from neighbouring countries. The source of these stone aggregates are quite variable depending on the availability and cost of transporting to the construction location. Although locally quarried stone aggregates are available in some regions of the country, the quality of the aggregates were observed to be variable and in most cased does not comply with local standards.

The stone aggregates used in this study were a combination of local aggregates (10 mm nominal size) and imported Vietnam aggregates (20mm nominal size) collected from Gaptoli in Dhaka.

The brick aggregates were also collected from Gaptoli, where a combination of first class bricks and picked Jhama brick were selected and machine crushed, such that the combined aggregates had a LA Abrasion value close to the LGED limit of 40. The physical characteristics of the stone aggregates and brick aggregates are presented in Table 3 and Table 4 respectively.

Fine Aggregates:
The fine aggregate used in the study was sourced from Sylhet. The physical properties of the fine aggregate are presented in Table 5.

Table 4. Physical characteristics of stone aggregates

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

Table 5. Physical characteristics of fine aggregate

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

Water:
Tap water suitable for drinking was used as mixing water in the production of concrete mixes.

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

Corrosion inhibitor:
Corrosion inhibitors are often used to prolong the initiation period to corrosion of reinforcement in concrete. In the context of this study, while corrosion inhibitors are unlikely to be added on-site in rural infrastructure projects, it is considered that there could be an opportunity to incorporate them in the bagged cement products. While calcium nitrite (commonly used CI) is an expensive constituent, which would preclude it from widespread application, there is evidence (Baghabra *et al.*, 2003) that the significantly cheaper calcium nitrate can be effective at extending the propagation period of the corrosion process. Moreover, calcium nitrate based corrosion inhibitors are available in granules, which can be easily inter-ground with clinker/cement to produce bagged cement product.

Two types of corrosion inhibitors are tested in this study. Calcium nitrate based corrosion inhibitor (powder sample) and commercially available amino alcohol based corrosion inhibitor (Sika ferro guard 901) was used in the study.

3.3 Batching, Mixing, Casting and Curing

The concrete mix design was based on yield method. All the concrete mixes were designed for a target slump of 75-100mm and therefore the W/C ratio for each mix was adjusted during the trial mixing to achieve this target slump. Material proportioning was done by pre-weighing bulk materials in a container on a digital scale to the nearest 0.01kg. Prior to batching of ingredients for each concrete mix, the moisture content of the aggregates was measured, a moisture correction was applied to the aggregates and water content of the mix was adjusted to achieve the saturated surface dry (SSD) mix proportioning. In addition to this, where liquid based chemical admixtures are used in the concrete mix the water contributed by the admixture is compensated in the total water content. Liquid based chemical admixtures were measured volumetrically to the nearest millilitre. All the constituents of the concrete were mixed in a 10/7 concrete mixer with a maximum capacity of 100 litres. Prior to each mixing, the concrete mixer was wetted using a damp cloth to prevent the absorption of water from the mix.

Each concrete mix was tested for fresh concrete density, nine concrete cylinders (100mm diameter and 200mm height) were cast for strength and durability testing (NT Build 492 test). All the cylinder moulds were cured by immersing in water containing saturated calcium hydroxide solution in large plastic drums until the age of testing. Concrete cylinders containing salt additions were cured in separate curing drums to avoid contamination of the other concrete specimens.

3.4 Durability testing of concrete

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

The concrete specimens used for the test were sliced from concrete cylinder samples, by eliminating top and bottom 50mm depth of concrete and the samples were prepared in accordance to the procedure described in NT Build 492 standard (NT Build 492, 1999, Tang, 1996).

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

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

where

D_{nssm} : non-steady state migration coefficient x 10^{-12} m^2/s

U : absolute value of the applied voltage, V

T : average value of the initial and final temperatures in the anolyte solution Deg C

L : thickness of the specimen, mm

X_d : average value of the penetration depths, mm

t : test duration, hour

3.5 Concrete mix details

Based on the various factors and variables considered in total 30 different concrete mixes are tested. Among the 30 different concrete mixes, first 15 mixes (R-01 to R-15) contained stone aggregates and second 15 mixes (R-16 to R-30) contained machine crushed brick aggregates. All these 30 concrete mixes vary in different levels of cement content, cement type, aggregate type, salt contamination levels and corrosion inhibitor type. The final W/C ratio and the proportions for each mix was obtained for a target slump of 75-100mm.

The final SSD mix details per cubic metre of concrete along with slump achieved for each mix for stone aggregate concrete mixes and brick aggregate concrete mixes are shown in Table 6.

4.0 RESULTS AND DISCUSSION

4.1 Stone aggregate vs Brick aggregate

The 28-day compressive strength results presented in Fig. 2, which suggests that the rate of strength gain with increase in cement content is low in the case of brick aggregate concrete as compared with stone aggregate concrete mixes.

4.2 Strength development with SCMs

The results of compressive strength tests of concrete with varying replacement levels of Fly ash and slag are shown in Fig. 3. Based on the strength results it can be observed that concrete mixes with slag additions produced slightly higher 28 days strength in comparison with 100% CEM I concrete mix. In the case of concrete mixes with Fly ash addition, the strength results are lower than 100% CEM I concrete mix and slag concrete mixes.

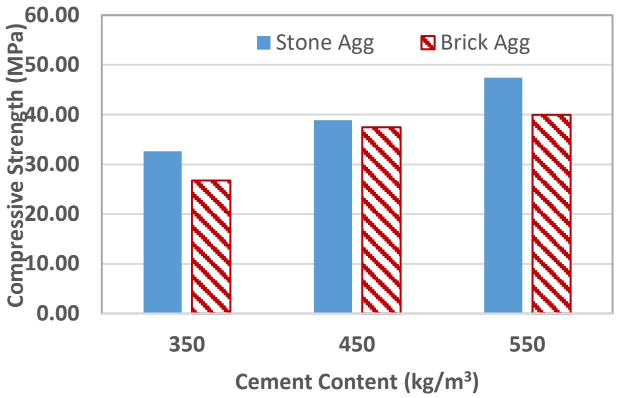


Fig. 2. Comparison of 28 day compressive strength between stone and brick aggregate concrete

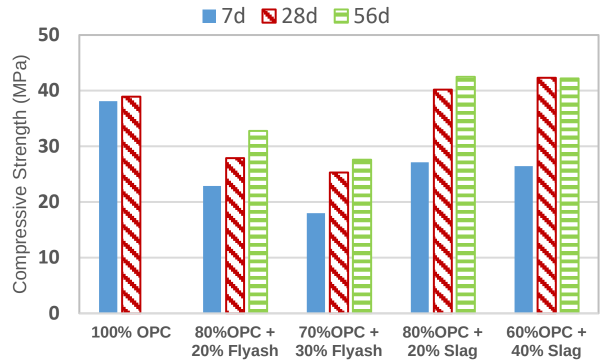


Fig. 3. Comparison of strength development in concrete with different replacement levels of Fly ash and slag

4.3 NT Build 492 – Migration coefficient of concrete

The results of NT build 492 testing of each concrete, which provide non-steady state chloride migration coefficient for concrete mixes containing stone aggregates and brick aggregate concrete mixes are presented in Table 7. These results show the average depth of penetration of chloride ions (average of two samples tested) and corresponding chloride migration coefficient, which is calculated based on equation (1), for each concrete mix. It should be noted that some of the concrete mixes contain varied proportions of salt and corrosion inhibitor added to the mix, however based on the test results, it can be observed that the influence of internal salts and corrosion inhibitor was found to be negligible on the migration coefficient of the concrete. The internal salt added in the mix was a low concentration of 0.5-1% cement content of concrete, whereas the NaCl concentration used in NT Build test is 10% by weight, which is many factors higher. On the other hand the corrosion inhibitors used in this study works by increasing the passivation of reinforcement bars in concrete. Thus, with increase in passivation, the

Table 6. Concrete mix proportions

Mix Ref	Free w/c ratio	Cement Content (kg)	CEM I (kg)	Fly ash (kg)	Slag (kg)	Coarse Aggregate (SSD) (kg)		Sand (SSD) (kg)	NaCl (Salt)	Calcium Nitrate	Set Retarder (kg)	Sika Ferro gaurd 901 (kg)
						20 mm	10 mm					
R-1	0.40	450	360	0	90	493.5	493.5	658	2.25	0	0	11.25
R-2	0.42	550	440	110	0	453.3	453.3	604.4	0	0	0	0
R-3	0.47	450	360	90	0	496	497	662	2.25	0	0	11.25
R-4	0.45	450	270	0	180	495.2	495.2	660.3	2.25	0	0	11.25
R-5	0.43	550	385	165	0	443	443	590.6	0	0	0	0
R-6	0.43	450	315	135	0	480.8	480.8	641	2.25	0	0	11.25
R-7	0.42	450	450	0	0	492	492	656	2.25	0	0	11.25
R-8	0.43	550	330	0	220	456.2	456.2	608.3	0	0	0	0
R-9	0.4	550	550	0	0	456.5	456.5	608.6	0	0	0	0
R-10	0.43	350	210	0	140	529.8	529.8	706.4	3.5	12.25	4.2	0
R-11	0.47	350	350	0	0	524.4	524.4	699.1	3.5	12.25	5.25	0
R-12	0.43	350	280	70	0	525.1	525.1	700.2	3.5	12.25	4.2	0
R-13	0.38	550	440	0	110	458.4	458.4	611.39	0	0	0	0
R-14	0.45	350	280	0	70	528.5	528.5	704.6	3.5	12.25	4.2	0
R-15	0.44	350	245	105	0	518.6	518.6	691.4	3.5	12.25	4.2	0
Brick Aggregate concrete mixes												
R-16	0.56	350	350	0	0	748.3		748.3	1.75	0	0	0
R-17	0.41	450	270	0	180	709.1		709.1	0	15.75	5.4	0
R-18	0.57	350	210	0	140	752.1		752.1	1.75	0	0	0
R-19	0.38	550	440	110	0	647.5		647.5	5.5	0	0	13.75
R-20	0.39	450	360	90	0	710.8		710.8	0	15.75	5.4	0
R-21	0.42	450	360	0	90	706.6		706.6	0	15.75	5.4	0
R-22	0.58	350	280	70	0	753.4		753.4	1.75	0	0	0
R-23	0.38	550	440	0	110	667.7		667.7	5.5	0	0	13.75
R-24	0.61	350	280	0	70	758.2		758.2	1.75	0	0	0
R-25	0.38	550	385	165	0	638.9		638.9	5.5	0	0	13.75
R-26	0.55	350	245	105	0	739.9		739.9	1.75	0	0	0
R-27	0.35	550	330	0	220	664.4		664.4	5.5	0	0	13.75
R-28	0.4	450	315	135	0	693.4		693.4	0	15.75	5.4	0
R-29	0.37	550	550	0	0	652.1		652.1	5.5	0	0	13.75
R-30	0.38	450	450	0	0	704.2		704.2	0	15.75	5.4	0

threshold chloride level to break the passivation increases.

The chloride migration test results for concrete mixes with 350 kg/m^3 cement content as presented in Fig. 4. suggests that stone aggregate concrete mixes performed much better as compared with brick aggregate. The significant difference in chloride diffusion coefficient values between stone and brick aggregate concrete are mainly attributed to porous characteristics of brick aggregates in concrete, which provide easier path for chloride ions to penetrate in the concrete. Comparison between different cement types used in these mixes suggest that Fly ash and slag additions in the mix reduced the migration coefficient values and improved the durability of the concrete. However, overall the performance of fly ash based concrete mixes performed better in resisting the ingress of chloride ions in concrete as compared with slag based concrete mixes.

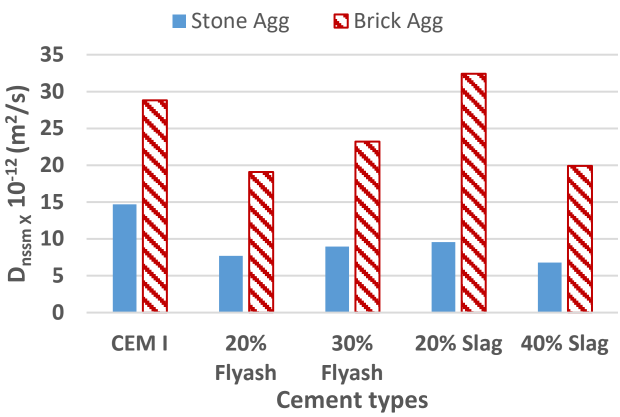


Fig. 4. Comparison of Migration coefficient for different concrete mixes with 350 kg/m^3 cement content

Table 7. Slump, non-steady state migration coefficient and durability cover for 75 year design life

Mix Ref	Free w/c ratio	Cement Content (kg)	CEM I (kg)	Fly ash (kg)	Slag (kg)	Slump (mm)	Chloride Penetration depth - xd (mm)	Migration Coefficient, Dnssm ($X10^{-12}$ m^2/s)
R-1	0.4	450	360	0	90	75	16.69	12.7
R-2	0.42	550	440	110	0	75	9.69	4.18
R-3	0.47	450	360	90	0	130	10.88	4.83
R-4	0.45	450	270	0	180	70	11.56	5.1
R-5	0.43	550	385	165	0	135	8.06	3.02
R-6	0.43	450	315	135	0	90	13	4.49
R-7	0.42	450	450	0	0	75	17.41	9.77
R-8	0.43	550	330	0	220	82	8.84	3.92
R-9	0.4	550	550	0	0	120	17	11.49
R-10	0.43	350	210	0	140	75	14.66	6.79
R-11	0.47	350	350	0	0	85	22.8	14.7
R-12	0.43	350	280	70	0	95	16.07	7.71
R-13	0.38	550	440	0	110	70	15.15	8.33
R-14	0.45	350	280	0	70	80	16.84	9.56
R-15	0.44	350	245	105	0	90	20.41	8.97
Brick Aggregate Concrete Mixes								
R-16	0.56	350	350	0	0	75	28.44	28.76
R-17	0.41	450	270	0	180	95	19.75	11.58
R-18	0.57	350	210	0	140	72	26.69	19.91
R-19	0.38	550	440	110	0	80	24.38	17.86
R-20	0.39	450	360	90	0	130	20.5	11.96
R-21	0.42	450	360	0	90	80	23.13	22.28
R-22	0.58	350	280	70	0	70	26.5	19.06
R-23	0.38	550	440	0	110	80	18.28	16.82
R-24	0.61	350	280	0	70	70	26.13	32.38
R-25	0.38	550	385	165	0	90	21.31	13.91
R-26	0.55	350	245	105	0	72	26.69	23.16
R-27	0.35	550	330	0	220	87	10.94	9.58
R-28	0.4	450	315	135	0	110	20.13	14.07
R-29	0.37	550	550	0	0	100	16.92	24.11
R-30	0.38	450	450	0	0	75	22.38	21.72

The comparison of migration coefficient of concrete mixes with 450 kg/m^3 cement content (presented in Fig. 5) suggests that overall the migration coefficient values reduced with increase in cement content of the concrete. The comparison between two different aggregate types used in the concrete clearly suggests that the stone aggregate concrete mixes have performed better with low migration coefficient values as compared with brick aggregate concrete mixes. The comparison between different cement types suggest that the concrete mix with Fly ash addition has performed the best with very low values of chloride migration coefficient.

The higher cement content of 550 kg/m^3 in concrete has marginally improved the performance of concrete as presented in Fig. 6. It is interesting to note that in the case of 100% CEM I mixes, the migration coefficient values slightly increased at higher cement content for both stone aggregate and brick aggregate concrete mixes. The performance of stone aggregate mixes was observed to be better than the brick aggregate concrete mixes. Moreover, stone aggregate mixes with blended cements performed better than the pure CEM I mix and concrete with 30% Fly ash has performed the best in terms of lowest migration coefficient among all the concrete mixes tested.

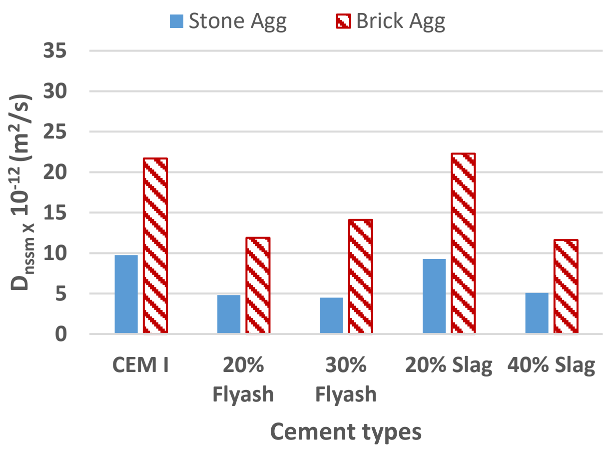


Fig. 5. Comparison of Migration coefficient for different concrete mixes with 450 kg/m^3 cement content

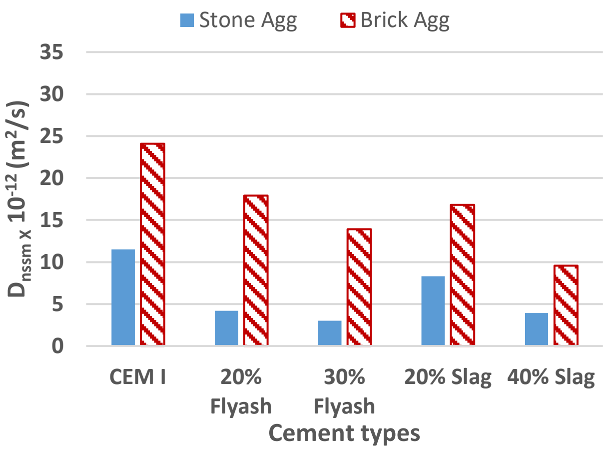


Fig. 6. Comparison of Migration coefficient for different concrete mixes with 550 kg/m^3 cement content

5.0 SERVICE – LIFE MODELLING

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

There are two distinct approaches to model the deterioration mechanisms:

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

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

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

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

In this study a bespoke stochastic approach based deterioration model "CorrPredict" was used to evaluate different concrete mixes for predicting service-life of concrete structures in coastal environment.

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

$$C_{crit} = C(x=a,t)$$

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

All variables in the limit state function are statistically quantified (mean, standard deviation, and type of distribution function). The input values used in the CorrPredict chloride model for predicting the service life of a concrete element in marine splash zone is shown in Table 8. A sample screen shot of the Corrpredict model used in this study is shown in Fig.7.

5.1 Influence of climate change

The sea level rise due to climate change will increase the salinity levels in river water. Based on climate change modelling, the effects of future climate change on river salinity was observed to be more predominant in southwest coastal region of Bangladesh (Dasgupta *et al.* 2014). Based on the climate change modelling for coastal districts in Bangladesh (Dasgupta *et al.* 2014), in the worst case scenario, salinity intrusions cover the exposed coastal districts, for example the 5ppt line (5000ppm) moves further inland covering most of the Bagerhat district by 2050. Therefore, to design climate resilient concrete structures in coastal regions of Bangladesh, the concrete specifications should consider future salinity levels as 5000ppm and design the concrete to resist the increased salinity and associated corrosion related deterioration.

Based on the salinity levels of water, chloride content of concrete tested in the condition survey phase and future salinity levels estimated by climate change models, the exposure conditions in coastal regions of Bangladesh has been classified into four different classes as presented in Table 8. For each exposure class the design surface chloride content of concrete was assumed based on interpolation of empirical values established for similar exposure conditions in Europe and Middle-eastern countries. The assumed

Table 8. Input values used in CorrPredict Chloride model for concrete element in marine splash zone

Variable	Description	Unit	Distribution	Mean value	Standard Deviation
d_c	Concrete cover	mm	Normal distribution	Target 50mm	6
Δx	Depth of convection zone (ingress not to Fick's Law)	mm	BetaD	8.9	3.6
C_{crit}	Critical chloride concentration	% by weight cement	BetaD: 0.2 ≤ C_{crit} ≤ 2	0.60	0.15
$C_{s,\Delta x}$	Concentration of chloride at depth Δx	% by weight cement	Log Normal Distribution	2.94 (slag) 2.1 (CEM I) 2.88 (Fly ash)	1.0
C_0	Background chloride	% by weight cement	Deterministic	0.15	-
b_e	Regression variable	K	Normal	4800	700
T_{real}	Temperature of the structural element or ambient	K	Normal	299	10
T_{ref}	Standard test temperature	K	Constant	299	-
$D_{RCM,0}$	Diffusion coefficient at time t_0	10^{-12} m^2/s	Normal distribution	Obtained from Table 6	
a	Aging factor		BetaD: 0.2 ≤ a ≤ 2	0.6	0.15 (depending on cement)
t_0	Time	years	Deterministic	0.0767	-
T	Design life	years	Deterministic	75	-

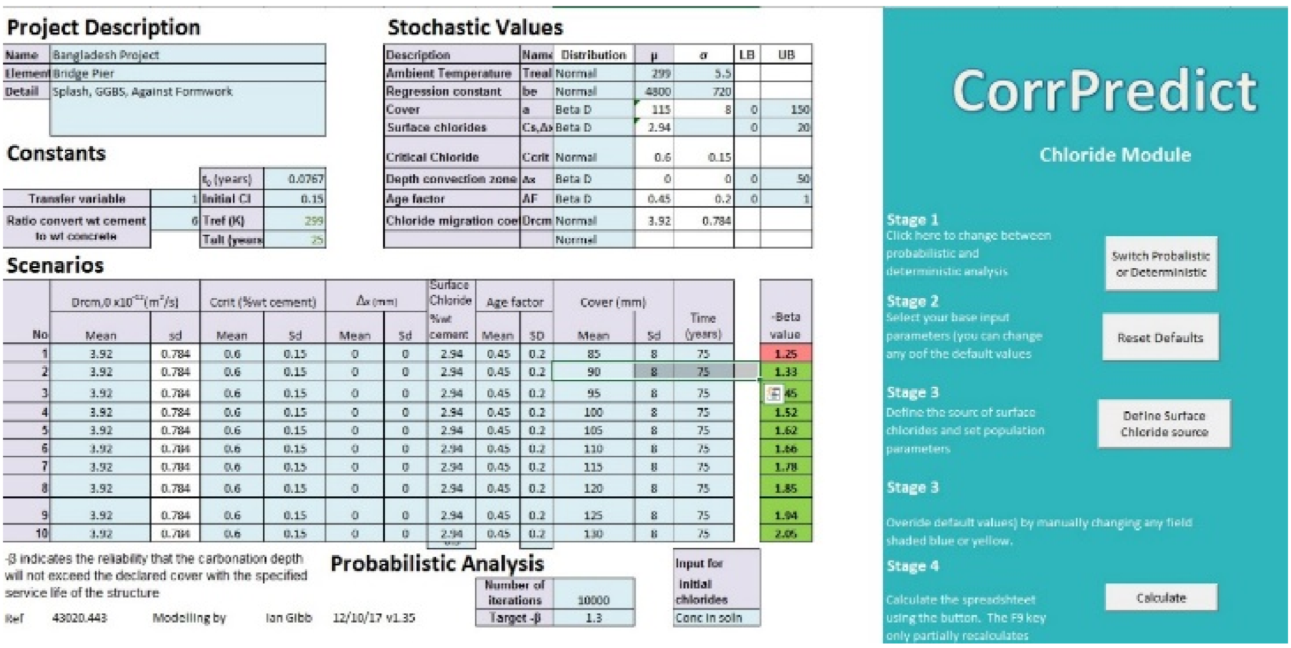


Fig. 7. Screen shot of the CorrPredict Chloride induced corrosion deterioration model

Table 9. Exposure classification in coastal regions of Bangladesh for chloride induced corrosion caused by external salts

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

values of surface chloride content of concrete and chloride concentration of water was used as input values in CorrPredict service life model.

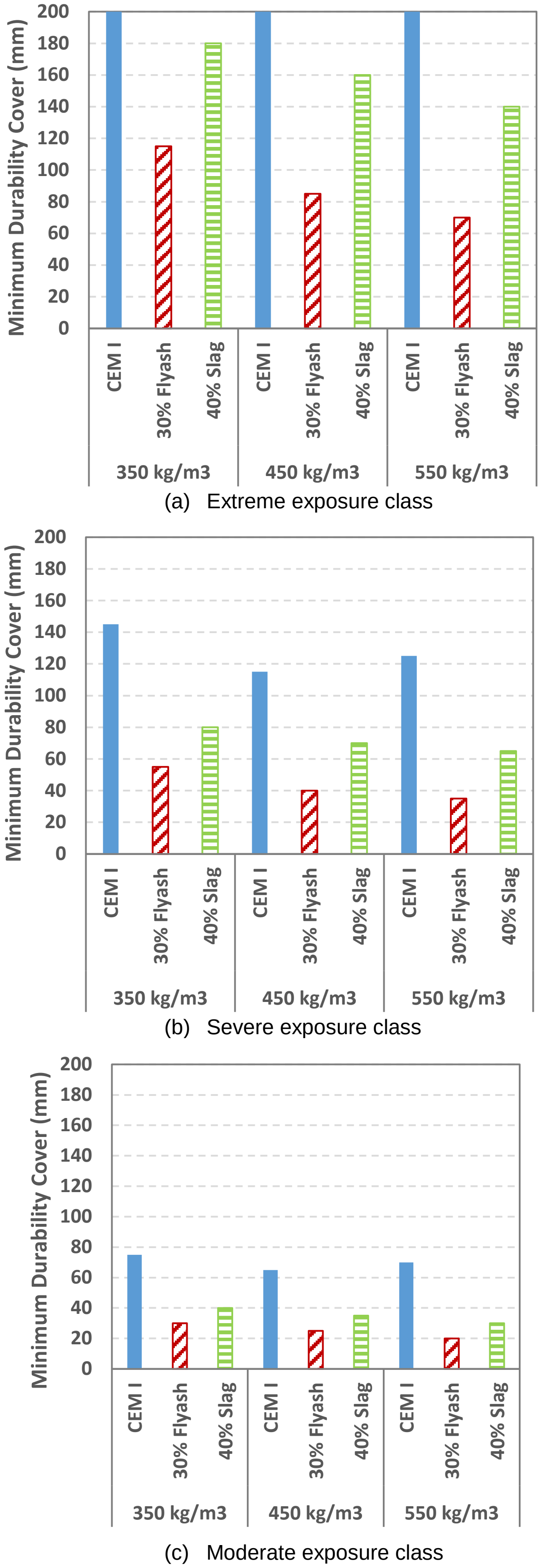
5.2 Service – life modelling results

Based on the input values for CorrPredict service life model as presented in Table 8, and exposure specific input values given in Table 9, the minimum durability cover for different variations in concrete mixes was assessed for design life of 75 years. The minimum durability cover required for different concrete mixes are presented in Fig.8. The service life assessment of concrete mixes to calculate the minimum durability cover helps in identifying concrete mixes that can resist chloride ingress to reach reinforcement for design life of 75 years with realistic levels of cover.

For example, the comparison of minimum cover value required for extreme exposure condition suggest that the best suitable concrete mix will be 70% CEM I + 30% Fly ash mix with stone aggregates and 550 kg/m^3 cement content at minimum cover of 70mm.

In general, for the three exposure conditions viz. Extreme, Severe and Moderate, the concrete mix with 30% Fly ash, stone aggregates and high cement content requires low minimum durability cover as compared with other concrete mixes. It can be observed from Fig.8, concrete mixes that contain 100% CEM I and/or brick aggregates require very high concrete cover, which will be impractical to implement and therefore cannot be recommended in all the three exposure conditions.

The comparison of minimum durability cover required for different concrete mixes with stone aggregates in extreme exposure condition is presented in Fig. 8(a).



(a) Extreme exposure class

(b) Severe exposure class

(c) Moderate exposure class

Fig. 8. Minimum durability cover required for concrete mix with stone aggregates for 75 year design life

It can be observed that the cover required in extreme exposure condition for most of the concrete mixes are quite high and impractical to specify. The lowest minimum durability cover of 70mm can be provided by concrete mix with 30% Fly ash and 550 kg/m^3 cement content. It should be noted that in situ nominal cover includes fixing tolerance depending on the construction technique. However, with the fixing tolerance the nominal cover for reinforced concrete element in extreme exposure can be very high and impractical to achieve. Therefore, in the case of extreme exposure conditions, the concrete mix have minimum durability cover with additional protection measures such as use of corrosion inhibitors in the concrete mix to achieve the 75 year design life.

The comparison of minimum durability cover required for concrete mixes in severe exposure condition as shown in Fig. 8(b) suggest that both CEM I and slag based concrete require high levels of cover. The minimum durability cover required for 30% Fly ash mix was observed to be low compared with other concrete mixes and therefore can be specified for severe exposure conditions experienced in exposed coastal districts of Bangladesh.

The comparison of minimum durability cover for moderate exposure class as shown in Fig. 8(c) suggest that 30% Fly ash and 40% slag mixes require cover lower than 40 mm and therefore can be specified for moderate exposure conditions experienced in inner coastal districts of Bangladesh.

6.0 CONCLUSIONS

The outcome of the durability testing and service-life assessment of various concrete mixes studied specifically for marine exposure conditions experienced in coastal regions of Bangladesh gives the following conclusions:

- This study confirms the importance of durability testing (NT Build 492 test) in designing the concrete mix for coastal regions of Bangladesh.
- The durability of brick aggregate concrete mixes was significantly poorer than the stone aggregate concrete mixes
- The durability performance of concrete improved with increase in cement content of the concrete. However, in the case of 100% CEM I concrete mix no further improvement in durability performance was observed with increase in cement content from 450 kg/m^3 to 550kg/m^3.
- Concrete mixes with Fly ash addition showed better durability performance in comparison to slag based concrete mix. In general, among the different cement types, 100% CEM I concrete mix showed poor durability performance as compared to blended cement based concrete mix.
- Among all the concrete mixes tested in the experimental programme, concrete mix with 30% Fly ash as cementitious addition and 550 kg/m^3 cement content showed the best durability performance to resist chloride induced corrosion.
- The service-life modelling assessment of different concrete mixes suggest that 30% fly ash mixes require more realistic and low durability cover as compared with 100% CEM I and slag mixes.

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