Journal of Civil Engineering (IEB), 47 (2) (2019) 155-166

Journal of Civil Engineering IEB

Effects of aggregate and cement types on mechanical properties and carbonation of concrete

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Received 22 August 2019

Abstract

Different types of aggregate and cement are used in Bangladesh for construction works. It is likely that mechanical properties of concrete will be varied based on the selection of materials. On the other hand, carbonation induced corrosion of steel bars in concrete was found as one of the main reasons against deterioration of concrete structures in Bangladesh. Therefore, a detailed study has been conducted to understand the effects of aggregates and cement types on mechanical properties and carbonation of concrete. Concrete samples were made with different aggregates, such as brick aggregate, black stone chips, round shaped stone, and recycled brick aggregate. Cement types were CEM Type I, CEM Type II B-M, and CEM Type II B-M (S-L), CEM Type IIA-S, CEM Type IIB-S, CEM Type IIIA, CEM Type IIIB, and CEM Type IIIC as per BDS: EN-197-2001. The samples were tested for compressive strength, tensile strength, and Young's modulus of concrete at the ages of 28, 60, and 180 days. Specimens were also exposed in a controlled accelerated carbonation chamber (3% carbon dioxide, 70% RH and 400C Temperature) and tested for carbonation depth after 24, 34, 45 and 65 days of exposure. Specimens made with CEM Type II B-S show the best performance in terms of mechanical properties of concrete. Brick aggregate and recycled brick aggregate show relatively poor mechanical properties compared to the other aggregates. The depth of carbonation was also higher for these aggregates. CEM Type I cement shows the best performance against carbonation. The depth of carbonation is increased and compressive strength is reduced with the increase of slag content (particularly for slag content $\geq$ 30%) in cement.

Keywords: Aggregate, compressive strength, carbonation, cement, concrete, slag.

1. Introduction

Stone chips, brick chips, and round shaped stone (knows as shingle) aggregates are used in Bangladesh as coarse aggregate for making concrete. Also, as binding material of concrete, different types of cement are specified in the cement standard of Bangladesh. It is likely that mechanical properties of concrete will be varied with the change of types of aggregate and cement. Therefore, a comprehensive study is necessary to understand mechanical properties of concrete made with the variation of types of aggregate and cement. On the other hand, from the viewpoint of sustainability of construction materials, it is also necessary to evaluate durability performance of concrete due to carbonation in concrete with the variation of types of aggregate and cement.

Table 1
Properties of coarse and fine aggregates

Type of aggregate		Specific gravity	Absorption (%)	SSD Unit weight (kg/m^3)	Abrasion	FM
Fine aggregate	Sand	2.46	3%	1574	-	2.58
Coarse aggregate	Black Stone (S)	2.82	1.5%	1551	14%	Controlled as per ASTM C33
	Round Shaped Stone/Shingle (RS)	2.65	1.1%	1674	27%	
	Recycled Brick Aggregate (RB)	2.14	22.4%	1204	42%	
	Brick Chips (B)	1.98	10.5%	1209	39%	

Table 2
Mineral compositions of different cements collected from a local market

Cement Type		Composition (% by mass)		
		Clinker	Slag, Fly ash, Limestone	Gypsum
OPC	CEM Type I	95~100	0	0~5
Blended Cement	CEM Type II B-M	65~79	21~35	0~5
	CEM Type II B-M(S-L)	72~79	21~28	0~5

Table 3
Blended cements prepared at lab

Cement Type		Composition (% by mass)	
		CEM Type I	GGBFS
Blended Cements	CEM Type II A-S	80	20
	CEM Type II B-S	70	30
	CEM Type III A	60	40
	CEM Type III B	30	70
	CEM Type III C	15	85

Carbonation of concrete is a chemical reaction in which carbon dioxide from air enters into concrete and reacts with calcium hydroxide of hydrated cement to form calcium carbonate. This reaction drops pH of concrete. When pH around the steel bars drops to 11, the protective oxide film (passive film or protection film formed at high pH) on the steel bars becomes unstable and the reactions of corrosion over steel can take place with the presence of oxygen and moisture. The rate of carbonation of concrete increases with the increase of the concentration of CO_2 (Schubert and Wesche 1974) as well as temperature. Also, the rate of carbonation is found at the maximum limit in the range of relative humidity of 60% to 70% (Neville 2003). Bangladesh is a hot and humid country. Therefore, carbonation induced corrosion of steel in concrete is found as one of the main reasons against deterioration of concrete structures in Bangladesh (Mohammed 2007). Several regular features on this issue are also printed in the daily newspaper (The Daily Star, 10 July 2018). For quantitative evaluation of the rate of carbonation of existing concrete structures, a study was conducted

(Mohammed et al. 2013). Concrete samples were collected from existing concrete structures and depth of carbonation was measured. It was found that carbonation coefficient is relatively high in Bangladesh. For further evaluation of carbonation and mechanical properties of concrete, a detailed experimental work has been planned considering different types of aggregate, such as brick aggregate, stone aggregate, round-shaped stone aggregate and recycled brick aggregate.

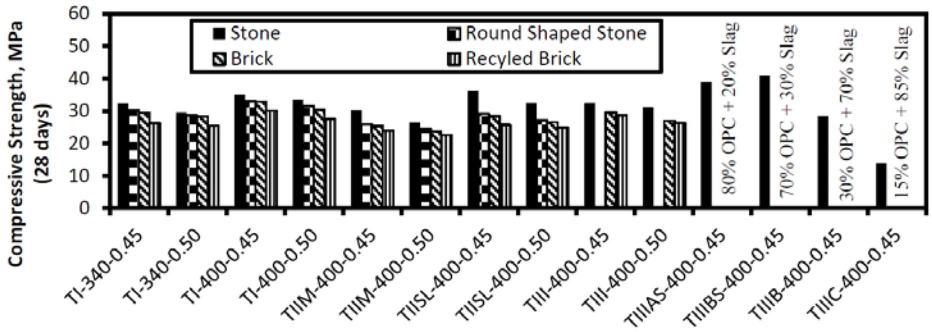

Fig. 1. Effect of aggregate and cement type on compressive strength (28 days).

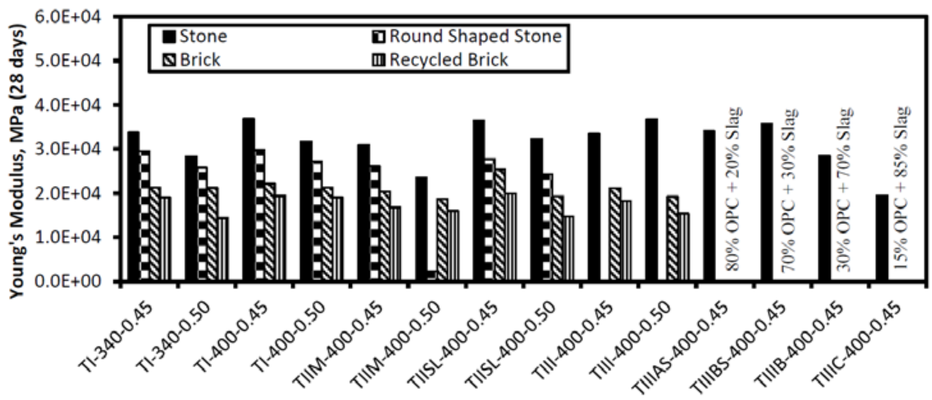

Fig. 2. Effect of aggregate and cement type on Young's modulus (28 days).

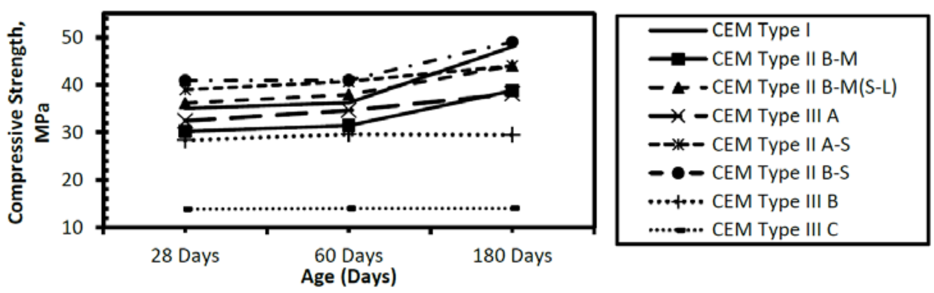

Fig. 3. Compressive strength of concrete - black stone (W/C = 0.45, Cement content = 400 kg/m^3).

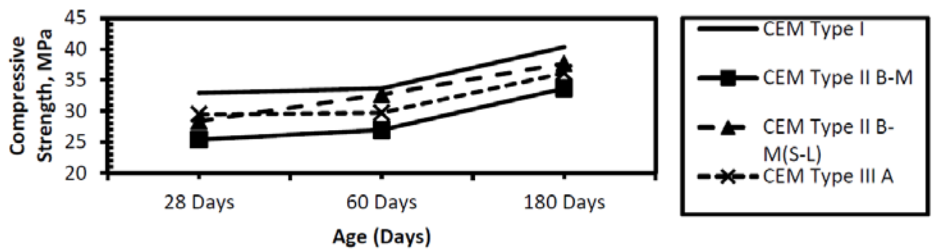

Fig. 4. Compressive strength of concrete - brick (W/C = 0.45, Cement content = 400 kg/m^3).

Also, different types of cement as specified in BDS EN 197-1:2001, such as such as CEM Type I, CEM Type II A-M, CEM Type II B-M, and CEM Type II B-M(S-L) were investigated. Also, cases with 20to 85% replacement of CEM Type I cement with ground granulated blast-furnace slag (GGBFS) were included in the experimental plan. These cements are specified as CEM Type II B-S, CEM Type IIIA, CEM Type IIIB, and CEM Type IIIC.

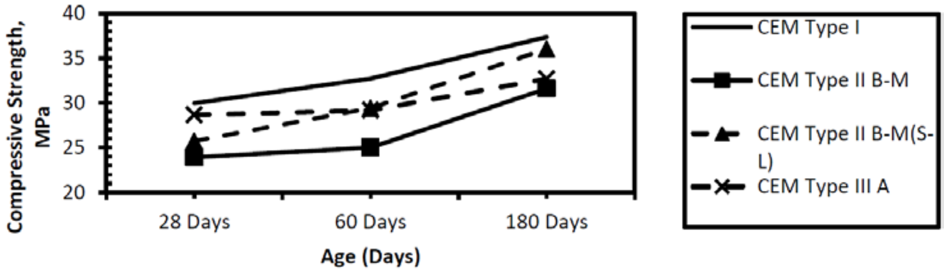

Fig. 5. Compressive strength of concrete - recycled brick aggregate (W/C=0.45, C cont. = 400).

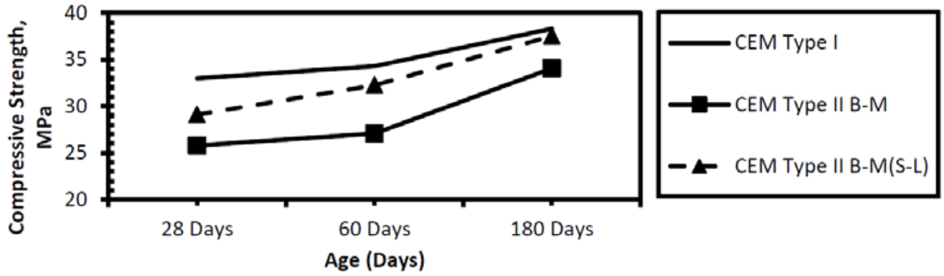

Fig. 6. Effect of age on compressive strength of concrete - round shaped stone.

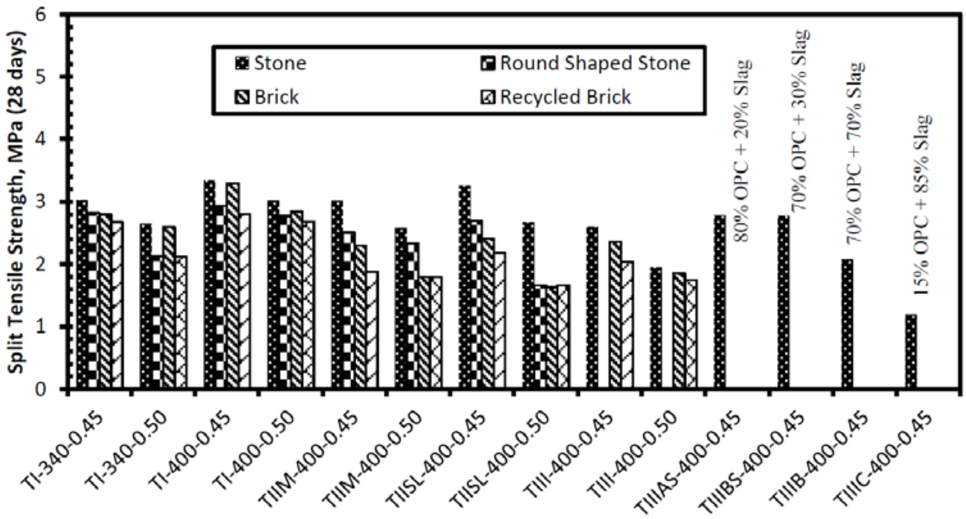

Fig. 7. Effect of aggregate and cement type on split tensile strength (28 days).

The specimens made with these variables were investigated for compressive strength, tensile strength, and Young's modulus of concrete and also exposed in a controlled carbonation chamber of 3% carbon dioxide, 70% RH and 400C temperature. Carbonation depths of split samples were measured after 24, 34, 45 and 65 days of exposure in an accelerated carbonation chamber. The results of this investigation will be very useful to understand the mechanical properties of concrete and the rate of carbonation of concrete made with different aggregates and different cement types.

2. Experimental methods

2.1 Materials

Brick aggregate, stone chips, and round shaped stone chips were collected from a local market. Recycled brick aggregate was prepared by crushing demolished concrete blocks manually. The grading of the samples was controlled as per ASTM C33/C33M-16. Natural river sand was used as fine aggregate. The specific gravity, absorption capacity, abrasion, unit weight and fineness modulus of both coarse aggregates and fine aggregates are summarized in Table 1. The natural gradation of fine aggregate follows ASTM C33/C33M-16 requirements. Mineral compositions of the investigated cements are summarized in Table 2 and Table 3. Cement types include CEM type I, CEM type II A-M, and CEM type II B-M, and slag based blended cements with 20~85% of replacement CEM type I cement by GGBFS as per BDS :EN 197-1:2001, such as 80% CEM type I + 20% slag (CEM Type II A-S), 70% CEM type I + 30% slag (CEM Type II B-S), 40% CEM type I + 60% slag (CEM Type III A),30% CEM type I + 70% slag (CEM Type III B), and 15% CEM type I + 85% slag (CEM Type III C). Potable tap water was used for mixing and curing of concrete.

Table 4
Cases investigated

Case No.	Symbol	Explanation
1-16	B-TI-340-0.45, B-TI-340-0.50,B-TI-400-0.45, B-TI-400-0.50, RB-TI-340-0.45, RB-TI-340-0.50,RB-TI-400-0.45, RB-TI-400-0.50, S-TI-340-0.45, S-TI-340-0.50,S-TI-400-0.45, S-TI-400-0.50RS-TI-340-0.45, RS-TI-340-50,RS-TI-400-0.45, RS-TI-400-0.50	B stands for brick aggregate, RB for recycled brick aggregate, S for stone aggregate, and RS for round shaped stone aggregate. TI stands for CEM Type I cement, The digit after TI indicates cement content in kg/m^3, and the last digits indicate water to cement ratio.
17-24	B-TIIM-400-0.45, B-TIIM-400-0.50	TIIM indicates CEM TYPE II B-M Cement.
25-32	B-TIISL-400-0.45, B-TIISL-400-0.50	TIISL indicates CEM Type II S-L Cement
33-38	B-TIII-400-0.45, B-TIII-400-0.50	TIII indicates CEM Type III A Cement
39	S-TIIAS-400-0.45	TIIAS indicates CEM Type II A-S cement.
40	S-TIIBS-400-0.45	TIIBS indicates CEM Type II B-S cement.
41	S-TIIIB-400-0.45	TIIIB indicates CEM Type III B cement.
42	S-TIIIC-400-0.45	TIIIC indicates CEM Type III C cement.

2.2 Mix proportions, specimen preparation and testing

For each types of aggregate, cylindrical concrete specimens of 100 mm diameter and 200 mm height were made with a fixed sand to total aggregate volume ratio (0.44); different W/C ratios (0.45 and 0.50), different cement contents (340 kg/m3 and 400 kg/m3) and different cements (CEM Type I, CEM Type II B-M, and CEM Type II B-M (S-L), CEM Type II A-S, CEM Type II B-S, CEM Type III A, CEM Type III B, and CEM Type III C. A total of 42 different cases were investigated. The investigated cases are summarized in Table 4. Mixture proportions of concrete are summarized in Table 5. After casting of the specimens, they were initially cured for 24 hours by covering the molds with wet clothes.

After 24 hours of initial curing, the specimens were demolded and cured under water till the age of testing. The compressive strength of concrete was measured at 28 days, 60 days and 180 days as per ASTM C39/C39M-16. The Young’s modulus of concrete was calculated from the stress-strain curve of concrete. The split tensile strength of concrete was also measured at 28 days, 60 days and 180 days using Universal Testing Machine (UTM).

Table 5
Mixture proportion

Case No.	Type of cement	Type of aggregate	Case Identification	W/C	Unit content (kg/m^3)			
					Cement	Water	Coarse aggregate	Fine aggregate
1	CEM Type I	B	B-TI-340-0.45	0.45	340	153	797	778
2			B-TI-340-0.50	0.50	340	170	778	760
3			B-TI-400-0.45	0.45	400	180	746	728
4			B-TI-400-0.50	0.50	400	200	724	706
5		RB	RB-TI-340-0.45	0.45	340	153	861	778
6			RB-TI-340-0.50	0.50	340	170	841	760
7			RB-TI-400-0.45	0.45	400	180	806	728
8			RB-TI-400-0.50	0.50	400	200	782	706
9		S	S-TI-340-0.45	0.45	340	153	1135	778
10			S-TI-340-0.50	0.50	340	170	1108	760
11			S-TI-400-0.45	0.45	400	180	1062	728
12			S-TI-400-0.50	0.50	400	200	1031	706
13		RS	RS-TI-340-0.45	0.45	340	153	1067	778
14			RS-TI-340-0.50	0.50	340	170	1041	760
15			RS-TI-400-0.45	0.45	400	180	998	728
16			RS-TI-400-0.50	0.50	400	200	968	706
17	CEM Type II B-M	B	B-TIIM-400-0.45	0.45	400	180	734	7177
18			B-TIIM-400-0.50	0.50	400	200	712	695
19		RB	RB-TIIM-400-0.45	0.45	400	180	793	717
20			RB-TIIM-400-0.50	0.50	400	200	769	695
21		S	S-TIIM-400-0.45	0.45	400	180	1046	717
22			S-TIIM-400-0.50	0.50	400	200	1014	695
23		RS	RS-TIIM-400-0.45	0.45	400	180	983	717
24			RS-TIIM-400-0.50	0.50	400	200	953	695
25	CEM Type II B-M(S-L)	B	B-TIISL-400-0.45	0.45	400	180	736	719
26			B-TIISL-400-0.50	0.50	400	200	714	697
27		RB	RB-TIISL-400-0.45	0.45	400	180	796	719
28			RB-TIISL-400-0.50	0.50	400	200	772	697
29		S	RB-TIISL-400-0.45	0.45	400	180	1049	719
30			RB-TIISL-400-0.50	0.50	400	200	1017	697
31		RS	RS-TIISL-400-0.45	0.45	400	180	985	719
32			RS-TIISL-400-0.50	0.50	400	200	956	697
33	CEM Type III A	B	B-TIII-400-0.45	0.45	400	180	736	719
34			B-TIII-400-0.50	0.50	400	200	714	697
35		RB	RB-TIII-400-0.45	0.45	400	180	796	719
36			RB-TIII-400-0.50	0.50	400	200	772	697
37		S	S-TIII-400-0.45	0.45	400	180	1049	719
38			S-TIII-400-0.50	0.50	400	200	1017	697
39	CEM Type II A-S	S	S-TIIAS-400-0.45	0.45	400	180	1049	719
40	CEM Type II B-S		S-TIIBS-400-0.45	0.45	400	180	1049	719
41	CEM Type IIIB		S-TIIIB-400-0.45	0.45	400	180	1049	719
42	CEM Type IIIC		S-TIIIC-400-0.45		400	180	1049	719

After two months of curing, cylindrical concrete specimens were sawn into 50 mm thick slices. The slices were sawn again along the diameter. All cut surfaces were covered with epoxy to prevent the movement of carbon dioxide through the cut surfaces. After that the samples were dried and placed in a controlled accelerated carbonation chamber. In the chamber, the carbon dioxide level was set at 3%, RH at 70% and temperature 400C. The carbonation depths were measured by spraying phenolphthalein indicator solution on the freshly fractured surface of each specimen after exposure in carbonation chamber for 24, 34, 45 and 65 days. The colourless depth as the depth of carbonation was measured by a digital scale.

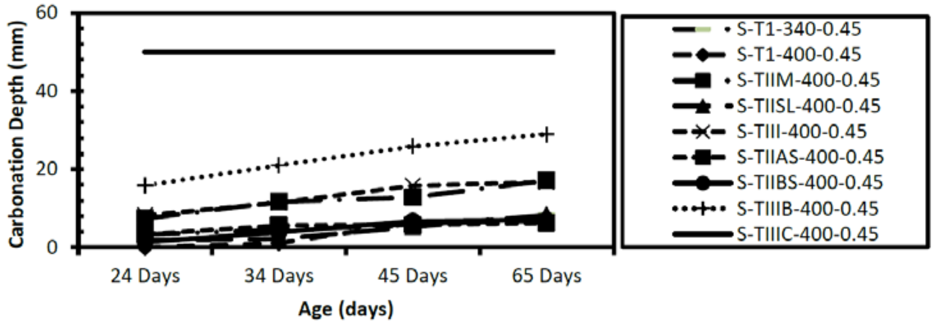

Fig. 8. Carbonation of concrete made with different types of cement: black stone aggregate.

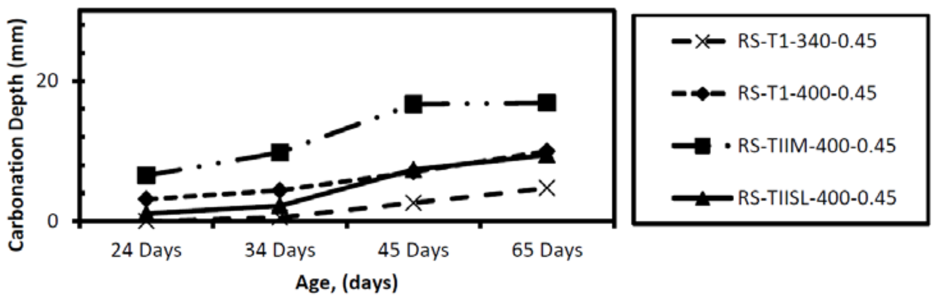

Fig. 9. Carbonation of concrete made with different types of cement - round shaped stone.

3. Results and discussions

3.1 Effect of aggregate and cement type on compressive strength and young's modulus of concrete

The variation of compressive strength and Young's modulus of concrete made with different aggregates and cement types at the age of 28 days are shown in Figure 1 and Figure 2 respectively. The lowest compressive strength and Young's modulus are found for concrete made with recycled brick aggregate and the highest compressive strength is found for concrete made with black stone. Next to black stone, shingles (round shaped stone aggregate) and brick aggregate show more compressive strength and Young's modulus than recycled brick aggregate. The properties of aggregate imply that black stone is the strongest among the aggregates investigated in this study. The stronger mechanical property of the black stone aggregate (S) (as summarized in Table 1) provided more compressive strength and Young's modulus of concrete. Comparing different types of cement, highest compressive strength and Young's modulus are found for the case with 70% CEM Type I – 30% Slag (CEM Type II B-S) blended cement. The cases made with a large amount of slag content (particularly for slag content ≥ 40%) show relatively lower compressive strength than other cements.

3.2 Effect of age on compressive strength of concrete

The variation of compressive strength with age for different types of aggregate and cement types are shown in Figure 3~6. Concrete made with more slag content, such as CEM Type

IIIA, CEM Type III B, CEM Type IIIC show less strength development (Figure 3). However, CEM Type II B-S (70% CEM Type I + 30% GGBFS) shows the highest strength compared to the other cements including CEM Type I cement.

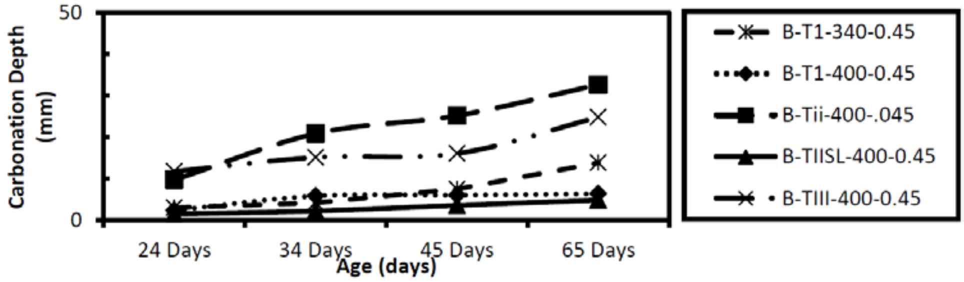

Fig. 10. Carbonation of concrete made with different types of cement - brick aggregate.

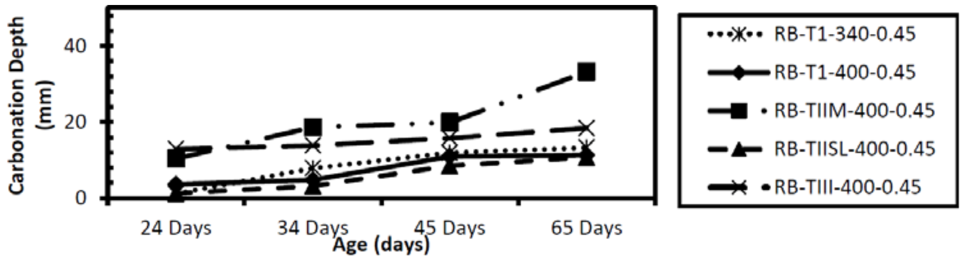

Fig. 11. Carbonation of concrete made with different types of cement: recycled brick aggregate.

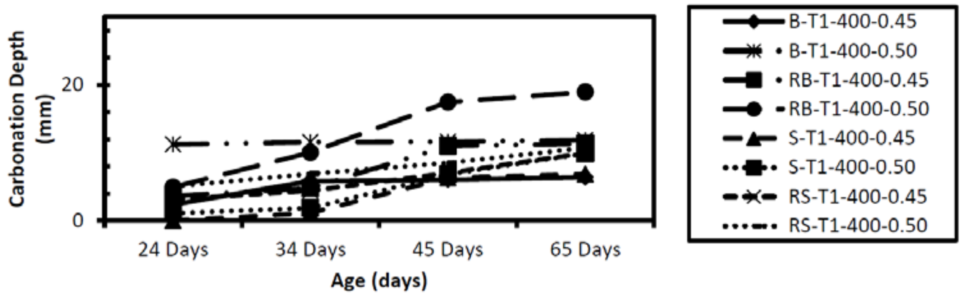

Fig. 12. Carbonation of concrete made with different aggregates and W/C - Type I cement.

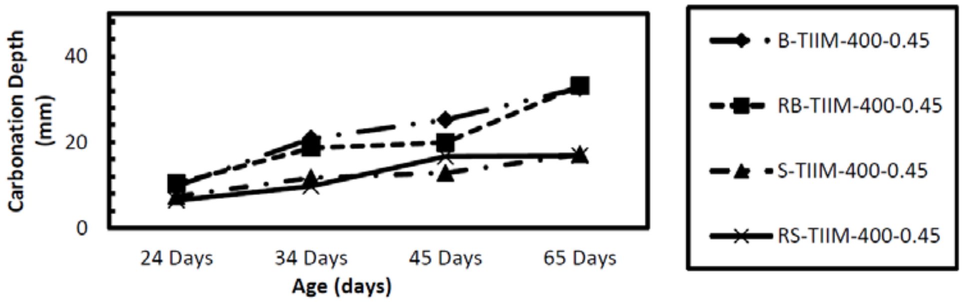

Fig. 13. Carbonation of concrete made with different aggregates: CEM Type-II B-M cement.

3.3 Effect of aggregate and cement type on tensile strength of concrete

The effect of aggregate and cement type on split tensile strength of concrete at the age of 28 days are shown in Figure 7. Comparing different types of aggregate, the lowest tensile strength is found for concrete made with recycled brick aggregate and the highest tensile strength is found for concrete made with black stone. Next to black stone, brick aggregate shows more tensile strength. It is expected that the angular shape of black stone and brick aggregate creates a stronger interfacial transition zone around the aggregates compared to the round shaped stone aggregate. Comparing cement types, CEM Type I cement shows comparatively more tensile strength.

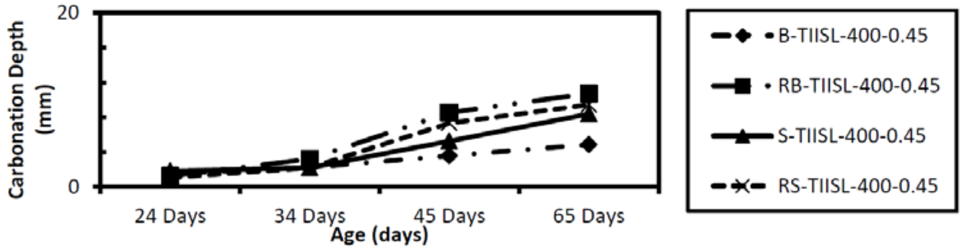

Fig. 14. Carbonation of concrete made with different types of aggregate: CEM Type-II B-M (SL).

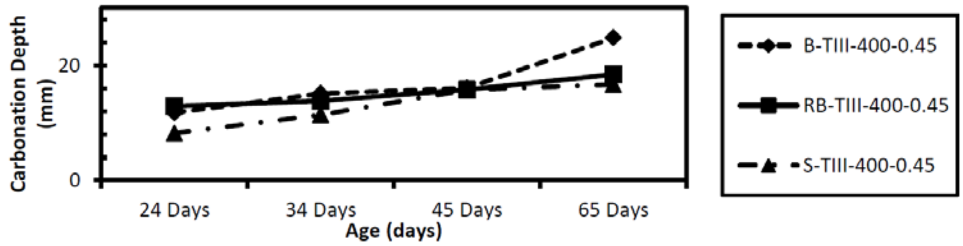

Fig. 15. Carbonation of concrete made with different types of aggregate: CEM Type-III A.

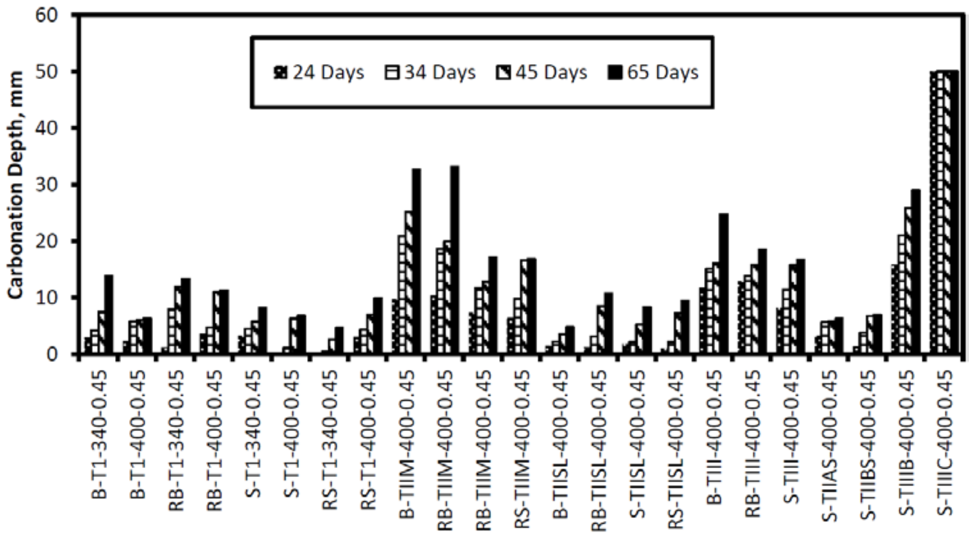

Fig. 16. Carbonation of concrete: Types of Aggregate and Cement Types – W/C=0.45

3.4 Effect of aggregate and cement type on carbonation of concrete

The variation of carbonation depth of concrete made with different types of aggregate, different types of cement, different water to cement ratio and different cement content at the age of 24, 34, 45 and 65 days are shown in Figure 8~17. Concrete made with brick aggregate and recycled brick aggregate show more carbonation depth compared to the other aggregates. Concrete made with stone aggregate shows comparatively more carbonation depth than round shaped stone. Again concrete made with Type-I cement shows less carbonation depth compared to the other cement types. With the decrease of clinker content in cement carbonation depth is increased. Less water to cement ratio shows less carbonation depth (Figure 12). Higher cement content in concrete shows less carbonation (Figure 17). Brick aggregate and recycled brick aggregate absorbs more water and are relatively porous (have more voids) compared to the black stone and round shaped stone aggregate. Therefore, the rate of diffusion of CO2 through the brick and recycled brick aggregate is higher than the other aggregate. This is the reason behind having more carbonation depth of concrete made with brick aggregate. Comparing different types of cement, blended cements with a large amount of slag (≥ 40%) such as CEM Type III A, CEM Type III B, and CEM Type III C show more carbonation depths. It is revealed that to reduce the depth of carbonation in atmospheric environment, the amount of slag content in cement is to be kept below 30%.

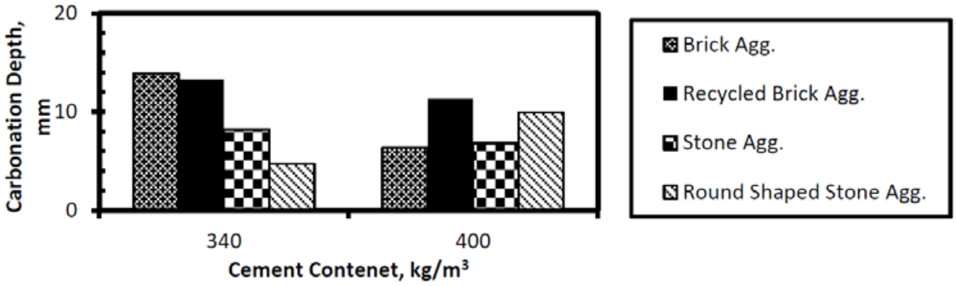

Fig. 17. Effect of cement content on carbonation of concrete: CEM Type-I cement.

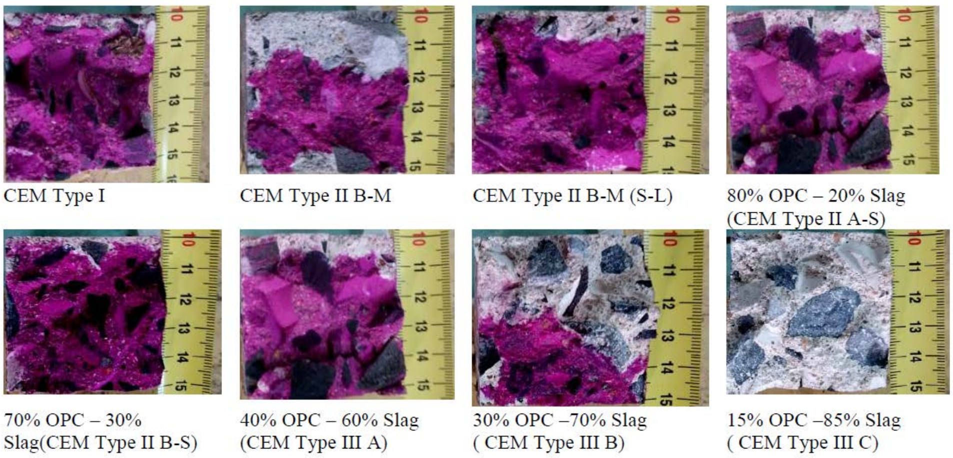

Fig. 18. Carbonation of concrete after 65 days with the variation of cement types (W/C = 0.45, C = 400 kg/m^3, Aggregate – Stone Chips)

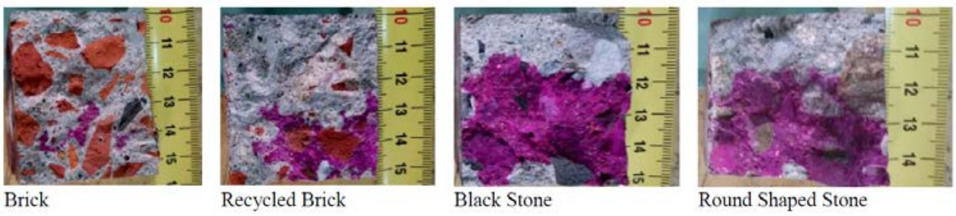

Fig. 19. Carbonation of concrete after 65 days with the variation of aggregate types (CEM Type II B M cement, W/C = 0.45, C = 400 kg/m^3).

The photographs of carbonation of concrete samples with the variation of types of cement, types of aggregates, and exposure age are shown in Figure 18 ~ Figure 23. It is found that CEM Type I (Figure 18) cement shows the least carbonation depth. With the increase of mineral contents in cement, the depth of carbonation is increased due to the reduction of calcium hydroxide produced from hydration of cement (Figure 18). However, CEM Type II B-S cement shows less carbonation depth compared to the other blended cements. From Figure 19, it is found that for concrete made with black stone, the depth of carbonation is the least compared to the other aggregates, such as brick aggregate, recycled brick aggregate, and round shaped stone aggregate. The depth of carbonation is increased with exposure age for concrete irrespective of the types of aggregate as shown in Figure 20, Figure 21, Figure 22, and Figure 23 for brick aggregate, recycled brick aggregate, black stone aggregate, and round shaped stone aggregate respectively. But, more carbonation depth is found for concrete made with brick aggregate and recycled brick aggregate. Compared to the black stone aggregate, round shaped stone aggregate (shingles) shows more depth of carbonation. In terms of carbonation depth in concrete, the aggregates can be ordered as brick aggregate, recycled brick aggregate >round shaped stone aggregate>black stone.

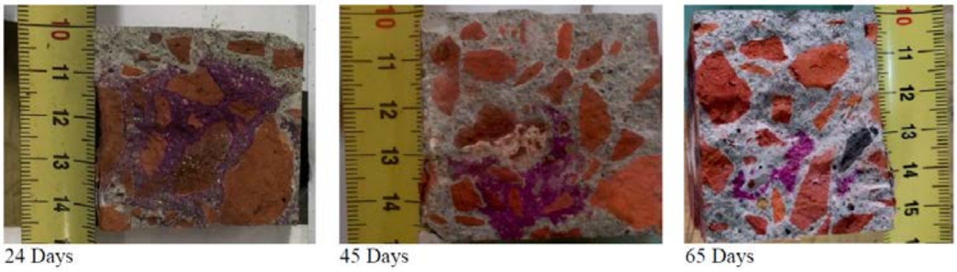

Fig. 20. Carbonation of concrete at different ages for brick aggregate (CEM Type II B M, W/C = 0.45, C = 400 kg/m^3).

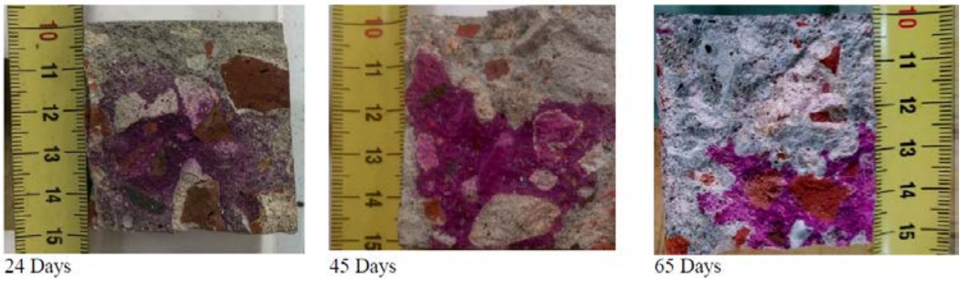

Fig. 21. Carbonation of concrete at different ages for recycled brick aggregate (CEM Type II B M, W/C = 0.45, C = 400 kg/m^3).

Fig. 22. Carbonation of concrete at different ages for black stone chips (CEM Type II B M, W/C = 0.45, C = 400 kg/m^3).

4. Conclusion

The following conclusions are drawn based on the results of an extensive experimental investigation conducted on mechanical properties and carbonation of concrete made with different aggregates and different cements: Concrete made with CEM Type II B-S cement (70% CEM Type I + 30% slag) shows the highest compressive strength. The lowest carbonation depth is observed for concrete made with CEM Type I cement compared to the other cements. The depth of carbonation is increased with the increase of slag content in cement, particularly for slag content ≥40%. However, CEM Type II B S (slag content = 30%) cement shows better performance against carbonation compared to the other blended cements.

24 Days 45 Days 65 Days

Fig. 23. Carbonation of concrete at different ages for round shaped stone (CEM Type II B M, W/C = 0.45, C = 400 kg/m^3).

In terms of depth of carbonation in concrete, the aggregate can be ordered as brick aggregate, recycled brick aggregate > round shaped stone aggregate > back stone aggregate. With the reduction of water to cement ratio and increase of cement content in concrete, the depth of carbonation is reduced.

Acknowledgements

The authors acknowledge the financial support and laboratory facilities provided by Department of Civil and Environmental Engineering of Islamic University of Technology (IUT) to conduct this study. This study is a part of the study related to a long-term plan for sustainable development of construction works in Bangladesh.

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