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Burnt Clay Brick Aggregate for Internal Curing of Concrete under Adverse Curing Conditions

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Abstract

In this study, properties of concrete with brick aggregate as internal curing medium has been investigated under adverse curing conditions. Brick aggregates, commonly known as brick chips (BC), have high porosity and absorption capacity. Desorption tests of different sizes of BC revealed that BC could desorb about 90% of its absorbed water. It was also observed that smaller size BC had higher desorption capacity than that of larger ones. Moreover, higher internal relative humidity was observed for all internally cured (IC) samples as compared to control samples made with 100% rock aggregate particles commonly known as stone chips (SC). Internally cured samples with three different percent replacements (15%, 20% and 25%) of SC with BC were prepared and subjected to six simulated adverse curing conditions. The performance of internally cured concrete under different curing conditions was evaluated in terms of compressive strength, rapid chloride permeability test (RCPT) and linear shrinkage test. The internally cured samples exhibited higher strength and less permeability and shrinkage as compared to their control counterparts under all adverse curing conditions considered in the study. Based on the findings of the study, 20% partial replacement of SC with BC of 9.5 mm in size can be recommended as a guideline for producing internally cured concrete under adverse curing conditions.

Keywords: *internal curing, brick chips, adverse curing conditions, partial replacement, permeability, shrinkage*

1. Introduction

Proper curing of concrete after placement is of utmost importance to achieve required mechanical properties. It ensures availability of sufficient amount of internal water within concrete to react with cement as well as prevents loss of water by evaporation. However, it is often difficult to provide enough curing water in large construction sites to counteract ongoing chemical shrinkage (Bentz *et al.*, 2005; ESCSI, 2012). Moreover, ensuring proper curing also requires stringent quality control protocol. Such quality control could be difficult to ensure in many construction sites particularly in small to medium scale projects in remote regions in developing countries like Bangladesh. The curing related quality control issues are primarily due to lack of training and knowledge of poorly skilled labours and unaware supervisors (Manzur, 2017; Manzur *et al.*, 2015; Iffat *et al.*, 2017a). Accelerated curing process like steam curing or curing agents could be used. However, such curing processes are expensive and also require proper supervision. Therefore, a cost effective alternative is vital to guarantee desirable quality of concrete in the absence of proper curing.

The internal curing process could be a viable solution to the problems associated with absence of proper curing conditions. In internal curing, hydration of cement is ensured by maintaining additional internal water (not part of the mixing water) within concrete matrix (Bentz *et al.*, 2005; Bentz, 2000). Internal curing assists distribution of extra water throughout the entire microstructure, thus maintaining saturation of the cement paste during hydration. This in turn prevents both paste self-desiccation and evaporation. At the same time, availability of water within concrete matrix results in proper hydration and eventually, ensures increased production of C-S-H gel. As a result, stronger and durable concrete is produced. Light weight aggregates (LWA) are usually used as internal curing medium since they are porous and absorbed substantial amount of water under submergence. The absorbed water of LWA is later desorbed during hydration and

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transferred to the paste. This is the fundamental mechanism by which LWA can ensure internal curing within concrete matrix (Iffat *et al.*, 2017a; Iffat *et al.*, 2017b; Mather, 2004). In internal curing process, the LWA act as water-filled reservoirs within the concrete that supply water from the time of mixing until the time when moisture equilibrium is achieved between the reservoirs and the surrounding cement paste (Jensen, 2013). There are a number of researches available on suitability of different kinds of LWA as internal curing agent (ESCSI, 2012; Bentz and Weiss, 2010; Schlitter, 2010; Lura, 2003; Bentz and Stutzman, 2008; Paul and Lopez, 2011; Espinoza-Hijazin *et al.*, 2012 etc.). Those studies mainly focused on investigating effectiveness of LWA as source of internal water, effect of different amount of LWA as internal curing medium and effect of internal curing on autogeneous and chemical shrinkage. The beneficial impact of internal curing on durability and shrinkage of concrete was also investigated in several studies (Kim and Chun, 2015; Zou and Weiss, 2014; Zou *et al.*, 2015 etc.). Most of the above mentioned studies were based on utilization of LWA either produced by thermal process like shale or obtained from industrial by products through mechanical treatment like pulverized fly ash, blast furnace slag etc. In addition, use of naturally occurring pumice aggregate as internal curing medium within cement composites can be found in number of studies (Zhutovsky *et al.*, 2004; Sahmaran *et al.*, 2009; Green *et al.*, 2011; Geoffrey *et al.*, 2012). Recent studies on utilization of expanded shale, normal weight porous aggregate, coal bottom ash etc. as internal curing agent to reduce autogenous shrinkage and enhance strength properties of concrete are also available in literature (Kim *et al.*, 2018; Zou *et al.*, 2018; Savva and Petrou, 2018; Savva *et al.*, 2018; Pepe *et al.*, 2014). It is evident from previous researches that internal curing mechanism has been primarily investigated to reduce self desiccation in low water content high strength concrete. However, it is apparent that internal curing has the potential to produce concrete with desired quality where proper supervision regarding curing of concrete is lax, appropriate curing condition is difficult to maintain and supply of water is not adequate.

Utilization of brick chips (BC) as coarse aggregate is quite common in several plain countries like Bangladesh due to unavailability of sufficient amount of stone aggregates. Bricks are produced from burnt clay and have high porosity and absorption capacity. Hence, concrete made with BC as coarse aggregate often exhibit less strength and durability issues (Manzur *et al.*, 2015; Afroz *et al.*, 2015; Hossain, 2012; Bosunia and Chowdhury, 2001; Masum and Manzur, 2019). However, BC is a popular construction material because of its wide availability even in remote places and low cost. Hence, alternative use of BC needs to be explored. The burnt clay brick has unit weight of about 1,120 Kg/m³ and water absorption capacity of more than 10%. Consequently, BC is considered as LWA with relatively high absorption capacity. Therefore, BC can be considered as an internal curing medium if it has sufficient desorption ability.

Water curing or external curing method is the most common method of curing and is employed in majority of the construction work. In water curing process, it is imperative to maintain the moist condition for a considerable period of time. Unfortunately, many local contractors in Bangladesh do not have the required awareness and workers often suffer from lack of skill to ensure proper external curing. As a result, general concreting work often exhibits durability concerns (Manzur *et al.*, 2015; Iffat *et al.*, 2017b; Masum and Manzur, 2019). Under this scenario, internal curing through addition of BC could improve the durability performance of any concreting work that suffers from absence of appropriate external curing. Moreover, internal curing process using BC can be suitable for area with water scarcity and may help construction during dry season. It is also obvious that internal curing process is environmentally friendly since it reduces the water usage for external curing. Previous studies by this research group found that internally cured (IC) concrete produced with partial replacements of stone aggregate with BC exhibited relative better performance in terms of strength, modulus of elasticity and permeability under different adverse curing conditions (Iffat *et al.*, 2017a; Iffat *et al.*, 2017b). However, except the above mentioned two studies, no significant research finding is available on BC as internal curing agent. Therefore, further comprehensive research initiative is required to foster practical application of BC as internal curing agent within concrete in the absence of proper curing. In this study, desorption of different size of BC was investigated. The internal relative humidity (RH) of internally cured concrete and normal concrete at different days of curing was also measured for comparison. Based on findings of the previous studies, three partial replacement levels (15, 20 and 25%) were considered to prepare IC samples. Moreover, chloride permeability and linear shrinkage tests were conducted to evaluate the durability performance of IC concrete made with BC as internal curing medium under six adverse curing conditions.

2. Materials, Desorption of BC and Experimental Approach

2.1 Material Properties

Ordinary Portland cement (OPC) with unit weight of 3.150 kg/m^3 was used as binding material. The normal consistency, setting time and compressive strength of cement were measured following ASTM C187 (ASTM, 2011), ASTM C191 (ASTM, 2013a) and ASTM C109 (ASTM, 2013b) standards, respectively. The normal consistency of the cement was found as 25.50%. The cement had initial setting time of 3.00 hours and final setting time of 6.00 hours. The 7 and 28 day compressive strength of cement mortar were found as 12.7 MPa and 28.5 MPa, respectively. Rock aggregate particles, commonly known as stone chips (SC) in this region, and burnt clay brick chips (BC) were used as coarse aggregates and sand was used as fine aggregates. Gradations of fine and coarse aggregates were obtained separately using method described in ASTM C136 (ASTM, 2006) standard. Fineness

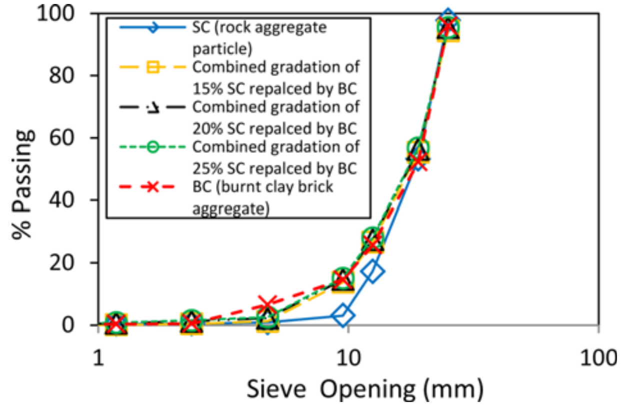

Fig. 1. Gradation Curves of SC, BC and Partially Replaced Coarse Aggregates

Table 1. Aggregate Property Test Results

	Unit Weight (Kg/m^3)	Bulk Specific Gravity (OD)	Bulk Specific Gravity (SSD)	Absorption Capacity %
SC	1545	2.60	2.63	1.10
BC	1120	1.65	1.95	18.50
Sand	1610	2.61	2.63	0.95

modulus (FM) of SC, sand and BC were found as 7.42, 2.75 and 7.26, respectively. The FM values of partially replaced rock aggregate particles (SC) with 15%, 20% and 25% BC were also measured and found as 7.29, 7.25 and 7.23, respectively. Gradation curves of SC, BC and partially replaced SC with BC are shown in Fig. 1. In case of partial replacement, SC were replaced by BC of 9.5 mm in size since this size of BC exhibited the highest amount of desorption as discussed in Section 2.2. Bulk specific gravity and absorption capacity of aggregates were determined following ASTM C128 (ASTM, 2012a) standard and are shown in Table 1. Unit weights of SC, BC and sand were obtained as per ASTM C29 (ASTM, 2009) standard and are also provided in Table 1.

2.2 Desorption Capacity of BC

A dehumidifier with relative humidity (RH) range from 22% to 90% and temperature range between 5°C and 40°C was used in this experiment. Total eight experiments were conducted to check the desorption capacity of BC with four different RH of 65%, 70%, 88% and 90% and at a constant temperature of 34° C. The temperature was kept constant based on previous test results (Iffat *et al.*, 2017a; Iffat *et al.*, 2017b). Four different sizes of BC

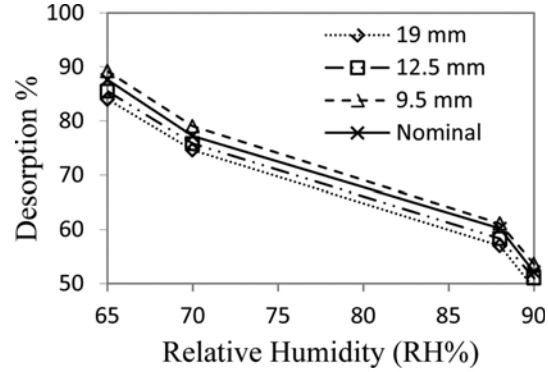

Fig. 2. Desorption Rate of BC with respect to RH

(19 mm, 12.5 mm, 9.5 mm and nominal mixed samples) were separated by ASTM sieve for desorption test in order to investigate the effect of size on desorption behavior. The BC samples were weighted and then made saturated surface dry with water. Then they were weighted again. Brick chips absorbed nearly 25% of water (vacuum saturated) of its weight. Then those samples were placed in the dehumidifier with different relative humidity and at constant temperature. Water loss was measured after each 30 minutes. From the experiment it is evident that, desorption rate increases with decrease in relative humidity and size of BC. Therefore, BC with 9.5 mm in size exhibited higher desorption rate as compared to other sizes. The desorption rate of different sizes of BC with respect to RH are shown in Fig. 2. The maximum desorption rate was obtained as 88.7% for BC having size of 9.5 mm at 65% RH. Therefore, it satisfied the requirement of ASTM C1761 (ASTM, 2012b). ASTM C1761 (ASTM, 2012b) requires that LWA to be considered as IC medium should desorb 85% of the absorbed water. Based on the desorption test results, BC of 9.5 mm in size was thus used as internal curing medium in this study.

2.3 Mix Design

A total of five mixes were prepared to conduct the experimental program. Mixes were selected based on the results of previously conducted studies by this research group (Iffat *et al.*, 2017a; Iffat *et al.*, 2017b). One mix was made with full SC using water cement ratio of 0.40 as control samples (CS). Three mixes were made with three replacement levels (15%, 20% and 25% replacement of SC with BC) with the same water cement ratio of 0.40 as internally cured (IC) samples. Finally, one mix was made using only BC as coarse aggregate with the same water cement

Table 2. Mix Design Data

Water Cement Ratio	Percent replacement of SC by BC	Water (Kg)	Cement (kg)	FA (kg)	SC (kg)	BC (kg)
0.40	0%	174.68	436.7	751.3	1109.2	0
	15%		436.7	751.3	942.8	166.4
	20%		436.7	751.3	887.4	221.8
	25%		436.7	751.3	831.9	277.3
	100%		436.7	751.3	0	1109.2

ratio for comparison. All specimens were kept under different adverse curing conditions as discussed in Section 2.4. Mix design details are shown in Table 2. The amount of aggregate was measure based on saturated surface dry (SSD) basis. Hence, aggregates were converted to SSD condition after collecting them in air dry condition. Moisture from surface of aggregates was removed properly before mixing. All BC, used as IC medium, was immersed in water for 24 hours and then wiped carefully with cloth to remove all surface water.

2.4 Simulated Curing Conditions

Seven curing conditions were selected in this study to simulate concreting work under exposed field condition. Details of each curing conditions are provided in Table 3. In curing condition referred to as WP, samples were placed outside the laboratory just after casting with polythene sheet covering. Conversely, in WOP curing condition, samples were placed outside the laboratory without any covering just after casting. In cases of 3-WP and 7-WP curing conditions, samples were placed under water for 3 and 7 days, respectively, and then kept outside the laboratory with polythene cover. For 3-WOP and 7-WOP conditions, the samples were submerged under water for 3 and 7 days and then placed outside without cover. All samples were also placed under normal external curing condition for comparison. For normal curing under water, specimens were submerged in water outside laboratory for 28 days. Fig. 3 shows both covered and uncovered test samples kept outside laboratory under WP and WOP curing conditions.

Table 3. Simulated Curing Conditions

Designation	Description
NC	Normal curing under water
WP	With polythene cover
WOP	Without polythene cover
3-WP	Three days normal curing under water then with polythene cover
3-WOP	Three days normal curing under water then without polythene cover
7-WP	Seven days normal curing under water then with polythene cover
7-WOP	Seven days normal curing under water then without polythene cover

Fig. 3. Samples Were Kept Outside with (WP) and without (WOP) Polythene Cover

2.5 Internal Relative Humidity Measurement

The internal relative humidity (RH) of concrete was measured using a digital hygrometer with digital sensor. The schematic diagram of setup is shown in Fig. 4(a). The internal RH was measured for all five mixes under WP and WOP curing conditions (Fig. 4(b)). For each mix, three cubes (150 mm × 150 mm × 150 mm) were prepared each having three circular hollow sections (18.75 mm in diameter). The hollow sections were sealed properly with insulating materials to prevent the contamination of temperature and relative humidity with proper conduit (PVC pipe) so that sensor can be inserted easily.

2.6 Compressive Strength Test

Compressive strength tests were conducted according to ASTM C39 (ASTM, 2005) standard. Cylindrical samples having dimension of 100 mm × 200 mm were used for compressive strength test. Compression tests were performed using universal testing machine at a loading rate prescribed in the code.

2.7 Rapid Chloride Permeability Test (RCPT)

The RCPT test was conducted according to ASTM C1202 (ASTM, 2012c) procedures. The setup developed by Iffat *et al.* (2014) was used for the test. For RCPT test, concrete slices of

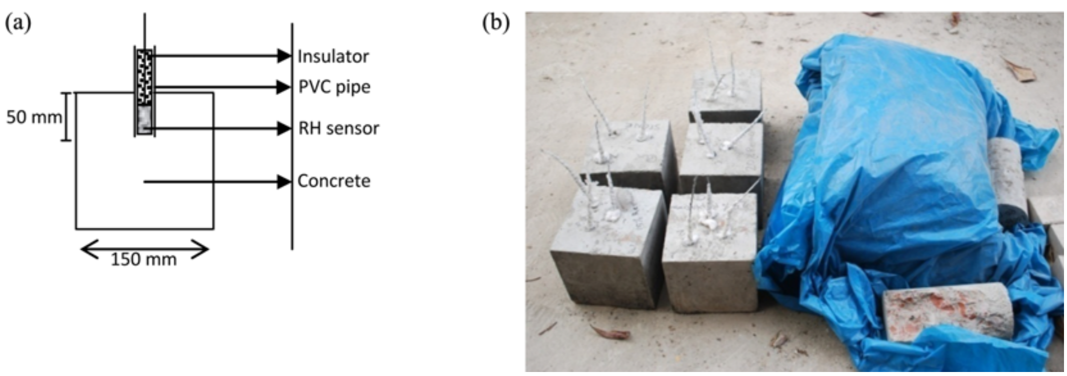

Fig. 4. Internal RH Measurement: (a) Schematic Diagram, (b) Cubes under WP and WOP Conditions

100 mm in diameter and 50 mm in thickness, cut from cylindrical samples, were used. The sides of the cylindrical specimen were coated with epoxy, and after the epoxy was dried, it was put in a vacuum chamber for 3 hours. The specimen was vacuum saturated for 1 hour with de-aerated water and allowed to soak for 18 hours. It was then placed in the test device. The left-hand side (−) of the test cell was filled with a 3% NaCl solution. The right-hand side (+) of the test cell was filled with 0.3N NaOH solution. A 60-volt potential was then applied for 6 hours. Readings were taken every 30 minutes. At the end of 6 hours, the sample was removed from the cell and the amount of columbs passed through the specimen was calculated.

2.8 Drying Shrinkage Test

Shrinkage test was conducted as per ASTM C 157/C 157M (ASTM, 2003) procedures. Length changes of concrete bars at different days were measured to evaluate linear shrinkage. For shrinkage test, prismatic concrete bars of 75 mm × 75 mm × 285 mm in dimension were used since maximum aggregate size was less than 25 mm. Specimens ware kept in lime saturated water for 30 minutes just after removal from the molds and after that initial readings were taken. After initial readings, specimens were kept under seven different simulated curing conditions and readings were taken at specified time intervals up to 84 days. One set was kept under air after 28 days and readings were taken simultaneously with other samples up to 84 days.

3. Results and Discussion

3.1 Internal Relative Humidity of concrete

In Figs. 5(a) and 5(b), the time evolution of RH in concrete (up to 28 days) for WP and WOP curing conditions are shown, respectively. It is evident from Fig. 5 that, internal relative humidity increased with increase in percent replacement. Maximum internal relative humidity was obtained from cube made with 25% replacement of SC with BC. Minimum relative humidity was observed for cubes made with full SC (no replacement) for all curing conditions. For example, internal relative humidity of 80%, 83% 85% 86% and 86% were obtained from 0%, 10%, 15%, 20% and 25% replacement of SC with BC, respectively under WOP condition after 7 days. Likewise, internal relative humidity of 84%, 87%, 89%, 90% and 90% were obtained after 7 days under WP condition from 0%, 10%, 15%, 20% and 25% replacement of SC, respectively. It is, therefore, obvious that BC as internal curing agent within concrete supplied additional water that eventually increased the RH within concrete matrix.

3.2 Compressive Strength

It was observed from the compressive strength tests that CS (control samples with SC as coarse aggregate) exhibited the maximum strength under NC condition at all days. However, the main objective of this study was to investigate and compare the performance of IC samples to that of CS under adverse curing conditions. The compressive strength of CS and IC samples at 7 and 90 days under different adverse curing conditions are shown in Figs. 6 and 7, respectively to illustrate the short and long term effect of internal curing on concrete strength. It was observed that all internally cured samples showed relative higher strength as compared to their CS counterparts under all simulated adverse curing conditions. Moreover, the effect of curing conditions was found to be more pronounced at later ages. At 7 day, CS and IC samples experienced almost similar compressive strength as

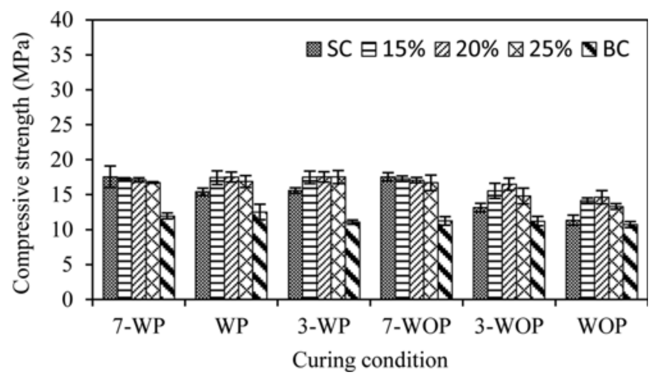

Fig. 6. Compressive Strength of CS and IC Samples at 7 Day

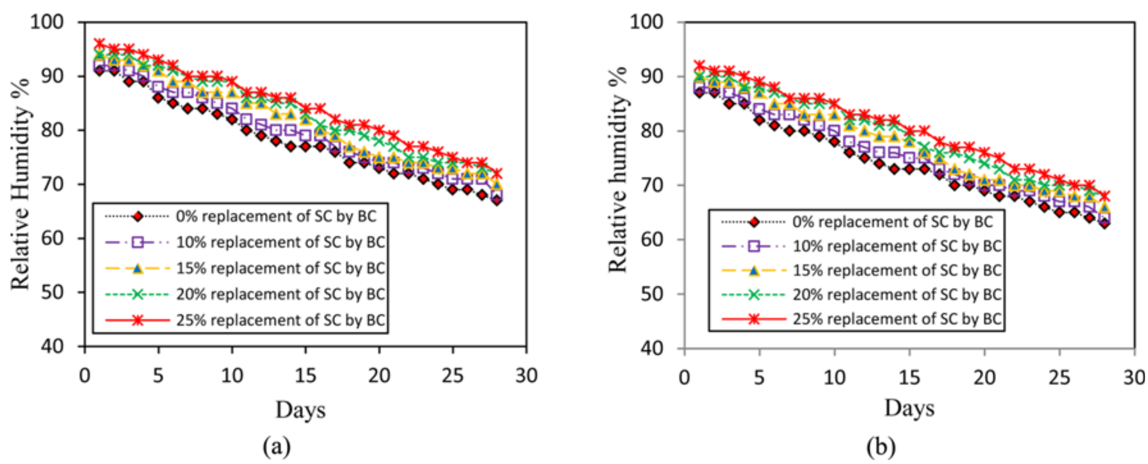

Fig. 5. Time Evolution of RH under: (a) WP Condition, (b) WOP Condition

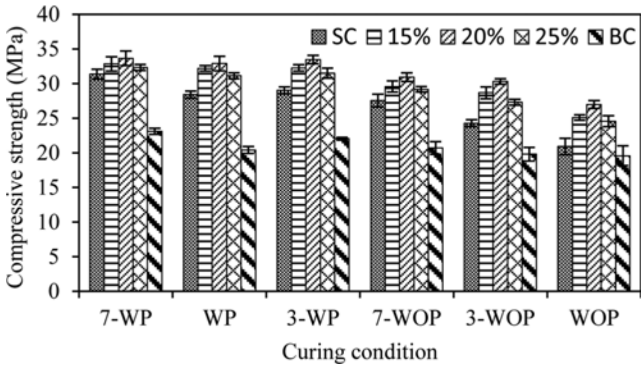

Fig. 7. Compressive Strength of CS and IC Samples at 90-Day

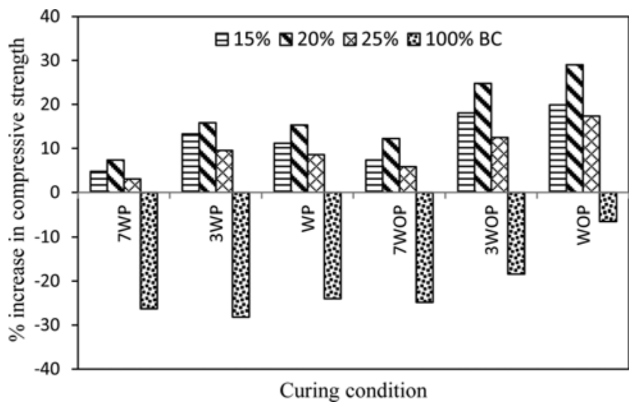

Fig. 8. Percent Increase in Compressive Strength with respect to Control Samples

evident from Fig. 7. However, at 90 day, IC samples exhibited significantly better performance than that of CS under similar adverse curing conditions. The highest difference between strength of IC and CS samples was observed for WOP condition and the lowest difference was observed for 7WP condition. The WOP condition was the most severe adverse curing condition considered in the study since samples were kept outside just after casting without any cover. On the other hand, in 7WP condition, samples were cured for 7 days under water and then kept outside with cover. The maximum strength was obtained from the IC samples with 20% replacement for all simulated adverse curing conditions. In all cases, minimum strength was obtained by samples having BC as coarse aggregates.

Figure 8 shows the percent increase in compressive strength of IC samples with respect to CS samples under similar curing conditions at 90 day. It is obvious that 20% replacement significantly increased the strength of IC samples in the absence of proper supply of external water. The maximum percent increase was obtained for WOP conditions for all partial replacements. The degree of internal curing was found to be varied with the amount of BC as internal curing agent. For example, 25% replacement resulted in relatively lower strength as compared to other two partial replacement. Concrete with BC only exhibited significant decrease in strength under all curing conditions. Hence, amount of BC must be controlled as partial replacement. Otherwise, larger quantity of BC is likely to produce weaker concrete.

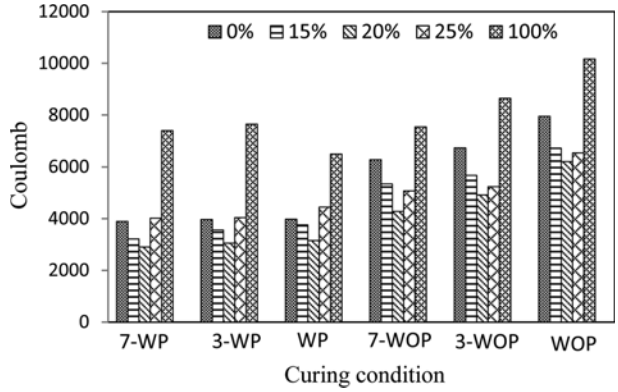

Fig. 9. RCPT Results of CS, IC and BC Samples under Different Curing Conditions

Table 4. Chloride Permeability Based on Charge Passed in RCPT (ASTM, 2012c)

Charge Passed (Coulombs)	Chloride Permeability
> 4,000	High
2,000 – 4,000	Medium
1,000 – 2,000	Low
100 – 1,000	Very low
< 100	Negligible

3.3 Chloride Permeability

As per ASTM C1202 (ASTM, 2012c) standard, concrete can be classified based on their permeability obtained from RCPT tests. Table 4 shows the classification of concrete as per ASTM 1202 (ASTM, 2012c). In this study, RCPT tests were conducted on 90 day cured specimens. Fig. 9 shows the RCPT results of all the samples under different curing conditions. The total charge passed through the samples (both CS and IC) kept without polythene covering (WOP, 7-WOP and 3-WOP) was found to be more than 4,000 coulomb (Fig. 9). So, these samples can be termed as high chloride permeable concrete. However, IC samples without covering showed considerable less amount of charges passed through them as compared to CS without covering. For examples, CS without covering experienced about 8,000 coulomb passed through them whereas IC samples with 20% replacement had about 6,200 coulomb passed through them. Control samples under NC exhibited the lowest amount of charge passed through them. On the other hand, concrete with BC only as coarse aggregates experienced the highest amount of charge passed through them among all samples considered in the study. Moderate chloride permeability was observed for internally cured samples with 15% and 20% replacement under covering. It was also found that IC samples experienced less amount of charge passed through them than that of CS under similar adverse curing condition with covering. Internally cured samples with 25% replacement showed high permeability even with polythene sheet covering.

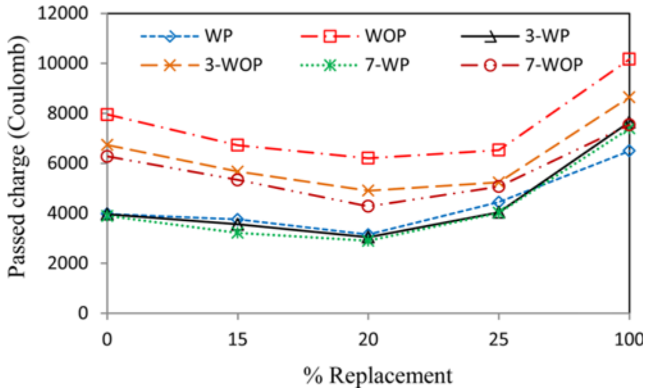

Fig. 10. Effect of % Replacement on Chloride Permeability of Control, BC and IC Concrete

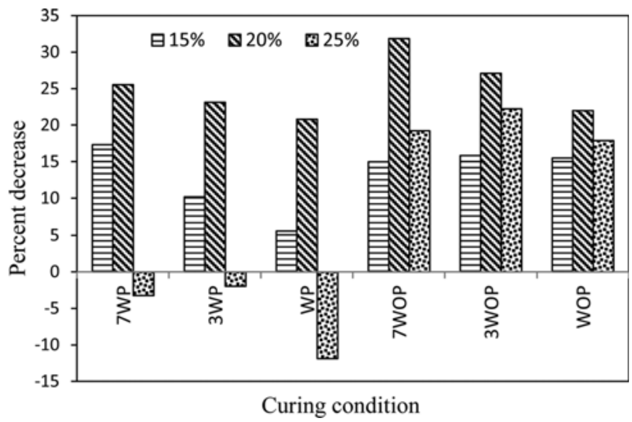

Fig. 11. Percent Decrease in Chloride Permeability of IC Samples with respect to CS

Figure 10 shows the variation in chloride permeability with respect to percent replacement for all simulated curing conditions. A particular trend is apparent from the Fig. 10. For all IC samples, it was observed that minimum chloride permeability was obtained from 20% replacement. It was also evident that covering of concrete resulted in less permeable concrete. Addition of BC as internal curing agent supplied sufficient quantity of water during curing period in the absence of external supply of water and thereby, ensured better hydration of cement. Such internal supply of water is more important when availability of external water is critical. Better hydration by internally available water results in less porous concrete and eventually, reduces permeability which is clearly evident from the RCPT results.

Figure 11 shows the percent decrease in chloride permeability of IC samples with respect to permeability of CS under similar adverse curing conditions. It is obvious that 20% replacement significantly decreases the amount of charge pass through the internally cured samples under adverse curing conditions. Similar to compressive strength test results, it has been found that 25% replacement is relatively less effective in producing better concrete. In case of curing conditions with cover, all IC samples with 25% replacement experieced slightly high permeability values as compared to their CS counterparts. Hence, the negative effect induced by high porosity of BC surpasses the beneficial effect of internal curing by the same aggregate at replacement level of 25%. On the contrary, under without covering curing conditions, 25% replacement level showed less permeability than that of corresponding CS samples. Nevertheless, the permeability of IC samples under without covering conditions was significantly higher than their covered counterparts. Therefore, a limit on amount of BC as internal curing medium within concrete must be recmmeneded. Otherwise, higher amount of BC may produce less durable concrete due to their lesser unit weight and high porosity.

3.4 Drying Shrinkage

In the absence of proper curing, drying shrinkage may become critical for a concrete member and therefore, reduction of shrinkage is of immense importance. It is expected that internal curing would have lessening effect on drying shrinkage of concrete by supplying additional water in fine capillary pores. For drying shrinkage test, samples were kept in lime saturated water for 30 minutes after preparation and initial readings were taken immediately after removal from lime saturated water. After initial readings, specimens were kept under seven different simulated curing conditions considered in this study. One set of the specimens were kept under water for 28 day according to ASTM standard (ASTM, 2003). After 28 days, those specimens were removed from water and kept in contact with air and is defined as air storage (AS) samples. After 28 days, shrinkage readings of all samples were taken at specified time intervals up to 84 day.

From shrinkage versus day graph for control samples i.e., 0% replacement of SC with BC specimens as shown in Fig. 12(a), the general trend of increment of shrinkage value with respect to time for various curing conditions was observed. In case of AS specimens, initial swelling effect was observed. This was due to the fact that specimens were kept submerged under water for first 28 days and as a result no evaporation of mixing water occurred. Drying shrinkage of internally cured concrete with 15%, 20% and 25% replacement level at different days is shown in Figs. 12(b) through 12(d), respectively. From Fig. 12, it is clear that after the initial swelling effect, the shrinkage of control sample at AS condition increased with time and finally reached to a value which was more than that of all IC concrete with covering. It was observed that all samples showed similar trend in shrinkage value with respect to time under simulated curing conditions. However, shrinkage values were different for different types of samples under the similar curing conditions. From shrinkage versus day graph, it is evident that shrinkage of concrete increases with increase in days. Furthermore, it was observed that initially, rate of increase of shrinkage was high and eventually, the rate decreased with time. From shrinkage graphs, it is also apparent that after 60 days there is insignificant change in drying shrinkage values for all samples. The lowest drying shrinkage value of -210 × 10^{-6} mm/mm was obtained from 20% replacement of SC with BC under 7-WP curing condition after

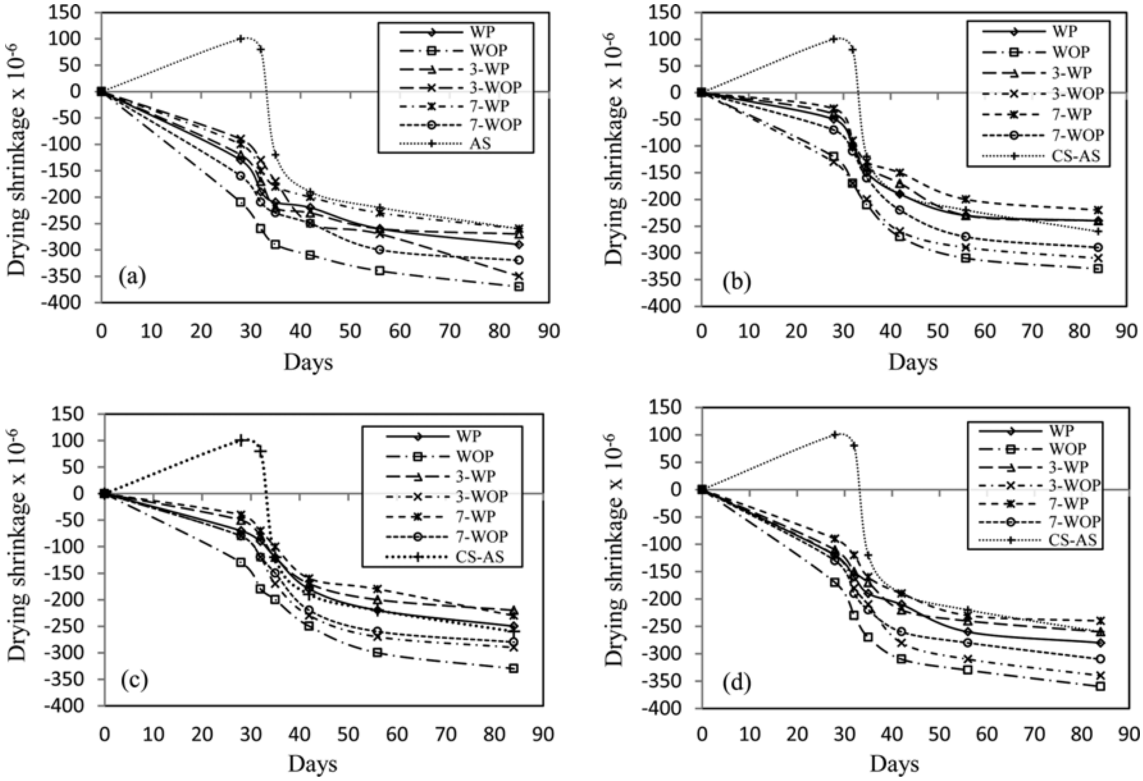

Fig. 12. Shrinkage vs Days Graph under Different Curing Conditions: (a) Control Samples, (b) IC Samples with 15% Replacement, (c) IC Samples with 20% Replacement, (d) IC Samples with 25% Replacement

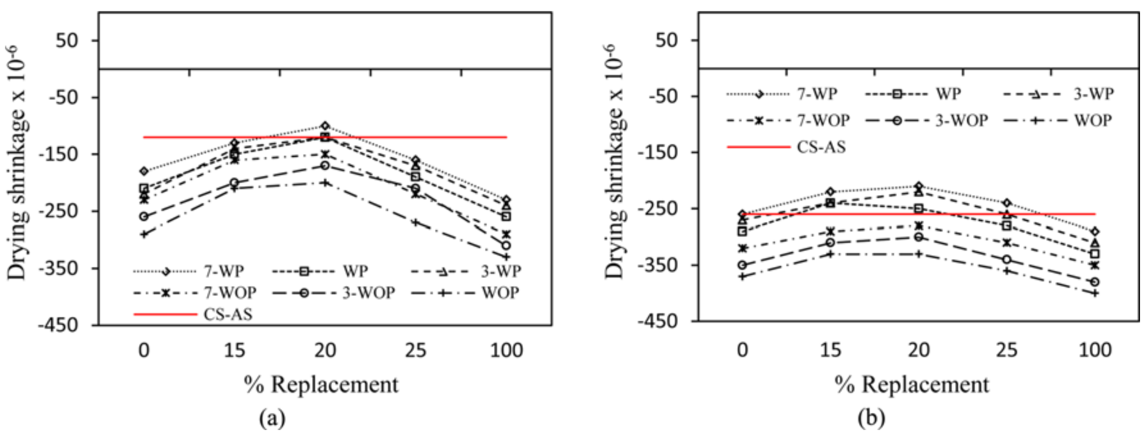

Fig. 13. Effect of % Replacement on Drying Shrinkage of CS, BC and IC Samples under Different Curing Conditions at 35 and 84 Days of Testing: (a) Drying Shrinkage after 35 Day, (b) Drying Shrinkage after 84 Day

84 days. The same IC samples (having 20% partial replacement) experienced drying shrinkage of -220 × 10^{-6} mm/mm and -250 × 10^{-6} mm/mm, respectively under 3-WP and WP curing conditions at 84 day.

Figures 13(a) and 13(b) show the variation in drying shrinkage with percent replacement for different curing conditions after 35 days and 84 days, respectively. The straight line in the Figs. 13(a) and 13(b) represent the shrinkage of CS samples under AS condition at respective days. The trend in shrinkage test results was similar at all days of testing. It was observed that, at 35 day, three IC samples (20% replacement under WP, 3-WP and 7-WP) experienced similar or less shrinkage than that of control samples under AS. Similar trend was evident for the shrinkage values at 42 day and 56 day. And finally at 84 day, IC samples with 15% and 20% replacement level and polythene covering experienced less drying shrinkage than CS-AS samples. Moreover, under any adverse curing condition, IC samples exhibited less shrinkage value than their CS counterparts. For instance, IC samples with 20% replacement level experienced about 19%, 12.5%, 18.5%, 14%, 13.8% and 11% less drying shrinkage as compared to CS samples under 7-WP, 7-WOP, 3-WP, 3-WOP, WP and WOP conditions, respectively at 84 day. Samples with 15% and 25%

replacement under WOP condition at 84 day showed about 11% and 3% less drying shrinkage than that of CS, respectively. Similar less drying shrinkage values were obtained for all IC samples as compared to corresponding CS samples under all adverse curing conditions at all days of testing. It is thus obvious that the ability of BC as internal curing agent ensures more water within concrete even at later ages. Sample with 100% BC, experienced the highest shrinkage value in all cases. Water can penetrate through brick aggregates due to their high porosity. It thus creates contineous path within the concrete matrix for water movement and eventually, results in high evaporation.

From Fig. 13, it is also evident that 20% replacement of SC with BC exhibited lowest drying shrinkage. Such behavior establishes the fact that there exists an optimum concentration of BC to partially replace SC for producing better internally cured concrete. It is also obvious that control samples in the absence of proper supply of external water are prone to severe drying shrinkage.

3.5 Discussion

It is, therefore, evident that saturated BC has internal curing ability and can be used as an internal curing agent within concrete. Moreover, it can be inferred that 20% replacement of SC with BC resulted in the best performing IC concrete among all percent replacement level considered in the study. Fig. 14(a) shows correlation between internal curing for different replacement levels and 90 day compressive strength and permeability whereas Fig. 14(b) presents the correlation between internal curing and 90 day compressive strength and shrinkage at 56 day. The correlations are shown for two adverse curing conditions i.e. 7WP and WOP in the figures of Fig. 14. The 7WP condition represents the least severe and the WOP represents the most adverse curing condition considered in the study. From both the graphs, the superior performance of 20% replacement level to produce internally cured concrete can be evidently substantiated. The saturated BC act as reservoir of internal water within concrete matrix due to their high absorption (18.5%) and eventually, release sufficient amount of water to maintain the moist condition necessary for hydration due to their high desorption rate (almost 90%). Nevertheless, both 15% and 25% replacement produced better concrete as compared to control samples when subjected to similar adverse curing conditions in most cases. This enhanced performance of internally cured concrete under adverse curing conditions both in terms of strength and durability is due to the supply of internal water by BC since presence of saturated BC is the only difference between control and IC samples. In comparison with 20% partial replacement, IC samples with 15% and 25% replacement showed relatively less strength, high permeability and high shrinkage values. The probable hypothesis for such behavior can be summarized as in case of 15% replacement, less water remains available to ensure internal curing which is necessary for proper hydration. On the other hand, 25% replacement produces weaker and permeable concrete due to higher amount of light weight aggregates. A continuous path becomes available for water to pass through paste and brick aggregate since water can penetrate through the brick aggregate due to its high porosity. The 100% replacement level i.e. concrete with BC only produces the least performing concrete. Hence, it is evident that BC as a coarse aggregate within concrete does not impart any advantage except making it lesser weight. Such behavior of BC-concrete was also evident from previous studies (Afroz *et al.*, 2015; Hossain, 2012; Bosunia and Chowdhury, 2001). As already mentioned, the beneficial effect of partial replacement in the absence of proper curing is due to the desorption of absorbed water by BC that ensures moist condition within concrete matrix.

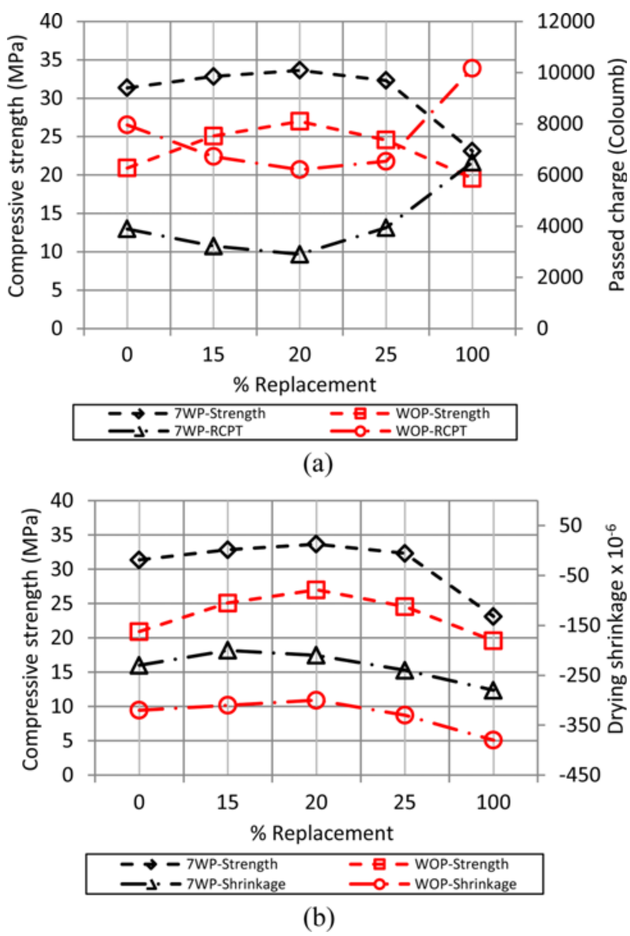

Fig. 14. Correlations between Internal Curing for Different % Replacement Level: (a) 90-Day Compressive Strength and RCPT Values, (b) 90-Day Compressive Strength and Linear Shrinkage at 56 Days for 7WP and WOP Curing Conditions

4. Conclusions

It has been found from the study that saturated BC can be effectively used as internal curing agent within concrete to significantly improve concrete properties under adverse curing conditions. The following conclusions can be drawn from the experiments performed in this study.

1. Burnt clay brick aggregate (BC) can be considered as a suit-

able internal curing material. From desorption test of saturated BC, it can be conferred that BC can desorb sufficient amount of absorbed water even at early stages which becomes available during hydration. Moreover, all internally cured samples with BC showed higher internal relative humidity as compared to control samples in relative humidity test.

2. Smaller sized BC was found to desorb higher amount of water than relatively larger sized ones. BC of 9.5 mm in size exhibited the maximum desorption rate.
3. Internally cured (IC) samples showed significantly superior performance as compared to control specimens under adverse curing conditions in terms of all the parameters considered in the study i.e., strength, permeability and shrinkage.
4. It was observed that 20% replacement of SC (rock aggregate particles) with BC produced IC concrete with relatively higher strength as compared to other percent replacements.
5. Similar to compressive strength test, it was found that 20% replacement resulted in the minimum amount of charge passed through the IC samples and minimum linear shrinkage of IC samples.
6. Polythene sheet covering can be used to ensure effective internal curing. Utilization of polythene sheet covering is a simple process since these sheets are less costly and can be used repetitively.
7. Finally, 20% replacement of SC with BC of 9.5 mm in size can be recommended as a guideline for producing better performing internally cured concrete under adverse curing conditions. In addition, polythene sheet covering should be used.

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