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Optimum Proportion of Masonry Chip Aggregate for Internally Cured Concrete

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Abstract: Proper curing of concrete is essential for achieving desirable mechanical properties. However, in a developing country like Bangladesh, curing is often neglected due to lack of proper knowledge and skill of local contractors. Consequently, general concreting work of the country has been found to have both strength and durability issues. Under such scenario, internal curing could be adopted using masonry chip aggregate (MCA) which is quite common in this region. It is observed that saturated MCA desorbs water under favorable relative humidity and temperature. This paper presents the effectiveness of MCA as internal curing medium and recommends a tentative optimum mix proportion to produce such concrete. The experimental study was conducted in two phases. It was found that 20% replacement of stone chips with MCA produced better performing internally cured concrete both in terms of strength and durability. Performance of internally cured concrete with recommended proportion of MCA is comparable to that of normally cured control concrete samples with conventional stone chips. In addition, internally cured concrete performed significantly better than control samples when kept under similar adverse curing conditions. In the absence of supply of external water for curing, compressive strength of internally cured concrete for 20% replacement can be as high as 1.5 times the strength of the control concrete samples. Significant better performance in permeability than that of control samples was also observed for this percent replacement under such adverse curing conditions.

Keywords: internal curing, lightweight aggregate, temperature, humidity, desorption, strength, permeability.

Abbreviations

IC	Internal curing
LWA	Light weight aggregate
IC1	Inside Laboratory with Polythene Cover
IC2	Inside Laboratory without Polythene Cover
IC3	Outside Laboratory with Polythene Cover
IC4	Outside Laboratory without Polythene Cover
IC3a	3 days under normal curing and then Outside Laboratory with Polythene Cover
IC3b	7 days under normal curing and then Outside Laboratory with Polythene Cover
IC4a	3 days under normal curing and then Outside Laboratory without Polythene Cover
IC4b	7 days under normal curing and then Outside Laboratory without Polythene Cover
RH	Relative humidity
SSD	Saturated surface dry
OD	Oven dry
MCA	Masonry chip aggregate
SC	Stone chips

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1. Introduction

Light weight aggregates (LWA) absorb considerable amount of water before mixing which can transfer to the paste during hydration (Expanded Shale, Clay and Slate Institute (ESCSI) 2012). On the other hand, internal curing (IC) is defined as a process where proper hydration of cement occurs due to availability of additional internal water within concrete matrix (Bentz et al. 2005; Bentz 2000). Therefore, a partial replacement of stone aggregate with saturated LWA might be an effective means for ensuring internal curing. Internal curing of concrete is usually done in two ways. One is by using lightweight aggregates (LWA) and other way is using super absorbent polymers (SAP). Both LWA and SAP absorb water before mixing and later, desorb absorbed water during curing (Mather 2004; Iffat et al. 2015; Manzur et al. 2015). When LWA is used as internal curing medium within concrete, usually small amount is required to supply the additional water (Bentz and Weiss 2010). A number of research are available that investigated the effectiveness of LWA as internal curing medium to produce concrete with desired properties. For example, structural lightweight aggregate was used on the Hibernia Offshore Platform in Newfoundland, Canada by replacing 50% of the coarse aggregate with a pre-wetted Expanded Shale, Clay and Slate-ESCS (Expanded Shale, Clay and Slate Institute (ESCSI) 2012). In another research at Purdue University, suitability of LWA to produce internally cured concrete was examined (Schlitter 2010). Expanded shale, crushed returned concrete aggregate and natural river sand were used in that experiment. A study by Lura (Lura 2003; Lura et al. 2003) at Delft University produced internally cured concrete using two different mixes with 11% and 25% of total volume of aggregate replaced by shale. Those samples (shale) at Delft released almost all (96%) of their absorbed moisture and therefore, it was concluded that water can leave the pores of the LWA if a large enough suction pressure (or a low enough internal relative humidity) exists. However, 1.6% reduction in compressive strength and 3.3% reduction in modulus of elasticity were observed. De Sensale and Goncalves (2014) showed the effectiveness of fine LWA and SAP as internal curing agent to reduce autogenous deformation of concrete. They also found that higher amount of LWA or SAP results in reduction of compressive strength of concrete. In another study, effectiveness of internal curing mechanism for making concrete pavement less susceptible to environmental conditions was showed by Chun and Kim (2015). Lower shrinkage and less damage of internally cured mortar were also observed by Zou and Weiss (2014) and Zou et al. (2015) in two different studies. Therefore, benefits of internal curing can be summarized as enhanced hydration of cement, higher strength development, reduction of autogenous shrinkage and cracking, decrease in permeability, and improvement of durability etc. (Bentz et al. 2005; Iffat et al. 2015; Manzur et al. 2015; Bentz and Weiss 2010; de Sensale and Goncalves 2014; Chun and Kim 2015; Zou and Weiss 2014; Zou et al. 2015; Geiker et al. 2004). The impact of internal curing begins immediately during the initial hydration of the cement, with benefits that are observed at ages as early as two days. However, till now, research on LWA as internal curing medium have mainly been conducted utilizing two types of aggregates. One type of LWA is produced by thermal process like shale and the other type of LWA is obtained through mechanical treatment of industrial by products like pulverized fly ash, blast furnace slag, industrial waste, and sludge (Obla et al. 2007). Also, in some studies, naturally occurring LWA have been utilized. Utilization of naturally occurring pumice aggregates for producing structural lightweight and internally cured concretes has been observed in some countries like New Zealand and Kenya (Green et al. 2011; Geoffrey et al. 2012).

Masonry chip aggregates (MCA) are very common in Bangladesh and in nearby regions due to their relative low cost and wide availability. MCA are produced from burnt clay and have been used as coarse aggregate for many years. Many construction works use MCA as primary coarse aggregate. However, MCA-concrete exhibits poor performance, both in terms of strength (Afroz et al. 2015; Hossain 2012) and durability (Afroz et al. 2015; Bosunia and Chowdhury 2001). On the other hand, external curing method is usually practiced in Bangladesh which requires additional water as well as proper awareness among the workers and construction supervisors for ensuring required quality control. Unfortunately, in many instances, appropriate quality control protocol to ensure proper curing is not maintained and often not considered as an essential part of concreting work due to lack of adequate knowledge of local contractors. There is also scarcity of water in many regions of the country, particularly in dry season. Therefore, concrete with MCA as primary coarse aggregate and/or without proper curing may experience considerable durability issues (Manzur et al. 2015; Iffat et al. 2016). However, MCA are produced in large quantity in the country and are very popular among the local contractors. Therefore, the use of MCA as coarse aggregate would be difficult to control. Under this circumstance, identification of potential avenues for using MCA as coarse aggregate is very important from perspective of Bangladesh. MCA are light weight and have porous structure. It was also observed that pore spaces of these aggregates absorb water during saturation and later can desorb water under favorable humidity and temperature (Iffat 2014). It is, therefore, evident that MCA has the potential to be used as internal curing medium within concrete and can be considered as an alternative but effective curing solution for general construction work in Bangladesh. In a very recent study, (Iffat et al. 2016) showed that utilization of MCA as internal curing medium can improve the permeability of concrete under adverse curing conditions. However, except this recent one, no other significant study is available on MCA as internal curing agent within concrete. In this article, the outcome of a comprehensive research program that studied the effectiveness of MCA as internal curing medium in terms of compressive strength, split tensile strength, modulus of elasticity and chloride permeability is discussed in order to recommend an appropriate mix proportion to produce internally cured concrete. It has been found that concrete with MCA as internal curing medium performed significantly well as compared to conventional stone aggregate concrete in the absence of proper external curing mechanism. Moreover, internally cured concrete having recommended mix proportions can achieve comparable strength and permeability values of proper externally cured conventional stone aggregate concrete.

2. Experimental Investigation

2.1 Material

Portland composite cement CEM II (2000) produced by a local manufacturer was used in this study. XRF analysis of cement was done using LAB CENTER XRF-1800 to evaluate the composition of used cement and is given in Table 1. The normal consistency of the cement was measured as per ASTM C187 (2011). The initial setting time was determined according to ASTM C191 (2013) and compressive strength of cement mortar was evaluated following ASTM C109 (2013).

Table 1 Composition of componentsofcement samples.

Component	Mass (%)
CaO	56.74
SiO_2	22.83
Al_2O_3	8.66
Fe_2O_3	2.89
MgO	4.40
SO_3	2.80
Na_2O	0.10
K_2O	0.73
TiO_2	0.58
P_2O_5	0.13
MnO	0.05
Cr_2O_3	0.017
SrO	0.045
ZnO	0.008
Cl	0.000

Normal consistency, initial setting time and 28 day compressive strength of cement mortar was obtained as 27.5%, 3 h and 29.3 MPa, respectively. Crushed stone chip was used as primary coarse aggregate and MCA (Fig. 1) was used as partial replacement of stone chips as internal curing medium. Locally available sand, known as Sylhet Sand, was used as fine aggregate. Gradations of both coarse and fine aggregates were determined through sieve analysis, according to ASTM C-136 (2006) and are plotted in Fig. 2. Fineness modulus (FM) of MCA, stone chips and sand were found as 6.37, 8.42 and 2.43, respectively. Bulk specific gravity of MCA was found as 1.693 on oven dry basis as per ASTM C128 (2012). The unit weight of MCA was determined following ASTM C29 (2009) and was found as 1110 kg/m^3.

2.2 Desorption of MCA

The absorption and desorption properties of LWA are important to determine its effectiveness as an internal curing

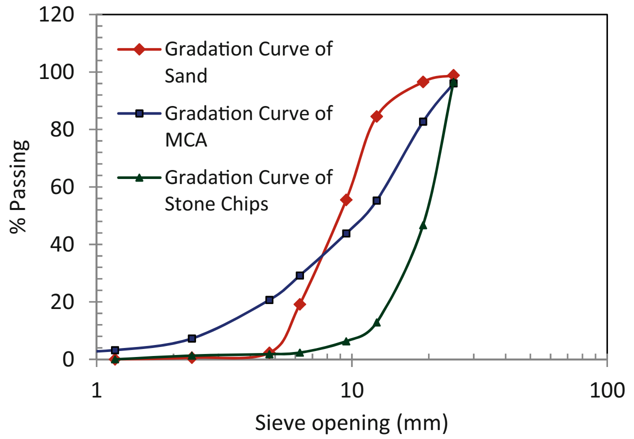

Fig. 2 Gradation *curves* of sand, masonry chip aggregate (MCA) and stone chips.

agent (Kim and Bentz 2008). Desorption test is considered as one of the most effective techniques for evaluating this property. Therefore, desorption test of MCA was performed following ASTM C1761 (2012). A dehumidifier with relative humidity (RH) range from 22 to 90% and temperature range from 5° to 40 °C was used for this test.

A total of 30 experiments were conducted using five different RHs of 60, 73, 77, 85 and 90% and six different temperatures of 14.5, 18, 24, 28, 31 and 34 °C. The MCA samples were weighed and made saturated surface dry with water. Then, they were re-weighed after saturation. It was found that MCA absorbed nearly 28.6% water in terms of its oven dry weight. These samples were then placed in the dehumidifier under different temperatures and relative humidities as mentioned above. Water loss was measured at every 30 min interval. It was observed that the rate of desorption increased with temperature and decreased with relative humidity (Figs. 3 and 4). It is evident from Fig. 3 that maximum desorption (minimum absorbed water remained) occurred when temperature was around 34 °C and RH was around 60%. The maximum and minimum desorption rates were found as 89.7 and 23.7%, respectively, with respect to the weight of absorbed water by MCA. According to ASTM C1761 (2012), LWA as internal curing medium should desorb more than 85% of absorbed water under the stated

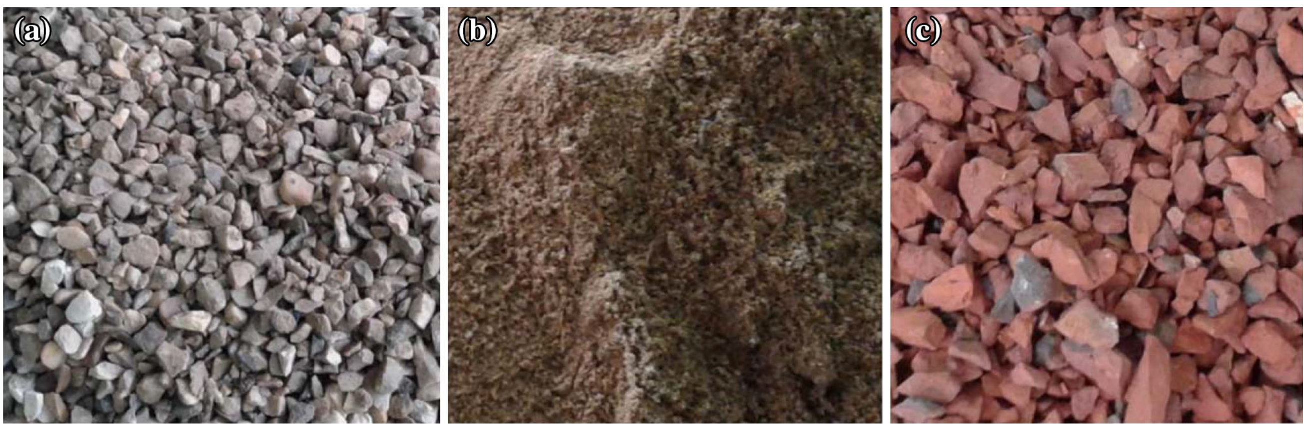

Fig. 1 Aggregates (**a**) stone chips (**b**) sand (**c**) masonry chip aggregate (MCA).

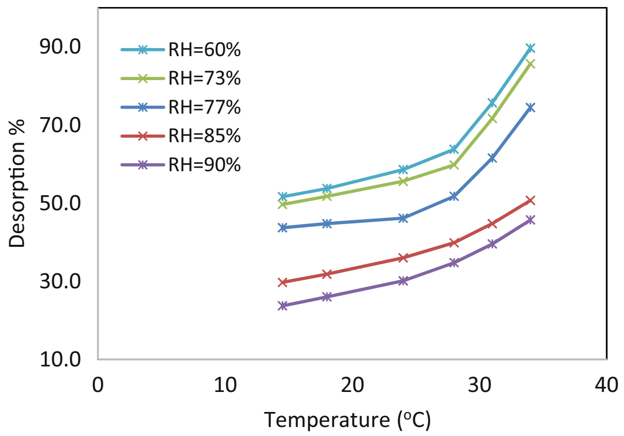

Fig. 3 Effect of temperature on desorption rate of MCA.

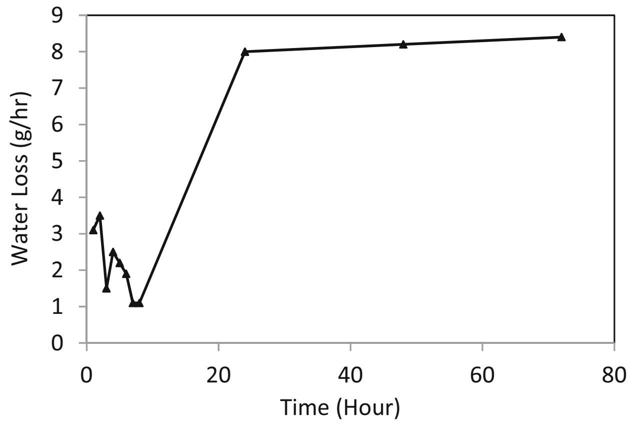

Fig. 4 Effect of time on desorption rate of MCA for a constant temperature (34 °C) and constant relative humidity (73%).

storage condition. From this experiment, it was observed that MCA desorbed around 90% of absorbed water at 60% RH and thereby satisfies the ASTM requirement. Even at higher RHs of 85 and 90%, MCA can desorb around 50 and 40% of absorbed water, respectively. So, additional water will be available from MCA during early curing periods when internal RH is higher within concrete. Figure 4 shows that, at early stage, the desorption rate remains low. But this rate increases rapidly between 10 and 20 h and reaches the equilibrium condition after around 65–70 h. Similar desorption behavior of MCA was observed for other temperatures and RH values, although the rates were found different.

2.3 Concrete Mixtures

Control samples were made with stone chips as primary coarse aggregate and a mix proportion of 1: 1.5: 2.3 for design compressive strengths of 20.5 MPa. The mix proportion was based on weight of the ingredients which means one proportion of cement was mixed with 1.5 proportion of sand and 2.3 proportion of conventional stone chips in terms of weight of the components. The experiments were conducted in two phases. For the 1st phase of the experiment, three different water to cement ratios (w/c) of 0.4, 0.45 and 0.5 were used. Compressive strength test, modulus of elasticity test and RCPT (Rapid Chloride Permeability Test) were performed in this phase. Downgraded crushed stone of 20 mm size was used as primary coarse aggregate. Nine mixes with three different partial replacements (10, 20 and 30%) of conventional stone chips with MCA for each w/c ratio were prepared using the mix proportion of 1: 1.5: 2.3. The MCA was made saturated surface dry (SSD) before mixing. At first, MCA were kept fully submerged in water for about 24 h. Then the surface of MCA were wiped properly with cloth and all surface water was removed to ensure SSD condition. Control samples with conventional stone chips as coarse aggregate were also made using the same mix proportions and three different w/c ratios. For each test age, three identical replicate samples were prepared. No admixtures were used in the mixes.

In the 2nd phase, only one w/c ratio (0.4) was selected which produced the best performing internally cured concrete in terms of compressive strength, elastic modulus and chloride permeability in the 1st phase. Three different percent replacements (15, 20 and 25%) of stone chips with MCA were utilized in order to find more accurate results. The mix design, RH and temperature during casting and curing were kept identical to Phase 1. Compressive strength and splitting tensile strength tests were performed in this phase. In addition, the internal relative humidity (RH) of both control and internally cured samples were investigated.

2.4 Experimental Setup

Adequate normal moist curing (NC) was ensured for control samples by keeping the samples fully submerged under water. Beside NC, four different curing conditions were simulated for both control and internally cured samples in the 1st phase to represent different field conditions, as provided in Table 2. Two sets of each type of samples were kept inside the laboratory to simulate curing under shading. Among the two sets, one set was covered with polythene sheets (IC1) and the other set was kept uncovered (IC2). The other two sets were kept outside the laboratory to simulate curing under exposed field condition. Exposed field condition denotes the typical exterior weather condition of the country during most part of the year. During the experiment, the average external (Exposed condition-Outside laboratory) temperature and RH were around 32 °C and 71%, respectively. The average internal (Inside laboratory) temperature was around 30 °C and RH was around 72%. Similar to the previous case, one set was covered with polythene sheet (IC3) and the other was placed without covering (IC4). Control samples (with no MCA) were also kept under similar (IC1, IC2, IC3, and IC4) curing conditions for comparison. In the 2nd phase of the study, only IC3 and IC4 conditions were considered since these conditions are mostly common in construction sites of the country. Moreover, besides IC3 and IC4 conditions, four additional curing conditions (termed as IC3a, IC3b, IC4a and IC4b) were simulated in the 2nd phase and are also listed in Table 2. In cases of IC3a and IC3b conditions, samples were placed under water for 3 and 7 days, respectively, and then kept outside the laboratory with polythene cover. For IC4a and IC4b conditions, samples were submerged under water for 3 and 7 days and then placed outside without cover.

Table 2 Details of different curing conditions.

Symbol	Experimental curing conditions	Simulated curing conditions
NC	Normal curing under water	Proper external curing
IC1	Inside with cover	Curing under shade with covering
IC2	Inside without cover	Curing under shade without covering
IC3	Outside with cover	Exposed field condition with covering
IC4	Outside without cover	Exposed field condition without covering
IC3a	3 days under normal curing and then outside with cover	Exposed field condition under covering after 3 days of NC
IC4a	3 days under normal curing and then outside without cover	Exposed field condition without covering after 3 days of NC
IC3b	7 days under normal curing and then outside with cover	Exposed field condition under covering after 7 days of NC
IC4b	7 days under normal curing and then outside without cover	Exposed field condition without covering after 7 days of NC

As mentioned above, performance of internally cured samples were evaluated and compared in terms of compressive strength, modulus of elasticity, tensile strength and chloride permeability. Compressive strength test was performed according to ASTM C39 (2005). Modulus of elasticity test was performed as per ASTM C469 (2002). For compressive strength tests, cylindrical concrete samples of 100 mm by 200 mm in size were made and kept under different curing conditions for up to 28 days. Compressive strength tests were done at 3, 7 and 28 days. Universal testing machine was used to apply compressive load on specimens at a loading rate of 0.15–0.35 MPa per second. Modulus of elasticity test was also performed using Universal testing machine with a lower loading rate as per Code requirement (2002). Axial stress strain method was used to determine modulus of elasticity (Iffat et al. 2015). Three specimens were tested for each variation. Chloride permeability test known as rapid chloride permeability test (RCPT) was carried out following ASTM C1202 (2012). For RCPT, 50 mm diameter cores were cut from top surfaces of 100 mm × 200 mm cylinders after 28 days of curing. Epoxy coated and vacuum saturated core specimens (Iffat et al. 2014; Grace 2006; Ptefier et al. 1994) were placed in the test device as per Code (2012) requirements. The vacuum process was carried out to remove the air voids and eventually, to fill those voids with water to make the concrete sample conductive to electrons. Readings were taken at every 30 min interval. At the end of 6 h, the sample was removed from the cell and the amount of coulombs passed through the specimen was calculated. Splitting tensile strength test was performed according to ASTM C496/C 496M (2011). Cylindrical samples of dimension 100 mm by 200 mm were used for the tensile strength test. In order to ensure that specimens remained on the same axial plane, diametrical lines were drawn on the two ends of the specimens. Plywood strips were kept on the lower plate of the testing device and specimens were placed on the plywood strip. The samples were placed so that the lines marked on the ends are vertical and centered over the bottom plate. Another plywood strips were placed above the specimen and loads were applied continuously till the specimens broke.

For investigating internal RH of samples, concrete cubes (150 mm × 150 mm × 150 mm) were prepared, each having three circular hollow sections (18.75 mm in diameter) inside. These hollow portions were held in reserve in order to measure the internal RH of concrete. The cubes were made with similar mix proportions as considered in this study. The hollow sections were sealed properly with cotton using conduit so that sensor can be inserted easily. The cube specimens were placed in the dehumidifier at constant temperature and RH of 34 °C & 65%, respectively.

3. Results and Discussion, Phase 1

3.1 Compressive Strengthand Modulus of Elasticity

Variations in compressive strengths are shown in Fig. 5. It was found that most of the internally cured samples under four different simulated conditions of the 1st phase achieved less compressive strength than that of control samples under NC. This pattern of behavior was expected since concrete with stone chips as coarse aggregate usually have higher compressive strengths due to greater unit weight. However, 20% replacement with MCA resulted in similar compressive strength of NC control samples under IC3 curing condition (Fig. 5a, c). Figure 6 shows the effect of MCA replacement on compressive strength of samples having w/c ratio of 0.40. This w/c ratio resulted in the maximum compressive strength. It may be observed that for lower w/c ratio, higher compressive strength was achieved for all samples. Samples under IC3 condition achieved the highest compressive strength for all MCA replacements. This is due to the fact that samples under IC3 condition were exposed to relatively higher temperature which was beneficial for proper hydration. In addition, polythene sheet covering prevented water

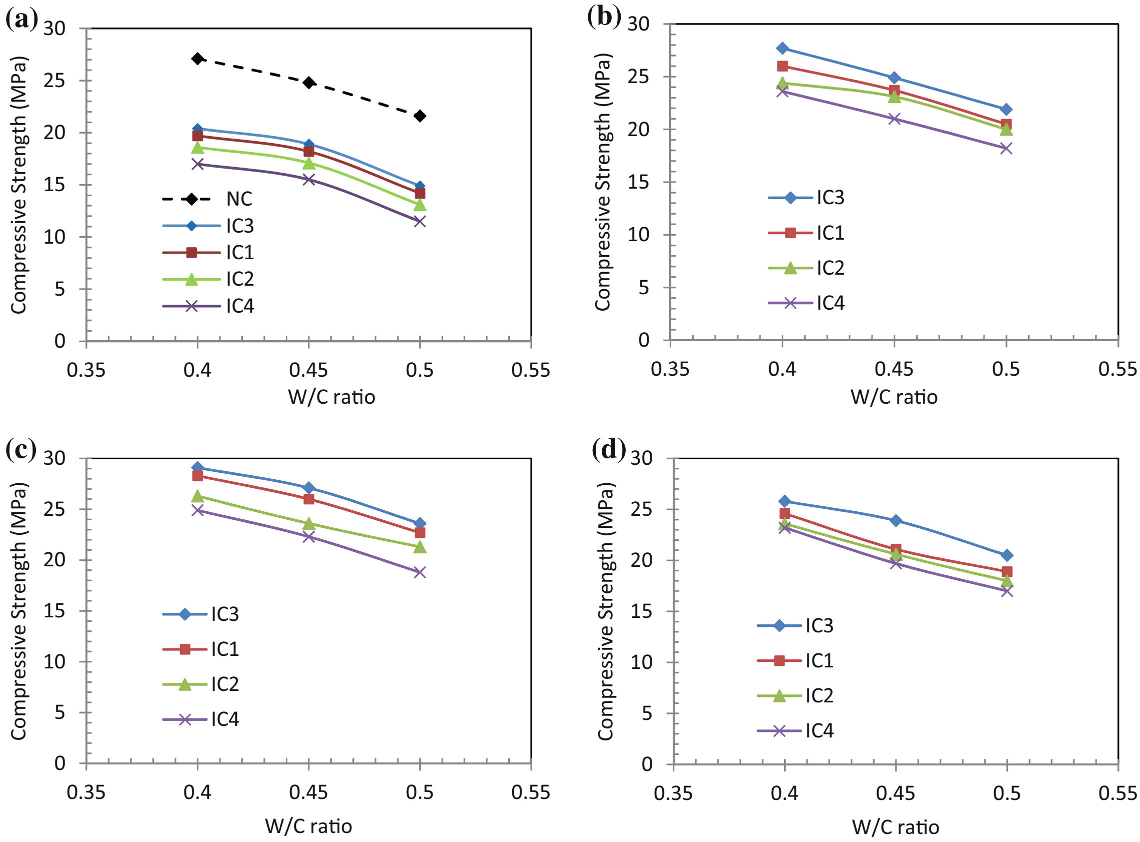

Fig. 5 Effect of w/c ratio on 28 day compressive strength of samples **a** control samples with 0% replacement **b** IC samples with 10% replacement **c** IC samples with 20% replacement **d** IC samples with 30% replacement.

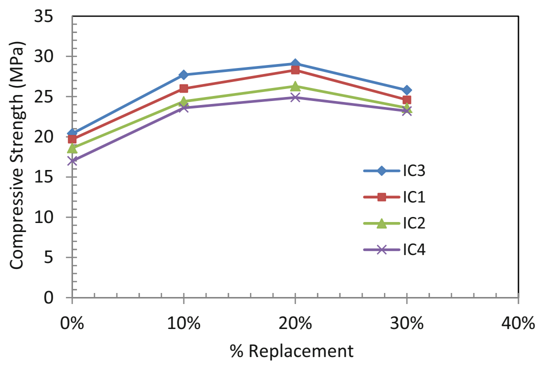

Fig. 6 Effect of percent replacement on compressive strength of control and internally cured samples with w/c ratio of 0.4 under similar curing conditions (Phase I).

loss due to evaporation. It is clearly evident that, with increase in percent replacement, compressive strength increased up to a certain value, and then declined. Maximum strength is observed for 20% MCA replacement.

Another significant observation of the study is that internally cured samples achieved considerable higher strength as compared to control samples when kept under similar curing conditions with no external supply of curing water. Control samples were kept under the four simulating curing conditions to study the effect of different curing condition on compressive strength of conventional concrete. Similar to internally cured concrete, the IC4 condition resulted in minimum compressive strength for control samples (Fig. 6). Unfortunately, curing condition analogous to IC4 prevails in some practical instances due to the absence of proper quality control. Usually, a layer of external water is poured on concrete and left without any covering. This external water evaporates very quickly, particularly during summer, leaving the concrete in almost similar to IC4 condition. Internally cured samples with 20% replacement under IC4 condition achieved 46% higher compressive strength than that of control samples. The 10 and 30% MCA replacement under IC4 condition also produced significantly higher strength (about 38 and 36%, respectively) as compared to control samples. Under IC3 condition, 20% partial replacement resulted in 42% more compressive strength than control samples. Table 3 shows increase in compressive strength for internally cured samples in comparison with control samples under similar curing conditions.

Modulus of elasticity of control and internally cured samples under different curing conditions are plotted in Fig. 7. Similar to compressive strength, it was found that 20% replacement under IC3 condition produced comparable modulus of elasticity of normally cured control samples. Control samples under IC4 condition produced the least modulus of elasticity (Fig. 8). The best performing internally cured samples (20% partial replacement and under IC3 condition) achieved about 19.5% higher elasticity than that of control samples placed under IC3 curing condition. The

Table 3 Percent increase in compressive strength with respect to control samples under similar curing conditions (w/c ratio 0.4).

Percent replacement (%)	Curing conditions			
	IC1	IC2	IC3	IC4
10	31.5	30	35	38
20	43	41	42	46
30	25	26	26	36

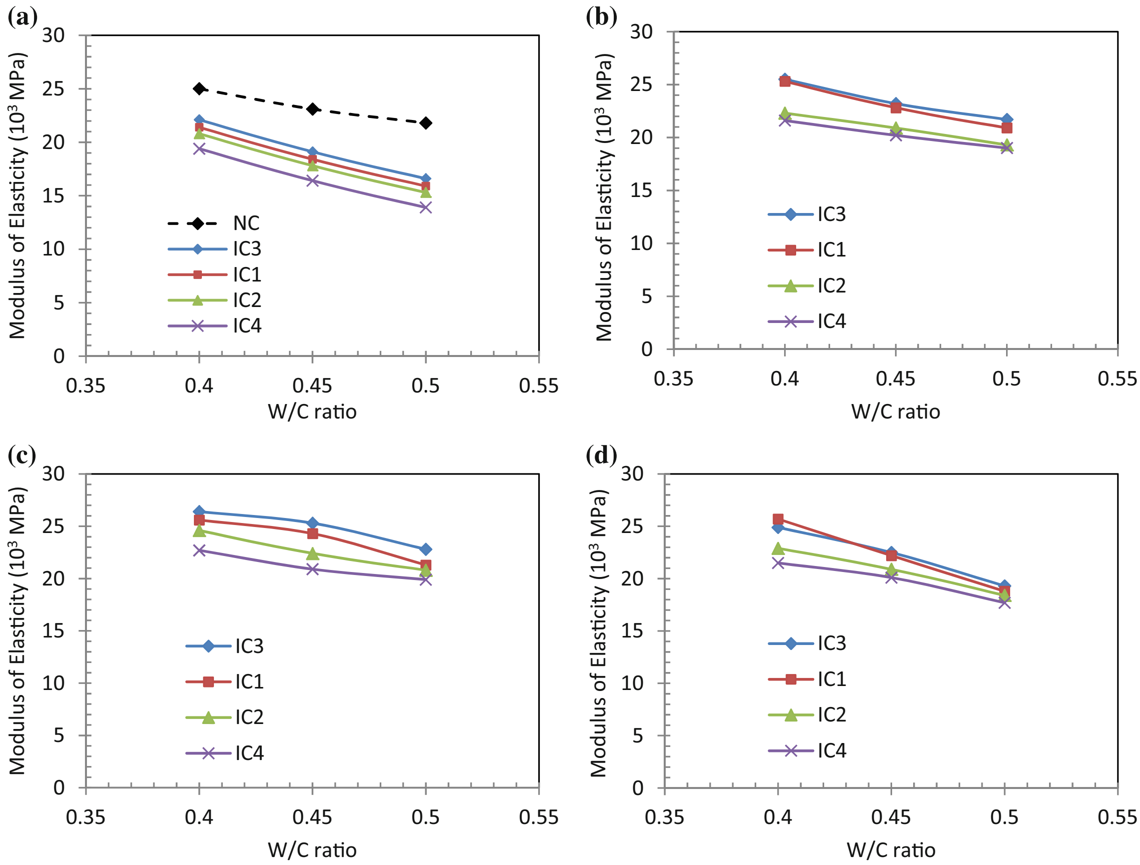

Fig. 7 Effect of w/c ratio on modulus of elasticity of samples **a** control samples with 0% replacement **b** IC samples with 10% replacement **c** IC samples with 20% replacement **d** IC samples with 30% replacement.

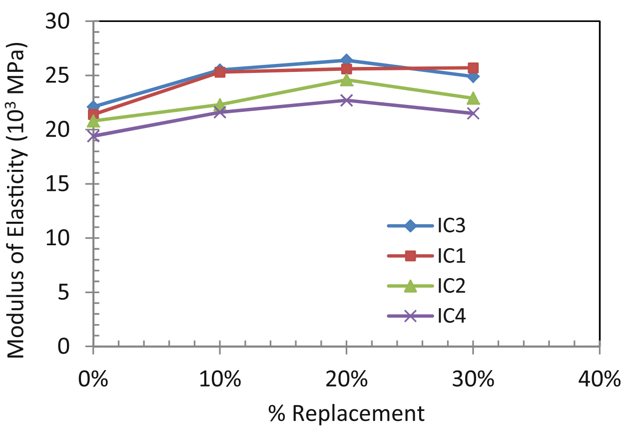

Fig. 8 Effect of percent replacement on modulus of elasticity of control and internally cured samples with w/c ratio of 0.4 under similar curing conditions.

least performing internally cured samples (30% partial replacement and under IC4 condition) had about 11% higher modulus of elasticity than IC4-control samples. Samples with 20% replacement under IC4 exhibited 17% higher elasticity value as compared to IC4-control samples. Similarly, 10% replacement also achieved relative high modulus of elasticity. Table 4 shows increases in modulus of elasticity for internally cured sampled as compared to control samples under similar curing conditions.

3.2 Chloride Permeability Test

The RCPT test results of control and internally cured samples for 0.4 w/c ratio are shown in Fig. 9. As per ASTM C1202 (2012), samples allowing less than 4000 C charge to pass through are termed as "moderate chloride permeable", and more than 4000 C to pass through as "high chloride

Table 4 Percent increase in modulus of elasticity with respect to control samples under similar curing conditions (w/c ratio 0.4).

Percent replacement	Curing conditions			
	IC1	IC2	IC3	IC4
10	18	7.5	15	11
20	19.5	18.5	19.5	17
30	20	10	12.5	11

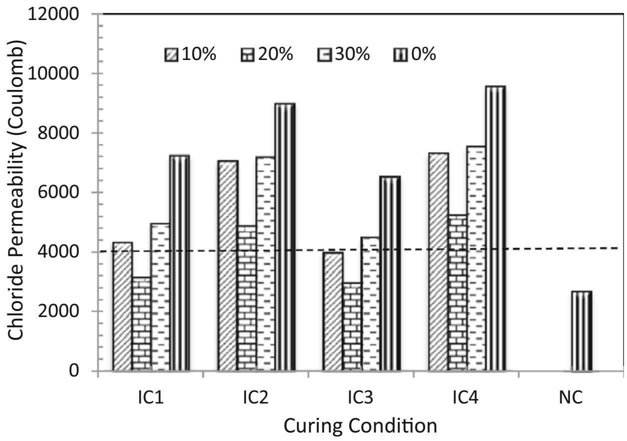

Fig. 9 Chloride permeability of samples for different curing conditions and different percent replacement at a constant w/c ratio of 0.4.

permeable". In Fig. 9, the bar corresponding to NC represents RCPT test results of control samples (samples with 100% stone chips) under NC condition. These samples (NC-control samples) experienced the least coulomb charge passed through them and fall into moderate chloride permeability region. Only internally cured samples with 20% replacement under IC1 and IC3 conditions showed permeability values comparable to NC-control samples. All control samples under simulated four curing conditions showed significantly high chloride permeability. In addition, all samples without polythene cover, both control and internally cured, experienced considerably high chloride permeability. It is, therefore, obvious that absence of proper external curing mechanism severely affect the durability performance of concrete. However, 20% replacement of stone chips with MCA showed potential to resolve such problem if proper covering can be ensured. The chloride permeability of these samples (under IC3 condition and having 20% replacement) was almost one-third of the chloride permeability of the control samples under IC3 condition. Similar to previous observations in strength and elasticity tests, control samples under IC4 condition showed the worst permeability performance as compared to all samples considered in this study. Thus, internal curing showed significant better performance in permeability tests in comparison with control samples when subjected to curing condition without supply of external water.

Although all partial replacement under IC3 condition showed higher compressive strength at lower w/c ratio, only 20% replacement exhibited comparable chloride permeability performance with respect to control samples. Such improvement in permeability can only be explained by better hydration of cement that produced denser concrete. It is obvious that better hydration was the result of internal curing ensured by MCA since addition of MCA was the only difference between the control and internally cured samples. It is also evident from the observed results that 20% replacement can be considered as the tentative optimum proportion of MCA to produce internally cured concrete. This amount of replacement appears to be resulted in better hydration of cement by providing required amount of internal water. Moreover, porosity of this amount of MCA had insignificant effect on permeability of concrete.

4. Results and Discussion, Phase 2

In order to reach more conclusive outcome, narrower bands of partial replacement (15, 20 and 25%) were used in the 2nd phase of the study. The w/c ratio was kept constant at 0.4 for all samples. Compressive strength and splitting tensile strength tests were performed. Moreover, only exposed conditions (IC3 and IC4) were considered in this phase, since such conditions mostly prevail in actual construction sites of the country. However, four additional curing conditions were investigated with samples having 3 and 7 days of proper external curing before exposed to outside conditions. The details of these additional curing conditions are listed in Table 2. The internal Relative Humidity (RH) of both control and internally cured samples were also studied in this phase for different partial replacements.

4.1 Internal Relative Humidity (RH)

Relative Humidity readings inside the hollow sections of cubes were taken at each day using hygrometer with digital sensor. Experimental setup for internal RH test is shown in Fig. 10. It is observed that RH of internally cured specimens was greater than RH of control samples for all replacement levels. The RH data of control samples and internally cured samples are plotted in Fig. 11 with respect to time. It is observed that maximum RH was obtained from samples with 25% replacement levels and the minimum RH was found from control samples with no replacement. It is, therefore, obvious that MCA as internal curing agent within concrete supplies additional water that eventually increases the internal RH within the concrete matrix.

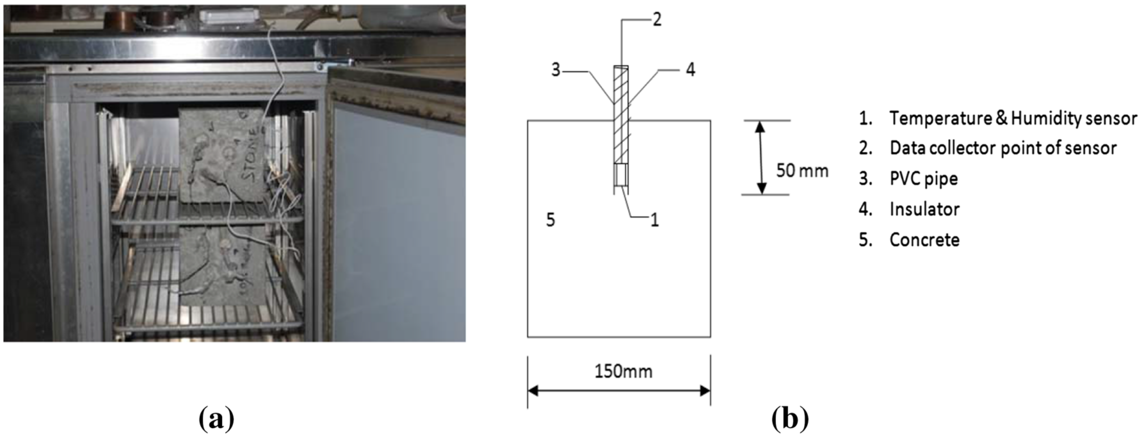

Fig. 10 Internal RH measurement **a** experimental diagram **b** schematic diagram.

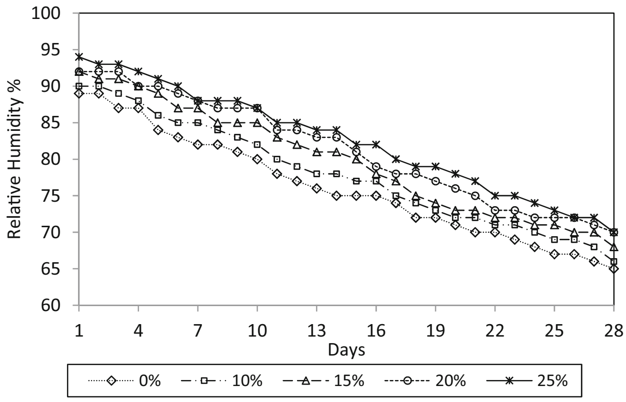

Fig. 11 Internal RH data of control samples and internally cured samples with respect to days.

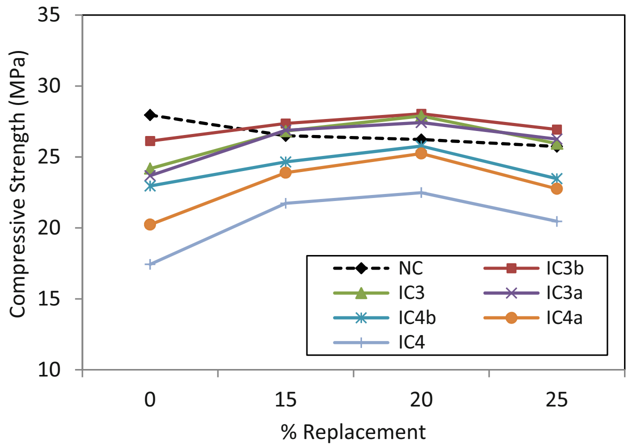

Fig. 12 Effect of percent replacement on compressive strength (Phase II).

4.2 Compressive Strength

Variations in compressive strengths with replacements of 15, 20 and 25% are shown in Fig. 12. It is again evident that the maximum compressive strength was achieved by the samples having 20% replacement for all curing conditions considered in phase II. Control samples under NC exhibited the highest strength which is expected. In the phase I, 20% replacement produced slightly higher compressive strength under IC3 condition than that of NC control samples. Such increment could be due to sample variation. However, it is apparent from outcomes of both phases that 20% replacement under covering could produce compressive strength comparable to that of control samples under NC. Further studies with more sample size would provide statistically significant difference between NC control samples and internally cured samples with 20% replacement under IC3. Covered samples exhibited higher compressive strength than samples without covering, when kept under similar curing conditions. Samples subjected to external curing for seven days and then kept outside under covering (IC3b) produced the maximum compressive strength. In fact, internally cured samples with 20% replacement under proper covering achieved almost similar compressive strength of control samples under normal curing. Control samples without any external curing and placed outside without cover (IC4) exhibited lowest compressive strength. However, under IC4 condition, internally cured samples with 20% replacement showed about 29% higher compressive strength than control samples. For both IC4a and IC4b conditions, 20% replacement resulted in about 12% and 25% higher compressive strength as compared to control samples, respectively.

4.3 Splitting Tensile Strength Test Results

The splitting tensile strengths of control and internally cured samples are shown in Fig. 13. Similar trend of compressive strength test results is observed for splitting tensile strengths . For all curing conditions except NC, internally cured samples with 20% replacement exhibited higher tensile strength than that of control samples (Fig. 13). Covered samples with 20% replacement produced comparable tensile strength of control samples under NC. When samples were kept without covering at exposed condition, significantly higher tensile strength was observed for 20% replacement as compared to control samples.

It is obvious from the above discussion that internally cured concrete performed better as compared to control samples when subjected to curing conditions without the supply of external water. The only difference between control samples and internally cured samples was the presence of saturated MCA. Therefore, the reason behind such improved performance was the additional water supplied by saturated MCA. The RH data of control and internally cured

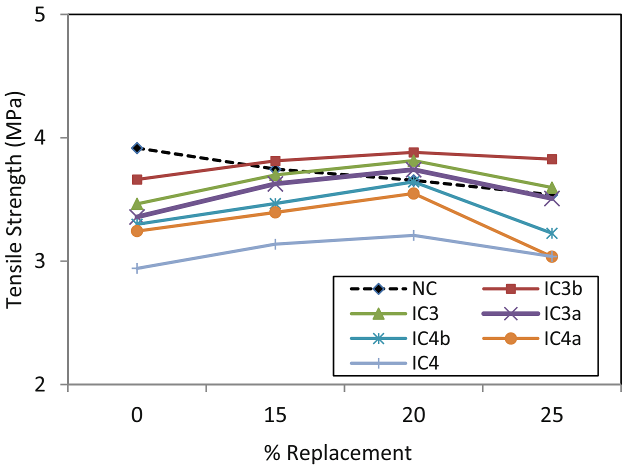

Fig. 13 Effect of percent replacement on splitting tensile strength (Phase II).

samples (Fig. 11) also reinforces this inference. Moreover, the internal temperature and RH of concrete also facilitate desorption of MCA since desorption rate of MCA increases with increase in temperature and decrease in RH. The additional water provided by desorption of MCA ensured proper hydration and eventually, resulted in concrete with better mechanical properties.

5. Economics of Internal Curing

Internal curing using MCA and polythene sheet covering is also a less costly method to implement. Both MCA and polythene sheets are cheap and readily available in Bangladesh. Typical price of MCA is $3.5 USD per cubic meter and price of polythene is $1.0 USD per square meter. Also, polythene covering can be re-used. So, production of this kind of internal cured concrete can be a promising solution to improve the quality of general concreting works of developing countries like Bangladesh.

6. Conclusions

The following conclusions may be made based on the findings from the current study:

- MCA has required desorption capacity to be considered as an effective internal curing medium. It is observed that desorption capacity of MCA depends on temperature and relative humidity. Higher temperature (in the range of 30–34 °C) and lower relative humidity (in the range of 60–73%) conditions are favorable to desorption by MCA. However, it is also found that considerable amount of water can be desorbed by MCA even at higher relative humidity of 85% or more.
- It is apparent from sample internal RH that internal curing ensures additional water within concrete. At all ages, internally cured samples experienced relatively high internal RH than control samples.
- Strength and durability of internally cured samples having MCA as internal curing medium and polythene sheet covering are significantly higher than those of control samples with conventional stone chips as coarse aggregate in the absence of proper external curing. The best performance was observed when 20% stone chips was replaced by MCA, which produced comparable compressive strength, elastic modulus and tensile strength as obtained by normally cured control specimens.
- It is evident from past experience that proper external curing is not practiced in number of general construction sites in Bangladesh which may result in poor performance. Field conditions in several construction sites, particularly in outskirts of major cities, are similar to IC4 condition considered in the study. In such cases, internal curing can produce about 30% or more increase in compressive strength at 28 days. Moreover, about 30% and 10% increase in modulus of elasticity and tensile strength, respectively, can be achieved through internal curing, as found from this study.
- Durability performance of MCA concrete is a concern because MCA as coarse aggregate increases the permeability due to its porous structure. Consequently, most of the internally cured samples showed higher permeability. However, moderate chloride permeability was achieved from 20% replacement of stone chips with MCA. This means that such proportion of MCA within concrete desorbs sufficient water to ensure proper hydration which eventually produces better performing concrete without requiring any external water. Proper covering should be employed for ensuring better performance through internal curing mechanism with MCA.
- Internal curing can be recommended in adverse curing conditions, because internally cured samples showed significantly better performance than that of control samples under similar curing conditions without supply of external water.
- Twenty percent partial replacement of stone chips with MCA, 0.4 w/c ratio and utilization of proper covering (preferably polythene) are recommended as optimum combination for producing internally cured concrete.
- Internal curing technique, considered in this study, can be very effective where curing water and skilled labor are not easily available, which is very common in many parts of the world.
- Internal curing using MCA is also a simple and inexpensive method to execute. Therefore, internally cured concrete can be a considered as a promising solution for improving the overall quality of general concreting work of Bangladesh.

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