The effects of internal curing using crushed brick on the structural behaviours of high performance concrete beams

A A Shareef¹, L Sh Rasheed² and A T Jasim³

¹Postgraduate student, University of Kerbela, Iraq, ahmedmadany87@gmail.com
²Asst.prof, University of Kerbela, Iraq, laith.alqarawee@uokerbala.edu.iq
³Asst. Prof, University of Kufa, Iraq, alit.albozwaida@uokufa.edu.iq

Abstract: The durability of concrete is an important factor in assessment of concrete elements that require long service lives, particularly elements used in infrastructure systems such as roads and bridges which have high construction costs. The purpose of this research is to investigate the potential for enhancement of the properties of high performance concrete (HPC) girders in terms of both their structural behaviours and mechanical properties using the internal curing method. In this research, crushed brick was implemented as a partial replacement for fine aggregate as an internal curing material. Three different mixes were made, and each mix was tested in the structural field within reinforced concrete beams (1700*150*100 mm), concrete cubes, and cylinders to examine the mechanical properties of the high performance concrete. The first reference mix had no crushed brick replacement, but the two others were brick mixes with 5 and 10% partial replacement of fine aggregate. Tests were carried out at three different ages (28, 90, and 150 days) to examine the effects of age on the enhancement of properties. A high improvement in ultimate load capacity was recorded at later ages with the 10% brick mix, which increased the load capacity by 18.5% at 90 days. Improvement of the compressive and tensile properties of 12.5% was seen for both mixes, despite the fact that the use of crushed brick decreased the ductility of the beams when compared with the reference mix. In general, the obtained results showed that using crushed bricks as an internal curing material can improve the structural and mechanical properties of high performance concrete and improve its durability by showing enhancement with respect to the age of the piece.

Key words: High performance concrete, Internal curing, Waste materials, Durability

1. Introduction

High performance concrete is well-known for its unique properties, which do not necessarily include high strength. The truly unique properties presented in this type of concrete are low permeability and high durability [1]. A key point in producing HPC is thus minimising the amount of water in the mix, which requires using certain admixtures to minimise the capillaries in the concrete; these include silica fume and fly ash. Water reducing admixtures are also required; however, these admixtures can cause further problems such as improper hydration and premature cracking. To overcome these problems, a modern approach has been shown to improve HPC; this is called internal curing, and it involves implementing the inner moisture of a light weight aggregate (LWA) into the hydration process. This method shows good improvements when used in many infrastructure projects, including concrete bridge parts such as girders and deck slabs [2]. Bridge girders are a major part of the infrastructure and, as with other concrete structures, they deteriorate with time, making it economically necessary to produce structures with durable concrete and fewer cracks that have longer lives. A case study in Oklahoma using HPC, for example, saw significant decreases in the number and severity of cracks compared to conventional concrete after one year [3].
2. Literature review

Using internal curing together with HPC offers great benefits to the structures concerned. One research project showed an increase in bridge deck service life of about 10 years, reducing the life cycle cost of the decks, due to the ability of internal curing to reduce initial cracking in the concrete [4]. Another case study for internal curing showed an increase in service life of an additional 23 years in comparison with conventional curing methods, using analytical predictive models to estimate shrinkage cracking, chloride diffusion, corrosion initiation, and corrosion propagation that would lead to cracking [5].

The most important property to evaluate in concrete is compressive strength, and many researchers have thus studied this in HPC. Research on using pumice materials as LWAs when pre-soaked in water showed that this efficiently reduced the autogenous shrinkage in concrete [6]. Another research approach showed that internally cured concrete using variable amounts of saturated LWAs significantly reduced autogenous shrinkage without affecting the strength or elastic modulus of the concrete [7]. In general, when dealing with HPC, the tensile strength is also important, however, as it is related to the propagation of cracks in the concrete and reduces durability. Some research has investigated the effects of silica fume replacement percentages on the tensile strength of concrete, showing improvement of tensile strength when using silica fumes [8],[9]. The addition of ground granulated blast furnace slag and SiO2 nanoparticles as binders in other research has also shown improved tensile strength [10]. The effect of internal curing on tensile strength has also been discussed, and its application shown to increase tensile strength [11]. Other research has used a variety of LWAs, including shale, clay, and slate to produce internally cured concrete mixes that offer similar or higher compressive strengths when compared to ordinary concrete [12].

Other vital concrete properties are related to the study of the relationship between load and deflections, the stress strain relationship of the concrete structural member, and failure crack patterns. The use of waste materials in improving sustainability by reducing the effect of waste has also been studied. The most common material used involves demolition materials, which are used to produce concrete made of recycled aggregates; this does not act as well as ordinary concrete, but can be reliable in some cases; research studying the structural behaviour of concrete beams made completely of recycled aggregates showed nearly the same behavior as ordinary concrete, with similar crack patterns observed in both aggregate types used in the work, despite the fact that more cracks were present in the beams composed of recycled aggregate [13]. Another research on concrete beam made with recycled materials determined that they behaved similarly to other RC beams made of conventional aggregate materials with respect to load-deflection behaviours, deflections thus compared reasonably well with BS 8110 requirements; however, the average crack widths under service loads were greater than the limit permitted by the code, indicating that such beams may encounter durability problems over time [14]. Another work on beams made entirely of fly ash aggregates showed that these beams show acceptable structural performance according to the ACI [15]. The New York State Department of Transportation (NYSDOT) constructed a series of bridges from 2009 to 2011 using LWA for internal curing; the mix designs for the bridges specified 30% LWA replacement (by volume) and a w/b ratio of 0.4. Using data from the report on these constructions showed that internal curing either had a negligible effect on strength or resulted in higher strength [16].

3. Objective of the research

The aim of this study is to investigate the possible advantages of using a local waste material (crushed brick) as an internal curing agent to improve the structural and mechanical properties of high performance concrete, as well as studying the effect of this material over time by testing it at three ages (28, 90, and 150 days). The present work uses clay brick waste as an internal curing
material due to its high ability to absorb water, which provides additional water for internal curing. The pores inside the grains of crushed bricks act as small internal reservoirs in the concrete mix.

4. Experimental methodology

This part discusses the steps of the experimental programme, including the material preparation, mix design, structural beam design, and experimental tests.

4.1. Materials

- Cement: ordinary Portland cement type I, commercially known as Taslouja, from the local markets was used in the mix design meeting Iraqi standards No. 5/1984 [17].
- Fine aggregates: natural aggregates from the Al-Ekhaider region tested according to Iraqi standards No. 45/ 1985 [18].
- Coarse aggregates: natural aggregates from the Al-Nibae region tested according to Iraqi standards No. 45/1985 [18].
- Crushed brick: crushed brick that has been sieved and graded to match the grading of the sand.
- Silica fume: MegaAdd MS (D) densified microsilica, a by-product of the reduction of high-purity quartz with coal in electric furnaces during the production of silicon and ferrosilicon alloys.
- Superplasticizer: the admixture used was GLENIUM® 51, which has been primarily developed for use with ready-mixed and precast concrete that requires the highest durability, being free from chlorides and complying with ASTM C494 Types A and F.
- Reinforced concrete: the steel bars used as reinforcement were Ukrainian steel (Grade 60) with diameters of 10 and 6 mm for main reinforcement and 6 mm for the stirrups; these conformed to ASTM – A615 specifications. Table (1) illustrates the steel bar test properties.

| Table (1): Reinforcement bars test properties |
|---------------------------------------------|
| Nominal diameter (mm) | Actual diameter (mm) | Cross section area (mm²) | Yield stress (MPa) | Ultimate stress (MPa) | Nominal weight (kg/m) |
|------------------------|----------------------|--------------------------|-------------------|---------------------|----------------------|
| 6                      | 5.6                  | 24.6                     | 520               | 540.4               | 0.195                |
| 10                     | 9.8                  | 75.4                     | 540               | 580                 | 0.616                |

4.2. Mix design

The research examined the effect of internal curing on high performance concrete by testing three different mixes. The first mix was made without crushed brick replacement to act as a reference mix, denoted by (R). This mix was designed according to ACI 211[19]. The two other mixes employed 5% and 10% crushed brick as a partial replacement for the fine aggregate, and these are denoted as BA and BB, respectively.

| Table (2): Mix proportions |
|-----------------------------|
| Sand (Kg) | Gravel (Kg) | Cement (Kg) | Silica fume (Kg) | Admixture. (L/100 Kg) | w/b | Strength at 28 MPa |
| Reference mix | 700 | 950 | 450 | 50 | 1.4 | 0.3 | 55 |
4.3. Structural design and testing

The experimental program was divided into two divisions of tests. The first examined the structural properties of high performance concrete by testing nine reinforced concrete beams of 1700 x 150 x 100 mm, reinforced with longitudinal reinforcement (2Ø10 mm and 3Ø6 mm) and stirrups (Ø6 mm @65 mm) for each beam. Each beam was loaded up to failure to obtain the ultimate load, ductility index, and toughness for each mix. The second division of tests examined the mechanical properties of each mix, including compressive and tensile splitting strength. All tests were done at three ages (28, 90, and 150 days), as shown in Figures (1) and (2).

![Beam test and cross section details](image1)

**Figure (1): Beam test and cross section details**

![Longitudinal reinforcement details](image2)

**Figure (2): Longitudinal reinforcement details**

5. Results and discussion

This section presents the results and data obtained from the structural testing of the concrete beams, including the ultimate loading, toughness, and ductility index. The compressive and splitting tensile strength for each mix was also estimated.

5.1. Structural test results

The structural beam test was intended to load each beam to failure in a four-point load test. The deflection of the mid span and the strain were measured by means of LVDTs gauges. These readings established Load-Deflection diagrams and Stress-Strain curves for each beam to help ascertain the ultimate load (P.ult.), the ultimate deflection (Δ.ult.), the maximum loading capacity, and toughness and ductility for each beam, as shown in tables (3) and (4):
Table (3): Results of deflection and load capacity for the tested beams

| Beam groups         | beam | Age (days) | P.cr KN | Δ. cr. mm | P.ult. KN | Δ.ult. mm |
|---------------------|------|------------|---------|-----------|-----------|-----------|
| 1. Normal mix       | R1   | 28         | 23.8    | 2.09      | 56.2      | 21.77     |
|                     | R2   | 90         | 30.9    | 2.98      | 58.3      | 21.02     |
|                     | R3   | 150        | 36.4    | 1.65      | 62.6      | 18        |
| 2. Crushed Brick (5%) | BA1  | 28         | 28.1    | 2.25      | 50.4      | 15        |
|                     | BA2  | 90         | 15.8    | 2.13      | 52.5      | 19        |
|                     | BA3  | 150        | 21.9    | 2.3       | 64.8      | 14.36     |
| 3. Crushed Brick (10%) | BB1  | 28         | 34.5    | 3.5       | 62.6      | 15.5      |
|                     | BB2  | 90         | 34.9    | 3         | 69.1      | 17        |
|                     | BB3  | 150        | 28.8    | 1.63      | 70.2      | 12.96     |

Table (4): Structural results of tested beams

| Beam groups         | beam | P. Ultimate (KN) | DI  | Toughness (MPa) | Ult. load increase (%) |
|---------------------|------|------------------|-----|-----------------|------------------------|
| 1. Normal mix       | R1   | 56.16            | 3.6 | 0.256           | -                      |
|                     | R2   | 58.32            | 3.3 | 0.311           | -                      |
|                     | R3   | 62.64            | 3.3 | 0.304           | -                      |
| 2. Crushed Brick (5%) | BA1  | 50.4             | 2.5 | 0.201           | -10.2                  |
|                     | BA2  | 52.56            | 2.9 | 0.271           | -9.8                   |
|                     | BA3  | 64.8             | 2.6 | 0.285           | 3.4                    |
| 3. Crushed Brick (10%) | BB1  | 62.64            | 2.8 | 0.263           | 11.5                   |
|                     | BB2  | 69.12            | 2.8 | 0.261           | 18.5                   |
|                     | BB3  | 70.2             | 2.5 | 0.348           | 12                     |

5.1.1. Effect of replacement percentage change
This research made a comparison between the two replacement percentages of crushed brick to begin to determine the optimum mix for highest results when compared to the reference mix. At 28 days, the beams’ ultimate loads were 56.16, 50.4, and 62.64 KN, and the toughnesses were 0.256, 0.201, and 0.263 MPa for beams R1, BA1, and BB, respectively. These results showed an increase in strength for the 10% crushed brick mix, while the 5% mix showed a decrease in strength. Figures (3) to (8) illustrate a more detailed comparison between the mixes.
At 90 days, the mixes showed the following characteristics: ultimate loads of 58.32, 52.56, and 69.12 KN and toughnesses of 0.311, 0.271, and 0.261 MPa for beams R2, BA2, and BB2, respectively. It can be seen that strength increase for the 10% mix was higher at this test age. Similarly, at the age of 150 days, the results were loads of 64.8, 62.64, and 70.2 KN and toughnesses of 0.304, 0.285, and 0.348 MPa for beams R3, BA3, and BB3, respectively. These results indicate that using 10% crushed brick is most effective in terms of improving beam properties.
5.1.2. Effect of age

The tests showed increases in ultimate loading and toughness of the beams over time for both mixes of crushed brick as compared to the reference mix. The mix of 5% crushed brick showed the following results: ultimate loading of 50.4, 52.56, and 64.8 KN and toughness of 0.201, 0.271, and 0.285 MPa at test ages 28, 90, and 150 days, respectively. The percentage increase in ultimate loading was 28.5% at 150 days compared to the 28 days test results. The 10% crushed brick mix showed, ultimate loading of 62.64, 69.12, and 70.2 KN and 0.263, 0.261, and 0.348 MPa toughnesses for test ages 28, 90, and 150 days, respectively. This mix had a percentage of increment in ultimate loading at 150 days equal to a 12% increase over the 28 days test results, while the highest toughness recorded was 0.348 MPa at the 150 days test age. Despite this, the highest DI was shown by the reference beam among the all beams tested, with a value of 3.6. Figures (9) through (12) show full details of the beams comparative results and behaviours.
5.1.3. Crack patterns
All beams failed at flexure. The first cracks were observed from the bottom side of each beam at the middle third of the beam, between loading points; then, the cracks began to get longer and wider as the loading increased. The cracks continued to form in diagonal and perpendicular shapes, reaching to the upper face of the beam. Some beams also showed crushing concrete failure at the tension zone of the cross-section. Figure (13) shows the failure patterns of the beams.

Figure (11): Stress-Strain of 5% brick beams

Figure (12): Stress-Strain of 10% brick beams

Figure (13): Failure patterns of tested concrete beams
5.2. Compressive strength

Compressive strength is considered to be one of the important properties for concrete valuation, and thus each mix was tested at every testing age by testing 27 cubes of dimensions 100 x 100 x 100 mm as per BS 1881[20], shown in Figure (14). The results showed that using crushed brick increased concrete strength at ages 90 and 150 days specifically. Table (5) and Figure (15) show that the mixes of 5% brick showed results of -0.6, 5.9, and 7.0 % while 10% brick mixes results were 2.4, 9.1, and 12.5% at testing ages 28, 90, and 150 days, respectively. It is clear from the results that using a 10% replacement ratio offer better results than the 5% ratio, especially at 150 days, where the 10% mix attained a 12.5% increase in compressive strength. This may be attributable to the maximum advantage of internal curing in terms of the enhancement of cement hydration at this later age.

![Figure (14): Mechanical properties testing machine](image1)

**Table (5): Compressive strength results**

| Mix         | 28 days MPa | Increase% | 90 days MPa | Increase% | 150 days MPa | Increase% |
|-------------|-------------|-----------|-------------|-----------|--------------|-----------|
| Ordinary    | 55.8        | 0.0       | 58.0        | 3.9       | 59.0         | 5.7       |
| 5% brick    | 55.5        | -0.6      | 59.1        | 5.9       | 59.7         | 7.0       |
| 10% brick   | 57.2        | 2.4       | 60.9        | 9.1       | 62.8         | 12.5      |

![Figure (15): Compressive strength results comparison](image2)
5.3. Splitting tensile strength

Splitting tensile strength was determined by testing 27 concrete cylinders of 100 mm diameter and 200 mm height according to ASTM C-496 [21]. The test results of all the testing ages are listed in Table (6) and shown in Figure (16). At 28 days, both the 5% and 10% mixes showed decreases of strength by -6.35% and - 8.2%, respectively, but these gained strengths at later ages, with the maximum increase for the 5% mix being at 150 days, with an increase in splitting tensile strength of 17.1%.

Table (6): Tensile strength results

| mix          | 28 days MPa | Increase % | 90 days MPa | Increase % | 150 days MPa | Increase % |
|--------------|-------------|------------|-------------|------------|--------------|------------|
| reference    | 4.70        | 0          | 5           | 6.5        | 5.2          | 10.7       |
| 5% brick     | 4.40        | -6.35      | 5.1         | 8.9        | 5.5          | 17.1       |
| 10% brick    | 4.31        | -8.2       | 5.2         | 11.4       | 5.3          | 12.5       |

Figure (16): Splitting tensile strength results comparison

6. Conclusions

- Using crushed brick as an internal curing material enhanced the overall structural and mechanical properties of high performance concrete, especially at later ages.
- Using 10% crushed brick replacement increased the ultimate loading by 18.5% at the age of 90 days.
- The effect of internal curing on the ultimate loading of beams with age differed depending on the percentage of crushed brick replacement ratio: the 5% mix showed a 28% increase at 150 days, while the 10% mix showed an increase of 12% at the same age as compared with their 28 days values.
- The use of internal curing materials decreased the ductility of the beams when compared to the reference concrete beams.
- The toughness of crushed brick beams increased noticeably over the reference mix; the 10% mix acquired the highest toughness, 0.384 MPa, at 150 days.
- The compressive strength of the mixes was improved by internal curing; for the 10% brick mix, the compressive strength was 62.8 MPa, a 12.5% increase.
- Using 5% crushed brick increased the splitting tensile strength by 17.1% at 150 days.
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