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INTERNAL CURING OF HIGH PERFORMANCE CONCRETE USING LIGHTWEIGHT AND RECYCLED CONCRETE AGGREGATES

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ABSTRACT

Concrete curing is of paramount importance in order for concrete to meet performance requirements. Conventionally, curing has been conducted by means of water sparkling, wet burlap or a curing compound. For performance and environmental reasons, internal curing has been gaining increased attention. However, more data is needed for the effectiveness of this curing technique when used in various concrete mixtures.

This investigation addresses potential utilization of internal curing in high performance concrete (HPC). Internal curing was introduced by means of three aggregates: perlite, pumice and recycled aggregates; all of which were incorporated into HPC mixtures. Conventional mixtures were prepared and were thoroughly cured either by water or by a curing compound or left non-cured. Fresh concrete and Hardened concrete properties were assessed including slump, unit weight, compressive and flexural strength, and durability tests such as shrinkage assessment, rapid chloride permeability test (RCPT) and abrasion resistance. Experimental work is backed up with a simplified feasibility analysis with case study, incorporating initial and future costs to better judge potential of this technique.

The outcome of this study uncovers that the addition of pre-wetted lightweight aggregates can prompt an enhancement in concrete workability and durability accompanied by a reduced shrinkage. Compressive and flexural strengths decreased with the increased replacement dosages, however several dosages were tested to reach a figure of optimum replacement. Results of this study reveal the potential of this technology in saving fresh water as well as the costs saved in maintenance and rehabilitation works

Keywords: Internal, Curing, High Performance, Concrete, Perlite, Recycled

1. INTRODUCTION

After placing and finishing of concrete, maintaining adequate moisture and temperature is of paramount importance; this happens through a process referred to as Curing. Concrete curing aids the chemical reaction between cement and water called hydration (Kovler et. al, 2007). The American concrete Institute (ACI) defines curing as the process by which hydraulic-cement concrete matures and develops hardened properties as a result of continued hydration of the cement in the presence of adequate water and heat (ACI 308R). Hence, an incomplete hydration process will affect both the strength and durability of produced concrete. Curing has a strong influence on hardened concrete; adequate curing will aid achieving desired durability, strength, water tightness, abrasion resistance, volume stability, and resistance to freezing and thawing and deicers (ACI 308R). Water loss, during or after concrete finishing (i.e. evaporation), may delay or prevent sufficient hydration. Proper curing should retain water or compensate water loss in the concrete to allow for a full hydration process. This will allow for strength development of concrete. Figure 1 shows the effect of different curing periods on strength gain; it improves quickly at early ages, and then continues slowly for an indefinite period.

There is an additional aspect of curing, which is sometimes overlooked. Curing is carried out not only to promote hydration, but also to minimize shrinkage (Kovler et. al, 2007). Water loss will cause the concrete to shrink introducing tensile stresses that may cause surface cracking. In High performance concrete (HPC); concrete with high cement content and low w/c ratio, a major concern is self-desiccation, which is internal drying of concrete due to the consumption of water by hydration (Neville 1996; Parrot 1986; Patel et al. 1988, Spears 1983). Self desiccation results in hindered strength development, reduced durability and potential for autogenous shrinkage and cracking (Schlitter, 2010). If no sufficient water is provided, the paste can self-desiccate preventing concrete from achieving targeted properties. Appropriate mitigation methods to reduce shrinkage in combination with careful curing practices should be used to minimize and control shrinkage (Huo and Wong 2000).

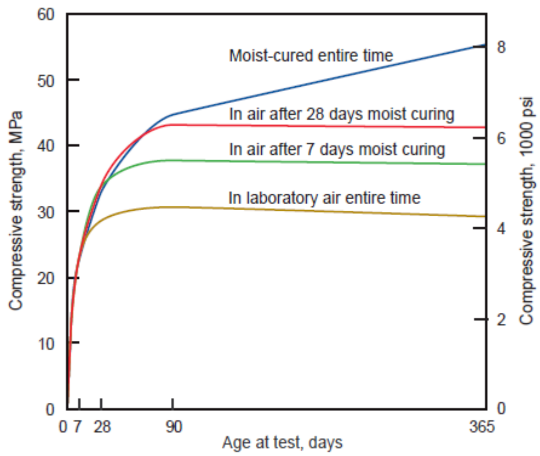

Figure 1: Effect of curing time on strength gain of concrete (Gonnerman & Shuman 1928)

There are various techniques for curing; external & Internal Curing. Most of the traditional methods are based on external curing. Generally, external curing can be grouped as follows (Aitcin 1998):

- Water Adding Curing – by supplying additional moisture to prevent/compensate water loss. This is achieved by water ponding, water spraying/sparkling, or by water coverings such as wet burlap.
- Sealed curing – by preventing the loss of moisture. This is achieved by Waterproof paper, plastic sheeting, and membrane forming compounds (also known as curing compounds)

Internal curing is another concept of curing concrete, which is basically incorporation of a component that serves as curing agent to the concrete mix. As defined by ACI as the process by which the hydration of cement continues because of the availability of internal water that is not part of the mixing water (ACI 213-03R). Internal curing can be classified as follows:

- Internal Water Curing – embedded component is a water reservoir that gradually releases water into the system. The most popular methods are pre-wetted light weight aggregates and super absorbent polymers (SAP).
- Internal Sealing – component is meant to delay or prevent water loss from the system by adding special types of chemicals to mixing water (Kovler et. al, 2007)

Internal curing proved to be promising in producing concrete with increased resistance to early-age cracking and enhanced durability (Bentz et. al, 2010). This is due to the enhanced curing reach inside the concrete section as illustrated in Figure 2, conventional external curing provides curing mainly to outer concrete surface whereas in internal curing, water is simultaneously distributed inside of concrete and hence provide more uniform and extended curing of concrete (Abou-Zeid, 2015)

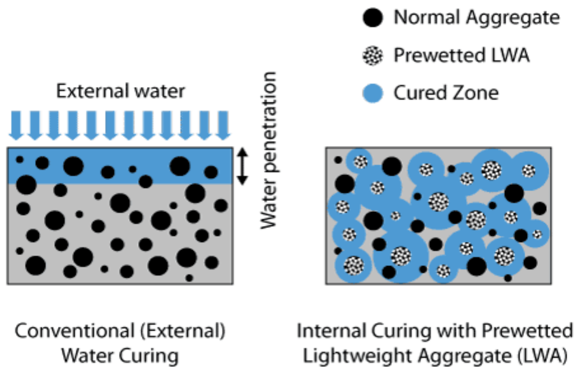

Figure 2: Illustration of the difference between external & internal curing (Wiess, 2012)

2. RESEARCH MOTIVATION

The main objectives of this study are to examine the potential use of pre-wetted/saturated lightweight and recycled concrete aggregates as reservoirs to provide internal curing for high performance concrete (HPC)

This study is of crucial importance particularly in countries of economical rise up. The need for infrastructure will increase the need for high productivity and high performing structures without compromising durability or feasibility. In addition to many countries scarcity of water resources, makes it very important to use resources wisely. Two main aspects have the major contribution behind this research: (1) The need for durable structures for strategic projects, and (2) Feasibility and Environmental aspects that should be carefully studied and adapted.

3. EXPERIMENTAL WORK

3.1 Materials

Ordinary Portland cement (ASTM C 150 Type I) was used. The cement was produced by Lafarge cement Egypt in Ain Sokhna plant. The cement had a specific gravity of 3.15 and a Blaine fineness of 313 m2/kg. The Bogue compounds of the cement were as follows: C3S = 61.07%, C2S = 14.99%, C3A = 2.06% and C4AF = 15.03%. Siliceous sand was used in all concrete mixtures. Fine aggregates were obtained from natural Wadi Sand, Bani Youssef. The sand had a fineness modulus of 2.547, a saturated surface dry specific gravity of 2.64 and a percent absorption of 0.52%. The conventional coarse aggregates used was a crushed dolomite aggregate. Coarse aggregates were obtained from OCI Crusher, Attakah. The dolomite had a maximum nominal size of 20 mm, a saturated surface dry specific gravity of 2.57 and a percent absorption of 1.98%. Concrete chunks resulting from the demolition of concrete which had an original strength 25-30 MPa was used. Recycled concrete aggregates were obtained from crushed concrete from demolishing works of science building in AUC’s old campus, Tahrir square. The crushed material had a maximum size of 38 mm, a saturated surface dry specific gravity of 2.36 and absorption of 5.3%. Perlite was obtained from The Egyptian Company for Manufacturing Perlite plant, located in industrial district of Burj Al Arab city, Alexandria. Perlite had a specific gravity of only 0.32, and absorption of 32% Pumice was obtained from Laval minning and quarrying company, Greece. Its pumice quarry is located in Yali, Nissiros, a natural pumice deposit located in northern Greece. Pumice had a specific gravity of 1.1, and absorption of 18%. The admixture used was a common ASTM C494 Type G admixture, its commercial name is BASF MasterRheobuild 2270. The product is a modified lignosulfonate based with an approximate solid content of 39% and a specific gravity of 1.21. Curing compound used was BASF MasterKure 181, with specific gravity of 0.82.

The fourteem concrete mixtures had w/c of 0.35, a Type “G” admixture, and cement content of 450 kg/m^3. First set is conventional concrete mixes; which was cured in three different ways: Full curing by submerging specimens in curing tanks, the use of a curing compound and with no curing. Second set constitutes 3 mixes of prewetted recycled concrete aggregates with dosages of 10%, 15% and 25%. Recycled aggregates replaced size 1 and size 2 aggregates because of similar size to obtain similar gradation. Perlite specimens come with 5 different dosages of prewetted pelite aggregates, 3%,7%,10%,15% and 25%. Perlite aggregates replaced crushed sand because of similar size to obtain similar gradation. The remaining 3 mixes contain prewetted pumice aggregates with concentrations of 10%, 15% and 25%. Pumice lightweight aggregates replaced size 1 and size 2 aggregates because of similar size to obtain similar gradation.

3.2 Specimens

Concrete specimens for each one of the 14 mixes. Each mix had the following specimens:

- Standard cubes complying with BS 1881 (150 x 150 x 150 mm) for testing 7,28 and 56 days
- Standard ASTM C 78 flexural strength beams (150 x 150 x 75 mm) for testing 28 and 56 days.
- Standard ASTM C 39 for preparing concrete cylinders (150 x 300 mm), for Rapid Chloride Permeability Test (RCPT) in 28 and 56 days.
- Standard tiles (200 x 200 x 25mm) for testing Abrasion resistance throughout age of specimen.
- Standard ASTM C157/C157M prisms of 100-mm square cross-section and approximately 285 mm long for testing shrinkage.

4. RESULTS & DISCUSSION

4.1 Slump Test

The results of slump test illustrated in figure 3. As can be seen in figure 3, the slump ranges from 130 to 250 mm. The highest values were obtained from the samples with lightweight aggregates replacements, especially perlite. Slump values are highest for perlite mixtures, followed by pumice then recycled aggregates. The lowest slump values were those of the concrete made with conventional aggregates. Slump values increased with higher replacements of saturated aggregates. The higher slump values of the pre wetted aggregate mixtures can be attributed to the desorption property of those types of aggregates, or their ability to lose their internal water. This water was released from the aggregates during mixing causing an increase in the flow ability of the concrete mixture.

Desorption shows to be lower for recycled aggregates and pumice compared to the perlite mixtures, thus yielding slightly lower slump values. Results also reveal that conventional concrete had the lowest slump of 130 mm. This is due to the absence of additional water in the aggregate, since the conventional aggregates were SSD state. Slump test results reveal an important advantage of using pre-wetted aggregates, which is enhanced workability that shall ease concrete handling and finishing.

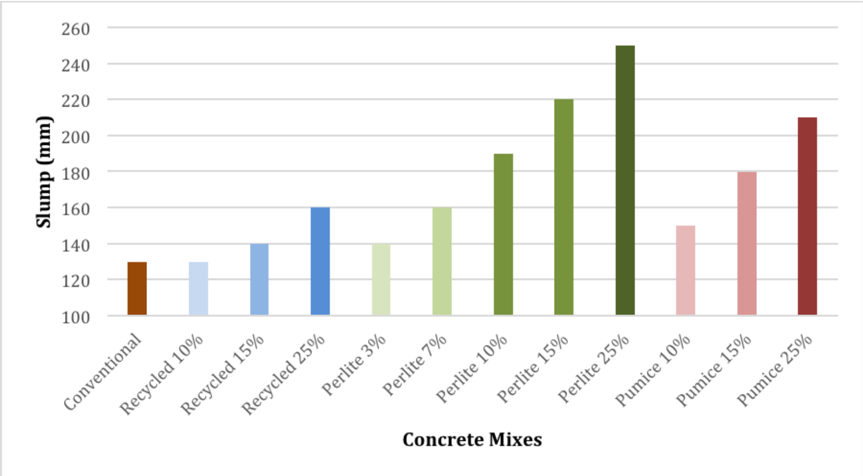

Figure 3: Slump test Results

4.2 Air Content

Results of Air content test are illustrated in figure 4. As can be seen in figure 4, the air content percentage ranges between 2 to 3.3%. The highest values were obtained for mixtures with pre-wetted lightweight and recycled aggregates, pumice, recycled and perlite mixtures, respectively. Generally, Air content increased with the elevated replacements. The lowest air content results were those of the conventional mixtures.

The increase in air content for mixtures with aggregates replacements can be attributed to the porosity of those types of aggregates. Lightweight and recycled aggregates are by nature mire porous than dolomite aggregates used in conventional concrete mixtures. This increased the entrapped air in the concrete mixture. Among the saturated aggregates mixtures, perlite mixtures appeared to be the least. This can be explained mainly because perlite replaced crushed sand, which occupies the least volume compared to the coarse aggregates. Also, from visual inspection, Pumice appears to be the most porous, which is reflected on the results. Generally, Air content results reveal that mixtures with replacements of lightweight and recycled aggregates yield slightly higher air content.

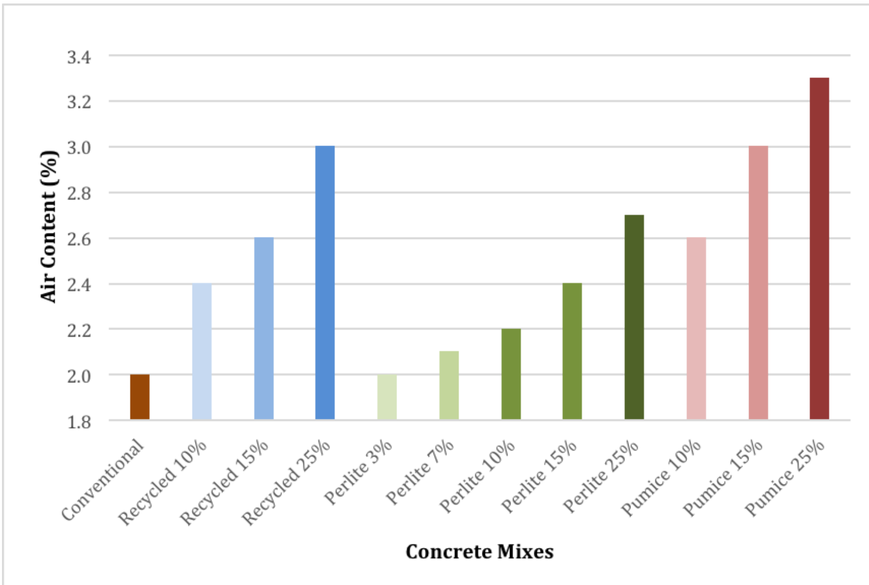

Figure 4: Air Content test results

4.3 Unit Weight

The results of unit weight test are illustrated in figure 5. As can be seen in figure 5, unit weight results range from 2248 to 23444 kg/m3. The highest value was obtained for concrete mixtures made with conventional dolomite aggregates. Unit weight values were slightly decreased for mixtures with aggregate replacements of recycled, perlite, and pumice, respectively. Also, unit weight dropped with increased replacement percentage of pre wetted lightweight and recycled aggregates. This behavior can be attributed to the increased porosity and decreased unit weight of the replacement aggregates compared to the dolomite aggregates used in conventional mixtures. Within the replacement aggregates mixtures, unit weight decreased for aggregates with lower unit weight. However, it is worth noting that the decrease in unit weight for replacing aggregates mixtures was slight compared to conventional dolomite aggregate mixtures. This happened mainly because the replacing aggregates were saturated with water, which makes such aggregates closer in density to those conventional aggregates. Generally, replacing conventional aggregates with recycled or lightweight aggregates led to slight drop in unit weight in the concrete mixture.

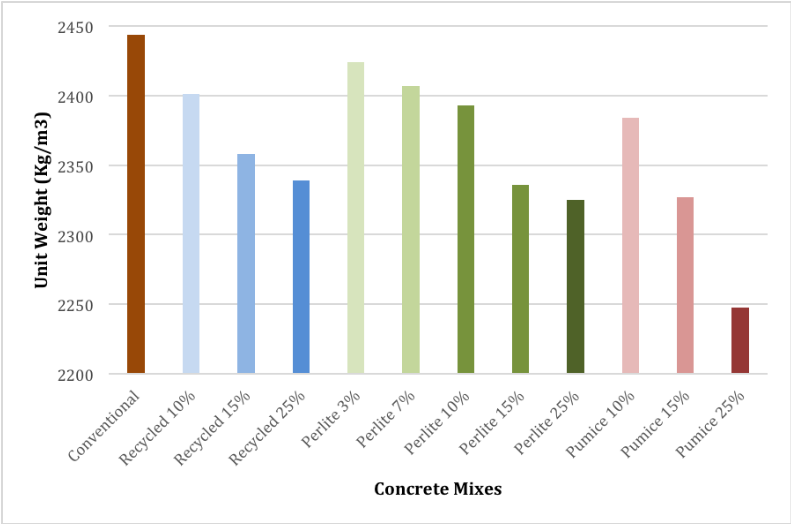

Figure 5: Unit weight test results

4.4 Compressive Strength

Results of the compressive strength test are illustrated in figure 6. As can be seen in figure 6, the 56-day compressive strength results range from 48.2 to 66.5 MPa. The highest value was obtained for the standard concrete mixture made with conventional dolomite aggregates namely full curing followed by curing compound and no curing modes. The high values of compressive strength can be attributed to the strength of the conventional dolomite aggregates compared to the replacement aggregates. Curing mode and its effect on the strength can be clearly outlined, a drop in strength is found between fully and non-cured samples. This can be explained through the incomplete hydration process in non-cured samples compared to curing compound or full curing samples.

As for the pre wetted lightweight and recycled aggregates results, as can be seen in figure 6, perlite showed the highest results followed by recycled then pumice aggregates mixtures. This is mainly due to the fact that both recycled and pumice replaces coarse aggregates size one and two contrasting to perlite, which replaces crushed sand. Coarse aggregates are the main load carrier and hence the replacement directly affected the strength. It is worth noting that 10% replacement with perlite aggregates surpassed the no curing sample of conventional concrete. This is primarily explained by the enhanced hydration process through the internal moisture supplied by water stored inside the perlite aggregates. Perlite is also considered to be better dispersed through the concrete section compared to the pumice and recycled aggregates due to its finer grain size. Generally, results show that compressive strength is mainly affected by the strength of the replacing aggregates and the replacing aggregate type (coarse or crushed sand). Dispersion is also an important factor that affect internal curing performance of the aggregates, the finer the aggregate the better dispersion and scatter through the concrete section. The 10% aggregate replacement with perlite lightweight aggregate showed to be promising after surpassing the non-cured sample after 56 days.

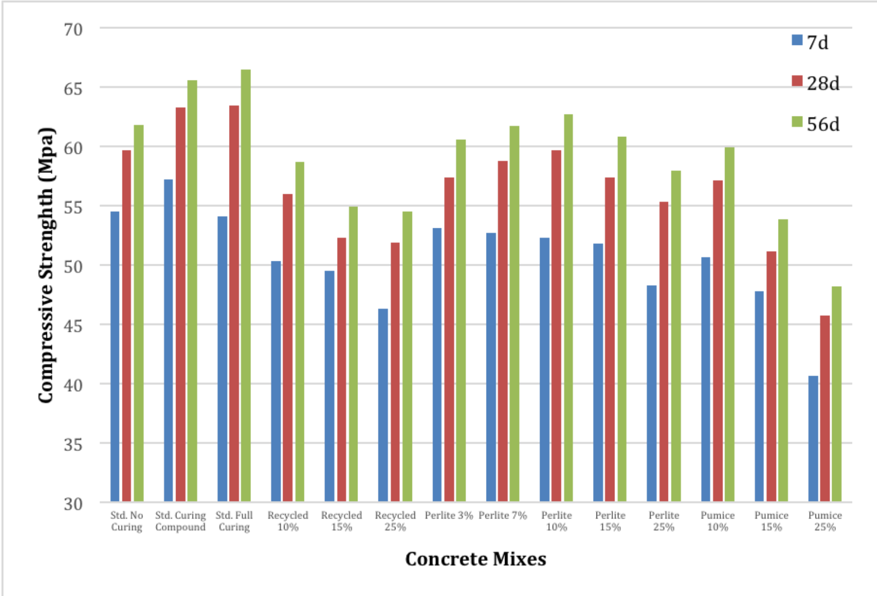

Figure 6: Compressive strength results

4.5 Flexural Strength

The results of the flexural strength test are illustrated in figure 7. As can be seen in figure 7, flexural strength results range from 4.6 to 8.0 MPa. The highest value was that of the 15% recycled aggregates. This can be attributed to the Interfacial Transition Zone (ITZ) between aggregate surface and concrete paste. The ITZ has enhanced the properties internally, which means less tendency of aggregate pop out, thereby higher flexural strength. Also, Recycled aggregates have a angular texture, causing better interlocking of aggregates with the paste. It is worth noting that flexural strength dropped for the increased replacement percentage, mainly because of the excessive replacement of dolomite aggregate which has higher strength compared to other replacing aggregates.

These outcomes have fairly comparable patterns to the patterns of the compressive strength as in increasing the percentage of perlite or recycled aggregates leads to some decrease in flexural strength. Contrastingly, a large portion of the mixtures made with perlite or recycled aggregates recorded a flexural strength that is higher than the conventional concrete mixtures. This highlights the internal curing impact of the perlite and recycled aggregates in minimizing cracking.. With respect to conventional mixtures, the impact of curing was more proclaimed than the compressive strength mixtures. Generally, the consolidation of perlite prompted a reduction in flexural strength while the replacements of recycled aggregates prompted flexural strength that is comparative or surpassing ordinary mixtures. The outcomes in this propose the flexural strength test has a superiority to distinguish the impact of internal curing than compressive strength.

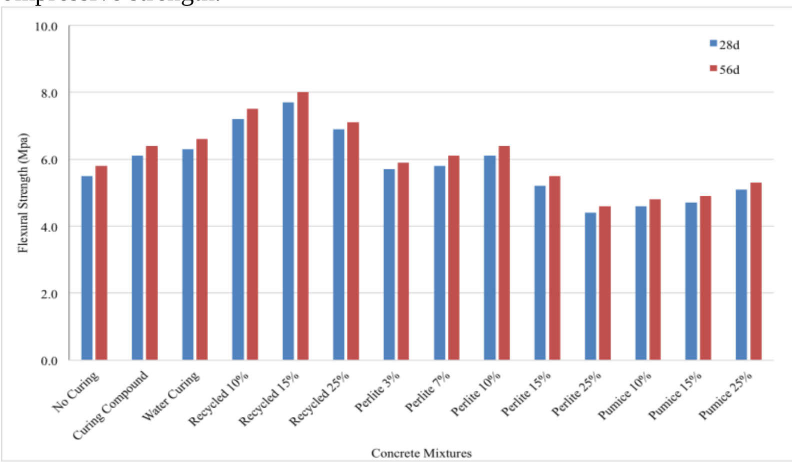

Figure 7: Flexural Strength Test Results

4.6 Shrinkage Assessment Test

The Results of shrinkage assessment test are illustrated in Figure 8. As can be seen in figure 8, the shrinkage values range from 1.57 to 3.69 (x0.01) mm. The highest values were obtained for cases of conventional concrete, particularly the non-cured specimens. This can be attributed to the poor hydration performance of the non-cured specimens. To the contrary, the internally cured mixtures showed decreased shrinkage; the mixtures with 25% recycled aggregates, with shrinkage of 0.0162 mm, had almost half of value of the conventional concrete shrinkage of 0.0369 mm. At the start, one can see that the vast majority of the shrinkage occurred until 28 days and less increment in shrinkage was seen in the interim somewhere around 28 and 56 days. All internal curing mixtures of perlite, pumice and the recycled aggregates had critical impact in decreasing shrinkage. Such reduction in shrinkage qualities was higher after increasing the perlite, pumice and reused aggregates dosages. The recycled aggregates and pumice, in any case, demonstrated the most reduced shrinkage of all mixtures notwithstanding when contrasted with perlite blend.

Shrinkage assessment test highlights the significance of internal curing. The internally cured concrete mixtures had the lowest shrinkage values and lowest shrinkage development through the 56 days. This is clearly due to the enhanced hydration process. The internal moist stored inside the concrete section helped in better commencement of strength and durability development of the mixture and lowered or eliminated self desiccation. Decreased shrinkage of internally cured concrete reveals the potential of this technology, especially in concretes with special functions that require minimizes shrinkage and accordingly, cracking.

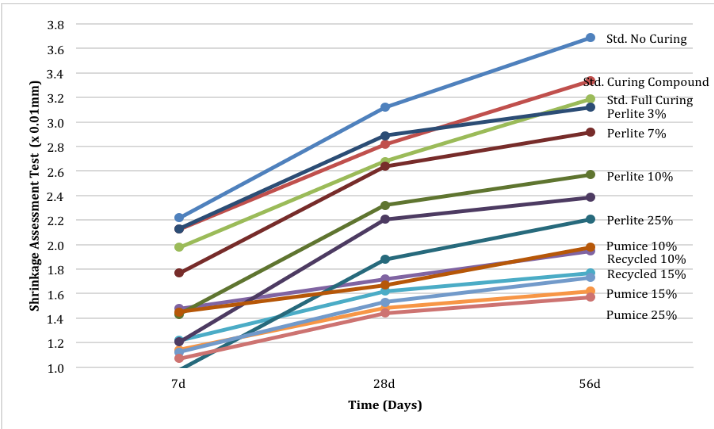

Figure 8: Shrinkage test results

4.7 Rapid Chloride Permeability Test (RCPT)

The results of RCPT are illustrated in figure 9. As can be seen in figure 9, the passing charges ranged from 1202 to 2598 coulombs. The case of lowest passing charges was that of concrete made with conventional dolomite aggregates, full curing followed by curing compound. This can be mainly because of the higher transport inside the porous replacing aggregates. The porous nature of lightweight and recycled aggregates made it easier for charges to pass through the section. However, results of RCPT strongly assures on the importance of curing. All cured specimens, whether internally or externally cured have shown decreasing penetrability through the 28 and 56 days testing, primarily reasoned through the enhanced hydration thus lowered cracking. Only the no curing specimen showed an increased penetrability as it passed 1588 charges in 56 days increasing by 24 units than the 28 days results. Conventional mixtures' passing charges, on average, decreased by 29 charges from 28 to 56 days. Perlite mixtures had the most decreased passing charges with 63 less passing charges from 56 to 28 days. Pumice showed the worst performance, this could be explained because of the high porosity of this kind of aggregate. It is concluded that curing, interlocking (voids percentage), and aggregate porosity are the main factors that affect the penetrability of the concrete section.

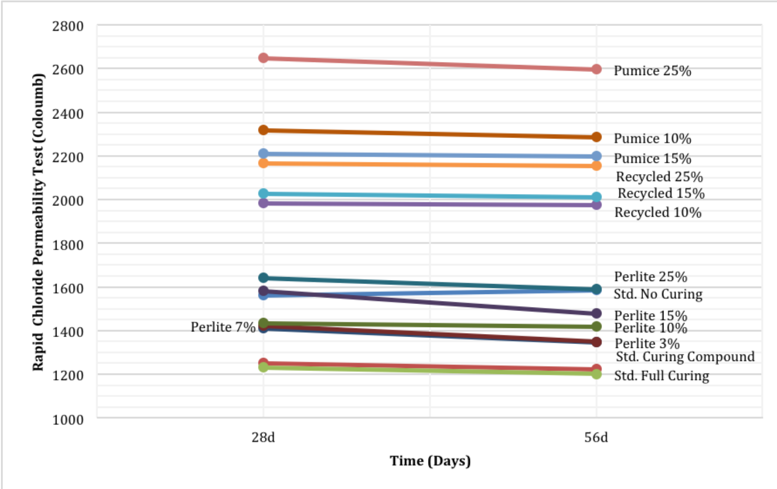

Figure 9: Rapid Chloride Permeability Test results

4.8 Abrasion Test

The Results of Abrasion Test are illustrated in Figure 10. As can be seen in figure 10, the Abrasion values range from 1.3 to 3.44 mm of lost thickness. Conventional concrete specimens have demonstrated the best abrasion performance as it lost only 1.6 mm on average that is the least amount, followed by perlite specimens with 2.36 mm, then recycled concrete specimens with 2.83mm. Pumice was at the worst at abrasion resistance, averaging almost 3mm of lost thickness. This behavior is explained through the abrasion resistance of the aggregates themselves. Dispersion plays an important role here. Perlite demonstrated similar behavior to the conventional specimens because of the well dispersion of perlite throughout the section, in contrast with both the Recycled concrete aggregates and the pumice specimens. Aging may also be a reason for the poor abrasion performance of specimens with recycled concrete aggregates. This recycled concrete dates back to the 60's, which is the time of construction of the famous AUC science building. Generally, abrasion was slightly affected with aggregates replacements, specifically the coarser replacements.

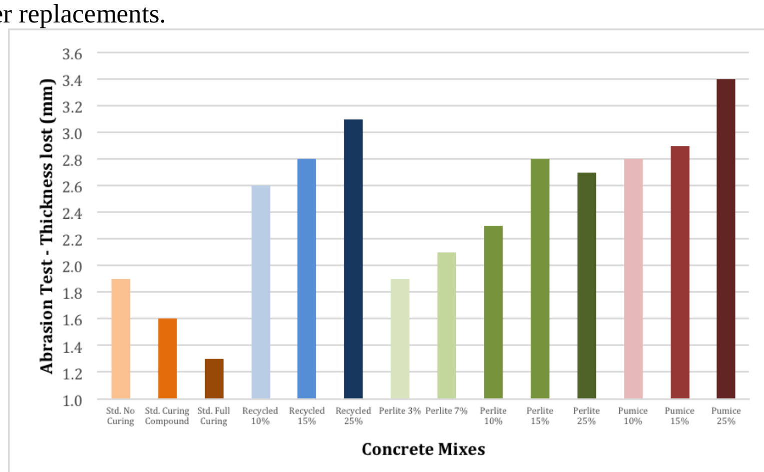

Figure 10: Abrasion test results

5. FEASIBILITY ANALYSIS

Results of this section are not built upon the testing, rather are estimated from different study by Cusson to demonstrate the monetary merits of this technology. The unit cost of HPC was evaluated to be 13% higher than that of ordinary C-40 concrete basically because of the increased amount of cement in the mix. The unit cost of HPCIC was set to that of HPC in addition to a 35% expansion to represent the cost contrast connected with the procurement and transportation of the lightweight aggregate used to substitute a small amount of the ordinary aggregates.

For this situation consider, an arrangement of different maintenance exercises were expected to occur over the life cycles. For normal concrete (NC) for example, destructive (NDT) assessment and protection exercises were planned to happen at regular intervals, while patch repairs were scheduled when 10% and 25% of the concrete surface would be spalled. In this study, replacement was esteemed vital when half of the concrete surface would be spalled. After replacement, it was expected that the concrete would be reconstructed with a similar initial construction cost considering inflation rate. Concrete thickness was assumed at 200mm to represent figures in m^2.

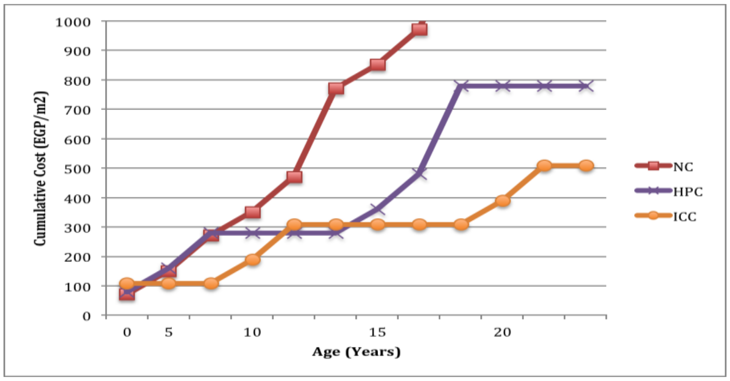

Figure 11: Cumulative Costs of different concrete mixes over time in years

It's obvious that the ICC has less frequent check, protection, maintenance and replacement times than the HPC and NC respectively. Costs of maintenance activities were estimated from average market prices. Over a 60-year examination period, the cumulative costs for the normal concrete deck is the most noteworthy, which is basically because of the shorter service life and the more incessant maintenance and replacement exercises. The HPC deck (no internal curing) diminished this cost by 35%, predominantly because of the more extended service life. The ICC deck further lessened the cumulative costs to be 31% less costly than the NC deck, or 11% less costly than the HPC deck because of the utilization of internal curing.

6. CONCLUSIONS AND RECOMMENDATIONS

In the light of scope, types and dosages of materials investigated as well as other experimental parameters and variability associated with this work, the following key conclusions can be warranted:

1. The concrete mixtures incorporating saturated lightweight and recycled concrete aggregates demonstrate increase in slump values and air content percentage and slight decrease in unit weight compared to conventional mixes
2. Compressive strength of internally cured concrete was lower than conventional concrete made with conventional aggregates. The drop in strength was higher as the lightweight and recycled concrete aggregates doses increased.
3. Internally cured concrete yielded similar strength development from 7-28 days compared to conventional concrete. However, the 28-56 days strength development is significant for internally cured concrete. Due to enhanced hydration process that maintained relative humidity levels in concrete.
4. Flexural strength results have fairly comparable patterns to those of compressive strength as increased doses yield lower strength. Recycled aggregates concrete promoted flexural strength that is comparative or surpassing conventional mixes.
5. Internally cured concrete mixtures had critical impact in decreasing shrinkage and shrinkage cracking. Such reduction was higher after increasing the replacement doses of lightweight and recycled concrete aggregates.
6. Internally cured concrete yielded slightly decreased permeability performance compared to conventional concrete. However, Internally cured mixtures yielded significantly better improvement from 56-28 days.
7. Abrasion resistance of internally cured concrete is similar to that of conventional concrete. This was the case for mixtures made with lightweight and recycled concrete aggregates.
8. With water scarcity in Egypt and elsewhere, internally cured concrete will contribute to efforts exerted in minimizing water consumption.

9. A simple Life-Cycle Cost Analysis reveals that internally cured concrete saves almost 42% of cost throughout its service life. The higher initial investment of internally cured concrete can be counterbalanced in just 5 years because of the lower maintenance costs associated.

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