INCORPORATION OF LIGHTWEIGHT AND RECYCELD AGGREGATES FOR CONCRETE CURING

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Abstract: Adequate curing of concrete is a fundamental step in concrete manufacturing to meet performance and durability requirements. Internal curing is an emerging technique that can provide water to concrete for extended durations towards thorough hydration of the cement and reduced cracking. This work addresses potential use of two types of aggregates for internal curing. Perlite light weight aggregates as well as recycled concrete aggregates were incorporated at three dosages each to replace the coarse aggregates.

Conventional concrete mixtures were prepared as fully cured by water, cured by a curing compound and with no curing. Fresh concrete and hardened concrete properties were evaluated including slump, unit weight, compressive and flexural strength as well as shrinkage. The results reveal that the incorporation of pre-wetted/saturated lightweight aggregates can lead to a significant enhancement in concrete workability and durability through reduced shrinkage.

Keywords: internal curing; shrinkage; lightweight aggregate; cracking

1 INTRODUCTION

Curing is of paramount importance for concrete to attain its targeted properties and performance both on the short and long terms. In conventional concrete production, this is commonly achieved by supplying moisture or by the use of a curing compound post the placement stage. Internal curing is a relatively new technique and is defined by The American Concrete Institute (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). In other words, internal curing can be described as supplying excess water throughout reservoirs of pre-wetted lightweight aggregates that readily release water needed for hydration or to replace moisture lost by evaporation or self-desiccation (Bentz et al., 2005).

Since the 1950's, internal curing had been unintentionally performed in lightweight concrete structures before its ability in curing was explored and acknowledged in the 1990's (Jensen, Roberts et. Cusson, 2007). Pre-wetted lightweight aggregate may be substituted for normal weight aggregates to provide "internal curing" in concrete having a high volume of cementitious materials. As well known, lightweight aggregates were originally used to decrease the weight of concrete structures and will doing that, aggregates were typically saturated before mixing to provide adequate workability. As a result, such lightweight concrete were found to exhibit enhanced durability and better long term properties. Time dependent improvement in the quality of concrete containing pre-wetted lightweight aggregates is greater than with normal weight aggregates. The reason is better hydration of the cementitious materials provided by moisture available from the slowly released reservoir of absorbed water within the pores of the lightweight aggregate.

Internal curing has a potential to enhance hydration and strength development, to reduce permeability and enhance durability through reducing autogenous shrinkage, reducing ingress of chloride ions, delaying the rate of steel corrosion, reducing tensile stresses thus improving construction robustness (Weiss, 2011, Cusson et. al, 2006 and Bentz et al., 2005). Internal curing by saturated lightweight aggregates can delay or prevent shrinkage cracking (Henkensiefken et. al, 2009). It was reported that a sufficient volume of saturated lightweight aggregates can reduce plastic shrinkage cracking, in both sealed and unsealed curing conditions, and water absorption, which could result in a more durable concrete (Henkensiefken et. al, 2009). According to Browning et al. (2011), the addition of the lightweight aggregate increases the amount of internal curing water when compared to conventional concrete. Notably, the strength and elastic modulus is not significantly reduced by adding saturated lightweight aggregates up to 20% (Cusson and Hoogeveen, 2006).

Nowadays, there exist two main techniques for internal curing of concrete. The first technique utilizes super-absorbent polymers, as these particles can absorb a vast quantity of water during concrete mixing and create large inclusions containing water, therefore reducing self-desiccation during cement hydration. The second technique is concerned with utilizing saturated absorbent lightweight aggregates in order to provide internal supply of water that substitutes the water consumed by the chemical shrinkage during cement hydration. This water is drawn during cement hydration from the relatively larger pores of the lightweight aggregate into the naturally smaller cement paste pores. For internal curing to be effective, the curing agent should have high water absorption capability and high water desorption rates. Based on work conducted by Cusson and Hoogeveen, saturated lightweight aggregates in the form of sand with a concentration of 20% can provide sufficient internal curing water to eliminate autogenous shrinkage. This allows for maintaining the tensile stress/strength ratio under 50%. They also suggested an optimum dosage of saturated lightweight aggregates to be around 25%. This was enough to eliminate tensile stresses resulting from the simultaneous effects of thermal, autogenous and creep strains (Cusson and Hoogeveen, 2006).

High cementitious concretes are vulnerable to self-desiccation and early-age cracking, and benefit significantly from the slowly released internal moisture. Blending lightweight aggregate containing absorbed water is significantly helpful for concretes made with low water-to-cementitious ratio or concretes containing high volumes of supplementary cementitious materials that are sensitive to curing procedures. This process is often referred to as water entrainment (Bentz et al., 2005). Internal curing is advantageous in low w/c concrete due to the shrinkage that is associated with Portland cement hydration and the low permeability of the calcium-silicate hydrates. When the w/c is lower than the normal-performance concrete mix, a marked self-desiccation may take place, leading to autogenous shrinkage (Cusson, 2006). To avoid this risk of early ages cracking in high-performance concrete, it is essential to minimize the internal relative humidity from decreasing during the cement hydration process. Using pre-wetted lightweight aggregates as internal tanks to supply water as the concrete dries, has been recommended for concretes where the expansion reaction is extremely susceptible to the presence of and accessibility to water.

As illustrated in Figure 1, 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. Internal curing was also found to be a technique that economical and environmental-friendly (Weiss 2011). Water saving is of prime global concern. While external curing consumes relatively large amount of water, internal curing consumes only a specific amount of water which is used once to saturate the lightweight aggregates. Another important environmental angle is the possible use of recycled materials as internal curing aggregates. When widely applied, this alleviates the demand for quarrying virgin aggregates which in turn contributes to decreased energy, pollution as well as the incorporation of waste materials and minimize the use of landfills.

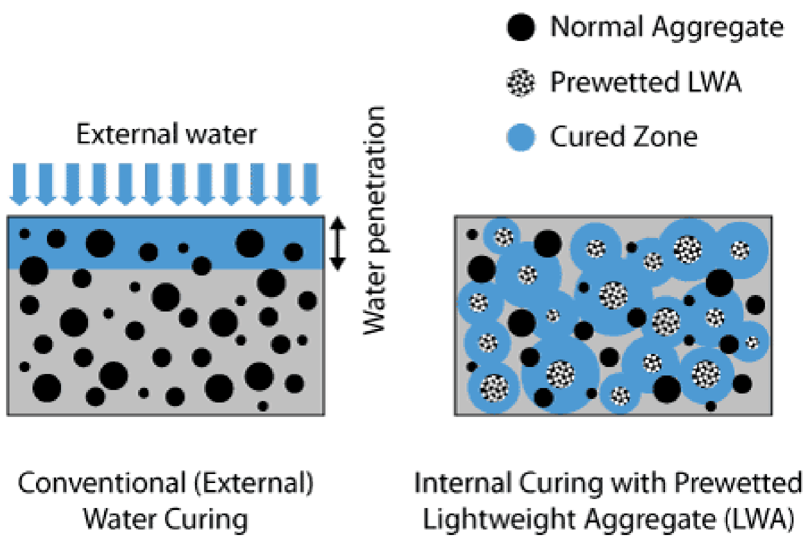

Figure 1: Internal Curing Versus External Curing

(Adopted from http://www.structuremag.org/Archives/2012-1/C-ConstrIssues-Weiss-Jan12)

2 RESEARCH SIGNIFICANCE

The main objectives of this study are to examine the potential use of pre-wetted/saturated lightweight aggregates as reservoirs to provide internal curing. Fresh and hardened concrete properties were evaluated. Adequate internal curing contributes to an enhanced concrete performance, less cracking and offers multiple environmental merits.

3 EXPERIMENTAL WORK

3.1 Materials

Cement type I normal Portland cement was used with a specific gravity of 3.14 and a specific surface area (Blaine fineness) of 375 m^2/kg. Typical Bogue compounds of the cement were as follows: C_3S = 53.7 percent, C_2S = 27.6 percent, C_3A = 6.1 percent and C_4AF = 10.1 percent. The alkali content (as Na_2O equivalent) was 0.45 mass percent. For the fine aggregates, natural siliceous river sand with a fineness modulus of 2.88, a saturated surface-dry specific gravity of 2.51 and absorption of 0.50 percent. For the coarse aggregate, crushed dolomite was used with a maximum size of 38 mm, a saturated surface dry specific gravity of 2.64 and absorption of 1.6 percent. Typical municipal tap water was used in all concrete works. A parrafin wax curing compound with specific gravity of 0.95 was used by coating concrete specimens upon concrete setting.

Pre-wetted/saturated perlite -lightweight aggregate- was used for internal curing by replacement of coarse aggregates at dosages of 3%, 5% and 7%. This lightweight material had a specific gravity of 0.9 and absorption of 28%. Also, recycled concrete was used for internal concrete curing at repalcemnet dosages of 10%, 15% and 20%. The recycled aggregate had a specific gravity of 2.24 and an absorption of 9.2%. The two previously mentioned mixes containing lightweight aggregates will be compared to a conventional concrete mix which was cured in three different ways: Full curing by frequenst waters plashing, the use of a curing compound and with no curing.

3.2 Specimens

The seven concrete mixtures had w/c of 0.4, a Type “X” superplasticizer, cement content of 450 kg/m^3, and air content of 2%. Concrete slump, air content and the fresh unit weight were conducted in accordance with ASTM standards C 143, C 231 and C 138, respectively. Cube sets of three cubes (150 mm) were prepared for compressive strength testing at 7, 28 and 56-day using a 2000 kN capacity testing machine. Beams of 150 x 150 x 750 mm in sets of two were prepared for 28, and 56-day flexural testing with a clear span of 600 mm during testing according to ASTM C 78. Shrinkage prisms of 100 x 100 x 280 mm were prepared in compliance with the ASTM C 157 to evaluate length change in increments after 3, 7, 14, 28 days towards the calculation of accumulated shrinkage.

Specimens were placed in a "hot weather simulation chamber” that was constructed for the purpose of this study. This intention was to expose the specimens continually to a steady hot environment of 60°C (140 °F) and to possibly accelerate the progression of shrinkage and manifestation of strains of the specimens under observation. The chamber had insulated sides and floorings using extruded polystyrene layer (XPS). Heating was provided by electric heaters. Sensors and safety measures were in place during the entire scheme of experimental program.

4 RESULT AND DISCUSSION

4.1 Slump Test

The sump test results are shown in Table 1 and illustrated in Figure 2. These results show that conventional concrete had the lowest slump of 15 mm. It has to be noted that the three fresh conventional concrete results included in the Table 1 and Figure 2 are in fact one value for one conventional mix since the full curing pattern does not appear at the fresh concrete stage. On the other hand, pre wetted perlite aggregates yielded the highest slump which ranged from 110 to 170 mm. The slump values increased as the Perlite replacement dosage increased. For example, the 3% perlite replacement mix had a slump of 110 mm while the conjugate mix made with 7% perlite replacement had a slump of 170 mm. The recycled concrete acted as an intermediary between the pre-wetted perlite and the conventional mixtures, with values towards the lower side. These results can be explained in light of the water absorption of the perlite and the recycled aggregates which is higher than the absorption of the conventional aggregates. Upon concrete mixing, some of the internal water within the aggregates is released; thus contributing to an increase in slump values. This can also explain the relatively lower results for the recycled aggregates compared to the perlite since the recycled aggregates had lower absorption than the perlite aggregates. Also, the recycled aggregates had somewhat rougher and more irregular surface than the perlite aggregates used. In summary, the slump test results demonstrate benefits incurred from adding saturated lightweight and recycled aggregates into the concrete mix in terms of higher slump values that reflect, on the whole, better workability.

Table 1: Fresh concrete test results

	Perlite			Recycled			Conventional Concrete
	3%	5%	7%	10%	15%	20%	
Slump (mm)	110	140	170	25	35	45	15
Unit Weight (kg/m^3)	2418	2411	2406	2444	2437	2428	2454
Percent Air Content	2.0	2.1	2.3	2.3	2.5	2.5	1.7

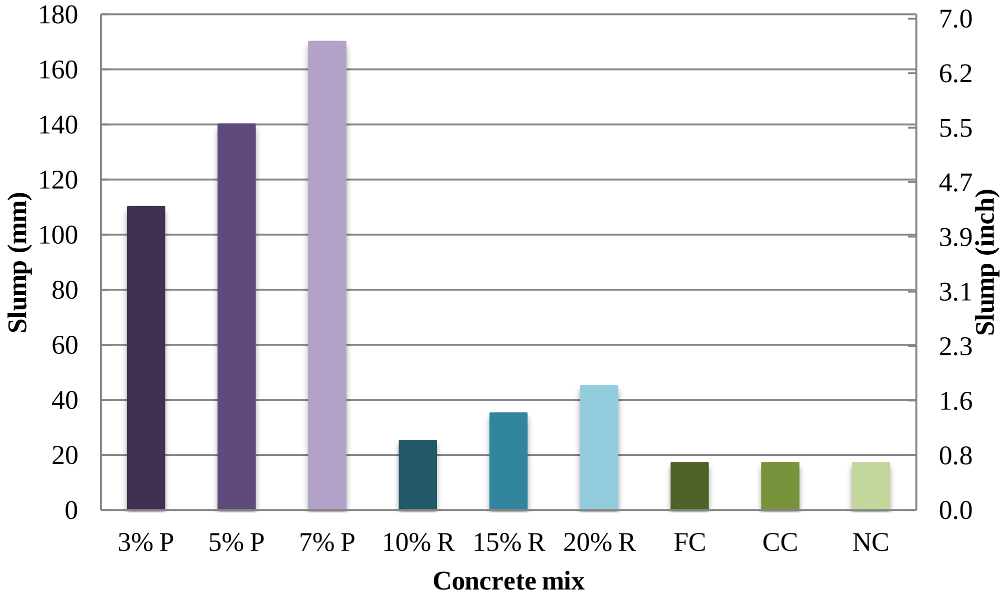

Figure 2: Slump results for the concrete mixtures

4.2 Air Content

The air content results are listed in Table 1 and illustrated in Figure 3 with values in the range of 1.7 to 2.5%. While air content values for all mixtures did not vary significantly, yet, al mixtures made with perlite or recycled aggregates had somewhat higher air content values. This can be due to the relatively rough surface of these aggregate compared to the conventional concrete. Such surfaces can entrap some air together with already-existing air voids within the perlite and recycled concrete aggregate particles. In summary, it can be concluded that the incorporation of pre-wetted perlite and recycled aggregates led to a slight increase in the air content values.

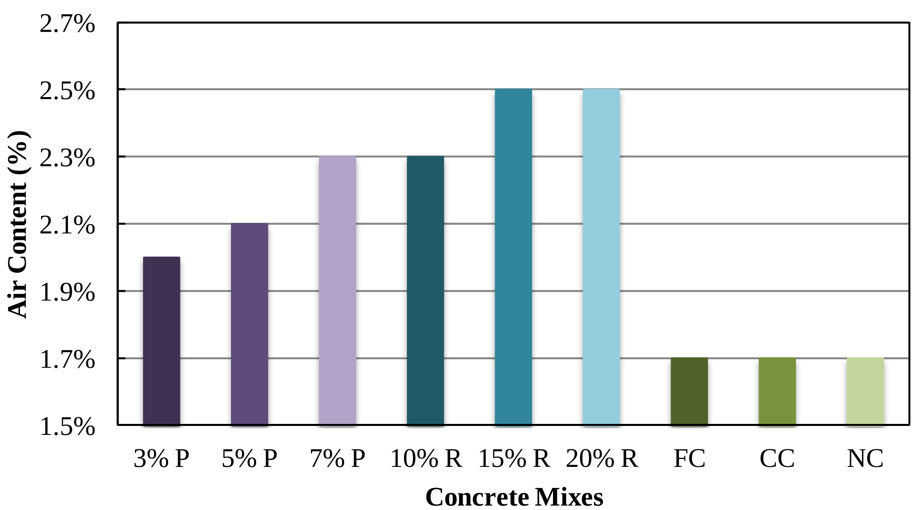

Figure 3: Air content results for the concrete mixtures

4.3 Unit Weight

The results of fresh concrete unit weight are shown in Table 1 and are illustrated in Figure 4. While the results are somewhat close in values, there is a slight decrease in the unit weight upon incorporation of perlite and recycled aggregates. The decrease in unit weight seems to be proportional to the increase in perlite and recycled aggregate dosages. It has to be noted that the decrease is slight since both the perlite and recycled aggregate were saturated with water which makes such aggregates closer in its density to conventional aggregates. In summary, the incorporation of the perlite and recycled aggregates at the dosages associated with this work led to a slight decrease in the unit weight.

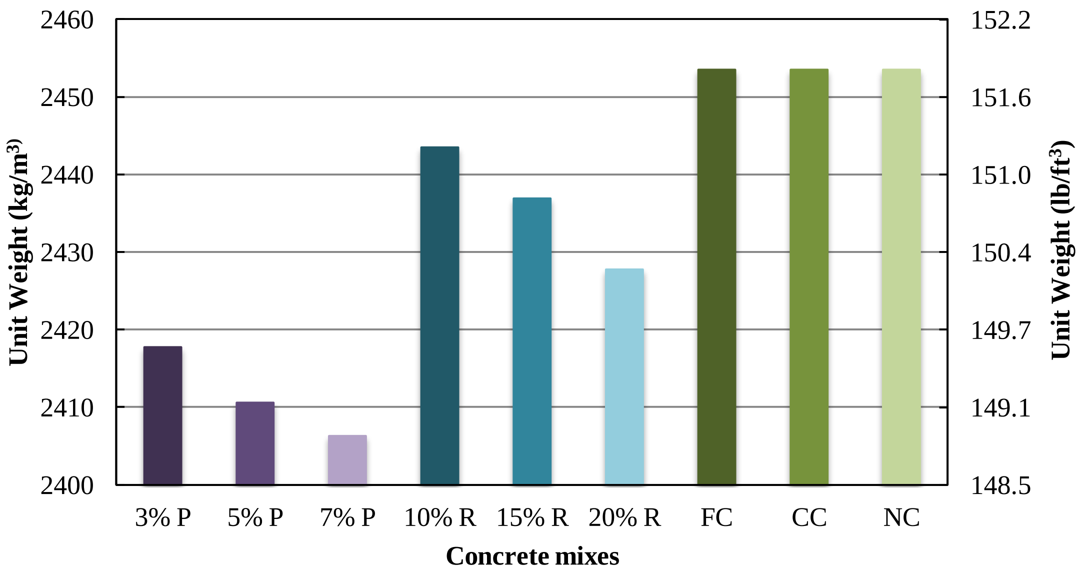

Figure 4: Unit weight results for the concrete mixtures

4.4 Compressive Strength

The 7, 28 and 56-day compressive strength results are listed in Table 2 and are illustrated in Figure 5. Based on these results, the following observations can be made. First, the conventional concrete mixtures made entirely with conventional aggregates had higher compressive strength than mixtures made with perlite or recycled aggregates. This was the case after 7, 28 and 56 days. The effect of curing of conventional mixtures was not witnessed in the compressive strength results where small cracks are likely to be closed than opened under compressive stresses. Also, it is well established that dry concrete cubes yield slightly higher compressive results than wet concrete cubes. It is also the case, on the whole, the increase in perlite and recycles dosage resulted in further decrease in compressive strength. This can be well explained by the fact that incorporation of weaker aggregates, such as perlite or recycled aggregates, contributes to some strength reduction compared to the stronger dolomite aggregates. It is of interest to note that there is a strength gap between the perlite mixtures and conventional mixtures, mixtures made with recycled aggregates had a strength that is similar to conventional concrete. Taking variations into consideration, it remains to be noted that -on absolute strength terms- compressive strength surpassing 50 MPa can be attained through incorporation of perlite and strength surpassing 60 MPa can be attained through incorporation of recycled aggregates. This shows that the incorporation of such aggregates should not a barrier against reaching good compressive strength values.

Table 2: Compressive strength test results

Time (days)	Compressive Strength in MPa								
	Perlite			Recycled			Conventional		
	3%	5%	7%	10%	15%	20%	FC	CC	NC
7	43.1	40.6	38.3	58.2	47.6	41.8	56.8	46.9	55.5
28	52.9	43.5	43.5	63.5	55.5	46.7	64.5	62.0	63.6
56	53.9	47.0	44.8	65.4	55.9	55.1	66.6	65.0	69.5

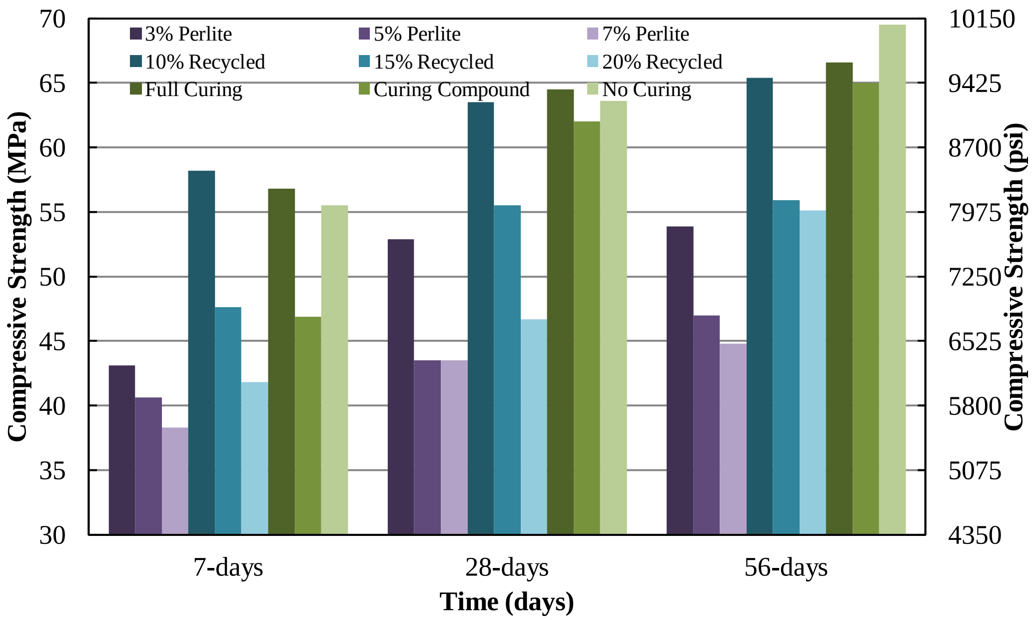

Figure 5: Compressive strength results for the concrete mixtures

4.5 Flexural Strength

The results of flexural strength are shown in Table 3 and illustrated in Figure 6 after 28 and 56 days. These results have somewhat similar trends to the trends of the compressive strength in the sense that increasing the dosage of perlite or recycled aggregates contributes to some decrease in flexural strength. However, most 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 effect of the perlite and recycled aggregates in minimizing cracking which led to relatively high flexural strength values. It is also to be noted that recycled aggregate mixtures, in particular those made with 15% coarse aggregate replacement, recorded the highest flexural strength in all mixtures. As for conventional mixtures, the effect of curing was more pronounced than the compressive strength mixtures. For example, the mix with no curing recorded 6.9 MPa while the two conjugate mixtures cured with water and curing compound recorded 9.4 and 9.7 MPa, respectively. In summary, the incorporation of perlite led to a decrease in flexural strength while the incorporation of recycled aggregates led to flexural strength that is similar or exceeding conventional mixtures. The results herein also suggest that the flexural strength test is a better means to detect the effect of internal curing than compressive strength.

Table 3: Flexural strength test results

Time	Flexural Strength in MPa								
	Perlite			Recycled			Curing		
	3%	5%	7%	10%	15%	20%	FC	CC	NC
28-days	5.4	4.5	3.4	8.3	7.8	7.2	6.3	6.6	4.7
56-days	6.9	6.2	5.5	10.6	9.3	8.8	9.4	9.7	6.9

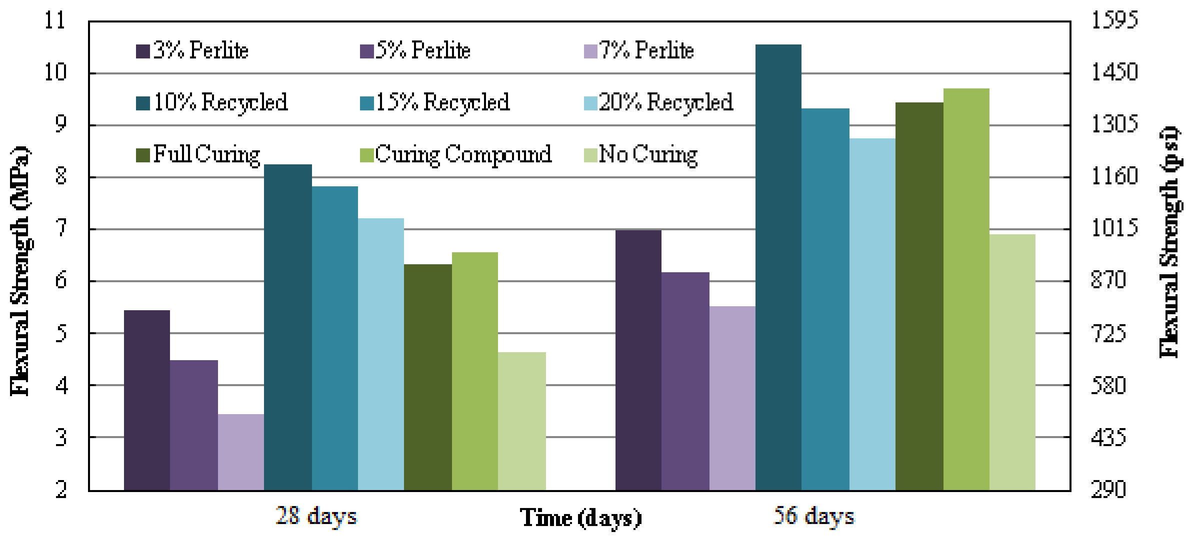

Figure 6: Flexural strength results for the concrete mixtures

4.6 Shrinkage test

The shrinkage test results are listed in Table 4 and are illustrated in Figure 7. At the outset, one can notice that most of the shrinkage took place until 14 days and less increase in shrinkage was witnessed in the interval between 14 and 28 days. The results show that uncured conventional concrete mixtures had the highest shrinkage values. For example, the conventional concrete had a shrinkage cracking of 0.0319 mm while the mix with 20% recycled aggregates had almost half that value (0.0155 mm). Both the perlite and the recycled mixtures had significant effect in reducing shrinkage cracking. Such decrease in shrinkage values was higher upon increasing the perlite and recycled aggregates dosages. The recycled aggregates, however, had the lowest shrinkage of all mixtures even when compared to perlite mixtures. Combining the results of compressive and flexural strength with the shrinkage results one can see the need of optimizing the replacement dosage of both perlite and recycled aggregates in order to achieve the low cracking while maintaining good mechanical properties.

Similar to other previous work, the findings of this study demonstrate that internal curing is a promising technique that can contribute to better concrete performance together with environmental merits. Further testing involving durability and long term properties and wider spectrum of mixtures and materials is highly recommended.

Table 4: Shrinkage test results (x 0.01 mm)

Cumulative Shrinkage (days)*	Perlite			Recycled			Conventional
	3%	5%	7%	10%	15%	20%	NC
Day 3	0.90	1.01	0.94	0.80	0.68	0.62	1.11
Day 7	2.13	1.77	1.51	1.46	1.21	1.12	1.98
Day 14	2.86	2.45	2.28	1.90	1.59	1.47	3.09
Day 28	2.95	2.57	2.39	1.95	1.77	1.55	3.19

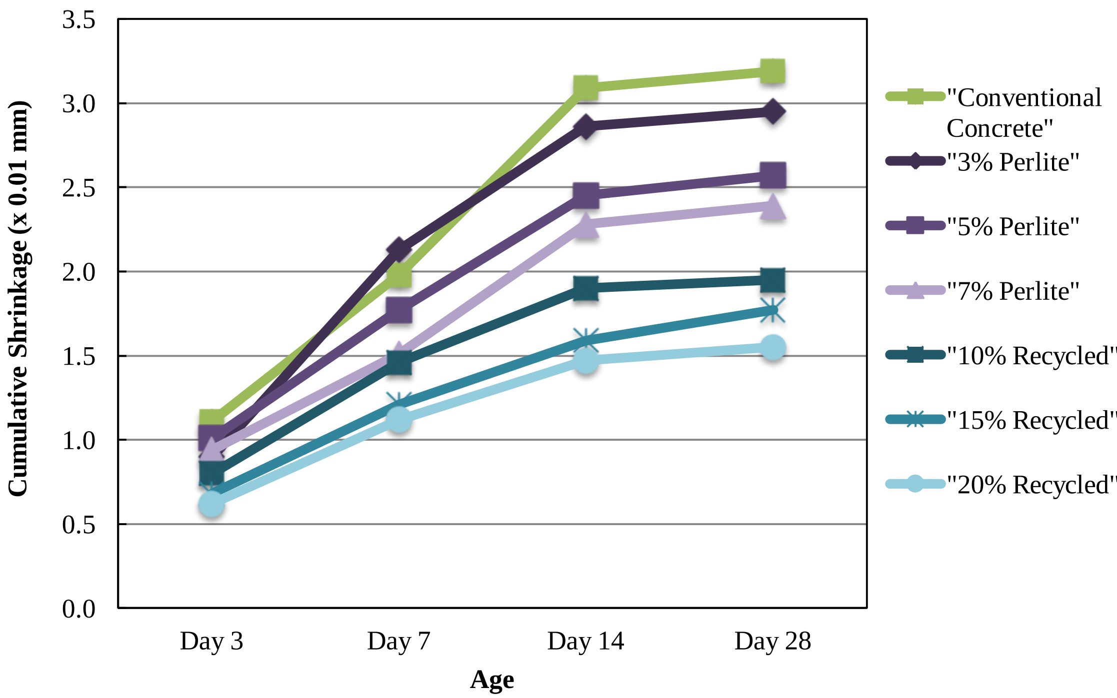

Figure 7: Shrinkage results for the concrete mixtures

5 CONCLUSIONS

In the light of the scope and based on the materials, curing techniques and other parameters associated with this work, the following conclusions can be warranted:

a. The concrete mixtures incorporating perlite and recycled aggregates had higher slump, slightly higher air concrete and unit weight than conventional mixtures.

b. Increasing the dosages of perlite and recycled aggregates led to a decrease in compressive strength. The reduction in strength was the lowest for perlite mixtures.

c. Compressive strength results surpassing 45 MPa was reached with both perlite and recycled aggregates. Such values are adequate for wide range of concrete applications.

d. Incorporating perlite and recycled aggregates yielded good flexural strength. The recycled aggregates mixtures had the highest flexural strength of all mixtures.

e. The flexural strength test seems more adequate in identifying potential merits of internal curing than compressive strength.

f. While there is no one specific dosage that should be considered as optimal, the 10% recycled materials mix seems to have a reasonable strength that is almost similar to the properly cured conventional mixes with less shrinkage cracking.

g. Mixtures that were internally cured by perlite or recycled aggregates had low cracking than conventional mixtures that were not cured. Reductions in cracking were as high as 50% for the recycled aggregates mixtures.

h. While increasing perlite or recycled aggregate replacement dosage resulted in a reduction in mechanical properties, increasing the dosages also led to reducing shrinkage cracking. This highlights the importance of adjusting replacement dosages to meet targeted properties.

6 RECOMMENDATIONS

It is highly recommended to further study internal curing and its feasibility as technique that can contribute to higher concrete performance together with its environmental merits. Future work should cover more materials, techniques and wider short and long term testing schemes.

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