2021

Incorporation of perlite and recycled aggregates for internal concrete curing

Yosra El Maghraby
yosra.elmaghraby@bue.edu.eg

Mohamed Nagib Abou-Zeid Prof.
The American University in Cairo AUC, mnagiba@aucegypt.edu

Mohamed Abdel-Raouf Dr.
The American University in Cairo AUC

Recommended Citation

El Maghraby, Yosra; Abou-Zeid, Mohamed Nagib Prof.; and Abdel-Raouf, Mohamed Dr., "Incorporation of perlite and recycled aggregates for internal concrete curing" (2021). *Civil Engineering*. 152.
https://buescholar.bue.edu.eg/civil_eng/152

Incorporation of Perlite and Recycled Aggregates for Internal Concrete Curing

Conference Paper · June 2021

DOI: 10.1061/9780784483541.021

7 authors, including:

Mohamed Abdel Raouf
Iowa State University
11 PUBLICATIONS **389** CITATIONS

Yosra el maghraby
The British University in Egypt
6 PUBLICATIONS **15** CITATIONS

Mohamed Nagib Abou-Zeid
The American University in Cairo
160 PUBLICATIONS **663** CITATIONS

INCORPORATION OF PERLITE AND RECYCLED AGGREGATES FOR INTERNAL CONCRETE CURING

Ahmed Hammam, BSc.[1], Mariam Ismail, BSc.[2], Marwan Roushdy, BSc.[3], Mohamed El Ghonemy, BSc.[4], Mohamed Abdel Raouf, Ph.D[5], Yosra El Maghraby, Ph.D[6] and Mohamed N. Abou-Zeid, Ph.D[7]

1 Department of Construction management, The American University in Cairo, P.O. Box 11835, AUC Avenue road, Cairo, Egypt; e-mail: ahmed.hammam@aucegypt.edu
2 Department of Construction management, The American University in Cairo, P.O. Box 11835, AUC Avenue road, Cairo, Egypt; e-mail: minush@aucegypt.edu
3 Department of Construction management, The American University in Cairo, P.O. Box 11835, AUC Avenue road, Cairo, Egypt; e-mail: marwanfroushdy@gmail.com
4 Department of Construction management, The American University in Cairo, P.O. Box 11835, AUC Avenue road, Cairo, Egypt; e-mail: mo_ghonemy@aucegypt.edu
5 Department of Construction management, Nile University, 26th of July Corridor, Al Sheikh Zayed, Giza Governorate; e-mail: araouf@aucegypt.edu
6 Department of Civil Engineering, The British University in Egypt, P.O. Box 11837, Suez road, El Shorouk, Cairo, Egypt; e-mail: yosra78@aucegypt.edu
7 Department of Construction management, The American University in Cairo, P.O. Box 11835, AUC Avenue road, Cairo, Egypt; e-mail: mnagiba@aucegypt.edu

ABSTRACT

Adequate curing of concrete is a fundamental step in concrete manufacturing to meet performance and durability requirements. Internal curing is a 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 substitutes of ordinary aggregates for internal curing. Perlite as well as recycled concrete aggregates were incorporated at three dosages each to replace the coarse aggregates. Sets of concrete mixtures were prepared as fully cured in three different techniques; water, applying a curing compound and with no curing. Fresh concrete and hardened concrete properties were evaluated. Results revealed that the incorporation of pre-wetted/saturated perlite and recycled aggregates can lead to significant enhancement in concrete workability and durability through reduced shrinkage. An enhancement of concrete strength at various stages was recorded, and recommendations were given for future use of perlite and recycled aggregates.

Keywords: internal curing; shrinkage; perlite; recycled aggregates; cracking; sustainable concrete.

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 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 (*1*). In other words, internal curing can be described as supplying excess water through reservoirs of pre-wetted lightweight aggregates that readily release water needed for hydration or to replace moisture lost by evaporation or self-desiccation (*3*).

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 (*7*). 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 while doing that, aggregates were typically saturated before mixing to provide adequate workability. As a result, such lightweight aggregates 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 that containing 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 as well as reduce permeability. It also enhances durability through reducing autogenous shrinkage, reducing ingress of chloride ions, delaying the rate of steel corrosion and reducing tensile stresses thus improving construction robustness (*12*), (*5*) and (*3*). Internal curing by saturated lightweight aggregates can delay or prevent shrinkage cracking (*6*). It was reported that a sufficient volume of saturated lightweight aggregates can reduce plastic shrinkage cracking, in both sealed and unsealed curing conditions. It also reduces water absorption as the addition of light weight aggregates increases the degree of hydration, producing a denser microstructure which results in less water absorption, and hence more durable concrete (*6*). According to Browning (4), 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% (*5*).

Nowadays, there exists 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 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 (*5*).

High cementitious concretes are vulnerable to self-desiccation and early-age cracking, and benefit significantly from the slowly released internal moisture (*9*). Incorporating 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 (*3*). 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 ratio is lower for normal-performance concrete mix, a marked self-desiccation may take place, leading to autogenous shrinkage (*5*). Also, to avoid this risk of early age cracking in high-performance concrete, it is essential to prevent 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 an economical and environmental-friendly technique (*12*). Water saving is of prime global concern. While external curing consumes relatively a large amount of water, internal curing consumes only a specific amount of water which is used once to saturate the lightweight aggregates.

According to the United States Environmental Protection Agency most lightweight aggregates are produced from clay, shale or slate. However, materials such as blast furnace slag, natural pumice, vermiculite, and perlite can be used as substitutes (*10*). In the current work, perlite was selected to substitute a percentage of the concrete mixture aggregates. Perlite is known for its light weight, low density, fire resistance, and thermal and acoustic insulation properties (*8*). Yet it should be indicated that perlite does not provide structural capacity unlike other lightweight aggregates that do (*2*).

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 a decrease in energy use, pollution as well as the incorporation of waste materials and minimizing the use of landfills.

RESEARCH SIGNIFICANCE

According to the literature internal curing proved to enhance hydration, durability, strength development and permeability. These enhanced properties result in better concrete performance. For that reason, this study aimed at examining the potential use of pre-wetted/saturated perlite and recycled aggregates as reservoirs to provide internal curing. Fresh and hardened concrete properties were evaluated to serve the objective of the current study.

EXPERIMENTAL WORK

Materials

Type I Portland Cement was used with a specific gravity of 3.14 and a specific surface area (Blaine fineness) of 375 m^2/kg. The Bogue composition of the cement was as follows: C_3S = 53.7 %, C_2S = 27.6 %, C_3A = 6.1% and C_4AF = 10.1%. The alkali content (as Na_2O equivalent) was 0.45 mass percentage (%). 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%. 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%.

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.

A 19 mm (0.75 inch) maximum size pre-wetted/saturated perlite was used for internal curing by replacement of coarse aggregates by mass of aggregates at dosages of 3%, 5% and 7%. Wetting was conducted by soaking in water for 24 hours. This lightweight material had a specific gravity of 0.9 and absorption of 28%. Also, recycled concrete was used for internal concrete curing at replacement dosages of 10%, 15% and 20%. Such dosage ranges were selected based on earlier preparatory trials. The recycled concrete 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 frequent water splashing, curing compound and with no curing. As for the mixes containing lightweight aggregates they were also exposed to external curing by frequent water splashing.

Specimens and Procedures

The seven concrete mixtures had w/c of 0.4, a Type "F" superplasticizer, cement content of 450 kg/m^3 (750 lb/yd^3), and air content of 2%. Concrete slump, air content and the fresh unit weight test were conducted in accordance with ASTM standards C 143, C 173/ 231 and C 138, respectively.

Sets of three, 150 mm (6 inch), cubes were prepared for compressive strength testing at 7, 28 and 56-day using a 2000 kN (449.61 kip) capacity testing machine.

Beams of 150 x 150 x 750 mm (6 x 6 x 30 inch) in sets of two were prepared for 28, and 56-day flexural testing with a clear span of 600 mm (23.6 inch) during testing according to ASTM C 78.

Shrinkage prisms of 100 x 100 x 280 mm (4 x 4 x 11.2 inch) were prepared in compliance with the ASTM C 157 to evaluate length change after 3, 7, 14, 28 days towards the calculation of accumulated shrinkage. Shrinkage was measured through measurement of specimen dimensions to accuracy of 0.1mm (0.004 inch). Specimens were placed in a "hot weather simulation chamber" that was constructed for the purpose of this study. The 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.

RESULTS AND DISCUSSION

Tests on Freshly Mixed Concrete

Slump test

The slump test results are shown in Table 1. These results show that conventional concrete had the lowest slump of 15 mm (0.6 in). It has to be noted that the three fresh conventional concrete results included in Table 1 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 (4.4 to 6.7 inch). The slump values increased as the Perlite replacement dosage increased. For example, the 3% perlite replacement mix had a slump of 110 mm (4.3 inch) while the conjugate mix made with 7% perlite replacement had a slump of 170 mm (6.7 inch). The recycled concrete aggregate acted as an intermediary between the pre-wetted perlite and the conventional mixture, 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.

Unit Weight

The results of fresh concrete unit weight are shown in Table 1. 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 their 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.

Air Content

The air content results are listed in Table 1 with values in the range of 1.7 to 2.5%. While air content values for all mixtures did not vary significantly, yet, all 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.

Compressive Strength

The 7, 28 and 56-day compressive strength results are listed in Table 2. Based on these results, the following observations can be made. First, the 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 tend to close 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, that the increase in perlite and recycled aggregates 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. Yet, 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 (7250 psi) can be attained through incorporation of perlite and strength surpassing 60 MPa (8700 psi) can be attained through incorporation of recycled aggregates. This shows that the incorporation of such aggregates should not be a barrier against reaching good compressive strength values.

Flexural Strength

The results of flexural strength are shown in Table 3 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 10% 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 (1000 psi) while the two conjugate mixtures cured with water and curing compound recorded 9.4 and 9.7 MPa, respectively (1360 and 1400 psi). 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.

Shrinkage Test

The shrinkage test results are listed in Table 4 and are illustrated in Figure 2. 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 (0.00125 inch) while the mix with 20% recycled aggregates had almost half that value (0.0155 mm/0.0006 inch). 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 low shrinkage while maintaining good mechanical properties.

The aforementioned data demonstrate that internal curing is a promising technique that can contribute to better concrete performance together with environmental merits. Due to remaining inconsistencies, a wider testing spectrum involving durability and long term properties is highly recommended.

CONCLUSIONS AND RECOMMENDATIONS

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

1. The concrete mixtures incorporating perlite and recycled aggregates had higher slump, slightly higher air concrete and slightly lower unit weight than conventional mixtures.
2. Increasing the dosages of perlite and recycled aggregates led to a decrease in compressive strength. The reduction in strength was the greatest for perlite mixtures.
3. Compressive strength results surpassing 45 MPa were reached with both perlite and recycled aggregates. Such values are adequate for a wide range of concrete applications.
4. Incorporating perlite and recycled aggregates yielded good flexural strength. The recycled aggregates mixtures had the highest flexural strength of all mixtures.
5. The flexural strength test seems more adequate in identifying potential merits of internal curing than the compressive strength test.
6. 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.

7. Mixtures that were internally cured by perlite or recycled aggregates had lower shrinkage than conventional mixtures that were not cured. Reductions in shrinkage were as high as 50% for the recycled aggregates mixtures.
8. 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.
9. It is recommended in future works to conduct similar tests using percentage volume replacement instead of percentage mass replacement and compare the validity of the results against the current findings.
10. It is highly recommended to further study internal curing and its feasibility as a 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.

REFERENCES

American Concrete Institute. “Building Code Requirements for Reinforced Concrete (ACI 201.2R-16)”, Detroit, Michigan, U.S.A, 2014.

Babock, A. and Taylor, P. Impacts of Internal Curing on Concrete Properties. National Concrete Pavement Technology Center Iowa State University, 2015.

Bentz, D., Lura, P., and Roberts, J. Mixture Proportioning for Internal Curing. Concrete International, Vol. 27, No. 2, February 2005,pp. 35-40.

Browning, J., Darwin, D., Reynolds, D., and Pendergrass, B. Lightweight Aggregate as Internal Curing Agent to Limit Concrete Shrinkage. ACI Materials Journal, Vol. 108, No. 6, Nov.-Dec. 2011, pp. 638-644.

Cusson, D., and Hoogeveen, T. Preventing Autogenous Shrinkage Of High-performance Concrete Structures By Internal Curing. Konsta-Gdoutos M.S. (eds) Measuring, Monitoring and Modeling Concrete Properties. Springer, Dordrecht. pp.83-89, 2006.

Henkensiefken, R,. Nantung, T,. and Weiss, J,. "Internal Curing- From The Laboratory To Implementation." LWC Bridges Workshop 2009 IBC. pp.1-13.

Jensen, Ole Mejlhede, D. Cusson, and J. M. Roberts.Internal Curing of Concrete. State of the Art Report. RILEM Technical Committee 196-ICC, 2007. 127-140. eBook.

Khonsari, V., Eslami, E. and Anvari, Ah. Effect of Expanded Perlite Aggregate (EPA) on the Mechanical Behavior of Lightweight Concrete. Proceedings of 7th International Conference on Fracture Mechanics of Concrete and Concrete Structures, ISBN 978-89-5708-182-2, 2010.

Lamond, J. F. and Pielert, J. H. Internal Curing Using Expanded Shale, Clay and Slate Lightweight Aggregate. Significance of Test and Properties of Concrete and Concrete Making Materials, Chapter 46 – “Lightweight Concrete and Aggregate,” American Society of Testing Materials, West Conshohocken, PA 2006.

United States Environmental Protection Agency, Mineral Products Industry: Lightweight Aggregate Manufacturing. https://www3.epa.gov/ttn/chief/ap42/ch11/final/c11s20.pdf. Accessed July 30, 2018.

Weiss, J., Anton, S., P, E., and Pietro, L. Internal Curing. Structure, Jan 2012. www.structuremag.org/article.aspx?articleID=1372. Accessed Feb. 5, 2012.

Weiss, J,. Internal Curing in Concrete: Improved Service Life through Reduced Cracking and Corrosion. School of Civil Engineering, Purdue University. November 2011. Accessed Feb. 10, 2012.

TABLE 1 Fresh Concrete Tests Results

	Perlite			Recycled			Conventional Concrete
	3%	5%	7%	10%	15%	20%	
Slump in mm (inch)	110 (4.3)	140 (5.5)	170 (6.7)	25 (1.0)	35 (1.4)	45 (1.8)	15 (0.6)
Unit Weight in kg/m^3 (lb/ft^3)	2418 (150)	2411 (149)	2406 (149)	2444 (153)	2437 (152)	2428 (151)	2454 (153)
Air Content (%)	2.0	2.1	2.3	2.3	2.5	2.5	1.7

TABLE 2 Compressive Strength Test Results

	Compressive Strength in MPa (psi)								
Time (days)	Perlite			Recycled			Conventional		
	3%	5%	7%	10%	15%	20%	FC	CC	NC
7	43.1 (6250)	40.6 (5887)	38.3 (5553)	58.2 (8440)	47.6 (6902)	41.8 (6060)	56.8 (8235)	46.9 (6800)	55.5 (8045)
28	52.9 (7671)	43.5 (6308)	43.5 (6308)	63.5 (9208)	55.5 (8048)	46.7 (6772)	64.5 (9353)	62.0 (8990)	63.6 (9222)
56	53.9 (7816)	47.0 (6815)	44.8 (6496)	65.4 (9483)	55.9 (8106)	55.1 (7990)	66.6 (9657)	65.0 (9425)	69.5 (10078)

TABLE 3 Flexural Strength Test Results

	Flexural Strength in MPa (psi)								
Time	Perlite			Recycled			Conventional		
	3%	5%	7%	10%	15%	20%	FC	CC	NC
28-days	5.4 (783)	4.5 (653)	3.4 (493)	8.3 (1204)	7.8 (1131)	7.2 1044)	6.3 (914)	6.6 (957)	4.7 (682)
56-days	6.9 (1001)	6.2 (899)	5.5 (798)	10.6 (1537)	9.3 (1349)	8.8 (1276)	9.4 (1363)	9.7 (1407)	6.9 (1001)

TABLE 4 Shrinkage Test Results

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

* Units: results are to be multiplied by 0.01 mm (4 x 10^{-4} inch)

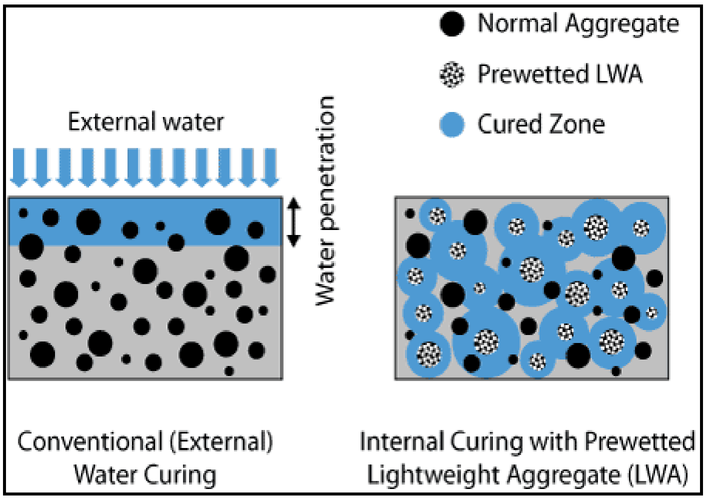

FIGURE 1 Internal curing versus external curing ***(12)***

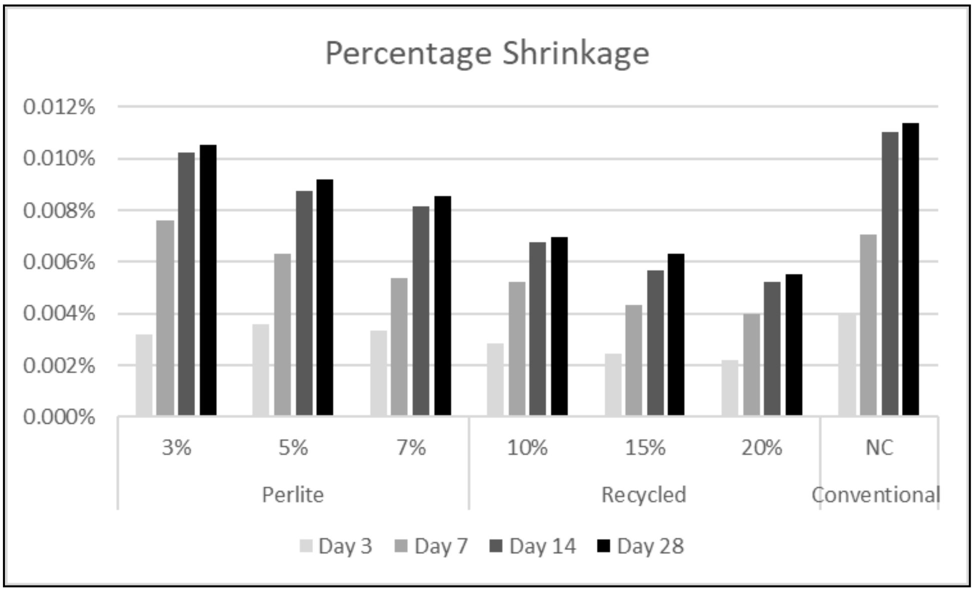

FIGURE 2 Comparison of Shrinkage Percentage