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Mechanical and drying shrinkage properties of structural-graded polystyrene aggregate concrete

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Abstract

Polystyrene aggregate concrete (PAC) is a lightweight concrete with good deformation capacity, but its application is usually limited to non-structural use because of its apparent low strength properties. The present study is an effort to develop a class of structural grade PAC with a wide range of concrete densities between 1400 and 2100 kg/m^3 through partial replacement of coarse aggregate with polystyrene aggregate (PA) in control concrete. Extensive laboratory tests have been carried out and the focus of this paper is to characterize the strength and long-term drying shrinkage properties of PAC. The parameters studied include PA content and curing conditions. The results show that the concrete density, concrete strength and elastic modulus of PAC decrease with increase of PA content in the mix. From the calorimetric test results, the increase in strength acceleration of PAC at early ages is due to the low specific thermal capacity of polystyrene aggregate. Besides, the long-term shrinkage and swelling of PAC are highly dependent on the PA content and the duration of water curing. Owing to the non-absorbent property of polystyrene aggregate, the ratio of reversible shrinkage to drying shrinkage observed for PAC was lower compared to the control concrete.

Keywords: PAC; Mechanical properties; Drying shrinkage; Swelling

1. Introduction

Polystyrene aggregate concrete (PAC) is a lightweight concrete with a density of more than 600 kg/m^3 consisting of cement, sand and expanded polystyrene aggregate having a diameter ranging from 1 to 6 mm [1,2]. In the late 1950s and early 1960s, research into the use of polystyrene beads as replacement aggregate in concrete was carried out in West Germany. To overcome the hydrophobicity of polystyrene beads and the proneness to segregation in polystyrene concrete mixes, a bonding agent such as epoxy resin or aqueous dispersions of polyvinyl propionate to coat the polystyrene beads has been adopted successfully [2–5]. Owing to its excellent deformation capacity properties, PAC has been used in various structural elements such as cladding panels, curtain walls, composite flooring systems, load-bearing concrete blocks, the sub-base material for pavements, floating marine structures, etc. [2–9].

The mechanical properties of PAC are highly dependent on the amount of polystyrene aggregate in the mix. When the bead content increases, both the density and strength are significantly reduced. Perry et al. [5] studied the mechanical properties of PAC over a density range from 850 to 1250 kg/m^3 and stated that the mechanical behaviour of PAC should be considered similar to that of cellular concrete as the polystyrene aggregate consists essentially of air. Similarly, Chen and Liu [6] investigated the strength properties of PAC at a constant water/binder ratio (i.e. 0.37) producing a series of PAC with compressive strengths of 10–25 MPa over a density range between 800 and 1800 kg/m^3. Lately, Babu and Babu [9,10] studied the strength and durability of PAC containing mineral admixtures with concrete densities varying from 550 to 2,200 kg/m^3 and the corresponding strength results were found to vary from 1 to 21 MPa. It seems that most studies reported

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to date have been essentially related to PAC of lower strength. To better use the advantages of PAC for both structural and functional requirements, a series of structural grade PAC of 1400–2100 kg/m^3 densities with corresponding strengths of about 17 MPa minimum [11] was designed and studied.

Apart from the strength, concrete shrinkage is of increasing concern when focusing on maintaining durable structures. Over time, shrinkage induces cracking which can severely decrease concrete life expectancy. These volume changes are often attributed to drying of the concrete over a long time period, however recent observations on PAC have focused on short-term measurement merely. Chen and Liu [6] studied the shrinkage of PAC for 90 days and reported that the drying shrinkage and swelling of PAC increased considerably with decrease in concrete density (i.e. the increase in volumetric proportion of polystyrene aggregate in concrete). Nevertheless, the slow development of shrinkage over time makes it difficult to obtain an accurate prediction for a given concrete from short-term laboratory measurements. Therefore, one goal of this work was to provide a clearer understanding of the drying shrinkage of PAC from long-term laboratory measurements.

2. Experimental details

2.1. Details of concrete mixes

In this research, a control concrete (C5) and four PAC mixes were studied. These four PAC mixes were proportioned by replacing 20, 40, 60 and 80% of normal coarse aggregate from the control concrete with an equal bulk volume of polystyrene aggregate, respectively. The polystyrene aggregate was made from small polystyrene beads or recycled granulates, coated with a non-toxic and patented chemical compound that was supplied by BST (East Asia) Ltd. The mean diameter and bulk density of the polystyrene beads were approximately 4 mm and 24 kg/m^3, respectively. The materials used in this study were ordinary portland cement (OPC) conforming to BS12:1991 [12] and Type I ASTM C150-92 [13], river sand with a fineness modulus of 2.75 and crushed granite with a nominal size of 10 mm. Table 1 shows the complete mix details used in this investigation.

2.2. Preparation of test specimens

Several standard test specimens of different sizes were chosen for investigating the various parameters. Cubes of 100 mm in size were used for studying the compressive strength at 1, 3, 7, 28, 90, 180 and 360 days. Split tensile strength and elastic modulus tests were conducted on cylinders of 100 mm in diameter and 200 mm long. Prisms of $75 \times 75 \times 285$ mm were cast for the determination of shrinkage of PAC at 1, 3, 7, 14, 28, 90, 180, 270, 360, 450 and 540 days. For the shrinkage test, two sets of identical specimens water cured for two different durations were prepared. After demoulding and measuring the initial readings, both sets of specimen were water cured at 27 ± 1 °C for 7 and 28 days, respectively. Then, all the specimens were stored in a controlled environment of 25 ± 2 °C and 50 ± 5% R.H for subsequent measurement. After 540 days of concrete ageing, all the shrinkage specimens were then cured in a water tank to determine the swelling properties. The shrinkage strain was calculated according to ASTM C490–93a [14].

3. Results and discussions

3.1. Fresh properties

The fresh concrete properties including slump value, wet density and air content of PAC are indicated in Table 2. The workability of concrete in terms of slump was studied. Without the use of admixtures and with other factors kept constant (i.e. water/cement ratio and cement content) the workability of PAC is generally similar to the corresponding normal weight concrete (C5) showing a range of 55–65 mm slump in most cases. The general high absorption capacity of lightweight aggregates reducing the workability of the mix due to their higher porosity is not expected to be encountered in PAC due to its closed cellular structure with negligible water absorption capacity [1,7,10]. All the PAC was flexible and workable which could be easily compacted with a tamping rod and could also be easily finished. In general, the polystyrene aggregate showed an even distribution in the mortar and concrete matrix and the cohesiveness of the PAC fresh mixes appeared similar to that observed in normal concrete. Similar observations were reported by Babu and Babu [9].

Table 1
Mix details of concrete tested

Mix code	Cement (kg/m^3)	10 mm agg. (kg/m^3)	Sand (kg/m^3)	Water (kg/m^3)	Bulk volume of PA in liters (V)	Absolute Volume of PA in mix (%)	Weight of PA used (kg)	Raw density (kg/m^3)
C5	390	1131	609	195	–	–	–	2325
PA20	390	905	609	195	152	9.7	3.65	2100
PA40	390	679	609	195	304	19.5	7.30	1880
PA60	390	452	609	195	456	29.2	10.95	1660
PA80	390	226	609	195	608	38.9	14.59	1435

Table 2
Properties of fresh PAC and control concrete

Mix code	Absolute Volume of PA in mix (%)	Slump (mm)	Wet density		Entrapped air content	
			p_w (kg/m^3)	Relative density (PAC/C5)	(%)	Relative air content
C5	0	55	2330	100	1.5	100
PA20	9.7	60	2094	90	4.5	300
PA40	19.5	65	1864	80	9.5	630
PA60	29.2	60	1626	70	12.5	830
PA80	38.9	55	1396	60	16.0	1065

Table 2 also shows the entrapped air content of PAC mixes. In general, the air content increases significantly with increase of PA content in the mix. The increase of air content may have a beneficial effect on the workability of concrete – the spherical air bubbles probably act as a fine aggregate of very low surface friction and high compressibility [15]. Nevertheless, the higher entrapped air content increases the presence of voids and reduces the strength of the concrete.

3.2. Compressive strength

Fig. 1 presents the strength development of PAC with age. Apparently, the rates of strength development of PAC mixes and control concrete (C5) have a similar trend. Most PAC mixes were able to develop approximately 80% of their corresponding 28-day strength at 7 days, which was similar to that of the control concrete. However, the early strength development of PAC was found to be slightly different from that of the control concrete. In Fig. 1, a comparison of strengths at 1 day displayed the fact that all PAC mixes developed above 20% of their 28-day strength, while the control concrete developed 17% only. The probable reason may be due to the presence of polystyrene aggregate which would decrease the specific thermal capacity of concrete, resulting in a reduced loss of heat to the ambient medium during the hydration process.

To verify this hypothesis, a simple and inexpensive calorimetric test with reference to the study of Wang et al. [16] was conducted to measure the temperature history of freshly-made PAC for 72 h. A 150 mm^3 concrete sample was placed in a wooden box insulated by 5 mm thick spray foam, where temperature development was then measured and recorded over time using thermocouples and datalogger, respectively. At the same time, the ambient temperature and the temperature of an identical concrete sample inside the steel mould were also recorded for reference purposes. The results of the temperature development for both PAC and control concrete samples are shown in Fig. 2. Fig. 2 clearly indicates that the peak temperature is increased by increasing the polystyrene aggregate content. On average, the peak temperature for PAC under the calorimetric test was around 1 to 5 °C higher compared to that of the control concrete. Therefore it can be deduced that concrete with polystyrene aggregate can exhibit higher strength acceleration at early ages due to the greater and more rapid heat of hydration generated. Nevertheless, there was no appreciable difference in strength development between PAC and the control concrete at and beyond 90 days (Fig. 1).

The variations of the compressive strength with the content of PA and concrete density are presented in Fig. 3. The strength of PAC appeared to decrease linearly with an increase in PA content, which is consistent with the results from other studies [6,9].

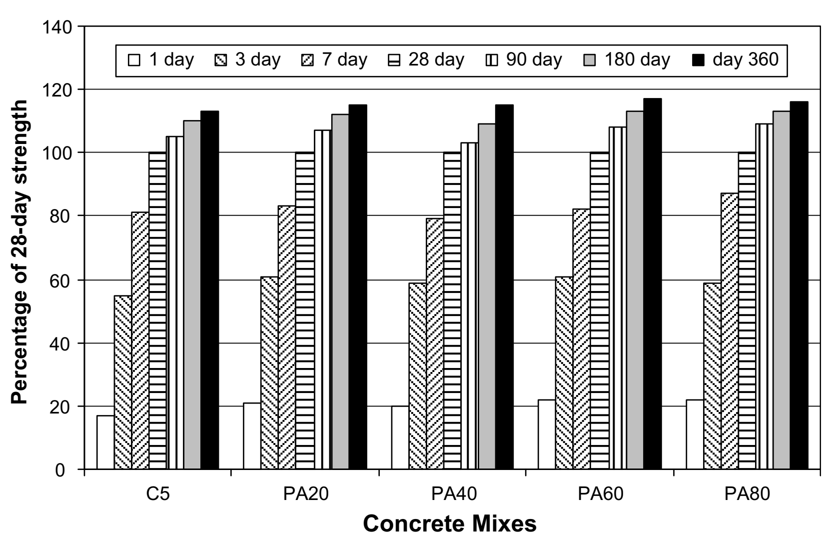

Fig. 1. Relative gain of 28-day compressive strength with time.

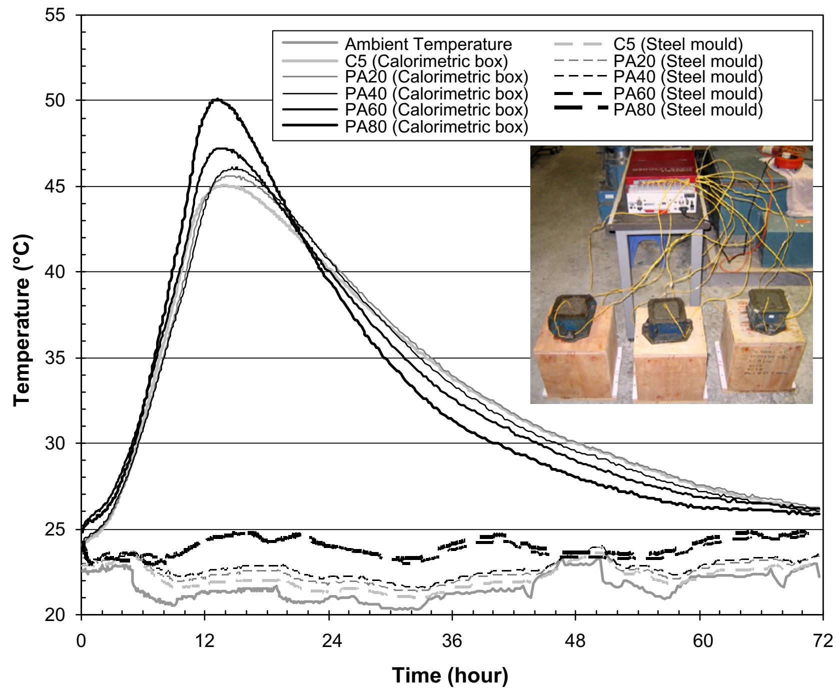

Fig. 2. Temperature histories of freshly made PAC and control concrete measured from calorimetric box and directly from steel mould.

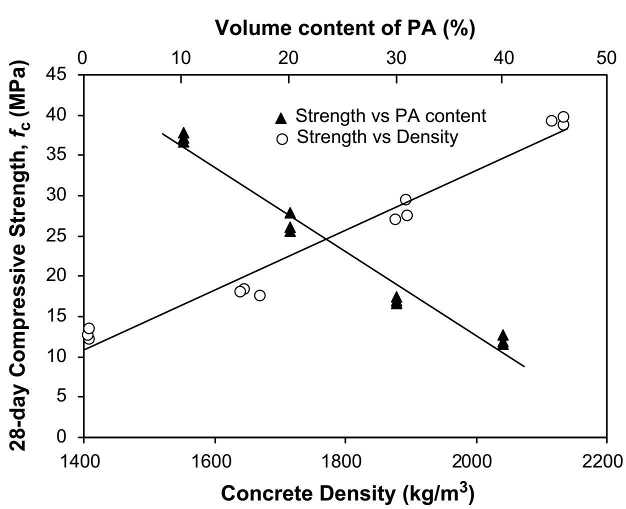

Fig. 3. Relationship of strength with PA content and density.

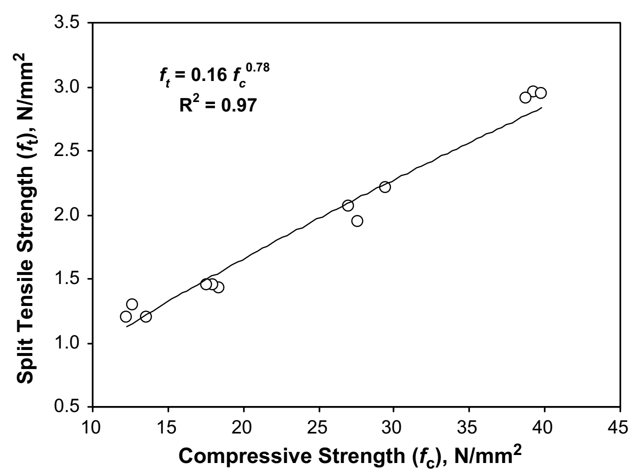

Fig. 4. Relationship of split tensile strength with compressive strength.

3.3. Split tensile strength

The variation of tensile strength (f_t) with the compressive strength (f_c) is given in Fig. 4. As the compressive strength increased, the tensile strength of PAC also increased but at a decreasing rate. As shown in Table 3, the tensile strength of PAC ranged from 7.4 to 9.2% of their corresponding compressive strengths, compared to 7.3% that was observed for the control concrete. The general observation for normal concrete that the ratio f_t/f_c decreases as the compressive strength level rises is also observed in PAC. In other words, the ratio f_t/f_c decreases as the PA content decreases.

3.4. Elastic modulus

Table 3 summarizes the results of static elastic modulus of PAC conducted from the experimental stress–strain relationship in compression. The elastic modulus values of PAC were found between 27 and 71% of that of the control concrete (C5). The modulus of elasticity of concrete is significantly affected by the properties of aggregate, cement paste matrix and transition zone. Because of the negligible elastic modulus of polystyrene aggregate, the increased incorporation of polystyrene aggregate in the mix increases the elastic incompatibility between the inclusion and the matrix, which thus increases the stress concentration at

Table 3
Mechanical properties of PAC and control concrete

Mix code	Absolute volume of PA in mix (%)	Dry density (ρ_D) kg/m^3	Compressive strength		Tensile strength		Ratio of $(f_t)/(f_c)$ in (%)	Elastic modulus $E_{c,D28}$ kN/mm^2
			$f_{c,\ D28}$ N/mm^2	Relative strength PAC/C5	$f_{t,\ D28}$ N/mm^2	Relative strength PAC/C5		
C5	0	2345	60.5	1.00	4.45	1.00	7.3	34.2
PA20	9.7	2120	39.3	0.65	2.95	0.74	7.5	24.1
PA40	19.5	1880	28.0	0.46	2.05	0.52	7.4	18.1
PA60	29.2	1650	18.2	0.30	1.45	0.37	8.0	14.5
PA80	38.9	1410	13.1	0.21	1.25	0.31	9.2	9.1

the bond interface [17]. As a result, the elastic modulus is reduced markedly.

3.5. Drying shrinkage

Various factors influence the drying shrinkage of hardened concrete but the most important influence for lightweight concrete, especially PAC is exerted by the aggregate itself, which restrains the amount of shrinkage of the cement paste that can be actually realized in the concrete [15,18]. Fig. 5 shows the development of the shrinkage strains with drying time for PAC and control concrete under different initial water curing conditions. Evidently the shrinkage rate is reduced gradually with elapsed time for all mixes. However, the shrinkage rates of PAC and the control concrete are quite different at earlier ages. Concrete with polystyrene aggregates of negligible elastic modulus and of a smoother surface is less resistant to the shrinkage process especially at early ages. Therefore, the higher the PA content, the greater the shrinkage rate at earlier ages. Another possible reason may be attributed to the enhanced development of plastic shrinkage in PAC as a result of more rapid heat generated during the hydration process as observed in the calorimetric test results. Nevertheless, there was no appreciable difference in shrinkage rates between PAC and the control concrete at later ages.

As seen in Table 4, the magnitude of drying shrinkage of PAC increases with the proportion of polystyrene aggregate in concrete and is comparatively greater than the control concrete by a range of 10–85%. Similar findings were reported by Chen and Liu [6] and Benfenier [7]. The main reason is the low stiffness and high compressibility of polystyrene aggregates which offer negligible restraint to the shrinkage process.

The effect of the initial water curing periods on shrinkage of PAC can be shown in Fig. 5. Apparently the 28-day water cured specimens showed a significant reduction in shrinkage when compared with those water-cured for only 7 days. Owing to prolonged moist curing, the strength and elastic modulus of the binding matrix in PAC were both increased gradually [7]. McGovern [19] reported that concretes wet cured for longer durations would have less shrinkage due to drying and autogenous effects than concrete that had less water curing. Therefore, the amount of shrinkage strains observed for 28-day water cured samples were lower than 7-day water cured specimens. This illustrates the importance of early wet curing to minimize shrinkage.

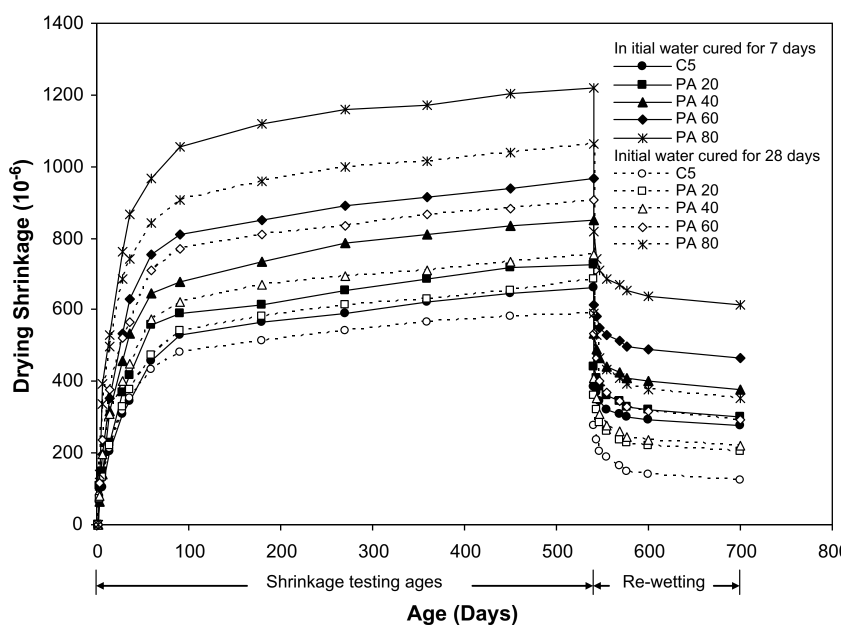

Fig. 5. Drying shrinkage and swelling of PAC and control concrete with time under different days of initial water curing.

Table 4
Drying shrinkage, reversible shrinkage and irreversible part of PAC and control concrete under different initial water curing days

Mix code	Curing conditions	Drying shrinkage at 540 (ε_{sh}), 10^{-6}	Reversible shrinkage (ε_{rsh}), 10^{-6}	Ratio of $\varepsilon_{rsh}/\varepsilon_{sh}$	Irreversible part of shrinkage, $1-(\varepsilon_{rsh}/\varepsilon_{sh})$
C5	Water cured	590	465	0.79	0.21
PA20	for 28 days	685	480	0.60	0.40
PA40		755	535	0.61	0.39
PA60		905	615	0.68	0.32
PA80		1060	710	0.67	0.33
C5	Water cured	660	385	0.58	0.42
PA20	for 7 days	725	425	0.59	0.41
PA40		850	470	0.55	0.45
PA60		970	505	0.52	0.48
PA80		1220	610	0.50	0.50

3.6. Swelling of preshrunk PAC

After 540 days of concrete ageing, the specimens were subsequently placed into water for the reversible shrinkage measurement. The period of measuring reversible moisture movement was 160 days. Table 4 gives the values of swelling for PAC, while Fig. 5 shows the typical curves for the reversible shrinkage of PAC and the control concrete after rewetting.

As seen in Table 4, the reversible shrinkage values for PAC water cured for 28 days were generally larger than the control concrete, but the ratio of reversible shrinkage (ε_{rsh}) to drying shrinkage (ε_{sh}) of PAC was comparatively lower than that of the control concrete irrespective of the initial curing condition. In fact, swelling occurs due to a combination of crystal growth, absorption of water and osmotic pressure [19]. Since polystyrene aggregates are a non-absorbent type, the possibility for lower $\varepsilon_{rsh}/\varepsilon_{sh}$ ratio may be due to the lower water absorption of PAC than normal weight concrete as reported by the recent studies of Babu and Babu [10] and Babu et al. [20]. As a result, the ratio $\varepsilon_{rsh}/\varepsilon_{sh}$ of PAC tends to decrease with increase of PA content in the mix. In other words, the ratio of the irreversible part of shrinkage for PAC increases with increase of PA content.

The effect of different curing conditions on the magnitude of reversible shrinkage is indicated in Table 4. It can be seen that the reversible shrinkage of test specimens that had been water cured for 28 days was higher than those cured for 7 days by about 17%. Because the 28-day water cured specimens had been well hydrated before being exposed to drying, the reversible moisture movement formed a greater proportion of the drying shrinkage. As a result, the irreversible shrinkage is less than that observed for 7-day water cured specimens.

4. Conclusions

This paper shows that structural grade PAC with a density of 1,400 to 2100 kg/m^3 and a compressive strength of 13–40 MPa can be made by partially replacing coarse aggregate from the control concrete with polystyrene beads. The main findings of this study are listed as follows:

1. By visual observation, the polystyrene aggregate, without adding special bonding agents or admixtures apparently showed an even distribution in the mortar and concrete matrix. In general, PAC showed good workability and could be easily compacted and finished.
2. Due to its low specific thermal capacity as verified by the calorimetric test, PAC showed higher strength acceleration at early ages than the control concrete with increasing significance in particular at high PA contents.
3. The concrete density, concrete strength and elastic modulus of PAC decreased considerably with increase of PA content in the mix. The ratio f_t/f_c observed in PAC decreased as the compressive strength level increased and the polystyrene aggregate content decreased. The compressive and splitting failures of the concrete specimens containing polystyrene aggregates showed a large compressibility of the material and did not exhibit a brittle failure.
4. The shrinkage rates of PAC are greater than the control concrete at earlier ages and the shrinkage strains of PAC increased significantly with the PA content.
5. Due to the non-absorbent properties of polystyrene aggregate, the ratio of reversible shrinkage to drying shrinkage observed for PAC was lower than that of the control concrete.
6. Specimens water cured for 28 days showed lower shrinkage strain but higher reversible shrinkage after rewetting when compared to that of 7-day water cured specimens.

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