

Effect of Prewetted Pumice Aggregate Addition on Concrete Properties under Different Curing Conditions

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Abstract

This study researches the effects of different curing conditions on the properties of high strength concrete containing presoaked pumice aggregate (PA). Fine normal weight aggregate is substituted by an equal volume of 1h and 24h presoaked PA at 50% and 100% fractions and a total of five concrete mixtures were prepared. After kept in water, air and hot weather, the performance of concretes were evaluated by determining their physical and mechanical properties at 28 days. Hot weather was found to be the most detrimental condition where the highest strength drops were observed. Frost resistance of concretes was improved with the use of presoaked PA at 50% replacement ratio. The use of presoaked PA also decreased the shrinkage values of concrete specimens. The results showed that the use of presoaked PA in high strength concrete at 50% replacement ratio could contribute to concrete properties when exposed to inadequate curing conditions.

Keywords

Curing conditions · frost resistance · mechanical properties · pumice · shrinkage

1 Introduction

As cement hydration develops, the necessary water to continue hydration is partially obtained from the capillary pores. In concretes with water to cement ratio (w/c) below approximately 0.42, there would be insufficient water to promote complete hydration of the Portland cement. In order to overcome this problem, it is necessary to supply additional water during curing [1, 2]. The placing of concrete must be followed by adequate curing in a suitable environment during the early stages of hardening [3]. Curing of concrete is important especially during the first hours after casting to maintain optimal conditions for cement hydration, for assuring required durability and strength of the hardened concrete [3, 5, 6]. Therefore, in order to maximize the degree of hydration of cement and to reduce early stage shrinkage cracking it is important to apply effective curing during an extended period of time. Insufficient external curing can produce an important drop in concrete's internal relative humidity and even interrupt the hydration process. The internal curing (IC) method was suggested to overcome this problem by supplying additional water during curing [7]. Philleo [7] suggested incorporating presoaked lightweight aggregate (LWA) in concrete to provide an internal source of water necessary to accommodate that consumed by cement hydration. Since then, a lot of research has been carried out in this area and LWAs [2, 3, 8–16], super absorbent polymers [17–19] and recycled aggregates [20, 21] were reported as appropriate IC agents. Bentz and Snyder [22] and Jensen and Hansen [17] proposed equations to determine and quantify the amount of water or LWA needed for IC. Detailed information about IC can be found in refs [7, 17, 22]. It has also been reported that the substitution of LWA by normal weight aggregates might reduce the shrinkage of concrete. Herrera et al. [8] and Browning et al. [14] found that a significant decrease in shrinkage of concrete can be achieved by using saturated LWA. After casting concrete, the environmental conditions and its curing significantly affects the properties of concrete. In this view, this study focused on the use of presoaked PA in high strength concrete to determine its effects on concrete properties when exposed to various environmental conditions. Therefore, concrete specimens that contain different amounts of presoaked

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PA were kept at three different conditions; under water, in air and in hot weather. The last two conditions were selected to simulate inadequate external curing and severe weather conditions respectively. Hardened concrete properties such as compressive strength, splitting tensile strength, ultrasonic pulse velocity, dynamic modulus of elasticity and total shrinkage were determined. In addition, concrete specimens were exposed to freeze-thaw (FT) cycles to assess their frost resistance.

2 Experimental procedure

2.1 Materials and mixture design

The materials used in this research include limestone coarse aggregate with a particle density of 2.75 kg/dm^3 , natural river sand with a particle density of 2.61 kg/dm^3 , PA, cement, and chemical admixture. PA had a particle size between 1 - 4 mm and was obtained from Nevşehir, Turkey. The 1 h and 24 h absorption of the PA was 22.5% and 32.5% respectively and the particle density corresponding to each saturation degree was 1.01 and 1.05 kg/dm^3 respectively. Particle size distributions of the aggregates are presented in Table 1. The type of cement used in all concrete series was CEM I 42.5 R and its properties is listed in Table 2. A commercially available modified polycarboxylate polymer based superplasticizer was also used at a constant ratio (% 1.3 of cement by weight) in all mixes.

Tab. 1. Particle size distribution of the aggregates

Sieve opening (mm)	Cumulative passing (%)		
	Normal weight coarse aggregate	Pumice aggregate	Normal weight fine aggregate
16	100	100	100
11.2	73	100	100
8	35	100	100
4	0	98	100
2	0	26	75
1	0	0	50
0.5	0	0	35
0.25	0	0	15

Before casting concrete, PA was dried in an oven at 100°C . After cooling the PA at room temperature, they were soaked in water for 1 h and 24 h to obtain different amounts of presoak water. The PA was then spread on paper sheets to provide the evaporation of the excess water and to obtain surface dry conditions.

Five different concrete mixes with a constant cement content (400 kg/m^3), aggregate volume fraction (70.6%) and w/c ratio (0.4) were prepared. The amount of PA introduced represents 50% and 100% of the total volume of fine normal weight aggregates, replacing partially and completely the 1 - 4 mm fraction. The mix proportions and fresh properties of concrete mixtures are presented in Table 3. In Table 3, R represents the reference concrete without PA. The other mixtures were coded in the form of PXX-YY; in which "P" represents the use of PA, "XX" and "YY" represents the presoaking time (in hours) of PA and the

Tab. 2. Chemical, physical and mechanical properties of cement

CaO (%)	64.48	
SiO ₂ (%)	20.12	
Al ₂ O ₃ (%)	4.92	
Fe ₂ O ₃ (%)	3.57	
MgO (%)	1.23	
SO ₃ (%)	2.88	
Cl ⁻ (%)	0.0425	
Na ₂ O/K ₂ O	0.24/0.89	
Loss on ignition (%)	1.72	
Insoluble residue (%)	0.92	
Specific gravity (g/cm ³)	3.14	
Blaine fineness (cm ² /g)	3942	
Setting time (min)	Initial	129
	Final	191
Compressive strength (MPa)		
2 days	29.6	
7 days	45.8	
28 days	56.1	

volume percent (%) of PA substituted with normal weight fine aggregates, respectively.

2.2 Specimen preparation, curing and testing

In order to determine the effect of PA substitution on concrete properties under various environmental conditions, compressive strength, splitting tensile strength, total shrinkage, and frost resistance tests were performed on 100 mm cube, 100/200 mm cylinder, $70 \times 70 \times 285$ mm prism, and 70 mm cube specimens respectively. Additionally, density, ultrasonic pulse velocity (UPV) and dynamic modulus of elasticity were determined on 100 mm cube specimens.

All specimens, except the ones for the frost resistance test, were stored at different curing conditions (see Table 4) until testing. Among these conditions "mode A" represents the standard water curing ($20 \pm 2^\circ\text{C}$), "mode B" represents drying in air at laboratory conditions ($23 \pm 2^\circ\text{C}$ and $50 \pm 5\%$ RH) and "mode C" represents drying in hot weather conditions ($40 \pm 2^\circ\text{C}$ and $20 \pm 2\%$ RH). In order to simulate hot weather conditions a laboratory type oven was used.

2.3 Test procedure

The specimens for shrinkage measurements were demolded 24 h after casting and stored at mode B and mode C conditions. The length changes were measured at 2, 7, 28, 56, 90 and 180 days using a comparator according to ASTM C 157 [23]. Additionally, mass loss measurements were performed at the same days. The measurements were conducted on two specimens for each concrete mixes. Density and UPV were determined according to EN 12390-7 [24] and ASTM C 597 [25] respectively at 28 days. Test specimens for each series were stored at three different conditions as shown in Table 4. Dynamic modulus of

Tab. 3. Mix proportions and fresh concrete properties

Mixture Code	Cement (kg)	Water (kg)	Admixtures (kg)	Aggregate				Presoak water (kg)	Slump (cm)	Fresh density (kg/m ³)
				Normal weight			Pumice			
				Coarse	Fine					
					4-16 mm	0-1 mm				
R	400	160	5.2	1068.3	414.8	414.8	-	-	19	2489
P1-50	400	160	5.2	1068.3	414.8	207.4	80.3	18.1	13	2369
P1-100	400	160	5.2	1068.3	414.8	-	160.8	36.2	15	2231
P24-50	400	160	5.2	1068.3	414.8	207.4	83.4	27.1	14	2376
P24-100	400	160	5.2	1068.3	414.8	-	166.8	54.2	17	2272

Tab. 4. Exposure conditions

Mode	Curing conditions	
	0 to 24 hours	24 hours to 28 days
	A	In mold at laboratory conditions
B		Drying in laboratory at 23±2°C and 50±5% RH
C		Drying in oven at 40±2 °C and 20±2% RH

elasticity was calculated according to the following equation:

$$E_d = 10^4 \times V^2 \times \left(\frac{\rho}{g}\right) \quad (1)$$

where E_d is the dynamic modulus of elasticity (MPa), V is the UPV (km/s), ρ is density of the specimen (kg/dm³) and g is the acceleration due to gravity (9.81 m/s²).

Compressive strength and splitting tensile strength

was determined on three 100 mm cube specimens according to EN 12390-3 [26] and on three 100/200 mm cylinder specimens according to EN 12390-6 [27] at 28 days respectively. These specimens, as well, were stored at mode A, mode B and mode C conditions.

FT cycles were conducted on three 70 mm cubic specimens for each mix to determine their frost resistance. In actual field practice the first FT cycle may occur as soon as the concrete is placed, therefore the cycles were started at the age of 24 h to simulate the actual severe environmental situations. There are a quite number of applications and standard procedures for determining the frost resistance of concrete [28–33]. In this study, specimens were first cooled at $-20 \pm 20^\circ\text{C}$ in a deep freezer for 24h and then immersed in water at $21 \pm 3^\circ\text{C}$ for another 24 h to complete a single FT cycle. The procedure is similar with that applied by Laoubi et al. [33]. FT cycles were repeated until 90 days, for 45 cycles and FT resistance of the concretes was evaluated by determining the compressive strength at the end of the FT cycles.

3 Results and Discussion

3.1 Total shrinkage and mass loss

Figs. 1 and 2 show the development of total shrinkage of the concrete mixes exposed to air drying (mode B) and hot weather drying (mode C) respectively. In both exposure cases the reference concrete (R) showed higher shrinkage values. In exposure

to mode B, shrinkage of concretes tends to increase by time, even at 180 days (Fig. 1). However at mode C, shrinkage tends to end at 90 days (Fig. 2).

Moisture loss is one of the underlying causes of shrinkage. At mode B, mass losses of concrete specimens tend to increase by drying time (Fig. 3) so as the total shrinkage. However at mode C, specimens tend to come to equilibrium considering their mass change values (Fig. 4) at 90 days, and further shrinkage development is negligible. The substitution of normal weight sand by presoaked PA led to a reduction in shrinkage at both exposure conditions. The improvement in the shrinkage behaviour of concrete by incorporation of prewetted PA is most likely due to the internal curing effect caused by moisture release from the aggregate during drying. Among all series P1-50 and P24-50 possessed the lowest shrinkage values when exposed to mode B and C respectively. Although 100% PA substitution revealed higher shrinkage than those substituted by 50%, their shrinkage values were still lower than the reference concrete (R). Herrera et. al [8] found that the substitution of 20% normal weight sand by lightweight sand by mass led to a shrinkage reduction of 40, 30, and 20% at the ages of 7, 28, and 91 days, respectively. In this research P1-50 and P24-50 provided 34% and 33% decrease in total shrinkage at 180 days at modes B and C respectively, in comparison to the reference concrete.

3.2 Density and UPV

The density values, as shown in Table 5, ranged from 2496 kg/m³ to 2189 kg/m³. The replacement of normal weight sand by PA and the change in the exposure conditions from mode A to mode C resulted in a reduction in the density values, as can be seen in Fig. 5. The reference concrete (R) had the highest density value while the lowest was measured for the P24-100 concrete exposed to mode C.

Tab. 5. Density and UPV of concretes

Mixture code	Density (kg/m ³)			Ultrasonic pulse velocity (m/s)		
	Mode A	Mode B	Mode C	Mode A	Mode B	Mode C
R	2496	2463	2444	4810	4780	4760
P1-50	2392	2359	2326	4560	4630	4570
P1-100	2236	2208	2203	4390	4530	4520
P24-50	2392	2350	2336	4600	4680	4690
P24-100	2251	2246	2189	4430	4600	4470

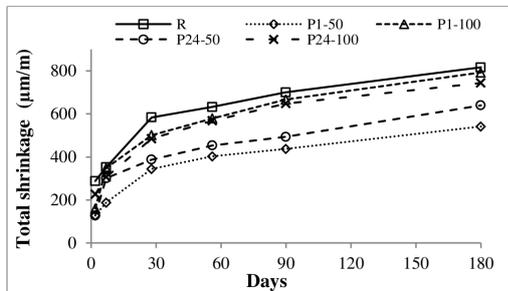


Fig. 1. Total shrinkage of concretes exposed to mode B

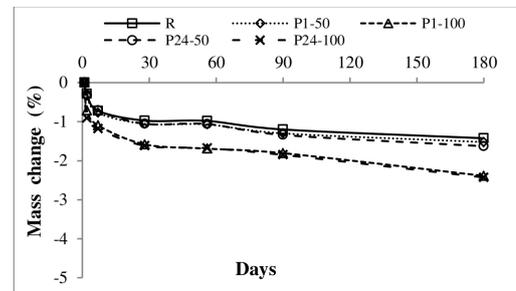


Fig. 3. Mass change of concretes exposed to mode B

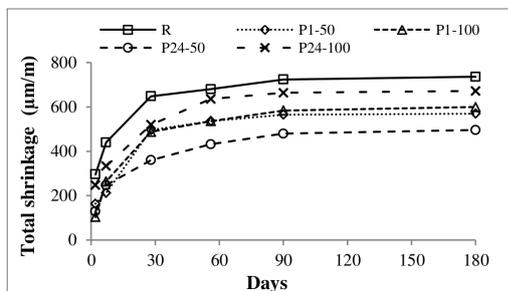


Fig. 2. Total shrinkage of concretes exposed to mode C

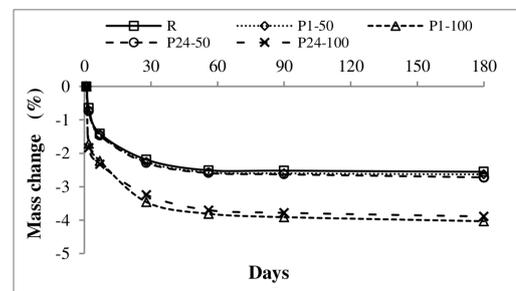


Fig. 4. Mass change of concretes exposed to mode C

The UPV values of the concretes, as presented in Table 5, ranged from 4390 m/s to 4810 m/s; the highest value belongs to the reference concrete cured in water (mode A) and the lowest to the P1-100 concrete exposed to mode C. The substitution of PA with normal weight sand caused a reduction in the UPV; the higher the substitution resulted in a higher reduction. Whitehurst [34] has classified concretes as excellent, good, doubtful, poor and very poor for UPV values of 4500 m/s and above, 3500–4500 m/s, 3000–3500 m/s, 2000–3000 m/s and 2000 m/s, respectively. According to this classification, all produced concretes can at least be classified as good, since all measured UPV values were greater than 3500 m/s (Fig. 6). The trend in UPV values is to increase with increasing compressive strength for all the mixtures (Fig. 7). Similar results have been obtained by other researchers [35,36]. Strong correlations were established between the compressive strength and the UPV as shown in Fig. 7.

3.3 Strength and dynamic modulus of elasticity

Mechanical properties of concretes at 28 days are summarized in Table 6. The compressive strength values were in the range of 74.2–45.6 MPa; where the lowest value belongs to the P1-100 mix exposed to mode C and the highest one to the

reference concrete (R) cured in water (mode A). Fig. 8 shows the change in the compressive strength of concrete with varying pumice content and presoaking time at different environmental conditions. It is clearly seen that there is a slight decrease in compressive strength with increasing PA content; the reference possessing the highest strength values for all curing conditions. It has been reported that the use of porous LWA with a lower intrinsic strength might limit the strength attained by the concrete [2]. The same findings have also been presented by several researchers [8,9].

The reduction in compressive strength can be seen in Fig. 9 where the relationship between compressive strength and PA content is displayed. However when we compare P1-100 and P24-100 series, the increase in presoak water content resulted

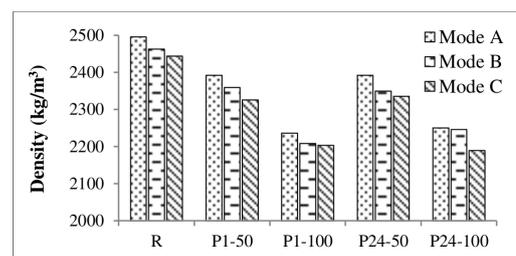


Fig. 5. Density of concretes exposed to modes A, B and C

Tab. 6. Mechanical properties of concretes for different exposure conditions

Mixture code	Compressive strength (MPa)			Splitting tensile strength (MPa)			Dynamic modulus of elasticity (MPa)		
	Mode A	Mode B	Mode C	Mode A	Mode B	Mode C	Mode A	Mode B	Mode C
R	74.2	71.7	68.5	4.3	4.2	4.0	58863	57362	56447
P1-50	61.6	61.7	60.0	4.3	4.4	4.3	50703	51550	49520
P1-100	47.4	47.1	45.6	3.5	3.6	3.3	46781	45985	43286
P24-50	62.7	60.6	60.3	4.8	4.8	4.3	53407	52683	50375
P24-100	50.5	50.5	48.6	3.9	3.9	3.8	48544	45742	43795

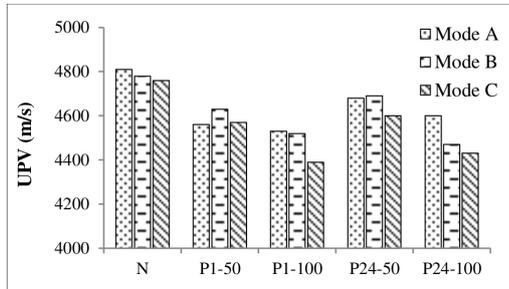


Fig. 6. UPV of concretes exposed to modes A, B and C

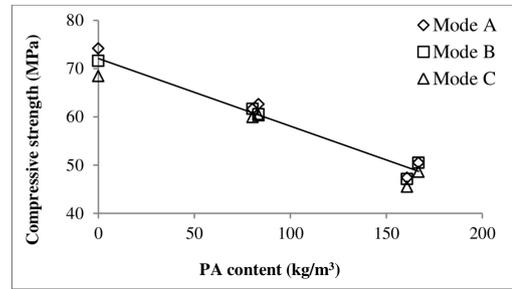


Fig. 9. Variation of compressive strength with PA content

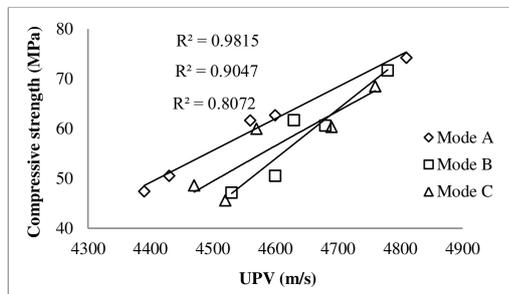


Fig. 7. Compressive strength–UPV relationship

in a slight increase in the compressive strength. Similar finding was reported by Kabay and Aköz [37] where they found that the increase in saturation degree of the LWA resulted in a higher strength. P24-100 achieved 6.5%, 7.2% and 6.6% higher strength values than P1-100 at modes A, B and C respectively. This behaviour can be attributed to the increased efficiency of the hydration due to the effective internal curing. But this trend was not observed in the samples with lower substitution ratio (P1-50 and P24-50).

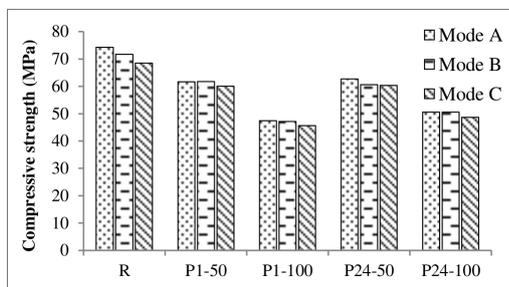


Fig. 8. Compressive strength of concretes exposed to modes A, B and C

The effect of curing conditions on compressive strength can be seen in Table 6. The compressive strength of the reference concrete (R) decreased by 3.4% and 7.7% when exposed to mode B and mode C respectively, in comparison to that at mode

A. The loss in the compressive strength of concrete mixes containing prewetted PA varied between 0% to 3.3% and 2.7% to 3.9% at modes B and C respectively; P1-50 performing the best. The worst exposure condition turned out to be mode C which simulates hot weather conditions, yielding the lowest compressive strength values for all concrete mixes. The results showed that the exposure conditions had a slight effect on the compressive strength, however it can be noticed that the mixes incorporating PA are less affected by changing the curing conditions from mode A to mode C.

The splitting tensile strength values of concretes are presented in Fig. 10. The substitution of 50% of fine aggregate by PA resulted in an increase in the tensile strength of concrete. The increase in tensile strength, particularly for P24-50 specimens, might be attributed to the higher bonding of aggregates and cement paste due to the better hydration caused by internal curing effect. The increase in the substitution ratio, on the other hand, resulted in drops. As in compressive strength, the increase in PA presoaking time from 1h to 24h contributed to the splitting tensile strength values; P24-50 possessed the highest values at all exposure modes. When we consider the reference concrete (R), the tensile strength slightly decreased by the change of the exposure mode in the order of A, B and C. However, when we consider the concrete mixes with PA, curing in air (mode B) did not adversely affect the tensile strength. The worst exposure condition, as in the compressive strength, turned out to be mode C.

The dynamic modulus of elasticity values of concretes are shown in Table 6. As expected the modulus of elasticity is reduced by the inclusion of PA and the reference concrete (R) possessed the highest values at all exposure conditions.

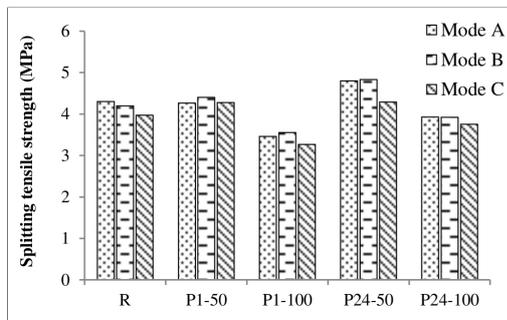


Fig. 10. Tensile strength of concretes exposed to modes A, B and C

3.4 Frost resistance

The relative residual strengths of concretes, at the end of the FT cycles, are presented in Fig. 11. According to Fig. 11, it can be noticed that the loss in strength was higher in the concrete mixes with 100% PA. While the reference (R) lost about 14% of its strength; P1-50 and P24-50 lost only about 2% of their strength after the FT cycles. Litvan and Sereda [38] and Kuboyama et al. [39] indicated that porous aggregates can be used to increase the frost resistance of concrete. The results obtained in our study also confirm this statement except for the concretes with 100% PA substitution. The highest deterioration was observed in P24-100 series, revealing a reduction of 34% in its compressive strength. This might be attributed to the higher amount of presoaked water content within the PA. This amount of water might possibly have caused an increased w/c ratio at the transition zone and caused excessive deteriorations during the FT cycles. The results showed that substituting 50% of fine aggregate with PA enhanced the FT resistance of concrete, however the increase in the substitution ratio had an adverse effect.

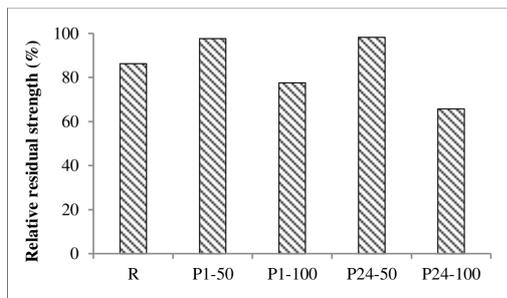


Fig. 11. Relative residual strength of concretes after FT cycles

4 Conclusions

Based on the test results of this study, the following conclusions may be drawn:

- 1 A reduction in compressive strength was observed when normal weight fine aggregate is replaced by pumice aggregate; the higher the replacement ratio resulted in higher reduction.
- 2 The effect of curing conditions considered in this research did not have a significant effect on the strength development of concretes; however addition of presoaked pumice aggregate decreased the strength drops when the curing conditions

changed from mode A to mode C, in comparison to the reference concrete.

- 3 Substituting 50% of fine aggregate with pumice aggregate resulted in a slight increase in the splitting tensile strength, compared to the reference, at all exposure modes. As in compressive strength, the increase in presoaking time from 1 h to 24 h contributed to the splitting tensile strength values and P24-50 possessed the highest tensile strength at all exposure modes.
- 4 Pumice inclusion provided a decrease in total shrinkage. P1-50 and P24-50 concrete mixes possessed the lowest total shrinkage values, when exposed to mode B and C respectively, providing more than 30% reduction in shrinkage, in comparison to the reference.
- 5 Frost resistance of the concretes was enhanced with the use of presoaked pumice aggregate at 50% replacement ratio; losing only 2% of their compressive strengths, where the reference lost 14%.

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