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RESEARCH ARTICLE

Experimental investigation on freeze–thaw durability of polymer concrete

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ABSTRACT Assessing the durability of concrete is of prime importance to provide an adequate service life and reduce the repairing cost of structures. Freeze–thaw is one such test that indicates the ability of concrete to last a long time without a significant loss in its performance. In this study, the freeze–thaw resistance of polymer concrete containing different polymer contents was explored and compared to various conventional cement concretes. Concretes' fresh and hardened properties were assessed for their workability, air content, and compressive strength. The mass loss, length change, dynamic modulus of elasticity, and residual compressive strength were determined for all types of concretes subjected to freeze–thaw cycles according to ASTM C666-procedure A. Results showed that polymer concrete (PC) specimens prepared with higher dosages of polymer contents possessed better freeze–thaw durability compared to other specimens. This high durability performance of PCs is mainly due to their impermeable microstructures, absence of water in their structure, and the high bond strength between aggregates and a polymer binder. It is also indicated that the performance of high-strength concrete containing air-entraining admixture is comparable with PC having optimum polymer content in terms of residual compressive strength, dynamic modulus of elasticity, mass loss, and length change.

KEYWORDS durability test, freeze-thaw resistance, polymer concrete, residual compressive strength, ASTM C666-15

1 Introduction

Concrete is the most widely used construction material globally due to its remarkable characteristics and low production and maintenance costs [1,2]. It is typically considered a composite material composed of aggregates, binding agents, and water [3]. Polymer concrete (PC) benefits from the polymeric materials as a binding agent instead of cement paste used in conventional concrete [4,5]. Various polymeric materials such as polymer resins, epoxy resins, furan resins, polyurethane resins, and urea-formaldehyde resins have been found since their first usage in the early 1950s [6–11]. Due to its several benefits, PC can be used in various applications, including repair and rehabilitation of the structures such as dams, bridges, pavements, and base foundations and building precast components used in bridge panels, waste containers, and machinery foundations [12–18].

It has been established that PC has superior advantages over conventional cement concrete in terms of mechanical behavior and durability [10,19,20]. PC benefits from a more ductile behavior and superior resistance to ions penetration and chemical attacks [10,21,22]. Additionally, the higher compressive and tensile strengths of PC and its superior durability properties, have made it appealing for repair purposes when the infrastructure is exposed to extreme environmental conditions [21–25].

The high cost of polymeric materials and consequently PC might bring all its desirable characteristics into question [26–29]. To overcome this issue, an optimum amount of polymeric materials is required to achieve superior characteristics at a reasonable cost [20,30–33]. PC's mechanical and durability characteristics depend on several factors such as aggregate properties, polymer content, and its properties, temperature, admixtures, and

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curing condition that need to be addressed [20]. In this regard, several studies [33,34] have been conducted to study the effects of various types of polymeric materials in the mixture to reach desirable mechanical characteristics including modulus of elasticity and compressive, tensile, flexural, and interfacial shear strengths. Among them, Shokrieh et al. [35] studied the effect of the size of the aggregates, percentages of epoxy resin, and glass fiber content on the mechanical properties (i.e., compressive, bending, and interfacial shear strengths) of the PC. They concluded that polymer content was the most significant factor affecting the mechanical behavior of specimens; while, the other two factors have minimal effect (less than 10%). Jafari et al. [20] investigated the effect of the temperature, polymer content, and different coarse aggregate sizes on the mechanical behavior of PC. They reported that temperature was the most influential parameter affecting the compressive, splitting tensile, and flexural strengths of PC. Recently, Ferdous et al. [36] optimized the mixture design of PC considering the cost of material, mechanical behavior, and durability. They exposed PC specimens with different resin-to-filler ratios and matrix-to-aggregate ratios to various environmental conditions (i.e., air, water, saline solution, and hygrothermal) to examine the durability performance of the different mixtures. They revealed that PCs, in general, show excellent durability in harsh environments. The optimal resin-to-filler ratio is 1.5:1.0 to achieve a homogenous material with uniform distribution of aggregates. Furthermore, the optimal matrix-to-aggregate ratio is 1.0:1.35 to ensure a good balance between the performance and cost.

Freeze−thaw (F/T) resistance is one of the high-priority durability concerns, especially in cold regions, that should be addressed for various types of concrete [37,38]. Repeating F/T cycles leads to concrete deterioration, and stiffness and strength loss, due to expansion of water presented in the porous structure of concrete [39]. Past research [40,41] has proven that the high-performance fiber reinforced concrete can also be used in repair and rehabilitation applications although limited information is available on its durability. Wu et al. [40] investigated the F/T durability of Portland cement pervious concrete (PCPC) and concluded that the proper content of admixtures and modifiers such as air-entraining agent, latex, and polypropylene fibers could enhance F/T durability of PCPC. Feo et al. [41] investigated the F/T durability of high-performance fiber reinforced concrete using 0%, 1.25%, and 2.50% fiber volume fractions through resonant frequencies and dynamic modulus of elasticity to assess the durability factors (DF) of the mixtures. They reported that using fibers leads to a sensible increase (i.e., ~25%) in compressive strength compared to the control mixture (0% fiber). Furthermore, it was concluded that in samples containing 1.25% and 2.50% fiber, the reduction in DF is quite negligible compared to the control mixture. Richardson et al. [42,43] investigated the optimum amount and particle size of crumb rubber as admixture to reach F/T protection along with maximum strength. They reported that crumb rubber induces protection against F/T cycles; however, there is no unique relationship between the size of crumb rubber particles and the compressive strength of the specimens. Richardson et al. [43] studied F/T resistance of self-consolidating concrete with different replacement levels (i.e., 0%, 30%, 50%, 65%, and 80%) of cement with ground granulated blast-furnace slag (GGBFS). They concluded that the amount of GGBFS used in the concrete has a reverse relationship with the F/T resistance of specimens and using more than 50% GGBFS revealed significant reduction in relative dynamic elasticity modulus and mass loss when exposed to F/T cycles.

A review of the studies mentioned above shows that although the F/T durability of several types of cement concretes has been recently investigated, no study is available on the F/T resistance of PC. To better understand PC, its durability against freezing and thawing needs to be investigated and compared with the ordinary cement concretes so that engineers and material suppliers have sufficient knowledge of PC's performance as a repairing material. Toward this goal, the objective of this study is to focus on the influence of successive F/T cycles on PCs containing various polymer contents (10%, 12%, and 14%) as well as conventional cement concretes. The evaluated properties are fresh and hardened properties of concretes, mass loss, length change, dynamic modulus of elasticity, and DF when subjected to F/T cycles. In addition, the percentage loss in compressive strength of both conventional and PCs after F/T cycles is determined.

2 Materials

In this study, four types of conventional cement concrete and three types of PC were used in the experimental program. Aggregates are considered a significant component of any concrete mixture to provide workability, strength, and durability. Thus, understanding aggregates' physical and mineralogical properties is necessary to obtain a desirable mixture (see Table 1). Particle size distribution of both coarse and fine aggregates presented in Fig. 1 meets the range specified by ASTM C33-18. Besides, according to ASTM C29-17 for PC mixtures, an accurate combination of coarse and fine aggregates is required to minimize the void ratio while optimizing the polymer content. As such, the optimum combination of coarse to fine aggregate ratio is 1.2:1.0 (by wt.%). The polymer used in this study consisted of two phases; a bisphenol A based resin and a polyamide hardener, with a resin-to-hardener ratio of 1.7:1.0 (by wt.%) which the supplier recommends. The compressive strength of polymer samples (without using

Table 1 Properties of the aggregates

property	coarse aggregate	fine aggregate
SSD specific gravity	2.64	2.59
water absorption capacity	1.12%	0.97%
fineness modulus	–	2.82

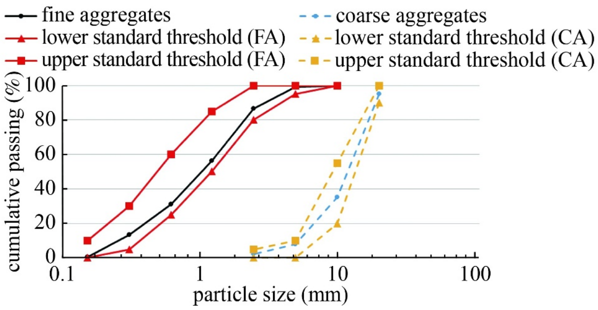

Fig. 1 Particle size distribution of the aggregates.

aggregate) was 71.1 MPa.

In HSC samples, the strength of samples was improved by replacing a part of cement with an ultrafine powder, called silica fume (SF), to improve the properties of concrete, particularly its compressive strength, bond strength, and abrasion resistance, through pozzolanic reaction [44]. The SF used in this study contains ~90% (by wt.%) reactive SiO_2 with a specific gravity of 2.23. Air entraining admixture was used in air-entrained cement concretes to provide stable microscopic air voids with proper spacing factor in the system. Moreover, for high-strength concrete, polycarboxylate-based super-plasticizer (SP) was used to reduce the water-cement ratio while maintaining the workability of the concrete.

3 Sample preparation and test method

The properties of concrete also depend on the preparation methods and curing conditions. Concrete mixtures used in this research are as follows.

Conventional cement concrete: Four types of cement concretes namely, normal concrete (NC), normal concrete with air-entrained admixture (NC-AE), high strength concrete (HSC), and high strength concrete with air-entrained admixture (HSC-AE) were designed according to the ACI 211.1 standard (see Table 2). In HSC mixture, the water to binder ratio decreased compared to NC mixtures to increase the strength of samples while providing the target slump of 75 ± 25 mm by adding proper SP dosage. The dosage of AEA was selected for NC-AE and HSC-AE mixtures to provide the air content of 5% ± 1% (by volume). All conventional cement concrete samples were cast and moist cured at 23°C ± 3°C for 24 h followed by demolding and curing in lime bathwater at 23°C ± 3°C until the test day.

PC: PC samples were prepared with three epoxy resin contents; 10%, 12%, and 14%, as shown in Table 3. For PC preparation, epoxy and resin were mixed for ~3 min until a homogenous material is obtained; it was then added to the aggregates. Next, the mixture was blended for ~5 min until all aggregates were coated with polymer. Generally, PC mixtures resulted in a lower slump due to the higher viscosity nature of polymeric binders compared to the cement paste. Samples were kept in the molds at 23°C ± 3°C for 24 h followed by demolding and curing at an elevated temperature (32°C ± 3°C) for 6 d.

The dimensions of concrete prisms for F/T-tests were 70 mm × 100 mm × 300 mm. For the compression test, the cylindrical specimens with 76 mm in diameter and 152 mm in height were prepared. For all tests, three replicate samples per mixture were cast to ensure the accuracy of the results, and the average results are reported.

3.1 Fresh properties of cement concretes

Concrete should have a proper balance between the plasticity and mobility for construction which depends on the selected type of aggregates, and a proper proportioning of its components (cement, aggregates, and water). As such, the workability of concrete mixtures is tested using the slump test (ASTM C143-15a). In addition, the air content in the fresh concrete was measured using the pressure method (ASTM C231-17a), in which the amount of air is determined from the change in volume of the concrete under a known pressure. Although cement concretes, in PC, slump and air content were not tested since the mixture is sticky and causes uncertainty.

3.2 Hardened properties of concretes

Hardened properties of concretes were measured using air

Table 2 Mixture design of conventional cement concretes

cement concrete	coarse aggregate (kg/m^3)	fine aggregate (kg/m^3)	cement (kg/m^3)	SF (kg/m^3)	water (kg/m^3)	SP (kg/m^3)	AEA (kg/m^3)	water/binder
NC	1070	670	350	0	164	0	0	0.47
NC-AE	1070	670	350	0	164	0	0.5	0.47
HSC	1070	670	315	35	120	1.8	0	0.34
HSC-AE	1070	670	315	35	120	1.8	0.5	0.34

Table 3 Mixture design of PCs (wt.%)

PC	coarse aggregate (%)	fine aggregate (%)	polymer content (%)
PC10	49.1	40.9	10
PC12	48.0	40.0	12
PC14	46.9	39.1	14

content at hardened state, compressive strength before and after exposure to F/T cycles, and F/T durability. For each mixture, cylindrical specimens were tested using compression test according to ASTM C39M-20 before and after the F/T cycles. For air-void in hardened concrete, the Rapid Air automated imaging system was used to analyze the air void distribution within the hardened concrete according to ASTM C457-16. For this purpose, a 70 mm × 120 mm × 10 mm section was cut from each concrete cylinder (perpendicular to the finished surface) and lapped using 75, 35, 17.5, and 12.5 μm grit sizes. Black marker and $BaSO_4$ powder were used to enhance surface contrast, resulting in a black surface with white air voids. After analyzing, the volume fraction of air voids (by volume) and their spacing factor (mm) were determined in the hardened concrete (see Table 4).

F/T resistance of the concrete mixtures was evaluated through the ASTM C666-15 test method, widely accepted in literature, especially for comparing the F/T resistance of various types of concrete [45,46]. According to ASTM C666-15 procedure A, prismatic hardened specimens are initially placed into metal boxes containing water up to 3 mm above the specimen in the F/T chamber, experiencing F/T cycles in accordance with the standard. The specimens were evaluated through non-destructive tests during testing, namely, mass loss, length change, and ultrasonic pulse velocity (UPV). Mass loss is computed through weighting specimens in thawed state and after cleaning the surface of the specimens. Length change is measured at given ages using a length comparator with an accuracy of 0.001 mm.

The F/T resistance of the concrete can also be evaluated by reducing the dynamic modulus of elasticity, namely, DF mentioned in Eq. (1). In this equation, N, $E_{\mathrm{d},x}$, and $E_{\mathrm{d},0}$ represent the number of cycles, dynamic modulus of elasticity at the xth cycle, and dynamic modulus of elasticity before the F/T-test, respectively. Dynamic modulus of elasticity at each state is computed using Eq. (2). In Eq. (2), ρ and v are density and passion ratio of concrete, respectively. According to literature, Poisson's ratio of cement and PC was reported 0.20 and 0.25, respectively [20,46]. Cylindrical specimens were also tested after the F/T cycles to evaluate their residual compressive strength.

$$DF = \frac{N \times \left(\dfrac{E_{\mathrm{d},x}}{E_{\mathrm{d},0}}\right) \times 100}{300}, \tag{1}$$

$$E_{\mathrm{d}} = \rho \times v_{\mathrm{us}}^2 \times \frac{(1+\nu)\times(1-2\nu)}{(1-\nu)}. \tag{2}$$

Table 4 Fresh properties of concretes

concrete type	slump (mm)	air content at fresh state (vol. %)	fresh density (kg/m^3)
NC	80	2.5	2380
NC-AE	90	6.1	2362
HSC	80	2.2	2408
HSC-AE	85	5.7	2398
PC10	–	–	2184
PC12	–	–	2236
PC14	–	–	2240

4 Result and discussion

4.1 Fresh properties of cement concretes

The slump and air content at the fresh state of the mixtures are presented in Table 4. The slump of concrete mixtures is in the desired range confirming the acceptable workability. In high strength concretes (HSC and HSC-AE), enough SP was added to compensate to reduce water content and provide good workability. Furthermore, the mixtures incorporated with AEA showed higher workability resulted in a denser and more uniform concrete mixture.

Moreover, adding AEA can enhance the air content from 2.5% in NC and 2.2% in HSC to 6.1% in NC-AE and 5.7% in HSC-AE mixtures. It has been confirmed that adding AEA is a common practice that increases the air content of the cement concrete from 2% to above 4% depending on the added dosages. Above the recommended range (usually above 6%), a reduction in mechanical properties (such as a reduction in strength) causes significant issues. Furthermore, the fresh density results show that PCs can be considered lightweight concretes (~10% less than cement mixtures).

4.2 Hardened properties of concretes

4.2.1 Air content in hardened state

Concrete resistance against F/T damage is related to two main factors: 1) adhesion between binder and aggregate which can be evaluated through compressive strength, and 2) air content and spacing factor. Table 5 illustrates the air content in 14 d samples of all mixtures. Overall, the porosity of PC is higher than that for cement concretes, and it depends on the polymer content, which

Table 5 Hardened properties of concretes

concrete type	air content at hardened state (vol.%)	spacing factor (mm)	7 d compressive strength (MPa)	14 d compressive strength (MPa)	strength development from 7 to 14 d (%)
NC	2.7	0.512	18.2	24.8	36.3
NC-AE	6.1	0.185	17.1	21.5	25.7
HSC	2.8	0.487	26.7	36.8	37.8
HSC-AE	6.3	0.192	24.5	32.9	34.3
PC10	8.4	0.194	48.9	50.8	3.9
PC12	7.5	0.224	61.8	62.7	1.5
PC14	6.9	0.231	66.7	67.3	0.9

can be seen in Table 5. As it can be seen, the porosities for cement concretes without AEA are 2.7%; while, adding AEA can enhance this value to above 6%. On the other hand, the air content at hardened state for PCs ranges from 6.9% to 8.4%. An increase in the polymer content from 10% to 12% resulted in a more significant reduction in air content than an increase from 12% to 14%. The reason is that aggregates were uniformly coated and provided a better bond according to previous study [20]. This indicates that the designed PC mixtures are more permeable compared to cement concrete mixtures. Furthermore, the spacing factor in concretes containing AEA is less compared to non-AEA mixtures suggesting proper F/T durability. However, PC samples contain higher air content and higher spacing factors, which means that the voids are larger and farther from each other than cement concrete mixtures.

4.2.2 Compressive strength

The compressive strength of specimens was tested at 7 and 14 d to ensure the accuracy of mix design proportions and strength development over time. As can be deduced from Table 5 and Fig. 2, the compressive strength of the cement concrete mixtures ranges from 17 to 27 MPa for 7 d and 21 to 37 MPa for 14 d; while for PCs, the compressive strength is higher and ranges from 49 to 68 MPa. In HSCs, the reduction in water content was quite effective in increasing the strength by almost 40%

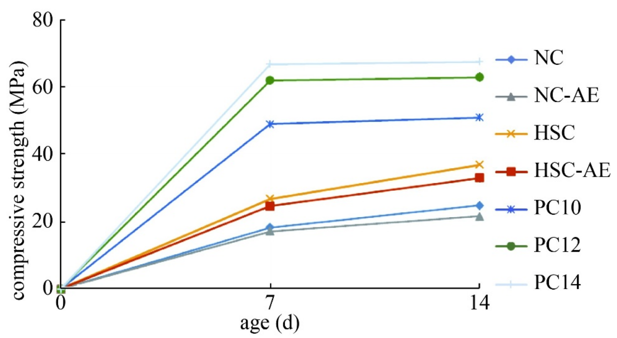

Fig. 2 Compressive strength of the specimens.

compared to NCs. As expected, the PC mixtures using a higher dosage of polymer content achieved higher compressive strengths than other mixtures. An increase in polymer content from 10% to 14% caused an almost 40% increase in compressive strength. The rate of increase in the compressive strength decreased with increasing polymer content, which means that the difference between the compressive strength of PC10 and PC12 is 12 MPa; while this value is 5 MPa when comparing PC10 to PC14.

The strength development with aging from 7 to 14 d for NC, HSC, and HSC-AE is between 34% to 37% and this value for NC-AE is only 23%. However, there is no significant difference (less than 4%) between PCs' 7 and 14 d strength, showing much lower strength development with aging. This is in accordance with the literature that the development of strength in PCs occurred in the first 7 d and slightly gained strength from day 7 to 14. It can also be concluded that in cement concretes, the addition of AEA slightly reduced the strength [45].

4.3 Freeze–thaw resistance

4.3.1 Failure mode

Figure 3 shows the HSC, HSC-AE, and PC14 samples at the end of 300 F/T cycles. It can be observed that in HSC, the detachment occurred mainly on the edges and corners of the sample. Also, on the sample's surface, some aggregates dislodged from the sample during the F/T cycles. However, in HSC-AE, only a slight loss with the separation of paste from the aggregate occurred on the surface. For PC14, there is no aggregate separation observed, and minor cracks occurred on the sample's surface. The main reason for pop-outs is that the expansion of saturated aggregates near the sample's surface disintegrates the surrounding binder. When the water inside aggregate freezes, it generates pressure surrounding the paste, which causes failure in both aggregate and paste.

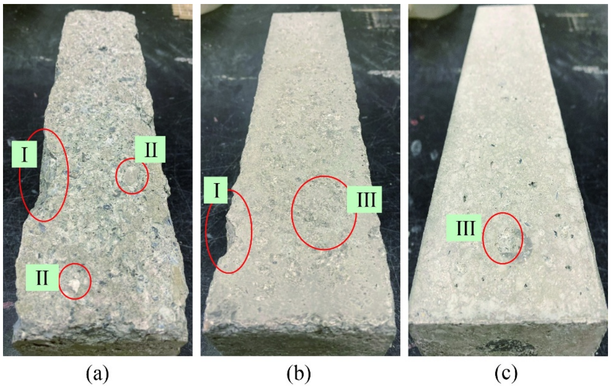

Fig. 3 Typical degradation of (a) HSC, (b) HSC-AE, and (c) PC14 specimens after 300 F/T cycles (I: damages on the edge, II: aggregate's pop-out and surrounding paste deterioration, III: paste deterioration).

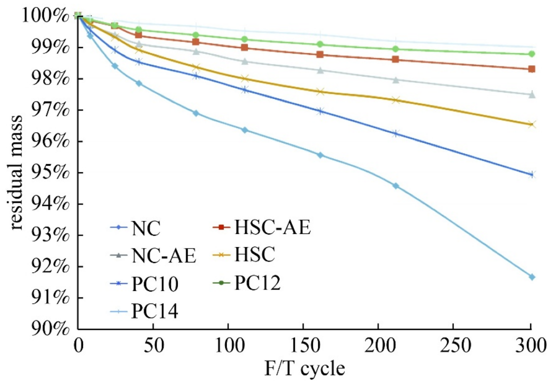

Fig. 4 Residual mass versus F/T cycle.

4.3.2 Residual mass

The residual mass ratio for all mixes has been presented in Fig. 4. The mass loss for NC, HSC, NC-AE, HSC-AE, and PC10 after the complete F/T cycles is around 8.5%, 3.5%, 2.5%, 1.5%, and 5.0%, respectively, while this value for PC12 and PC14 is about 1.0%. At the initial cycles, the mass of the specimens decreased with a steep slope up to 50 cycles. After that, the curves followed almost a linear trend for all samples until the end of the test except for NC. Moreover, the slope of the line after 50 cycles is higher for NC and PC10 compared to the other specimens. For NC samples, after 200 cycles, a significant reduction occurred in mass which is related to surface pop-outs. This effect occurs when the air voids are not distributed properly in the hardened samples and are not sufficient near the sample's surface. In addition, the strength of concrete can also play an important role since there is a positive relationship between the strength of concrete and the bond between aggregate and paste. As a result, NC, which had the lowest strength and air voids, showed more severe deterioration and reduction in mass among mixtures. The performance of HSC was a bit better than NC since the bond between aggregates and pastes is stronger and can prevent the cracks from propagation up to some extent. As such, the deterioration can be slightly controlled. It should be noted that adding AEA improves F/T resistance in both normal and high strength cement concretes due to the expansion of water molecules when freezing. The expansion releases in the air voids inside the concrete; otherwise, the concrete distresses and cracks.

It is evident that PC10 showed a 5% reduction in mass as a result of F/T cycles. This is because some aggregates dislodged from the sample, especially from the corners, during the test since the polymer content was not sufficient to coat all the aggregates, and relatively weak interface bond between aggregates and binder was formed. As such, the internal stress caused deterioration and separation. On the other hand, 12% and 14% PC showed superior performance against F/T durability due to the strong adhesion between aggregate and polymer binder and impermeable microstructure of polymer that prevents water transport and thus did not allow having partially or fully water-saturated pores.

4.3.3 Length change

The expansion of the specimens after the F/T action occurred since the water in capillary pores freezes at a higher temperature compared to that in gel pores. This resulted in water movement from the gel pores (higher energy state) to the capillary pores (lower energy state) to neutralize the created energy gradient. Usually, the hardened product in binder is not strong enough to offset the expansion caused by the freezing of the water; as such, an overall expansion occurs in the system [47]. As a result of this phenomenon, the length change values are important during the F/T-test presented in Fig. 5. During the first few cycles, contractions were observed for all mixes. This can be explained by the lower temperature of the specimens at the time of measurement when compared to the initial measurement obtained before subjected to freezing and thawing. In general, concretes containing higher strength showed more continuous contraction; as for PC14, it continues until 50 cycles. This is because the expansion of the high-strength specimens during the initial stages is not enough to offset their contraction.

Moreover, it is confirmed that concrete samples without AEA are not F/T resistant as the water in the pores needs to move a longer distance to be released. Thus, the expansion value is much higher than those containing AEA which resulted in larger cracks and complete failure. Despite both NC-AE and HSC-AE mixes reported better performance in this regard, only HSC-AE could meet the maximum length change recommended by the ASTM C666-15 standard. The air voids incorporated in

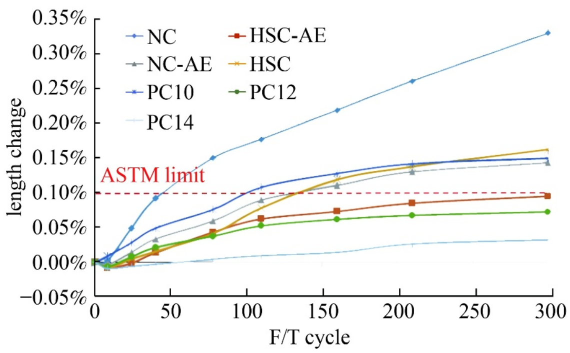

Fig. 5 Length change of samples exposed to consecutive F/T cycles.

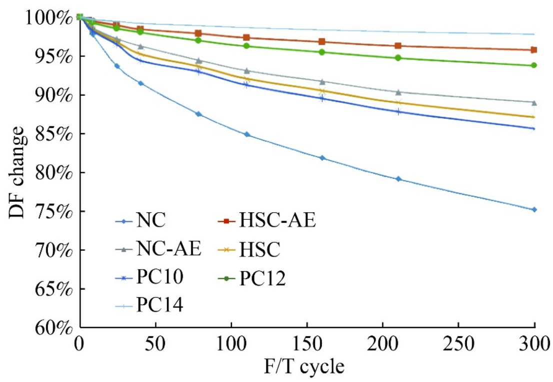

Fig. 6 DF of samples exposed to consecutive F/T cycles.

concrete allow hydraulic pressure dissipation, preventing the expansion of the system [45,47]. The length change for PC10 after 300 cycles is 0.15% which is above the recommended limit. However, PC12 and PC14 possessed the final expansion of 0.07% and 0.03%, respectively, showing proper F/T resistance. It can be concluded that the F/T action is less important in PCs because they can easily dissipate hydraulic pressures.

4.3.4 Dynamic modulus of elasticity

To evaluate the ability of concretes in resisting F/T attacks as a measure of degradation, the DF was calculated at various cycles, and the results are summarized in Fig. 6. According to ASTM C666-15, the specimens are considered to be F/T resistant when the residual dynamic modulus of elasticity does not diminish to less than 60 percent of its initial value after 300 cycles. Considering this limit, all specimens are F/T resistant, and this is not in agreement with the results of the length change discussed earlier. From this contradiction, it can be concluded that for the F/T-test, all the parameters/measurements should be evaluated to accept or reject an individual mixture for F/T resistance. The DF values for PC12, PC14, and HSC-AE are above 90%, showing superior characteristics in F/T cycles, the NC-AE, HSC, and PC10 are in the range of 85% to 90%; while, this value for NC is 75% suggesting the low performance of this type of concrete against F/T cycles. Using polymer as a binder in the mixtures instead of cement paste revealed a significant improvement in F/T durability. In addition to that, using AEA indicates a lower reduction in DF during F/T cycles when compared with non-AEA cement concretes.

4.3.5 Residual compressive strength

In this section, compressive strength was performed on 14 d specimens before F/T cycles (presented in the compressive strength section above) and after exposure to 300 cycles of F/T to calculate the residual strength. The advantage of measuring residual strength is that it can provide invaluable information regarding the internal bond between aggregates and paste. As shown in Table 6, the compressive strength of NC decreased about 45%, which means that the F/T phenomenon is destructive due to intense internal damages, and this is somehow in agreement with the results of Bogas et al. [47]. The reduction in strength for HSC is 30%, confirming the low resistance against F/T. However, adding AE can decrease the reduction in strength as the reduction in strength for NC-AE and HSC-AE is in the range of 11% to 14% indicating that these mixtures would likely have moderate F/T durability. On the other hand, in PC samples, the higher polymer content samples showed less strength reduction. In PC10, the strength reduced ~20% after exposure to 300 F/T cycles, which showed moderate resistance against F/T cycles. However, PC12 and PC14 showed a 9% and 4% reduction in strength, respectively, indicating adequate F/T resistance.

5 Conclusions

The F/T durability of concrete has attracted significant attention in cold-climate regions over the past several decades. Concerning the testing results, the following major conclusions can be drawn.

Table 6 Residual strength of samples after F/T cycles

concrete type	14 d compressive strength (MPa)	compressive strength after exposing to F/T cycles (MPa)	residual strength (%)
NC	24.8	13.8	55.6
NC-AE	21.5	18.4	85.6
HSC	36.8	25.8	70.1
HSC-AE	32.9	29.2	88.8
PC10	50.8	41.5	81.7
PC12	62.7	57.2	91.2
PC14	67.3	64.6	96.0

1) The comparison between cement and PC shows that the presence of water in the former and its involvement in the reactions and the impermeable micro-structure later accelerate the deterioration of cement concrete under F/T cycles. The comparison between NC and HSC mixtures reveals that the improvement in F/T resistance has occurred by reducing the water to binder content, adding SP, and using air-entrained admixture. There is a strong positive correlation existed between the strength and F/T durability of specimens.

2) Based on the results of mass loss, length change, and DF change obtained from the F/T-test, the NC sample indicates severe internal damages, which results in complete deterioration (0.34% increase in length and 25% loss in DF); while NC-AE and HSC reveal moderate damage when exposed to F/T cycles by having ~0.16% increase in length and ~12% loss in DF. HSC-AE can effectively resist against F/T cycles with 0.10% length change and 4% reduction in DF among cement concretes.

3) The results show that PC10 can be subjected to F/T damages due to its high porosity, high spacing factor, and low bond between aggregates and polymer content. However, PCs containing 12% and 14% polymer contents show outstanding resistance against F/T in terms of minor length change (below 0.08%), negligible mass loss, and only 6% and 2% reduction in DF for PC12 and PC14, respectively.

4) According to the residual compressive strength results, NC and HSC have the lowest performance among mixtures by reducing almost 50% and 30% in their strengths, respectively. However, adding AEA to these mixtures improves the reduction in strength to a value of 14% and 11% in NC-AE and HSC-AE, respectively. In addition, PC10 shows a 20% reduction in strength after F/T cycles, while both PC12 and PC14 indicate superior resistance by only 9% and 4% reduction in their strength, respectively.

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