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Performance of blended cement concretes prepared with constant workability

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ABSTRACT

The use of supplementary cementing materials, such as silica fume, fly ash, blast furnace slag, and natural pozzolans, has been promoted by their technical and economic advantages. However, in certain parts of the world, where these materials are not available locally, their utilization is solely based on their technical superiority. The practice in such regions is to replace part of the cement with the selected supplementary cementing materials while maintaining constant water-to-cementitious materials ratio. In such cases, the advantage of a reduction in the water requirement of certain materials is not utilized. In the reported study, fly ash, silica fume, or a highly reactive finely pulverized fly ash replaced part of the cement. The concrete mixtures were designed for a constant workability of 75–100 mm slump. The performance of ordinary Portland cement (OPC) and silica fume (SF), fly ash (FA) and very fine fly ash (VFFA) cement concretes was evaluated by measuring the compressive strength development and reduction in both compressive strength and pulse velocity after exposure to moisture and thermal variations, and sulfate (SO_4^- = 1%, 2%, and 5%) solutions. The effect of curing regime, namely water ponding and application of a curing compound, was also evaluated. It was noted that the water requirement of FA cement concretes was less than that of OPC and SF cement concretes. Consequently, the mechanical properties and durability characteristics of the former cements were better than those of the latter cements. It was also noted that a longer curing period, prior to the application of a curing compound, is beneficial to OPC, SF, FA, and VFFA cement concretes. Curing with water tended to improve the quality of OPC, SF, FA, and VFFA cement concretes; and as the curing period increased the quality improved further.

1. Introduction

The reduction in the useful service-life of reinforced concrete structures, caused by aggressive environments and other factors, is a well-recognized phenomenon. In Europe and North America, deterioration of highway structures is attributed to the use of deicer salts. In the other parts of the world, including the above two continents, reinforcement corrosion is noted in marine and other structures exposed to chloride environments [1,2]. In the coastal areas of the Arabian Gulf, deterioration of reinforced concrete is attributed to the following inter-related factors: (i) severe climatic and geomorphic conditions, (ii) poor quality of construction materials, particularly the aggregates, and (iii) inappropriate construction practices [1,2]. The premature deterioration of reinforced concrete construction in this part of the world has resulted in considerable resources being diverted towards the repair and rehabilitation of these structures. The main forms of concrete deterioration are cracking and spalling due to reinforcement corrosion, cracking and softening due to sulfate attack, and cracking due to environmental effects. However, deterioration of concrete due to reinforcement corrosion outweighs that caused by all the other factors [3,4]. In such environments, concrete needs to be designed for durability rather than strength alone and the first step towards achieving this goal is to produce quality concrete.

The quality of concrete can be improved by using suitable materials and appropriate mix proportions. Parameters that affect the quality of concrete include: water to cementitous materials ratio, cementitious materials content, and size and grading of aggregates. Incorporating supplementary cementing materials, such as fly ash, blast furnace slag and silica fume, can further decrease the permeability of concrete to water, and diffusion of oxygen, chloride, carbon dioxide, etc. The former aspect, namely, the effect of mix design on concrete durability, has been extensively studied at the international level and in the Arabian Gulf [5]. However, the use of supplementary cementing materials in the semi-arid and arid areas of the world, to improve concrete durability, deserves special attention for two reasons. Firstly, the climatic conditions of such regions make curing a difficult process and, secondly, in some places, such as in the Arabian Gulf, these materials are used purely for their technical merits. As such, it is prudent to utilize these materials properly.

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Supplementary cementing materials are often used in concrete to enhance its durability. Initial studies on the use of supplementary cementing materials, such as fly ash and blast furnace slag, in the Arabian Gulf were conducted at King Fahd University of Petroleum and Minerals [6,7]. These studies [6,7] indicated that proper characterization of these materials is essential, since not all the materials performed as expected. Subsequent studies were concerned with the use of silica fume, fly ash, and blast furnace slag to enhance concrete durability. Results of these studies [1,8] indicated that these materials could be beneficially utilized to significantly improve the durability of concrete. Among the industrial by-products investigated in these studies, silica fume performed better than others. However, concerns were raised regarding the performance of silica fume cement concrete in magnesium sulfate-bearing soil and groundwater [9,10]. The second concern is the increased plastic and drying shrinkage of silica fume cement concrete under hot and dry conditions [11,12]. Shekarchi et al. [13] investigated the long-term chloride diffusion in silica fume cement concrete in harsh marine climate. It was reported that partial cement replacement, up to 7.5%, with silica fume decreased the chloride diffusion coefficient [13]. It was further reported that for higher replacement levels the diffusion coefficient did not decrease significantly [13].

Another concern regarding the supplementary cementing materials is regarding their water requirement. While some materials decrease the water demand, others require more water to produce the desired workability. As such, it is important to compare the properties of blended cement concretes proportioned for similar workability for a fair comparison. Reduction in the volume of water required for certain workability, in a certain material, may enhance its properties over those that require more water. Another concern is with regard to the curing method and duration on the properties of blended cement concretes, as these concretes require early and extended curing compared to OPC concrete.

This study was conducted to assess the water requirement of some blended cement concretes and consequently assess the improvement in their properties due to the reduction in the volume of mix water. The effect of curing regime on the properties of both OPC and blended cement concretes was also studied.

2. Casting of concrete specimens

Concrete mixtures were prepared with silica fume from one source and fly ash from two sources (normal and very fine fly ash). Table 1 summarizes the chemical composition and the physical properties of OPC, silica fume (SF), and the two fly ashes selected for evaluation in this study.

The selected SF cement concrete contained 7.5% SF, by weight of the cementitious materials. The regular fly ash (FA) was used as a 30% replacement of cement, while the very fine FA (VFFA) was used as 10% replacement. The concrete mixtures were designed for a constant cementitious materials content of 370 kg/m^3. A coarse-to-fine aggregate ratio of 1.62 was kept invariant in all the concrete mixtures. Crushed limestone with a specific gravity of 2.42 and water absorption of 2.5% was used as the coarse aggregate. Dune sand with a specific gravity of 2.64 and water absorption of 0.5% was used as the fine aggregate. Prior to their use, the coarse aggregates were sieved to various sizes and washed to remove the dust and loose particles. They were then remixed to obtain the desired grading that corresponded to size #67 of ASTM C 33.

Table 1
Composition of selected cement and supplementary cementing materials.

Property	Value			
	OPC	Silica fume	Fly ash	Very fine fly ash
Moisture content (%)	–	0.95	<0.1	<0.2
Loss on ignition (%)	1.06	1.76	0.8	0.4
SiO_2 (%)	21.92	89.4	52.8	53.5
Fe_2O_3 (%)	2.92	2.90	3.5	3.6
Al_2O_3 (%)	4.53	1.20	34.3	34.3
CaO (%)	65.03	1.20	4.4	4.4
MgO (%)	1.74	0.07	1.1	1.0
Na_2O (%)	–	0.12	0.4	–
K_2O (%)	–	0.034	0.5	–
SO_3 (%)	–	0.30	0.10	–
Material retained on # 325 sieve (%)	–	0.50	9.5	–

The water content in the concrete mixtures was adjusted to obtain workability in the range of 75–100 mm slump in order to compare the water requirement of the selected supplementary cementing materials. The constant slump was obtained through the adjustment of water content, without the use of any superplasticizer. The water requirement will, consequently, affect the effective water-to-cementitious materials ratio and, hence, the properties of fresh and hardened concrete. It is generally known that the water requirement of FA for a particular workability is less than that of SF [14–16]. However, the influence of the water demand on the properties of blended cement concretes is not very well documented in the literature.

3. Testing of concrete

Concrete specimens, 75 mm in diameter and 150 mm high, were cast from each of the concrete mixtures. These concrete specimens were tested after 3, 7, 14, 28, 90, 270, and 450 days of water curing to evaluate the strength development. Three specimens were tested at each age and the average values are reported. The standard variation between the test results was within acceptable limits.

To assess the performance of OPC, SF, FA, and VFFA cement concretes in the structural components exposed to groundwater and soil contaminated with sulfate salts, concrete specimens, 75 mm in diameter and 150 mm high, were water-cured for 28 days and, thereafter, exposed to solutions containing 1%, 2%, and, 5% $MgSO_4$. After 90, 270, and 450 days of exposure to the sulfate solutions, they were tested in compression to assess the effect of exposure solutions on the strength of concrete.

The performance of OPC, SF, FA, and VFFA cement concretes in salty environments was evaluated by placing specimens, 75 mm in diameter and 150 mm high, in a 15.7% Cl^- plus 0.55% SO_4^{--} solution [17] after being water-cured for 28 days. These concrete specimens were exposed to the sulfate–chloride solution for 6 h and then allowed to dry in the laboratory environment (22 ± 3 °C) for 18 h. This wet-dry period constituted one cycle. After 90, 270, and 450 cycles of exposure, the concrete specimens were retrieved and tested to determine the reduction in compressive strength. This exposure represents marine conditions in the hot regions of the world.

To evaluate the effect of the method and duration of curing on the properties of OPC and blended cement concretes, the specimens were cured under the following conditions:

(i) Water ponding for 7, 14, and 28 days.
(ii) Application of a curing compound directly after demolding and storing the specimens in the air-dry laboratory environment for two more days.
(iii) Curing the specimens with wet burlap for 3 days and thereafter applying the curing compound.
(iv) Curing the specimens with wet burlap for 7 days and thereafter applying the curing compound.

After the designated curing, the concrete specimens were exposed to thermal variations (70 °C for 3 h and 25 °C for 9 h). After

Table 2
Total and effective water-to-binder ratio in OPC, SF, FA, and VFFA cement concretes.

Concrete	Total water-to-cementitious materials ratio	Effective water-to-cementitious materials ratio
OPC	0.486	0.40
OPC + silica fume	0.528	0.442
OPC + fly ash	0.428	0.342
OPC + very fine fly ash	0.451	0.365

Table 3
Chloride permeability of OPC, SF, FA, and VFFA cement concretes.

Concrete	Chloride permeability, Coulombs	ASTM C 1202 classification
OPC	1400	Low
OPC + silica fume	912	Very low
OPC + fly ash	496	Very low
OPC + very fine fly ash	1038	Low

90, 270, and 450 thermal cycles, the specimens were tested to determine: (i) compressive strength and (ii) pulse velocity. The pulse velocity was measured according to ASTM C 597 using PUNDIT pulse velocity measuring device. Transducers of 100 MHz were utilized.

The chloride permeability of the OPC and blended cement concrete specimens was determined according to ASTM C 1202, after 28 days of water curing.

4. Results

4.1. Water requirement

The water required to maintain a workability of 75–100 mm slump in the OPC concrete, i.e. without supplementary cementing materials, was 178.9 l/m^3 of concrete, while 194.3 l of water was required for the SF cement concrete. The water required to obtain a slump of 75–100 mm was 154.7 and 165.8 l, respectively, for the 30% FA and 10% VFFA cement concretes. The lower water requirement of the FA and VFFA cement concrete resulted in a lower water-to-cementitious materials (w/cm) ratio in these concrete mixtures compared to OPC and SF cement concrete mixtures. The effective and total w/cm ratios in the OPC, SF, FA, and VFFA concrete mixtures are summarized in Table 2. The effective w/cm ratio is obtained by deducting the water absorbed by the aggregates from the total w/cm ratio. The effective w/cm ratios in the FA (0.342) and VFFA (0.365) cement concretes were less than that in the OPC (0.40) and SF (0.442) cement concretes. The reduction in w/cm ratios may contribute to the increased strength and enhanced durability of the concrete structures incorporating FA and VFFA.

4.2. Compressive strength development

The compressive strength development in the OPC, SF, FA, and VFFA cement concretes is plotted in Fig. 1. The compressive strength of SF, FA and VFFA cement concretes was generally more than that of the OPC concrete, particularly after 14 days of curing. The compressive strength of SF cement concrete specimens was initially less than that of OPC concrete up to 7 days of curing. However, it increased later. The data in Fig. 1 indicate the superior performance of SF, FA and VFFA cement concretes compared to OPC concrete. The improved performance of FA and VFFA cement concretes may be attributed to their lower w/cm ratio, as shown in Table 2.

4.3. Chloride permeability

The chloride permeability of OPC, SF, FA, and VFFA cement concretes is summarized in Table 3. This table also shows the chloride permeability classification according to ASTM C 1202. According to this classification, the chloride permeability was very low in the SF and FA cement concrete specimens while it was low in the OPC and VFFA cement concretes. As expected, the highest chloride permeability was measured in the OPC concrete specimens. The highest reduction in the chloride permeability was noted in the FA cement concrete, followed by the SF and VFFA cement concretes. The addition of supplementary cementing materials to OPC concrete results in a decrease in the permeability of blended cement concrete due

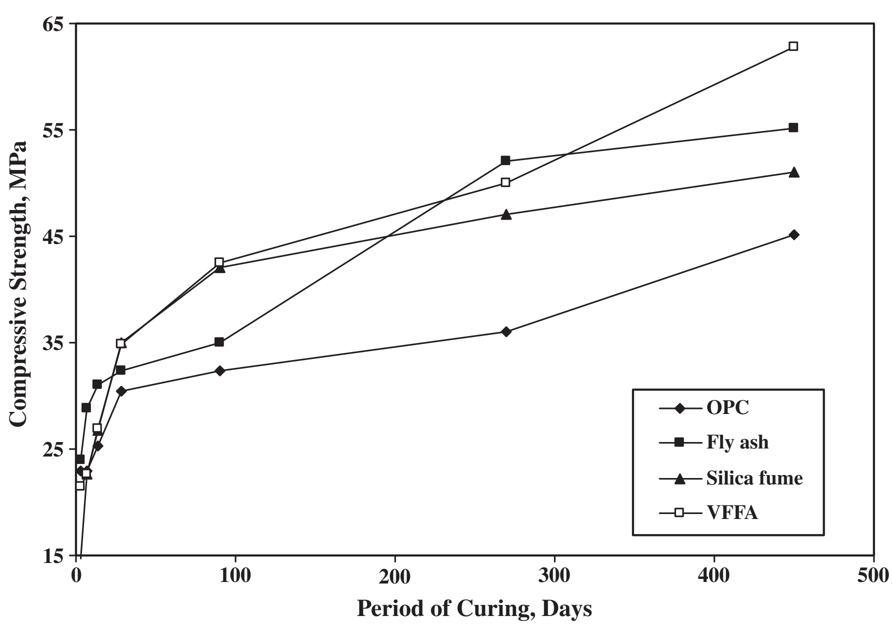

Fig. 1. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens.

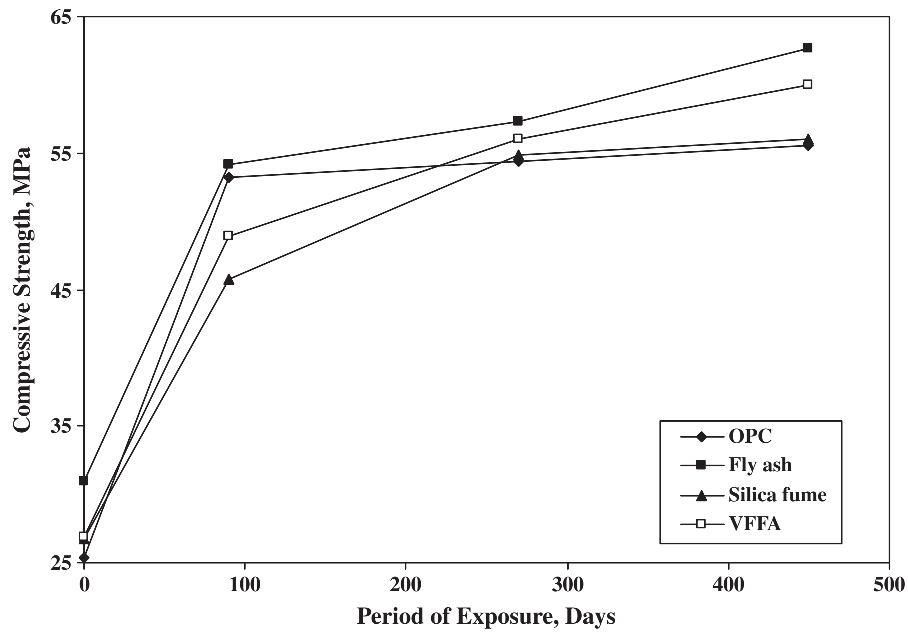

Fig. 2. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 1% $MgSO_4$ solution.

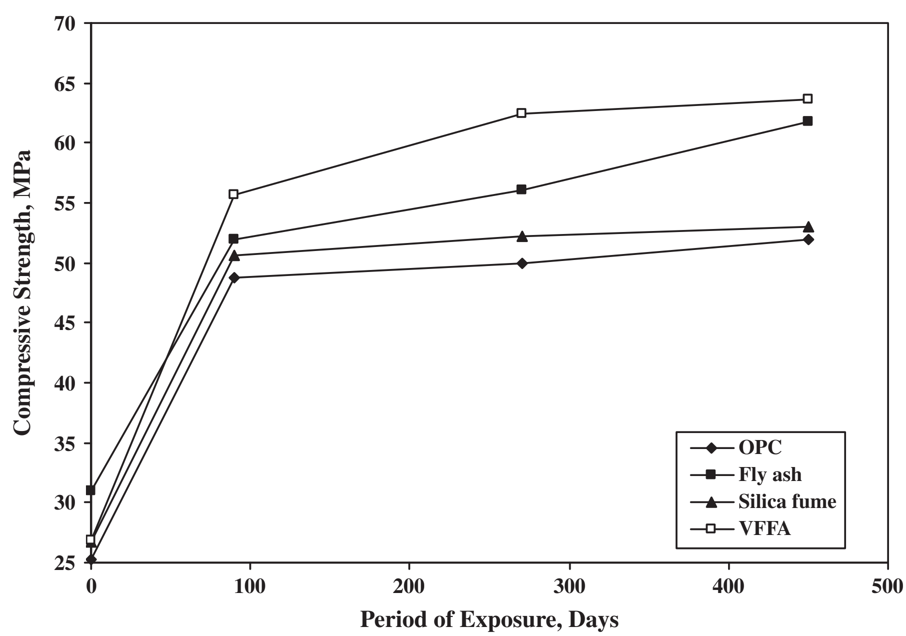

Fig. 3. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 2% $MgSO_4$ solution.

to the conversion of $Ca(OH)_2$ to secondary calcium-silicate-hydrate [18,19]. The dense pore structure of blended cement concrete decreases its electrical resistivity. Further, the reduced chloride permeability, as noted in the blended cement concretes, indicates that the rate of reinforcement corrosion in these concretes will be lower than that in the OPC concrete [20].

4.4. Sulfate resistance

The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 1% $MgSO_4$ solution is plotted in Fig. 2. The compressive strength increased with the period of exposure, indicating that the low concentration of $MgSO_4$, in this case 1%, did not significantly affect the compressive strength within the exposure period of 450 days. Further, the compressive strength of FA and VFFA cement concrete specimens was more than that of OPC and SF cement concretes even after 450 days of exposure to 1% $MgSO_4$ solution.

The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 2% $MgSO_4$ is plotted in Fig. 3. In these specimens also the compressive strength increased with the period of exposure. After 450 days of exposure, the compressive strength of VFFA and FA cement concrete specimens was more than that of OPC and SF cement concrete specimens.

The compressive strength of OPC and blended cement concrete specimens exposed to 5% $MgSO_4$ is plotted in Fig. 4. The compres-

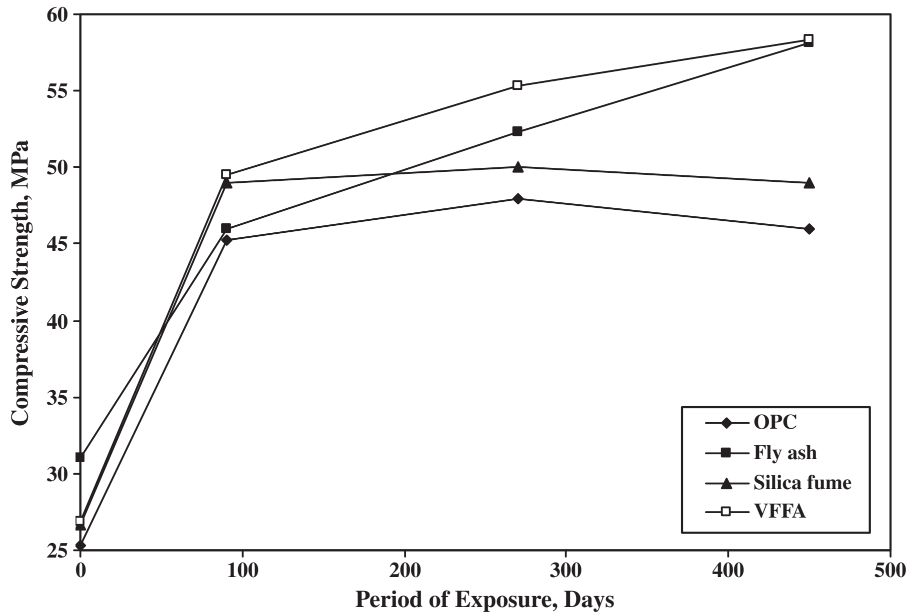

Fig. 4. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 5% $MgSO_4$ solution.

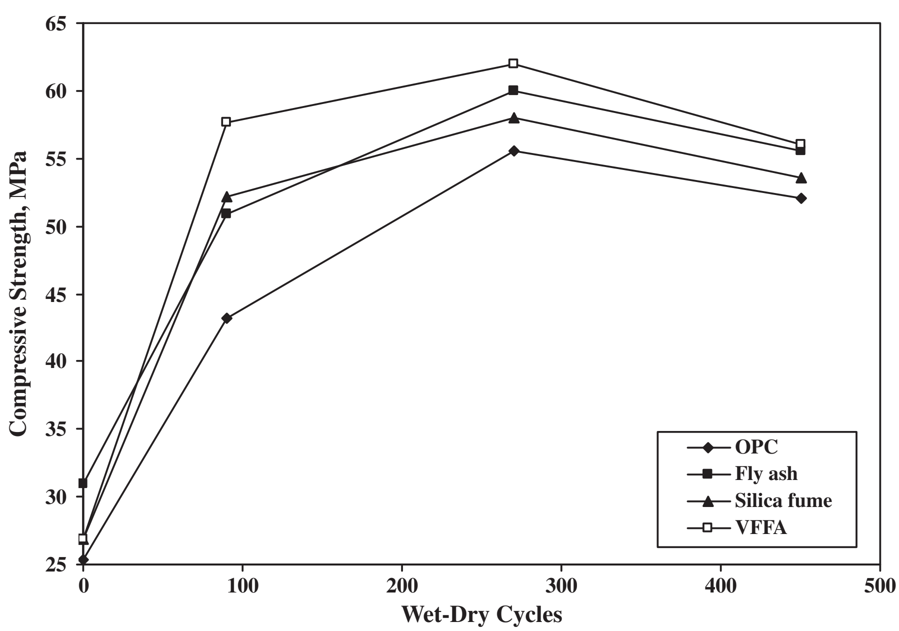

Fig. 5. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to moisture variation.

sive strength of FA and VFFA cement concrete specimens increased with the period of exposure while a reduction in strength was noted in the OPC and SF cement concrete specimens. The increased sulfate resistance of FA and VFFA cement concretes may be attributed to their dense microstructure resulting from the low water requirement as compared to OPC and SF cement concrete, as detailed in Table 2. The susceptibility of SF cement to $MgSO_4$ solution has been discussed by the authors elsewhere [9,21].

4.5. Exposure to moisture variation

The compressive strength of OPC SF, FA, and VFFA cement concrete specimens exposed to moisture variations is plotted in Fig. 5. The compressive strength of all the concrete specimens increased up to 270 wet/dry cycles while a reduction in the strength was noted thereafter for all types of cements. However, after 450 cycles, the compressive strength of OPC and SF cement concretes was less than that of FA and VFFA cement concretes.

4.6. Exposure to thermal variation

The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to thermal variation after initial water curing for 7, 14, and 28 days is plotted in Figs. 6–8. The compressive strength of all the concrete specimens increased due to exposure to thermal variations. Also, the increased initial curing resulted in higher compressive strength. Further, the compressive strength of VFFA and FA cement concrete specimens was more

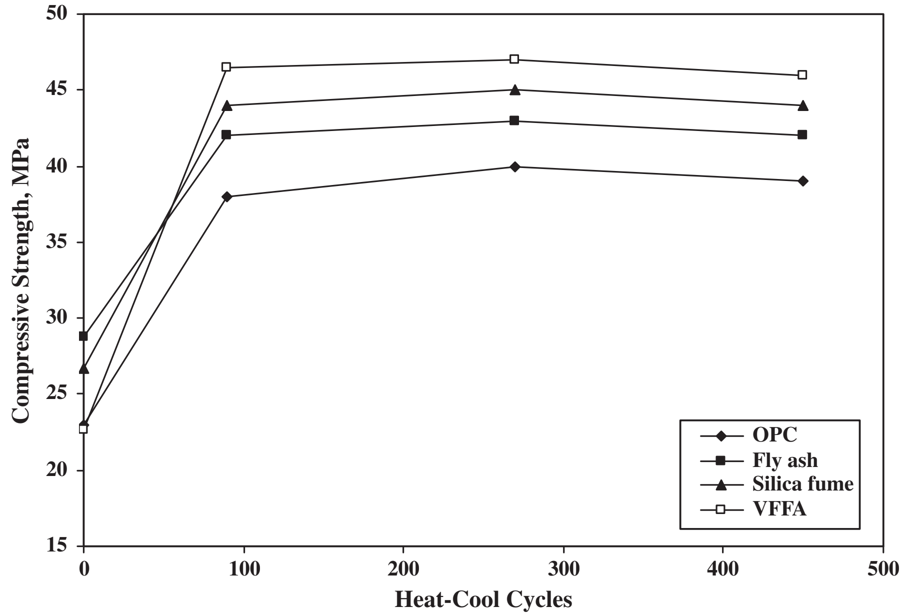

Fig. 6. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to thermal variation after 7 days of initial water curing.

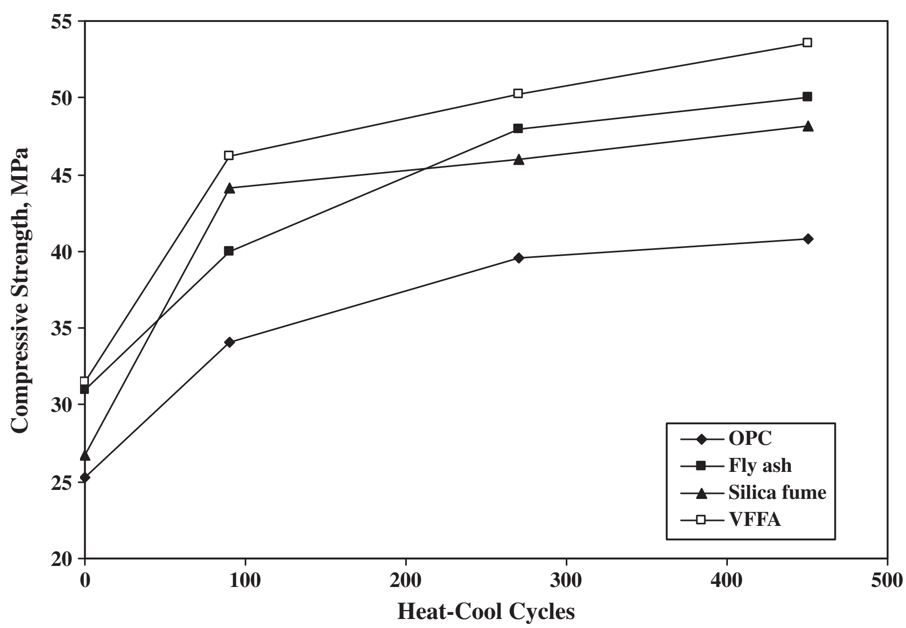

Fig. 7. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to thermal variations after 14 days of initial water curing.

than that of SF and OPC concrete specimens. This was particularly noted in the FA and VFFA cement concretes (see Fig. 7).

As shown in Fig. 9, the compressive strength of OPC, FA and VFFA cement concretes, coated with the curing compound and thereafter exposed to air for 3 days, increased with the extended exposure to thermal variations, up to 450 heat-cool cycles.

The compressive strength data shown in Fig. 10, for the concrete specimens cured under wet burlap for 3 days and then coated with a curing compound, also exhibited a trend similar to that indicated by the concrete specimens coated with the curing compound (Fig. 9). However, the compressive strength of the latter batch of specimens was more than that of the former group of specimens.

The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens cured under wet burlap for 7 days prior to the application of a curing compound, as shown in Fig. 11, increased with increasing exposure period to thermal variations. It is to be noted that the compressive strength of all the specimens, including SF cement concrete specimens, increased with an increase in the number of thermal cycles.

4.7. Effect of curing and thermal variation on pulse velocity

The effect of curing period on the pulse velocity in OPC, SF, FA, and VFFA cement concrete specimens cured with water for 7, 14, and 28 days, is plotted in Figs. 12–14. These data indicate that the pulse velocity of all the cement concretes decreased with the period of exposure to the thermal variation. This could be attributed to the formation of micro-cracks due to exposure to thermal

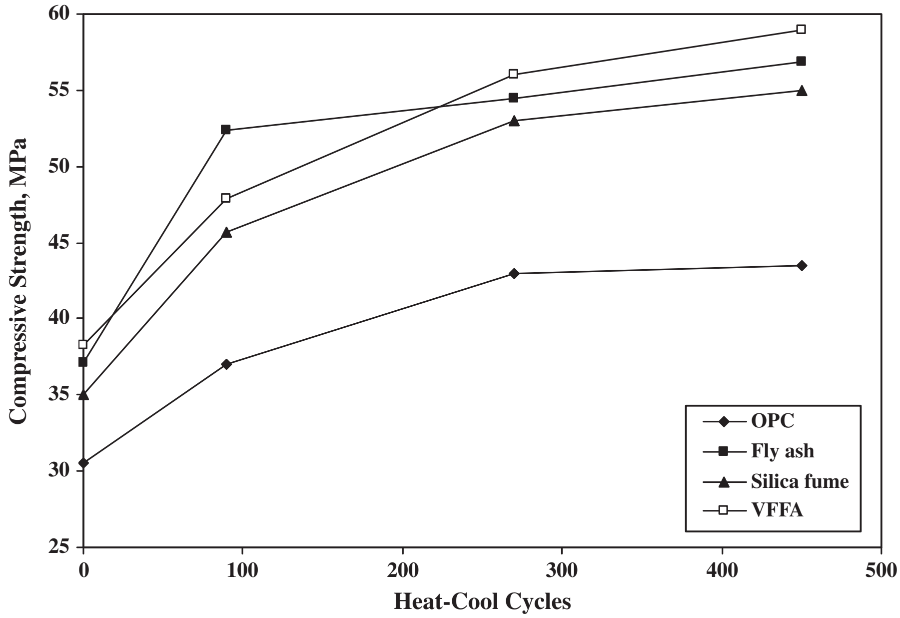

Fig. 8. Compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to thermal variation after 28 days of initial water curing.

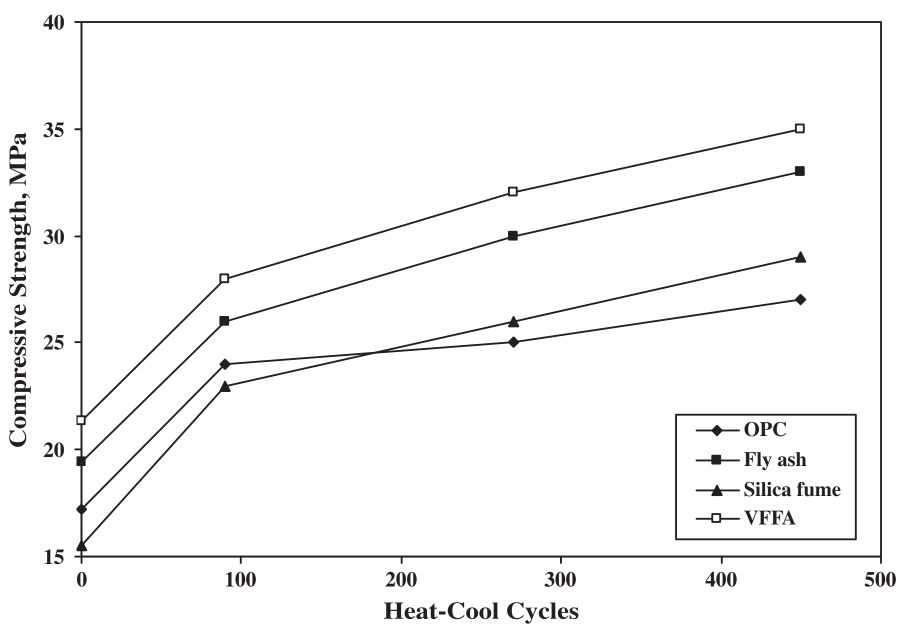

Fig. 9. Effect of thermal variation on the compressive strength of concrete specimens coated with a curing compound and exposed to air for 3 days.

variation. Generally, the pulse velocity in FA and VFFA cement concretes was more than that in the OPC concrete. The lower pulse velocity in SF cement concrete specimens could be attributed to the higher water-to-cementitious materials ratio in these specimens (Table 2).

It is to be noted that the pulse velocity in FA and VFFA cement concrete specimens was more than that in the OPC and SF cement concrete specimens, both before and after exposure to thermal variations.

Figs. 15–17 show the pulse velocity in concrete specimens cured by the application of a curing compound and then exposed to thermal variation. The pulse velocity in the VFFA cement concrete specimens was more than that in OPC, SF, and FA cement concrete specimens. Further, the pulse velocity in all the concrete specimens decreased due to exposure to thermal variations. The decrease in the pulse velocity may be attributed to the development of micro-cracks.

5. Discussion of results

The results of tests conducted on the selected materials will be discussed with respect to the benefits accrued from a reduction in the volume of mix water due to the material properties and curing regime.

5.1. Water requirement

To compare the performance of OPC, SF, FA, and VFFA cement concretes, mixtures with a constant workability of 75–100 mm

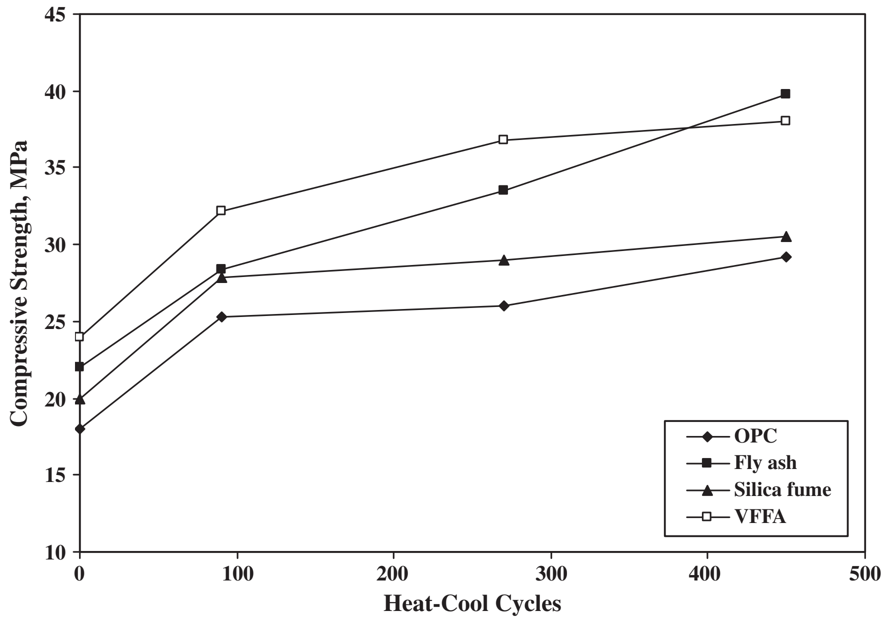

Fig. 10. Effect of thermal variation on the compressive strength of concrete specimens cured under wet burlap for 3 days and coated with a curing compound.

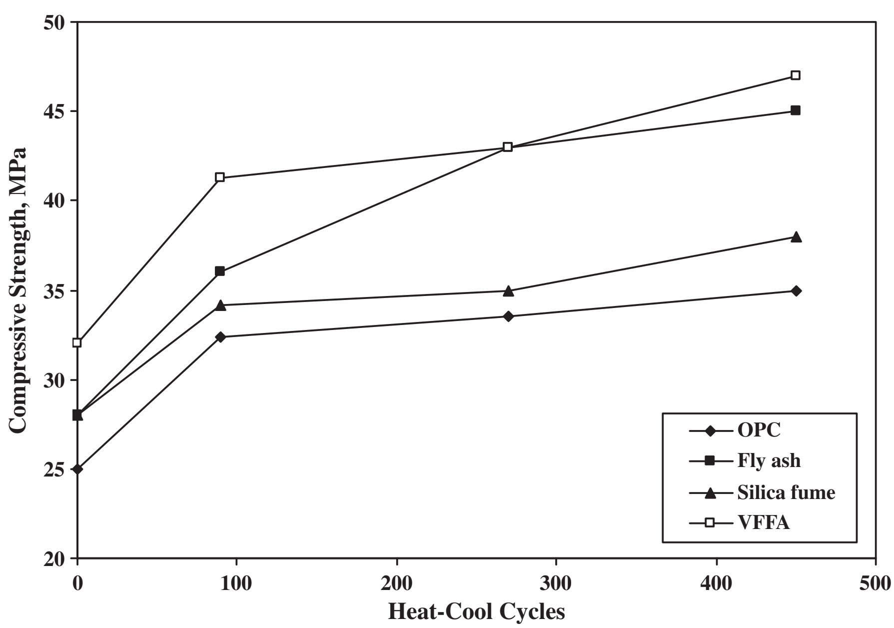

Fig. 11. Effect of thermal variations on the compressive strength of concrete specimens cured under wet burlap for 7 days and coated with a curing compound.

slump were prepared. The effective w/cm ratio of OPC concrete was 0.40, while it was 0.44, 0.34, and 0.365 in the SF, FA, and VFFA cement concretes, respectively. The increased water requirement in the SF cement concrete may be attributed to its fineness, which increases the water demand [14–16,19]. The reduced water demand for the FA and VFFA cement concretes may contribute to an increase in the strength and durability of these mixtures, as is discussed in the results presented earlier.

5.2. Strength development

As expected, the compressive strength of OPC, SF, FA and VFFA cement concretes increased with the period of water curing. The compressive strength of SF, FA, and VFFA cement concrete specimens was more than that of OPC concrete specimens. However, the early age strength of SF cement concrete was less than that of other cement concrete specimens. The lower early strength of SF cement concrete specimens may be attributed to the high effective water-to-cementitious materials ratio. Therefore, when SF cement concrete is to be utilized in structures, it is advisable to use them at low water to cementitious materials ratio. The required workability may be obtained by using suitable dosage of a high range water reducer or a superplasticizer. The low w/cm ratio will also result in enhanced durability of this cement concrete. On the other hand, the higher compressive strength of SF, FA, and VFFA cement concretes, compared to OPC concrete, indicates the superior performance of the investigated supplementary cementing materials, particularly the VFFA and FA, when used at a constant workability.

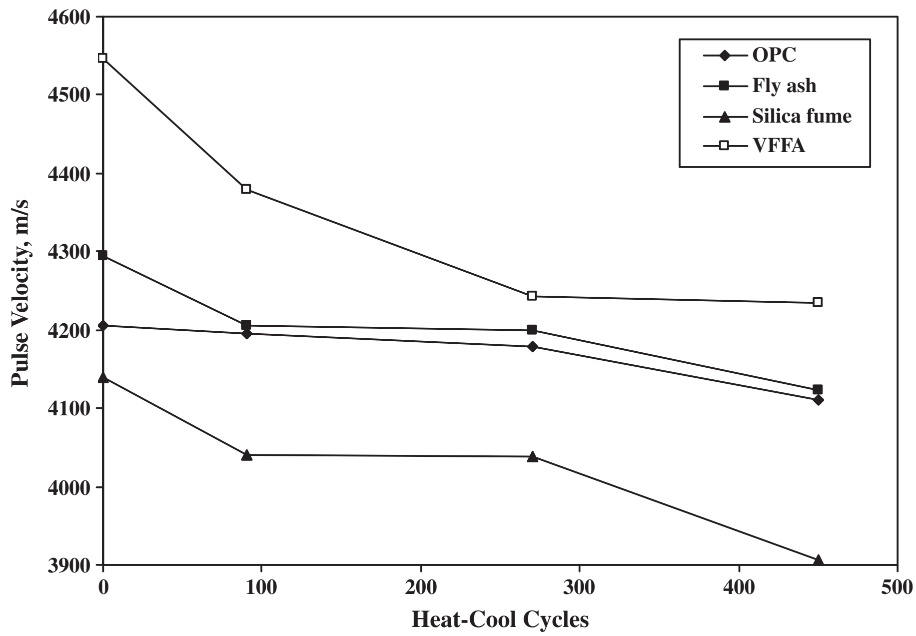

Fig. 12. Effect of thermal variations on pulse velocity in the concrete specimens cured with water for 7 days.

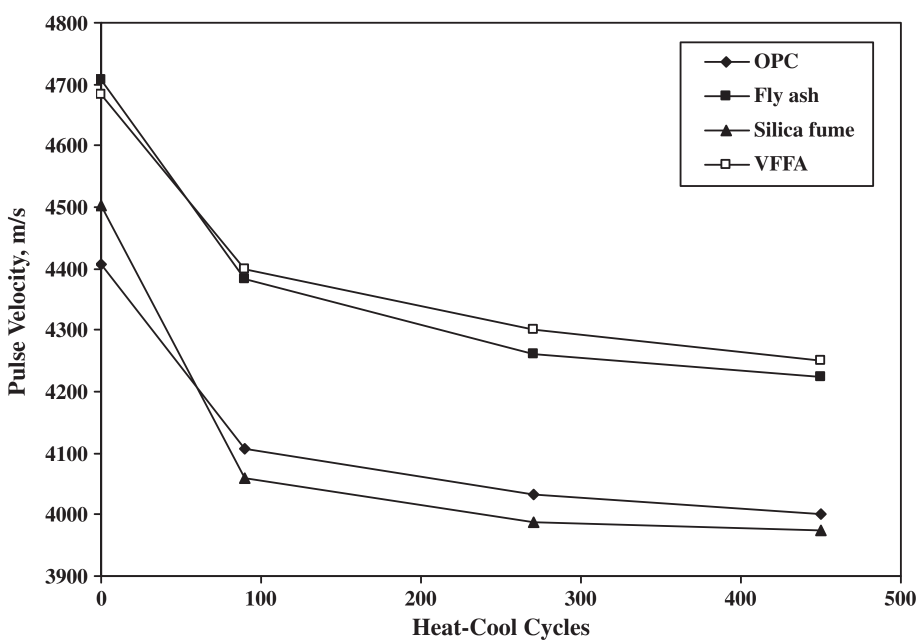

Fig. 13. Effect of thermal variations on pulse velocity in the concrete specimens cured with water for 14 days.

5.3. Performance under moisture variation

Concrete structures are often exposed to moisture variation, such as in marine environments and shallow groundwater regions. The concrete in such structures is susceptible to sulfate attack, salt weathering, and deterioration due to wet-dry cycles thereby leading to its micro-cracking. To evaluate the performance of OPC and blended cement concretes under such situations, the concrete specimens were exposed to wet/dry cycles. As shown in Fig. 5, the compressive strength of SF cement concrete was more than that of OPC concrete even after 450 wet/dry cycles. Furthermore, the compressive strength of OPC, SF, and FA cement concretes exposed to moisture variation, increased up to 270 wet/dry cycles. Thereafter, a decrease in the compressive strength was noted. After 450 wet/dry cycles, the compressive strength of FA and VFFA cement concretes was more than that of OPC and SF cement concretes. The reduction in compressive strength of all concrete specimens, after 450 cycles, may be attributed to the combined effect of the development of micro-cracks at the mortar-aggregate interface and the crystallization of the salt solution (Cl^{-} = 15.7% and SO_4^{--} = 0.55%) in the pores of concrete specimens.

5.4. Exposure to thermal variation

The performance of OPC, SF, FA, and VFFA cement concrete specimens exposed to thermal variation was evaluated by measur-

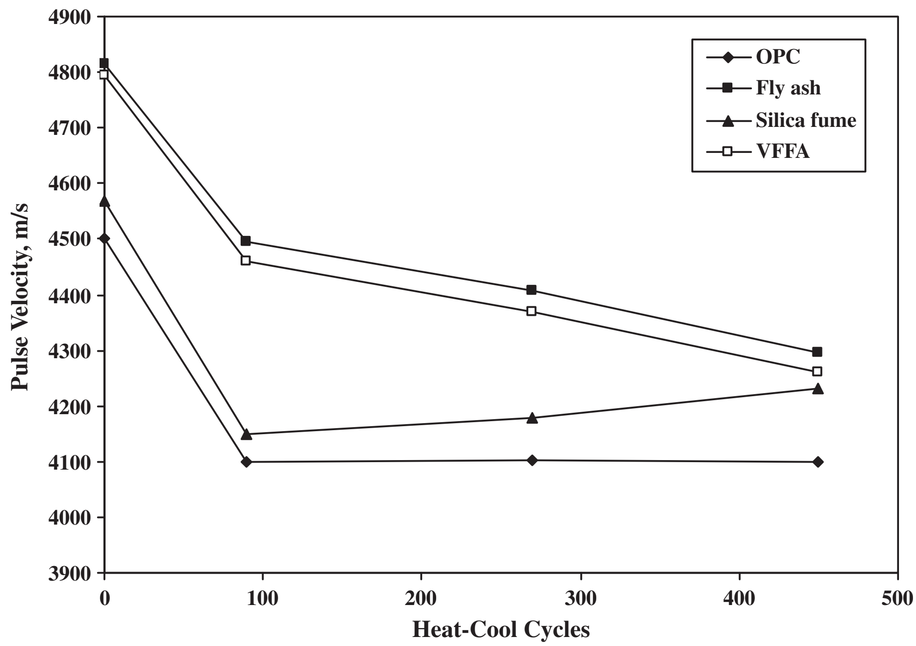

Fig. 14. Effect of thermal variations on pulse velocity in the concrete specimens cured with water for 28 days.

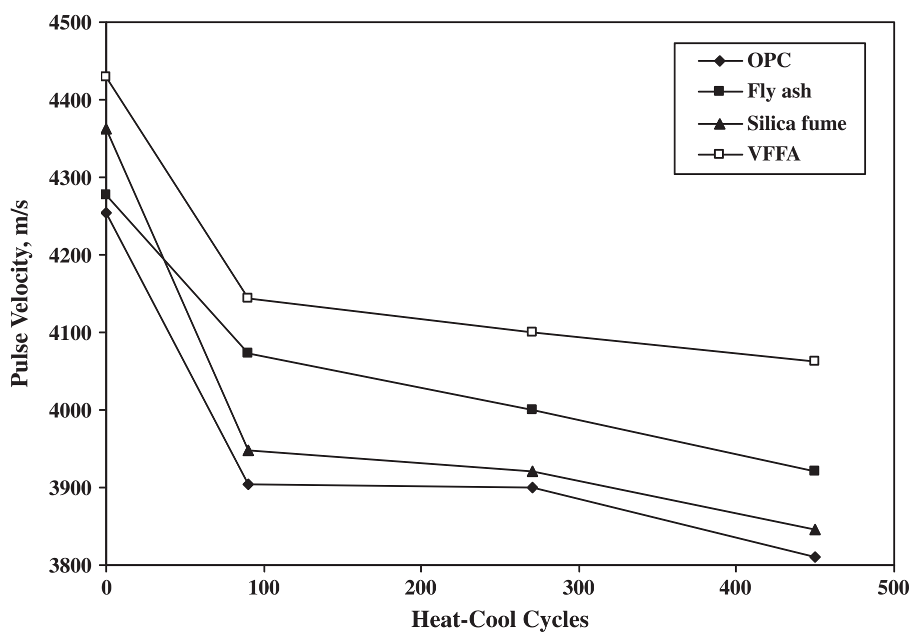

Fig. 15. Effect of thermal variations on pulse velocity in the concrete specimens coated with a curing compound and exposed to air for 3 days.

ing compressive strength and pulse velocity. The effect of curing method and duration on the performance of these cement concretes was also evaluated.

The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens continued to increase with the period of exposure irrespective of the duration of initial water curing. A similar trend was noted in the concrete specimens that were coated with a curing compound and exposed to thermal variation.

In the concrete specimens that were cured under wet burlap for 3 days prior to the application of a curing compound, the compressive strength continued to increase with the extended period of exposure to thermal variation. Similarly, the compressive strength increased with the extended period of exposure to thermal variation in the concrete specimens cured under wet burlap for 7 days and then coated with a curing compound.

In summary, the compressive strength of OPC and blended cement concrete specimens exposed to thermal variation (heat-cool cycles) did not decrease, even after 450 cycles. This trend was noted in all the concrete specimens irrespective of initial water curing period (7, 14, or 28 days) or curing regime (application of curing compound after 1, 3 or 7 days of pre-curing with wet burlap) or cement type.

Another point to be noted is that the compressive strength of all the cement concretes increased with the initial period of water curing, as shown in Figs. 6–8. Also, the data in Figs. 9–11 indicate that increased period of initial water curing was beneficial in

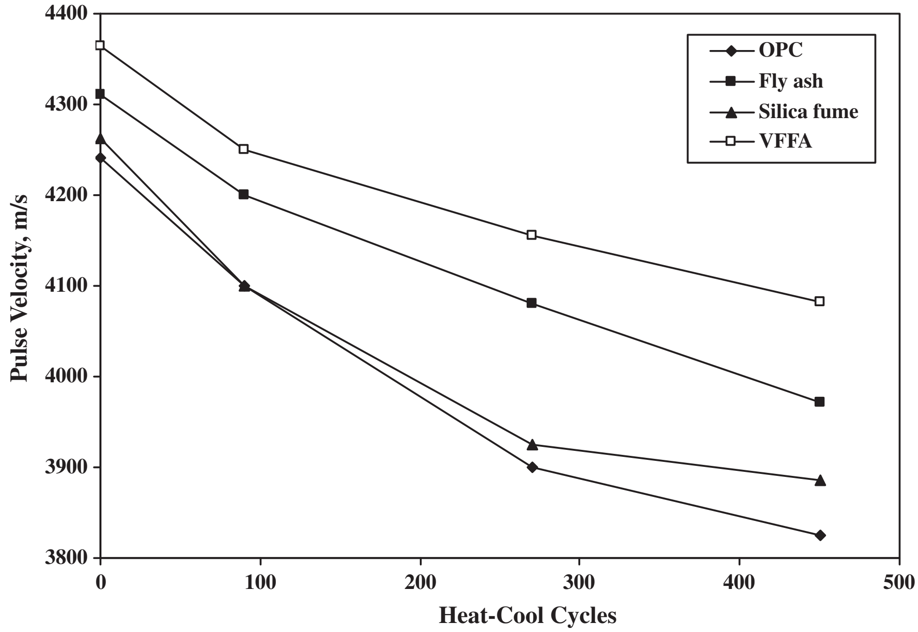

Fig. 16. Effect of thermal variations on pulse velocity in the concrete specimens cured under wet burlap for 3 days and then coated with a curing compound.

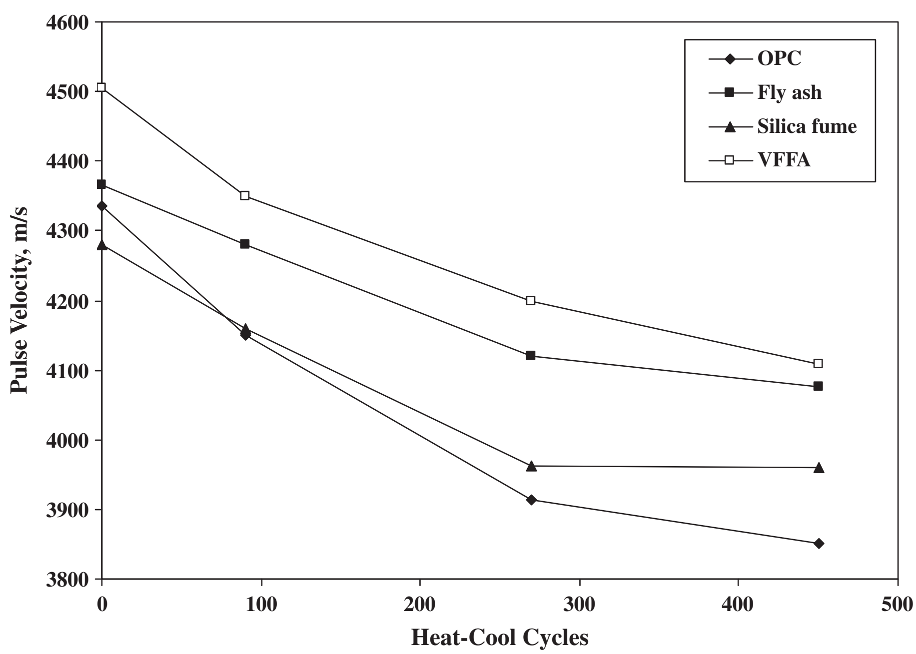

Fig. 17. Effect of thermal variations on pulse velocity in the concrete specimens cured with wet burlap for 7 days and then coated with a curing compound.

increasing the compressive strength of the concrete specimens cured by applying a curing compound.

Contrary to the results of compressive strength, the pulse velocity decreased with the number of thermal cycles. This decrease was noted in all the cement concrete specimens. The reduction in the pulse velocity indicates that the pore structure of concrete was deleteriously affected by exposure to thermal variation, which might have created micro-cracks that did not influence the compressive strength. Further, the pulse velocity of SF cement concrete specimens, exposed to thermal variation after 7, 14, and 28 days of water curing, was less than that of OPC and FA cement concrete specimens similarly cured and exposed. However, VFFA cement concrete performed distinctly better than all other cements, this was followed by FA cement concrete.

The pulse velocity in all the concrete specimens cured under wet burlap for 7 days and thereafter coated with a curing compound (Fig. 17) was more than that of concrete specimens cured under air for 3 days after being coated with the curing compound (Fig. 15) or cured under wet burlap for 3 days and then coated with a curing compound (Fig. 16). The implication of these data is that retrogression of the denseness of concrete is imminent due to exposure to thermal variation. Further, a longer curing period prior to the application of a curing compound is beneficial to concrete. Curing with water tended to improve the quality of concrete; and as the curing period increased the quality improved further.

5.5. Chloride permeability

The durability of OPC, SF, FA, and VFFA cement concrete specimens was evaluated by measuring their chloride permeability and sulfate resistance. The data on chloride permeability, shown in Table 3, indicate the superior performance of SF, FA, and VFFA cement concretes compared to OPC concrete. Among blended cement concretes, the performance of FA was better than that of SF and VFFA. The lower chloride permeability of SF, FA, and VFFA cement concretes means that their electrical resistivity would be less than that of OPC concrete. Consequently, the rate of corrosion in the former cements would be less than that in the latter cement [19]. The decrease in the chloride permeability of FA and VFFA cement concretes may be ascribed to the combined effect of: (i) lower water-to-cementitious materials ratio, and (ii) pozzolanic reaction, as explained earlier.

5.6. Sulfate resistance

The sulfate resistance of OPC, SF, FA, and VFFA cement concretes was evaluated by immersing them in 1%, 2%, and 5% $MgSO_4$ solutions and measuring the compressive strength after 90, 270, and, 450 days of exposure. The data in Figs. 2–4 indicate that the exposure of concrete specimens to 1% and 2% $MgSO_4$ solutions, for 450 days, did not deleteriously affect their compressive strength. In fact, the compressive strength continued to increase, due to sulfate exposure, though at a low rate.

The compressive strength of concrete specimens exposed to 5% $MgSO_4$ solution increased up to 270 days of exposure. However, after 450 days of exposure, a reduction in the compressive strength was noted in OPC and SF cement concrete specimens. FA and VFFA cement concrete specimens did not exhibit any reduction in the compressive strength, even after 450 days of exposure to 5% $MgSO_4$ solution. The superior performance of FA and VFFA cement concrete specimens may be partly attributed to their dense microstructure resulting from the low water-to-cementitious materials ratio.

6. Conclusions

The experimental program was designed to evaluate the performance of two fly ashes (a normal FA and a very fine FA) in relation to SF and OPC concretes prepared with similar workability. The following conclusions could be drawn based on the data developed in this study:

1. The water requirement of FA and VFFA cement concretes was less than that of SF and OPC concretes. This has resulted in better mechanical properties and enhanced durability of former cements.
2. The compressive strength of SF, FA, and VFFA cement concretes was more than that of OPC concrete. In particular, the highest compressive strength was noted in VFFA and FA cement concretes from the initial period of curing.
3. The compressive strength of OPC, SF, FA, and VFFA cement concretes, exposed to 450 wet/dry cycles (cyclic exposure to chloride-sulfate solution), decreased marginally. The reduction in the compressive strength may be attributed to the formation of micro-cracks due to sulfate attack and salt crystallization. Furthermore, the compressive strength of SF, FA, and VFFA cement concretes was more than that of OPC concrete, even after 450 wet/dry cycles.
4. The compressive strength of OPC, SF, FA, and VFFA cement concretes was not significantly affected by exposure to thermal variation (70–25 °C). In fact, the compressive strength of all concrete specimens increased with the number of thermal cycles. However, the pulse velocity decreased with an increase in the number of thermal cycles. This is attributed to the formation of micro-cracks due to temperature variation. These micro-cracks, however, did not influence the compressive strength.
5. The compressive strength of OPC, SF, FA, and VFFA cement concretes increased with the initial period of water curing. Further, initial water curing was found to be beneficial in increasing the compressive strength of concrete specimens cured by applying a curing compound. A similar trend was noted in the pulse velocity data. The implication of these data is that a longer curing period prior to the application of a curing compound is beneficial to OPC, SF, FA, and VFFA cement concretes.
6. The chloride permeability of SF, FA and VFFA cement concretes was less than that of OPC concrete. The chloride permeability of FA cement concrete was less than that of SF and VFFA cement concretes.
7. The compressive strength of OPC, SF, FA, and VFFA cement concrete specimens exposed to 1% and 2% $MgSO_4$ solutions was not affected. However, after 450 days of exposure, a reduction in the compressive strength was noted in the OPC and SF cement concrete specimens exposed to 5% $MgSO_4$ solution. Furthermore, a reduction in the compressive strength was not noted in FA and VFFA cement concrete specimens even after 450 days of exposure to 5% $MgSO_4$ solution.

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