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Influence of a fine glass powder on the durability characteristics of concrete and its comparison to fly ash

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Abstract

A detailed investigation carried out to ascertain the durability characteristics of fine glass powder modified concretes is reported in this paper. Tests were designed to facilitate comparisons between concretes modified with either glass powder or fly ash at the same cement replacement level. The optimal replacement level of cement by glass powder is determined from strength and hydration tests as 10%. The later age compressive strengths of glass powder and fly ash modified concretes are seen to differ by only 5%. The durability characteristics are ascertained using tests for rapid chloride permeability, alkali–silica reactivity, and moisture transport parameters. The chloride penetrability values indicate some amount of pore refinement. The potential of glass powder to reduce the expansion due to alkali–silica reaction is established from tests conducted in accordance with ASTM C 1260, but fly ash is found to perform better at similar replacement levels. Glass powder–fly ash blends that make up a 20% cement replacement level are found to be as efficient as 20% fly ash in reducing expansion. The control concrete is seen to exhibit the lowest overall moisture intake after 14 days of curing, and fly ash concrete the highest, with the glass powder concrete in between. The trend is reversed at later ages, demonstrating that both the replacement materials contribute to improved durability characteristics. The sorptivity and moisture diffusion coefficient values calculated from the moisture intake-time data also demonstrate a similar trend. These studies show that fine glass powder has the potential to improve the durability of concretes.

Keywords: Glass powder; Fly ash; Hydration; Durability; Alkali–silica reaction; Moisture transport

1. Introduction

The disposal of waste materials presents a complex problem for many agencies worldwide. In 2005, approximately 12.8 million tons of waste glass were disposed in the United States, while only 2.75 million tons were recycled [1]. The remaining waste glass was land-filled at tremendous cost to individual corporations and municipalities. With the number of land-fills in the United States decreasing nearly 80% since 1988 [1], the need to recycle and reuse waste materials like glass is imperative. The efforts to use such non-conventional materials which are typically of local or regional origin in concrete will get a boost if there are systematic and comprehensive studies to quantify the performance of concretes containing such materials.

A number of previous studies have examined the use of waste glass in concrete. The use of waste glass as an aggregate replacement [2–6], inert filler [7,8], or partial cement replacement [9–11] has been investigated. Increasing amounts of waste glass as coarse aggregates in concretes have been reported to decrease the mechanical properties, primarily because of a weak interface. Also, larger particle sizes of glass (greater than 1.2–1.5 mm) are found to facilitate alkali–silica reaction (ASR) in concretes [12,13]. Thus, when using ground glass or glass powder in cementitious systems, the particle size is not conducive for ASR to occur, but the potential of high alkali content of glass

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powder to cause deleterious expansions need to be accounted for. The pozzolanic properties of glass powders also have been explored in some studies [10,14–16]. Recent studies have investigated the influence of varying dosages of fine glass powder on cement hydration, and have modeled the degree of hydration of cement pastes containing glass powder [17,18].

The mechanical properties of the concretes containing glass powder and its alkali–silica reactivity have been investigated in some of the publications mentioned earlier. However, there is a lack of information on the overall durability performance of glass powder modified concretes, and how it compares with the durability of concretes containing fly ash, which is the most commonly used supplementary cementing material. This study is an attempt in that direction. The resistance of glass powder modified concretes to chloride penetrability and moisture ingress, and those of mortars to alkali–silica reactivity are studied in detail, and the performance is compared to mixtures containing similar replacement levels of a Class F fly ash. Such a quantitative comparison between glass powder and fly ash modified concretes is expected to help material designers in choosing optimal dosages as well as lead to better confidence in the use of glass powder in concrete.

2. Mixture proportions and test methods

Type I ordinary Portland cement conforming to ASTM C 150 was used in the concrete mixtures discussed in this study. The fine glass powder used in this study is a by-product of glass bead manufacturing from post-industrial and post-consumer window plate glass. The fine glass powder as well as the fly ash have similar particle size distributions, and are slightly coarser than the cement. The particle size distribution curves of cement, fine glass powder, and fly ash are shown in Fig. 1. The chemical composition and physical characteristics of cement, glass powder and fly ash are given in Table 1.

2.1. Choosing the glass powder replacement level

The optimal glass powder dosage for the concrete mixtures was arrived at based on studies on cement pastes with a water-cementing materials ratio (w/cm) of 0.42. Fig. 2 shows the 90 day compressive strengths of glass powder and fly ash modified cement pastes normalized by the compressive strength of the plain paste. While higher replacement levels of glass powder results in reduced compressive strengths as compared to plain pastes because of the dilution effect [18], the 90 day strength of pastes containing 20% fly ash is comparable to that of the plain paste

Table 1
Physical and chemical characteristics of cement, glass powder, and fly ash used in this study

Composition (% by mass)/property	Cement	Glass powder	Fly ash
Silica (SiO_2)	20.2	72.5	50.24
Alumina (Al_2O_3)	4.7	0.4	28.78
Iron oxide (Fe_2O_3)	3.0	0.2	5.72
Calcium oxide (CaO)	61.9	9.7	5.86
Magnesium oxide (MgO)	2.6	3.3	1.74
Sodium oxide (Na_2O)	0.19	13.7	0.96
Potassium oxide (K_2O)	0.82	0.1	–
Sulfur trioxide (SO_3)	3.9	–	0.51
Loss on ignition	1.9	–	2.8
Fineness, % passing 45 μm	95	72	74
Density (kg/m3)	3150	2490	2250

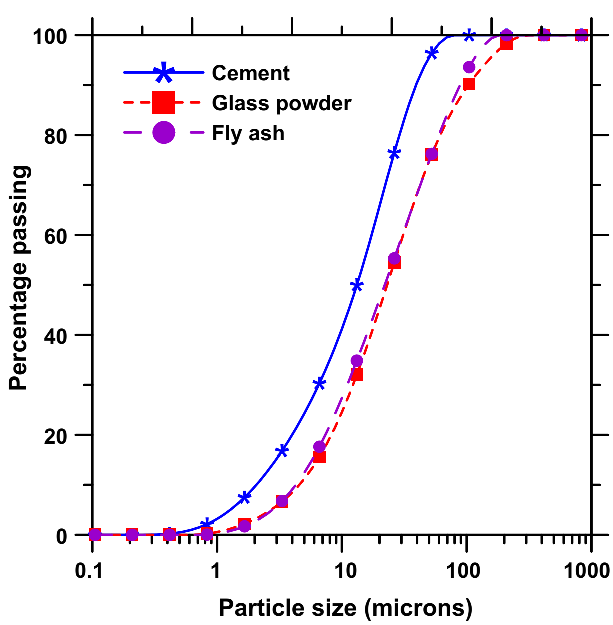

Fig. 1. Particle size distributions of cement, glass powder, and fly ash used in this study (one out of every five data points shown by a symbol).

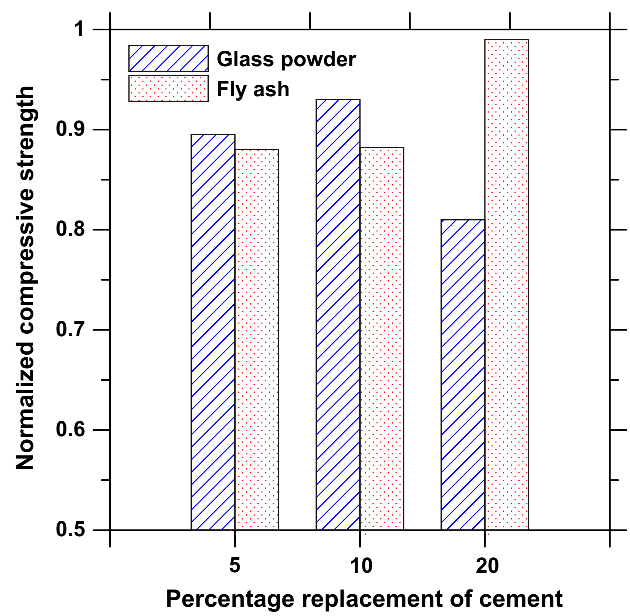

Fig. 2. Normalized compressive strengths of fine glass powder and fly ash modified cement pastes at 90 days.

(normalized strength close to 1.0) because of the secondary reaction. At replacement levels equal to or less than 10%, glass powder modified pastes exhibit similar or higher compressive strength than the corresponding fly ash modified pastes, suggesting that a 10% replacement of cement by glass powder is feasible.

The non-evaporable water contents (w_n) and the calcium hydroxide (CH) contents of cement pastes were evaluated using thermogravimetric methods. Fig. 3a shows the w_n values of plain cement paste and the pastes modified with 10% glass powder or fly ash at 14, 28, and 90 days of curing. At both 14 and 28 days, it is seen that the glass powder modified paste has a similar w_n to that of the plain paste while the w_n of the fly ash modified paste is less than that of both the plain and glass powder modified pastes. This shows that the replacement of 10% cement by glass powder facilitates an enhancement in cement hydration caused by the negligible water absorption of glass powder thereby providing more water for cement to hydrate. At 90 days, the w_n of fly ash and glass powder modified pastes are very similar. While there is an increase in w_n of fly ash modified paste between 28 and 90 days due to the secondary hydration, the w_n of glass powder modified paste does not change much in this time period, showing that the primary effect of glass powder is in enhancing the cement hydration early on. However, the close values of w_n of 10% glass powder and fly ash pastes render these replacement levels in concrete suitable for a comparison.

Fig. 3b shows the CH contents as a percentage of the ignited mass for plain cement paste and the pastes modified with 10% glass powder or fly ash at 14, and 90 days of curing. At early ages, it can be seen that the CH contents in glass powder and fly ash modified pastes are almost the same, and are lower than that of the plain paste. Even when the glass powder is enhancing the hydration of cement as observed from the w_n values (which will result in more CH), it is seen that the CH content determined from thermal analysis is lower than that of the plain paste. The difference between the CH contents of plain and glass powder modified pastes is more than 10%, which is the cement replacement level, which suggests that glass powder is undergoing its secondary reaction also. At later ages, secondary hydration of fly ash results in reduced CH contents for the fly ash paste. The 10% glass powder modified paste shows a reduced CH content than the plain paste at later ages also. Based on the comparison of strength ratios, non-evaporable water contents, and CH contents of glass powder and fly ash modified pastes, it is decided that a 10% replacement of cement by glass powder can be adopted in the further studies on concrete mixtures.

2.2. Concrete mixture proportions

Five concrete mixtures were proportioned as part of this study. A plain concrete mixture with a w/cm of 0.40 was used as the control concrete. Ten percent of cement by mass was replaced by glass powder and fly ash in two other mixtures without changing the w/cm (mixtures designated as 10GP and 10FA, respectively). In another two mixtures, 10% of cement by mass was replaced with glass powder and fly ash, and the w/cm also reduced so as to provide the same slump as the control mixture (mixtures 10GPR and 10FAR, respectively). All the mixtures were proportioned using 12.5 mm nominal maximum size aggregates. The mixture proportions are given in Table 2. The concrete mixtures were mixed in accordance with ASTM C 192, in a 4 ft^3 (0.11 m^3) drum mixer. After mixing, the concrete was cast in twenty cylindrical molds (100 mm

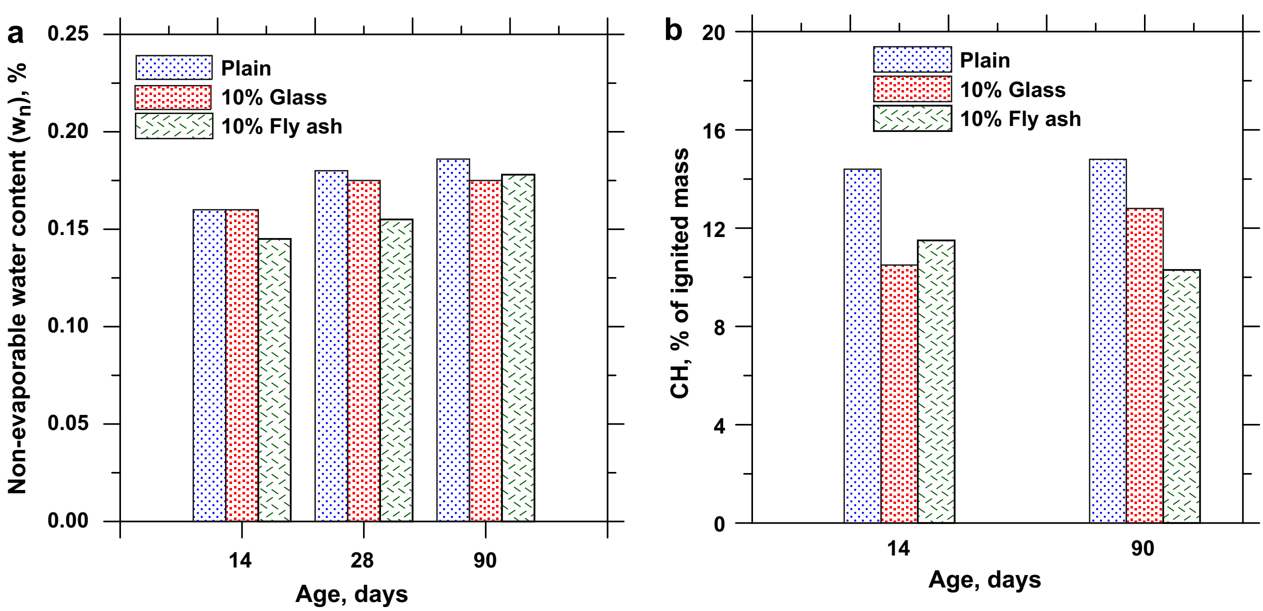

Fig. 3. (a) Non-evaporable water contents, and (b) calcium hydroxide contents of plain, and 10% glass powder and fly ash modified cement pastes at early and late ages.

Table 2
Mixture proportions for 1 m^3 of concrete

	Composition of the binder	Cement (kg)	Fine aggregates (kg)	Coarse aggregates (kg)	Glass powder (kg)	Fly ash (kg)	Water (kg)
Control	100% cement	416.52	816.38	928.25	0.00	0.00	166.61
10GP	10% cement replaced by glass powder	374.83	816.38	928.25	41.65	0.00	166.61
10FA	10% cement replaced by fly ash	374.83	816.38	928.25	0.00	41.72	166.61
10GPR	10% cement replaced by glass powder (reduced w/cm)	374.83	816.38	928.25	41.72	0.00	149.92
10FAR	10% cement replaced by fly ash (reduced w/cm)	374.83	816.38	928.25	0.00	41.72	160.11

R – reduced w/cm mixtures.
For all the mixtures, 1057.4 ml of high range water reducing admixture, and 135.68 ml of air entraining admixture per m^3 of concrete was used.

Table 3
Fresh concrete characteristics

	w/cm	Slump (mm)	Air content (%)	Unit weight (kg/m^3)
Control	0.40	178	8.0	2289
10GP	0.40	215	7.5	2321
10FA	0.40	215	6.8	2286
10GPR	0.36	165	6.2	2302
10FAR	0.39	165	6.8	2290

diameter × 200 mm long) and six beam molds (75 mm × 75 mm × 250 mm). Slump (ASTM C 143), air content (ASTM C 231), and unit weight measurements were also carried out on fresh concrete, the values of which are shown in Table 3.

2.3. Test methods

The compressive strengths of various concrete mixtures were determined at 3, 14, 28, and 90 days in accordance with ASTM C 39. Rapid chloride permeability test (RCPT), as per ASTM C 1202 was carried out after 28, 56, and 90 days of curing. This test provides an indication of the penetrability of chloride ions through concrete under a potential difference of 60 V. The potential for expansion of glass powder and fly ash modified mortars due to alkali–silica reaction with a reactive aggregate was evaluated using the accelerated mortar bar test according to ASTM C 1260.

The moisture transport characteristics of concretes were evaluated using a combined sorption–diffusion approach [19,20]. This method provides the values of moisture transport parameters including the sorptivity, and the moisture diffusion coefficient. The specimens were cured for either 14 or 90 days before the start of the moisture transport tests. Thick specimens (50 mm) were cut from 100 mm diameter × 200 mm long cylinders, dried at 75 ± 5 °C in an oven for at least 48 h, and cooled in a dessicator. Heating at 105 °C as is commonly adopted for sorptivity tests was not done to avoid microcracking. After cooling, the specimens were covered on the bottom face and the sides with waterproof tape while creating a dyke around the open face. Water was then poured on the open face and allowed to seep into the concrete. The mass of the specimens were determined at frequent intervals throughout a 28 day period from the start of the testing (after the respective curing duration). The moisture transport at earlier times is predominately through sorption, whereas at later times, diffusion through smaller pores dominates. Eq. (1) combines the effects of both the mechanisms [19]

$$\left(\frac{M}{A}\right)_t = B\left[1-\exp\left(\frac{-S\sqrt{t}}{B}\right)\right] + C_0L\left\{1-\sum_{n=0}^{\infty}\frac{8}{(2n+1)^2\pi^2}\times\exp\left[\frac{-D_m(2n+1)^2\pi^2t}{4L^2}\right]\right\} \quad (1)$$

where $\left(\frac{M}{A}\right)_t$ is the cumulative normalized water intake at time t, L is the specimen length, B is a constant related to the distance from the absorbing surface over which the capillary pores dominate initial sorption, S is the sorptivity coefficient, C_0 is the constant surface concentration of the diffusion species, and D_m is the moisture diffusion coefficient. The first term in Eq. (1) is the classical expression for sorptivity based on the parallel tube model of porous media. The second term is the solution of Fick's second law for diffusion through a cylindrical specimen with one end sealed and other end maintained at a constant concentration.

3. Results and discussion

3.1. Compressive strength of concrete mixtures

Fig. 4 illustrates the compressive strength development for all the concrete mixtures used in this study. The compressive strength of the control concrete is seen to be greater than those of modified concretes at all ages. For the first 28 days, the 0.40 w/cm concrete with 10% glass powder shows greater compressive strength than the corresponding 10% fly ash concrete, indicating enhancement of cement hydration in the presence of glass powder as reported before [18]. However, at 90 days the 0.40 w/cm mixture with 10% fly ash shows a greater compressive strength than the mixture with 10% glass powder, indicating that the pozzolanic reaction of fly ash is more effective than the secondary reaction of glass powder. This can also be attributed to the particle sizes of the fines used in this study – the glass powder has only 25% of the particles finer

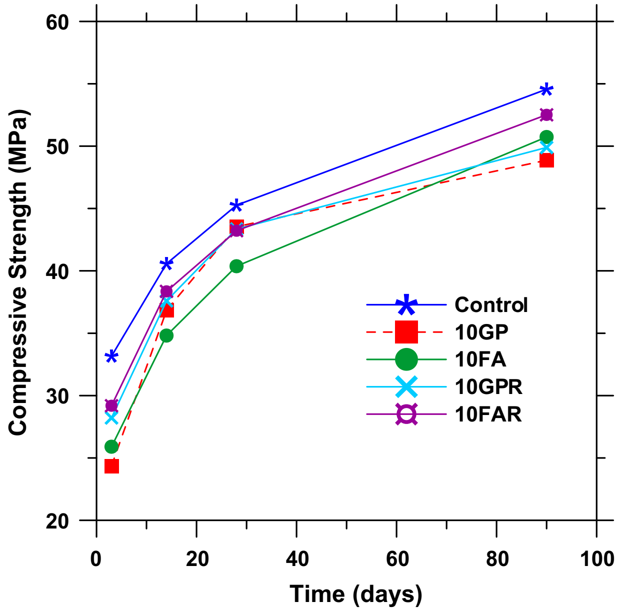

Fig. 4. Compressive strength development of concretes with glass powder or fly ash replacing cement.

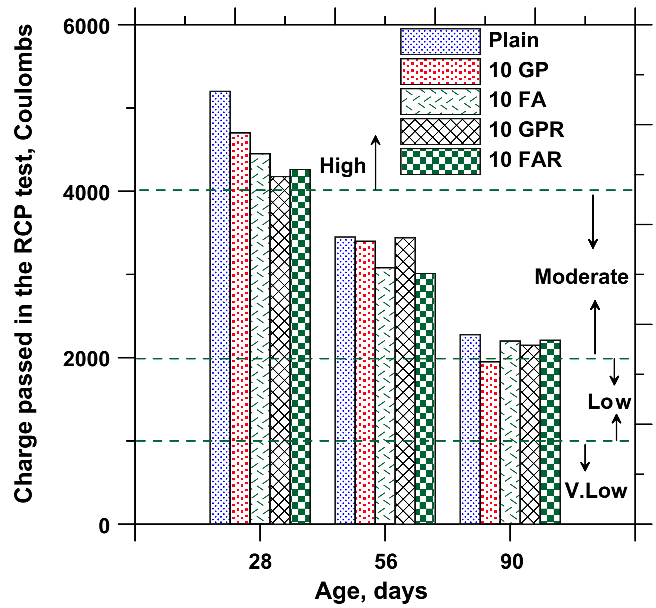

Fig. 5. Rapid chloride permeability values for plain and modified concretes.

than 10 μm, while the fly ash and cement have 30% and 40%, respectively of particles finer than 10 μm. The above mentioned trend of compressive strength can also be seen in the set of concretes with reduced w/cm. Until 28 days, both the reduced w/cm mixtures show relatively the same strength, but the fly ash modified mixture shows higher strength than the glass powder modified mixture at 90 days, for the reason mentioned earlier. While the 28 day strengths of glass powder modified concretes are equal to or greater than the fly ash modified concretes for the respective w/cm, the 90 day strength of fly ash modified concretes are slightly higher. It can be seen from Fig. 4 that there is only a 5% difference or less between the compressive strengths of glass powder and fly ash modified concretes at 90 days. Hence it can be safely stated that from the viewpoint of compressive strength, glass powder will perform in an analogous manner to fly ash at this replacement level.

3.2. Rapid chloride permeability

Rapid chloride permeability test (RCPT) was conducted on specimens at ages of 28, 56, and 90 days in accordance with ASTM C 1202. Fig. 5 shows the rapid chloride permeability values (charge passed through the specimens, in Coulombs) for all the concrete mixtures used in this study. For specimens moist cured for 28 days, highest RCP values are obtained for the control concrete specimens. The RCP values for the glass powder and fly ash modified mixtures are lower, indicating some degree of pore refinement in these mixtures at this age. This can be attributed to the early age enhancement of cement hydration by glass powder, and the pozzolanic reactions of glass powder and fly ash. The 28 day RCP values of all the mixtures are in the "high" category as per ASTM C 1202. The RCP values at 56 and 90 days of moist curing are found to be lower than the 28 day value as expected. The trend between the mixtures is also similar to that at 28 days. All the mixtures exhibit "moderate" RCP values at 56 days, and "moderate" to "low" values after 90 days.

The results of RCPT depend both on the microstructure of the concrete as well as the conductivity of the pore solution [21]. A concrete with same microstructure can show increased RCP values if the pore solution conductivity is higher. More alkali ions are released into the aqueous phase by a certain amount of glass powder than the alkali contribution from the same amount of cement it replaces [18], thus increasing the pore solution conductivity of glass powder modified concretes. However, Fig. 5 shows that the glass powder modified concretes show lower or similar RCP values as compared to control concrete at all ages. This again shows that the glass powder is beneficially impacting the material microstructure.

3.3. Alkali–silica reactivity

The potential of expansion due to alkali–silica reaction of glass powder and fly ash modified mortars was investigated using the accelerated mortar bar test (ASTM C 1260). A reactive siliceous sand was used as the aggregate. In this test method, higher temperature (80 °C) and increased alkalinity (1 N NaOH) accelerates the reaction. ASTM C 1260 method is not intended to capture the effect of increased alkalis from glass powder, rather it is used in this study to understand the expansion characteristics of plain and modified mortars. This test method can be used to evaluate the effectiveness of supplementary cementing materials in reducing the expansion due to ASR [22–24].

Tests were not conducted as part of this study to find out if the glass powder itself will contribute to deleterious expansions. However, it has been reported that the use of fine glass powder with a high Na_2O content (about 14%, similar to the glass powder used in this study) does not result in expansion when long-term mortar bar expansion tests were conducted at 38 °C and 100% RH for over a year [9]. It has also been shown that when the aggregate is reactive, and a low-alkali cement is used, the presence of even higher dosages of glass powder does not release enough alkalis to trigger deleterious reaction [9]. Flame photometry and electrical conductivity tests carried out earlier [18] also has shown that the glass powder does not release a large amount of alkalis into the pore solution.

In this study, glass powder and Class F fly ash have been used to replace 5, 10, and 20% of the cement in mortar mixtures prepared according to ASTM C 1260. In one set of mixtures, ternary binders containing glass powder and fly ash were also used. Fig. 6a, b, and c depict the expansions of mortar mixtures. At 14 days, the expansion of the plain mortar mixture was 0.22%, while it was 0.27% at 21 days. From Fig. 6a, it could be observed that an increase in glass powder content reduces the expansion of the mortar mixtures. This is consistent with the findings that glass powder can suppress the ASR tendency of reactive aggregates [9,10,25]. The reduction in ultimate expansion (at the end of 14 or 21 days) is found to be proportional to the replacement level of cement with glass powder. The mechanisms

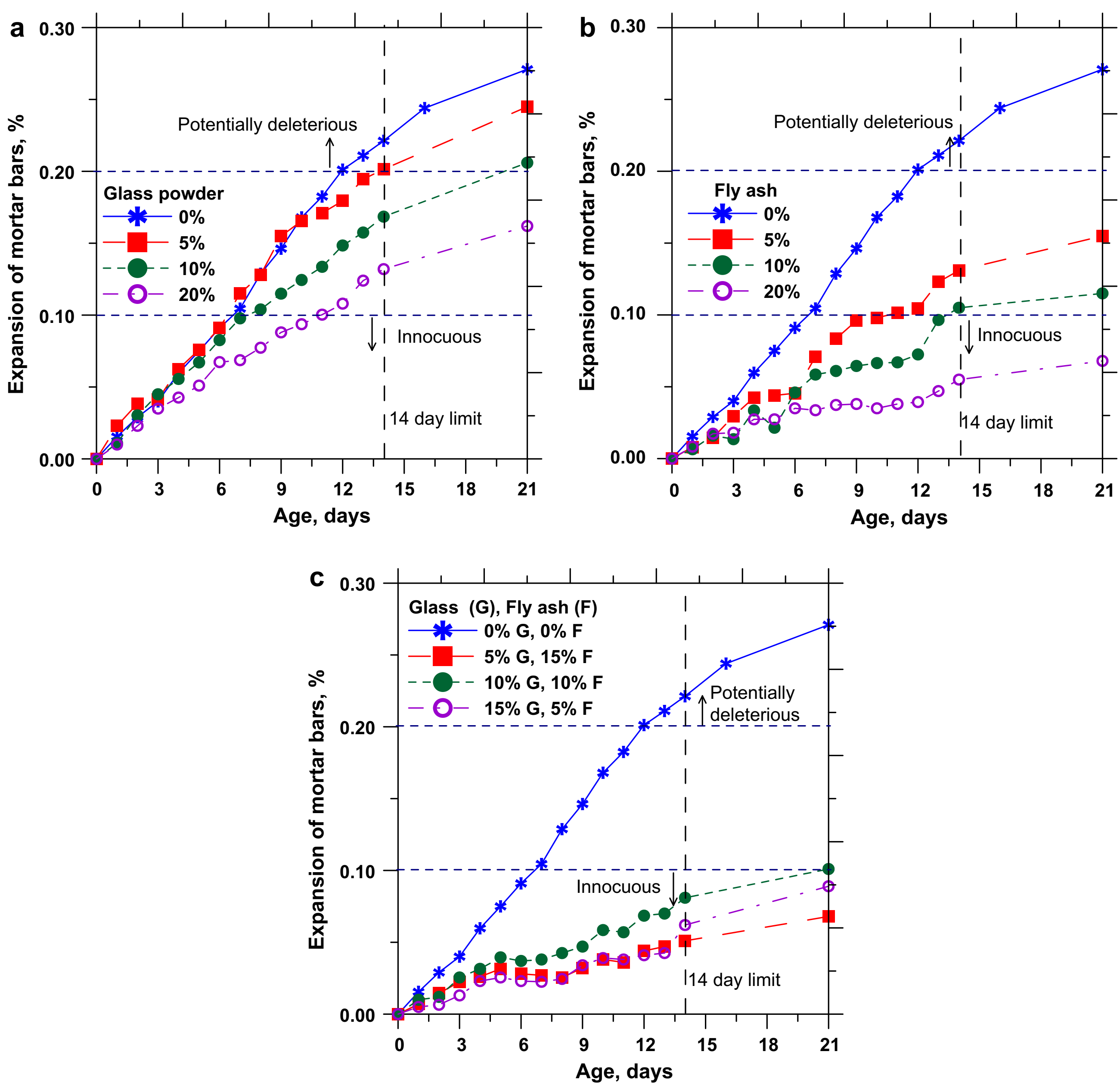

Fig. 6. ASR expansion measurements carried out as per ASTM C 1260 test method for: (a) glass powder modified mortars, (b) fly ash modified mortars, and (c) ternary mixtures of glass powder and fly ash.

commonly attributed to the reduction of ASR expansion when supplementary cementing materials are used are the reduction in the alkali hydroxide concentration in the pore solution, alkali dilution, and consumption of CH through the pozzolanic reaction [22,26–28]. For glass powder modified mixtures, it is unlikely that reduction in alkali hydroxides will be achieved. However, it is known that the expansion decreases with increase in SiO_2 content and reduction in CaO content [24]. The very high silica content and the low CaO content of glass powder can be expected to play a role in reducing the expansion.

For this particular aggregate, the chosen replacement levels of cement by glass powder is not found to be efficient in reducing the expansion to less than 0.10%. From the trends observed in Fig. 6a, more than 30% replacement of cement by glass powder will be required to limit the expansion below 0.10%. Also, the presence of an aggregate more reactive than the one used in this study might demand an even higher dosage of glass powder. The implications of such higher dosages of glass powder on other concrete properties need to be considered.

Fig. 6b shows the expansion of mortars containing fly ash as the cement replacement material. It is immediately evident from Fig. 6b that fly ash at a given replacement level is more effective than the glass powder at the same replacement level in suppressing expansion due to ASR. The effectiveness of low-calcium, low-alkali fly ashes in reducing the expansion due to ASR is well known. Increasing amounts of fly ash in the mixture is seen to reduce the expansion, and the ultimate reduction in expansion is proportional to the fly ash content. A 20% replacement of cement by fly ash is found to limit the expansion to less than 0.10%. It has been suggested that if the expansions of mortars are less than 0.10% at the end of 14 days when evaluated as per ASTM C 1260, they are more likely to meet the ASTM C 1293 expansion criterion of concrete prisms of 0.04% after two years [29].

It has been reported that ternary blends containing fly ash and silica fume are more effective in reducing expansion [28,30], than either of the replacement materials alone. To evaluate the effectiveness of ternary blends containing glass powder, mortars containing 20% replacement of cement by a combination of glass powder and fly ash were made. The expansion results for ternary blends containing glass powder and fly ash are shown in Fig. 6c. The ultimate expansion values of all the ternary blend mortars are found to be lower than 0.10% after 14 days. Any combination of glass powder and fly ash that make up the 20% replacement level is found to be as efficient as 20% cement replacement by fly ash in reducing the expansions.

Fig. 7 shows the 14 day expansions of all the mortars as well as the reduction in expansion as compared to the plain mortar (the difference in expansion between the plain mortar and the modified mortar). A lower value of expansion and a higher value of reduction in expansion indicate that the replacement material (or the combinations) is efficient in reducing the expansion. In that respect, the ternary blend mortars as well as the 20% fly ash mortar are found to be the most effective. The expansion and reduction in expansion due to the replacement of 20% cement by glass powder is equivalent to that of 5% replacement by fly ash. It can also be observed from Fig. 7 that the mortars containing 5% glass powder + 15% fly ash, and 5% fly ash + 15% glass powder showed almost the same amount of expansion, and reduction in expansion. It is seen that the use of glass powder supplemented with a small amounts of Class F fly ash can be used to reduce the expansion due to ASR.

3.4. Moisture transport

Moisture transport characteristics of the plain and modified concretes were evaluated using the method outlined in [19,20], after 14 and 90 days of moist curing and applying

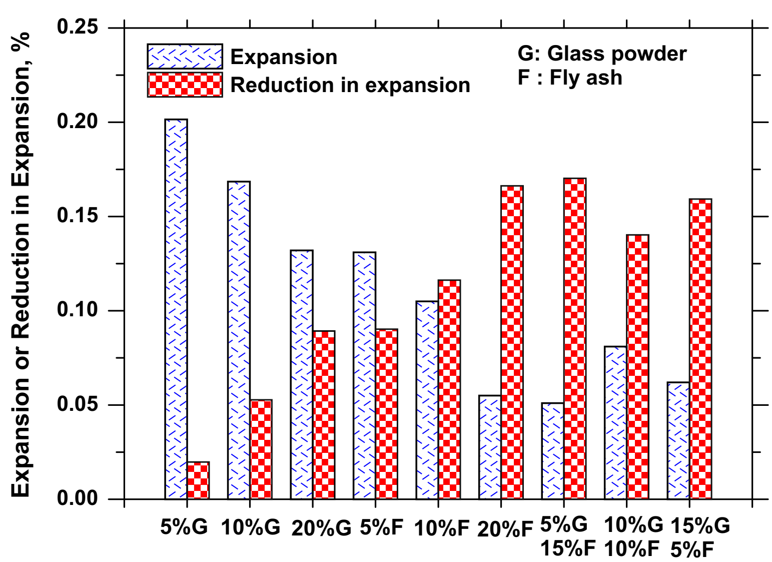

Fig. 7. Expansion and reduction in expansion for the binary and ternary blend mortars.

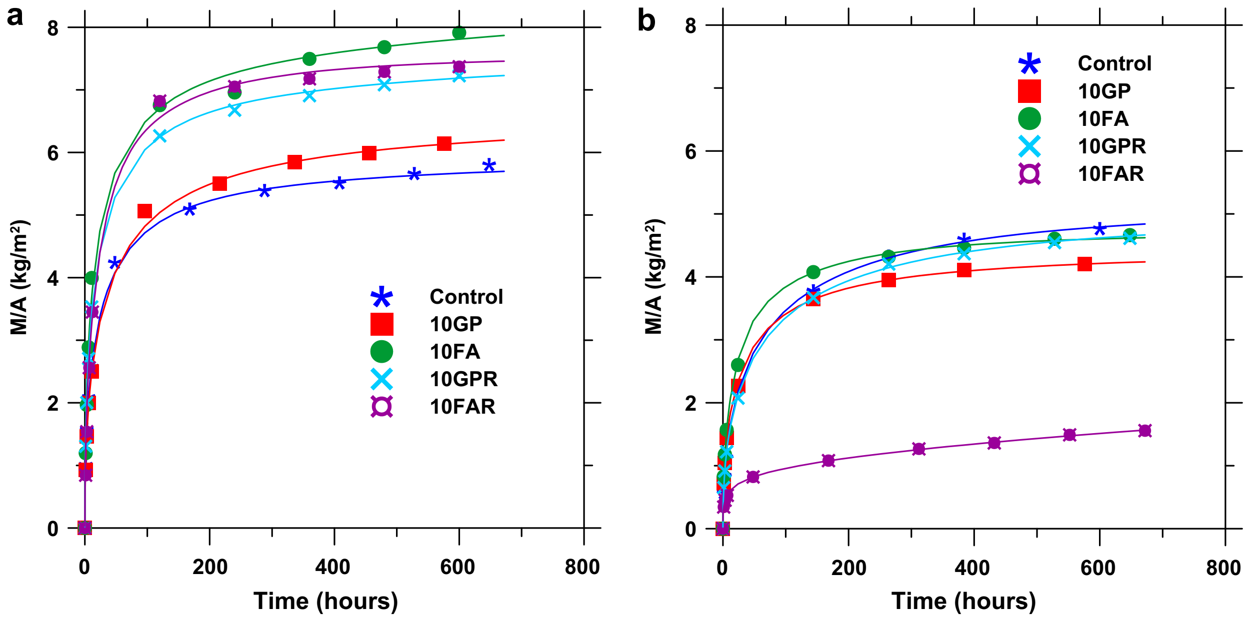

Fig. 8. Moisture intake as a function of time after: (a) 14 days, and (b) 90 days of curing (one out of every five data points shown by a symbol, the solid lines are the fits of Eq. (1) to the data).

the conditioning procedure stated in Section 2.3. Fig. 8a shows the cumulative moisture intake as a function of time for the concrete specimens that are moist cured for 14 days where as Fig. 8b provides the data for specimens after 90 days of curing. The experimental data points as well as the fit of Eq. (1) to the data are shown in these figures.

From Fig. 8a, it can be observed that the total moisture intake for the control concrete is the lowest when tests are carried out after 14 days of curing. The fly ash modified concretes show the highest moisture intake, showing that the effect of dilution of cement content by fly ash has not been compensated by any secondary reaction at this age. The total moisture intake for the glass powder concretes are in between those for control and the fly ash modified concretes. Fig. 8b shows the moisture intake data after 90 days of curing. The order of moisture intake is reversed, and the cumulative moisture intake for the control concrete specimen is now found to be the highest. The fly ash modified concretes have the lowest moisture intake as expected, and the glass powder modified concretes show values in between those two, but closer to that of the control concrete. A comparison of Fig. 8a and b shows that the fly ash modified concretes have the largest reduction in total moisture intake between 14 and 90 days. The fact that the glass powder modified concretes show lesser reduction in moisture intake than the fly ash concretes (though higher than the control concrete) between 14 and 90 days of curing serve as an indication of better effectiveness of fly ash as a pozzolan when compared to the glass powder used in this study.

From these trends in moisture intake, it can be seen that the 10% glass powder modified concretes perform similar to or better than control concrete at later ages and better than 10% fly ash modified concretes at early ages. Glass powder provides an enhancement in cement hydration at early ages while fly ash is only a filler at these times. The beneficial effects of secondary reaction of fly ash are evident at later ages where as the secondary reaction of the glass powder is not as efficient as that of fly ash.

3.4.1. Moisture transport parameters

The solid lines in Fig. 8a and b represent the fits of Eq. (1) to the experimental data. The equation fits the experimental data with a great deal of accuracy, and the R^2 values are greater than 0.98. The moisture transport parameters – B (the distance from the surface to which the capillary pores control initial sorption), S (the sorptivity coefficient), C_0 (the surface concentration of the diffusing species), and D_m (moisture diffusion coefficient) – can be extracted from the fits of Eq. (1). The parameters S and D_m are helpful in describing the amount and rate of moisture transport through the concretes, while the constant B provides some information about the near surface microstructure.

Fig. 9 shows the values of the constant B for the concrete mixtures obtained from the fit of Eq. (1) to the moisture intake data for both 14 and 90 day moist cured specimens. A larger value of B indicates that the capillary pores dominate the initial sorption over a larger depth from the surface exposed to infiltrating moisture. This means that the moisture intake during the first few hours is likely to be higher for such specimens. Among the 14 day cured specimens, the value of B is lowest for the control concrete, slightly higher for the glass powder modified concretes, and the highest for fly ash modified concretes. From the values of B for specimens cured for 90 days, it can be seen that the control concrete has the highest B value, and fly ash modified mixtures the lowest,

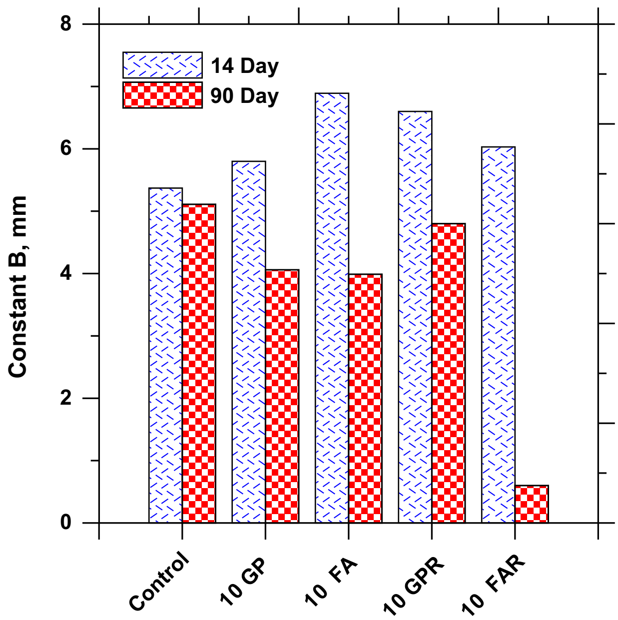

Fig. 9. Values of the constant *B* (distance to which the capillary pores control sorption) at 14 and 90 days of curing.

which is an indication of pore refinement in fly ash mixtures. The variation in the values of *B* is similar to that of the overall moisture intake described earlier.

Fig. 10a and b depicts the sorptivity of concretes after 14 and 90 days of curing, respectively. Both the short-term and long-term sorptivities are indicated in these figures. The short-term sorptivities are calculated from the slope of the moisture intake-square root of time curves, as is conventionally done to determine sorptivity. Only the first 4 h is considered here. The long-term sorptivity is obtained from the fit of Eq. (1) to the mass gain data over 672 h. It can be seen from these figures that the long-term sorptivity is always higher than the short-term value, irrespective of the material composition. Fig. 10a shows that both the short-term and long-term sorptivities are lower for the control concrete than the fly ash and glass powder modified concretes when tested after 14 days of curing, similar to the trend in the values of the parameter *B*. It is the combination of the values of sorptivity and *B* that determines the absorption through concrete in the early stages after subjected to moisture.

Fig. 10b shows the sorptivities of the concretes after 90 days of curing. It can be seen that the fly ash modified mixtures have similar or lower long-term sorptivities as compared to the control concrete. The reduction in sorptivities between 14 and 90 days are highest for the fly ash modified concretes, followed by the glass powder modified concretes, once again establishing the relative efficiency of these supplementary cementing materials in long-term microstructure improvement.

The diffusion coefficient (D_m) values obtained from the fit for all the concrete mixtures cured for both 14 and 90 days are shown in Fig. 11. A reduction in diffusion coefficient with time of curing is evident for all the mixtures. The D_m values for 14 day cured specimens are roughly the same for all mixtures expect for the 0.40 w/cm fly ash concrete which shows a value higher by an order of magnitude. The reason for this can be found in Fig. 8a. The overall moisture intake curves after 14 days of curing for all the mixtures except that for the 0.40 w/cm fly ash mixture are parallel to each other and essentially parallel to the *X*-axis after about 200 h of ponding. For the 0.40 w/cm fly ash mixture, it can be seen that the moisture intake curve keeps rising even after about 600 h of ponding, showing more moisture intake later on, and consequently a higher

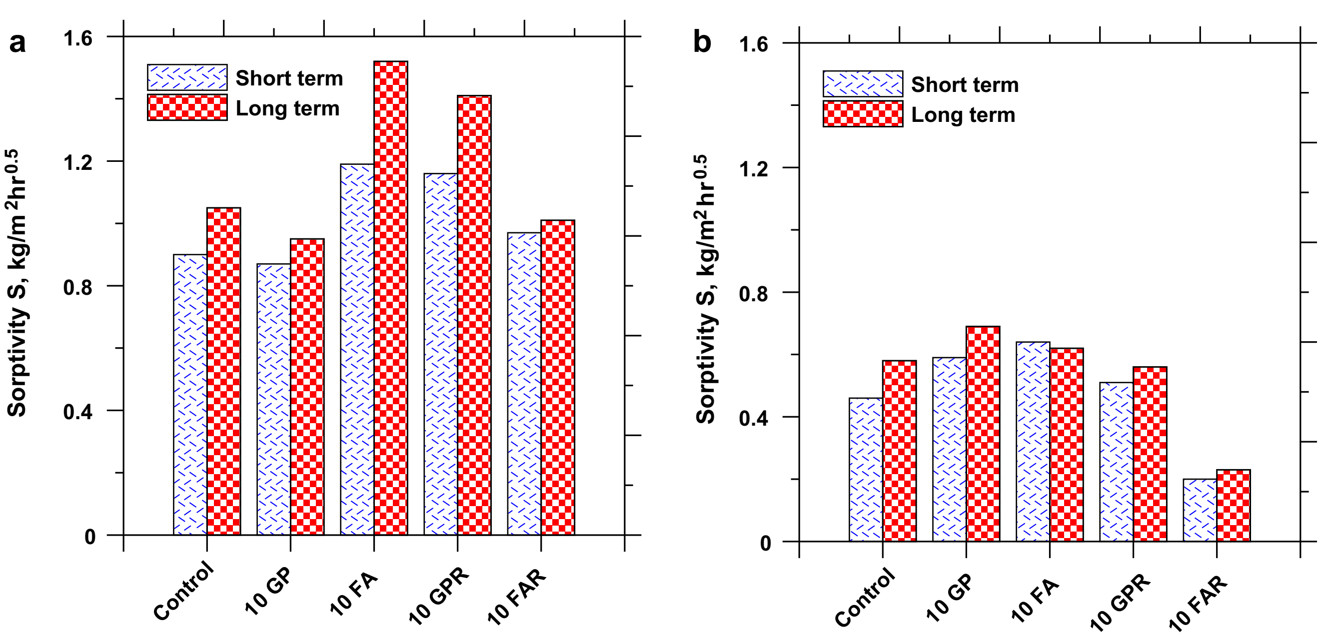

Fig. 10. Short-term and long-term sorptivity values after: (a) 14 days, and (b) 90 days of curing.

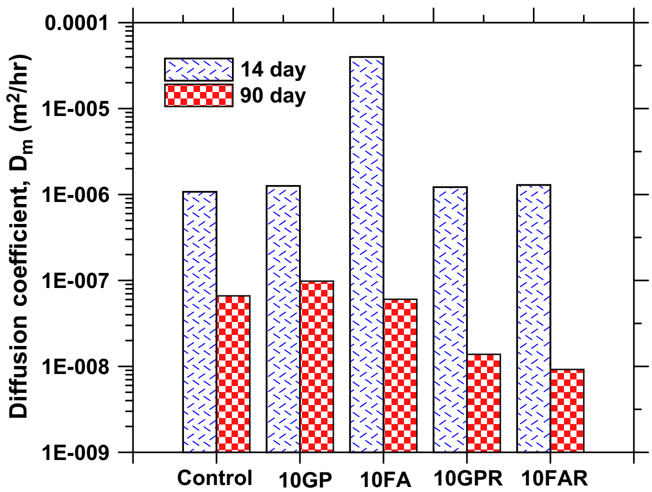

Fig. 11. Moisture diffusion coefficients after14 and 90 days of curing.

diffusion coefficient. This mixture also shows a higher value of the constant B as well as a higher sorptivity after 14 days of curing as can seen from Figs. 9 and 10a. The higher total amount of water intake for this mixture is due to the combined effect of higher sorptivity and diffusion coefficient. After 90 days of curing, the low w/cm mixtures show reduced moisture diffusion coefficients, which is expected. The reduced w/cm fly ash mixture is found to have the least diffusion coefficient at this time. The 0.40 w/cm glass powder modified mixture shows a slightly higher diffusion coefficient than the corresponding fly ash mixture. The general observation made earlier that the glass powder modified concretes perform similarly or better than the control concrete at later ages, and better than fly ash modified concretes at earlier ages, is found to be satisfied for moisture diffusion also.

4. Conclusions

The salient conclusions from this study on comparing the effects of a fine glass powder and Class F fly ash on the durability of concretes is presented in this section.

(i) Based on the early and later age compressive strengths, non-evaporable water contents, and the calcium hydroxide contents of the plain, glass powder modified, and fly ash modified cement pastes made with a w/cm of 0.42, it was observed that a 10% replacement of cement with the glass powder used in this study is feasible in cementitious systems. The non-evaporable water contents showed that the glass powder facilitates an enhancement in cement hydration at early ages, owing to its very low water absorption.

(ii) The 28 day compressive strengths of concretes with 10% glass powder replacing cement were found to be higher than that of fly ash concretes at the same replacement level, whereas the 90 days strength of fly ash modified concretes were higher than the corresponding glass powder modified concretes. However, the strength difference was only of the order of 5%, suggesting that concretes with 10% of cement replaced either by glass powder or fly ash will behave in a similar manner as far as mechanical properties are concerned.

(iii) With increasing curing duration, the rapid chloride permeability values of the plain and modified concretes were observed to decrease. The RCP values of the modified concretes were lower than the control concrete at early ages while they show essentially similar values at later ages. The enhancement in cement hydration as a result of the glass powder addition, and the secondary reaction of fly ash compensates for the dilution of cement content.

(iv) Glass powder as a cement replacement material demonstrated the potential to reduce deleterious expansion due to alkali–silica reaction. The reduction in expansion was proportional to the dosage of glass powder. Similar amounts of fly ash as replacement for cement showed larger reduction in expansion, which proved that fly ash is more effective than glass powder in suppressing ASR expansion. The reduction in expansion was found to be proportional to the fly ash content also. For the reactive aggregate used in this study, a 20% replacement of cement by fly ash was found to limit the expansion to less than 0.10% after 14 days. Higher glass powder dosages would have been necessary to produce the same effect.

(v) Ternary blends containing glass powder and fly ash were found to be very effective in reducing expansion due to ASR. Any combination of glass powder and fly ash that make up the 20% replacement level was observed to be as effective as 20% cement replacement by fly ash.

(vi) At early ages (moist cured for 14 days), the control concrete was seen to have lowest amount of moisture intake when subjected to the one-dimensional moisture intake test, where as the modified mixtures had higher values. At later ages (moist cured for 90 days), this trend was reversed, demonstrating the influence of the replacement materials in pore structure refinement. The total moisture intake of the glass powder concretes were in between those for control and the fly ash modified concretes at all times. From the trends in moisture intake, it can be concluded that the 10% glass powder modified concretes perform similar to or better than control concrete at later ages and better than 10% fly ash modified concretes at early ages.

(vii) The moisture transport parameters including the distance from the exposed face to which capillary pores control sorption (B), sorptivity (S), and the moisture diffusion coefficient (D_m) were extracted from a combined sorption–diffusion equation. The value of B at early ages was lowest for the control concrete, and highest for the fly ash modified concretes. The trend reversed at later ages, similar to that of the overall moisture intake. Between the early and later ages, the reduction in sorptivities were highest for the fly ash modified concretes, followed by the glass powder modified concretes, showing the relative efficiency of glass powder and fly ash in microstructure modification. The moisture diffusion coefficients at early ages were roughly the same for all mixtures except the 0.40 w/cm fly ash concrete. The low w/cm concretes showed lower moisture diffusion coefficients at later ages, as expected. For the moisture transport parameters also, the trend described for moisture intake, i.e., glass powder modified concretes perform equal to or better than fly ash modified concretes at earlier ages, and control concrete at later ages, was found to be valid.

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