Durability characteristics of high early strength concrete

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High early strength concrete (HESC) is a type of high performance concrete, which attains its specified strength earlier than normal concrete. This type of concrete is normally used in precast and prestressed concrete industries. Many studies have been performed on the production of high early strength concrete, but information on performance of high early strength concrete in durability tests is limited. This article deals with evaluation of durability index characteristics of high early strength concrete mixtures made with two different cements. Durability index tests such as oxygen permeability, sorptivity, rapid chloride permeability and water absorption tests were performed on three HESC mixtures made with two different cements and compared with a reference concrete. Our results reveal that high early strength concrete using steam curing is better than concrete produced using accelerator. The microstructural studies also revealed that steam-cured concrete is better than accelerator-cured concrete supporting the durability index properties of concretes tested.

Keywords: Chloride permeability, high early strength concrete, oxygen permeability, sorptivity, water absorption.

HIGH early strength concrete (HESC) is a high performance concrete, which attains its specified strength earlier than normal concrete[1]. HESC is normally used in precast and prestressed concrete industries. There is limited information on the performance of high early strength concrete in durability tests compared to normal concrete.

Durability problems can be attributed to either physical or chemical mechanisms[2], although the two types of mechanisms often act together to bring about the development of distress. Concrete that is permeable to air, water, or other substances is more likely to suffer some kind of durability distress[3]. There are various methods to measure the durability index parameters of concrete. These include oxygen permeability, water sorptivity, rapid chloride permeability, water absorption, etc. Absorption is a measure of the volume of pore space in concrete irrespective of the interconnectivity of pores[4]. Thus, although absorption and permeability are commonly correlated, they are not necessarily related. The absorption test is commonly used as a quality control test for precast members. Steam curing affects the size of pores, making them coarser and consequently increasing water absorption[5]. However, moist curing after steam curing is known to result in refinement of pores and concretes of this type usually do not suffer from the same problem.

There is another type of test to measure the absorption of concrete by capillary suction, termed as sorptivity. Sorptivity is defined as the rate of movement of a waterfront through a porous material under capillary action[6]. Ronne and Alexander[7] observed lower sorptivity values for steam cured concrete (steam cured above 60°C) than normal water curing. Ho *et al.*[8] found that steam-cured concretes containing ordinary Portland cement, fly ash and blast furnace slag, were more porous with sorptivity depths about twice those of specimens with three days of standard curing. There were obvious benefits in the use of silica fume in improving the pore structure of concrete under steam or standard curing conditions.

The rapid chloride permeability method is widely used to assess the durability characteristics of concrete[9]. The rate of ingress of chlorides into concrete depends on the pore structure of the concrete, which is affected by factors including materials, construction practices and age. Although accelerated curing has negative impacts on the chloride resistance of concrete (even when a proper preset time is used), the use of supplementary cementing materials can be effective in terms of mitigating these negative effects[10].

The oxygen permeability test is a gas permeability test that provides an indication of the degree of pore connectivity in a concrete matrix. Githachuri and Alexander[11] found that oxygen permeability index (OPI) was reduced with the reduction of w/b ratio and increase in the age of concrete. In addition, they also observed that the addition of supplementary cementitious materials reduced the gas permeability values to a certain extent. Similar results were reported by San Nicolas *et al.*[12] – inclusion of metakaolin enhanced the durability by reduction in OPI values.

This article deals with the evaluation of durability index characteristics of high early strength concrete mixtures made with two different cements. Durability index tests such as oxygen permeability, sorptivity, rapid chloride

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permeability and water absorption tests were performed on three HESC mixtures made with two different cements and compared with a reference concrete.

Experimental programme

Materials

The cements used were 53 grade Ordinary Portland Cement (OPC), conforming to IS:12269 (1987)[13]. Locally available river sand was used as the fine aggregate for concrete mixtures. The specific gravity of this sand determined as per IS: 2386-1968 Part III (ref. 14) was 2.63, while the fineness modulus using the sieve analysis method described in IS: 2386-1968 Part III was determined to be 2.57. The dry rodded unit weight of the coarse aggregate, as determined by IS: 2386-1968 Part III, was found to be 1630 kg/m^3. The maximum size of coarse aggregate was 20 mm and the coarse aggregates were blended in the ratio 60 : 40 of 20 mm and 10 mm respectively. A naphthalene sulphonate based high range water-reducing admixture (HRWR) was used in concrete mixtures to obtain the necessary workability. A non-chloride hardening accelerator meeting the requirements of type C ASTM C 494-1999a (ref. 15) was used in some concrete mixtures to accelerate the early strength development of concrete.

Clinker characteristics

The chemical composition of clinkers was determined by X-ray fluorescence test. The compound composition of the clinkers was estimated using quantitative X-ray diffraction analysis (Rietveld refinement) and the results are shown in Table 1. The heat of hydration of the two clinkers was also examined with the help of adiabatic calorimetry. The clinker characteristics are presented in Table 1. It can be seen that the primary difference in the two cements is with respect to the C_3A content, as well as the crystal form of C_3S, which could have implications on the reactivity of these cements. The heat of hydration characteristics of two clinkers revealed that the cement C1 falls in the low heat category, whereas the cement C2 falls in the medium heat category[16]. The physical characteristics of the cements used in the preparation of HESC mixture are presented in Table 2.

Concrete mixture proportioning

Concrete was proportioned as per ACI 211.4R-1999 (ref. 17) and the mixture proportions were arrived at based on preliminary studies on concrete. Central composite design was done to optimize the steam curing cycle. The details regarding optimization of steam curing cycle were reported earlier (ref. 18). The selected concrete proportions were named as HC for high cement content mixtures, AC for concrete containing accelerator, SC for steam-cured concrete and RC for reference concrete. There were a total of three high early strength concrete mixtures HC, AC and SC, and the final mixture RC was the reference concrete mixture for SC and AC. Two different brands of cements were used in the study. Hence, the above mixture designations will be prefixed with C1 and C2 to differentiate the concrete made using these cements. The final mixture proportions used in this study are presented in Table 3. The superplasticizer dosage was adjusted to obtain a slump range of 75–100 mm for all the mixtures.

Durability tests

The following durability tests were conducted for specimens from all the concretes: (i) Rapid chloride permeability tests were performed on 100 mm diameter and 50 mm thick slices as per ASTM C1202-97. (ii) Oxygen permeability tests were done on 68 mm diameter and 25 mm thick slices cut from 68 mm diameter cores that

Table 1. Compound composition (%) of clinkers determined from quantitative XRD

Characteristics	C1	C2
C_3S–M	34.9	42.3
C_3S–T	22.3	12
C_3S–total	57.2	54.3
β-C_2S	23.5	24.2
C_3A–C	3.0	5.8
C_3A–M	0.9	3.1
C_3A–total	3.9	8.9
C_4AF	13.7	11.4
Maximum heat rate (W/kg)[13]	2.73	3.22
Total heat evolved (kJ/kg)[13]	270	300

M, Monoclinic; T, triclinic; C, cubic.

Table 2. Physical characteristics of cements used in this study

Characteristics	C1	C2
Fineness (m^2/kg)	304	294
Standard consistency	30	29.5
Setting time (min)		
Initial	200	250
Final	260	320
Soundness		
Le-chatelier expansion (mm)	1.0	1.5
Autoclave Expansion (%)	0.08	0.032
Compressive strength		
3 days	37.0	40.5
7 days	47.0	52.0
28 days	67.5	72.0

Table 3. High early strength concrete mixture proportions

Mixture ID	Cement (kg/m^3)	w/c	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Superplasticiser (kg/m^3)	Accelerator (kg/m^3)
HC	450	0.35	798	1088	6.75	–
AC	420	0.40	795	1088	2.10	8.40
SC	420	0.40	795	1088	4.20	–
RC	420	0.40	795	1088	4.20	–

SC, Steam cured at 66°C after a delay period of 4 hrs for a period of 14 h followed by 6 h cooling; following this, the specimens were moist cured until 28 days[18].

were removed from 150 mm cubes, in the permeability cell designed by Ballim[19]. The specimen conditioning and test method were as prescribed in the South African Durability Index Manual[20]. (iii) Water sorptivity tests were conducted on the same specimens that were tested for oxygen permeability. The test procedure described in South African Durability Index Manual[20] was followed. The apparent porosity was also determined in the same experiment. (iv) The water absorption test as per ASTM C642-97 was performed on 100 mm cube specimens.

Microstructural observations using scanning electron microscopy

Concrete specimens at the age of 1 and 28 days were viewed under an environmental scanning electron microscope. The specimens were studied in the backscatter electron mode, in order to differentiate the various phases by the compositional contrast provided by this mode. Different phases in concrete (CSH, CH, unhydrated cement grains and pores) can be easily distinguished in this mode. Unhydrated cement, which has the highest atomic number amongst all cementitious phases, appears the brightest. CSH shows a range of grey shade, depending on the type and density, whereas CH is significantly brighter than CSH and pores are dark.

Results and discussion

Compressive strength

Compressive strength results of the high early strength concrete mixtures with cements C1 and C2 at various ages are presented in Figures 1 and 2 respectively. At the end of the first day, the strengths of all concrete mixtures containing cement C1 (except SC) were higher than those with C2. The higher C_3S content in case of C1 than C2 was probably responsible for the early strength behaviour. With respect to steam curing, C2SC showed 23% higher strength than C1. The presence of higher C_3A content in C2 is expected to have contributed to the early age response to steam curing. At the end of 180 days, the strength of all concrete mixtures containing cement C2 (with the exception of AC) was higher than C1.

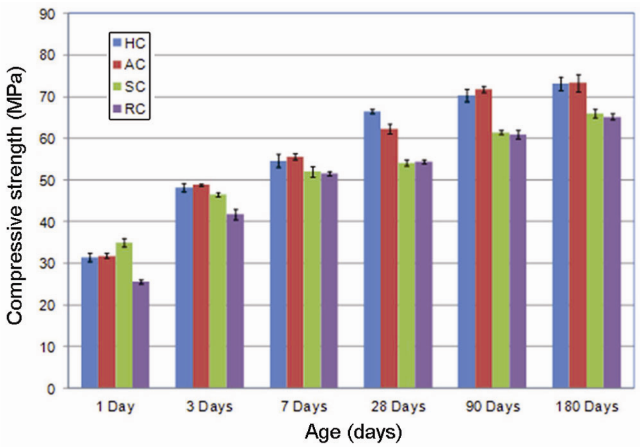

Figure 1. Compressive strength results of HESC mixtures with cement C1.

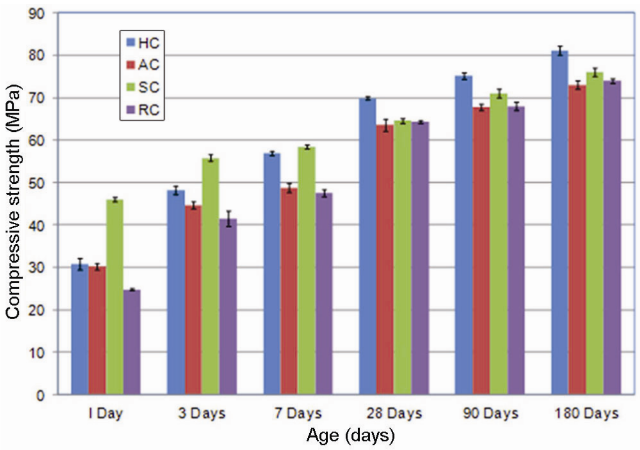

Figure 2. Compressive strength results of HESC mixtures with cement C2.

Figures 1 and 2 also indicate that the rate of strength gain after 1 day (or maximum 3 days) drops for the steam-cured concrete; all other concretes show a steady rate of increase in strength, at least until 28 days. In case of both C1 and C2, the best long-term strengths were attained by the high cement content (HC) mix. Additionally, the mix with accelerator also shows similar performance as HC in the case of C1. After 28 days, the strengths of RC are almost equal to the SC and AC mixes.

Sorptivity

Figure 3 shows the sorptivity values of the concretes with cement C1 at 1 and 28 days. On the first day, RC was found to have higher sorptivity values than other concrete. This was expected, as RC has the highest w/c. Chan and Ji[21] also reported higher sorptivity for higher w/c due to the more porous nature of the concrete. HC and SC mixtures on the first day showed approximately 26% lower sorptivity values than RC, whereas AC was found to have 5% lower sorptivity than RC. On day 28, AC showed higher sorptivity values than RC, SC and HC. AC was found to have 11% higher sorptivity values than RC on day 28. This was due to the poorer microstructure of concrete that is expected with accelerator[22]. The sorptivity values decrease with respect to time due to hydration as expected due to refinement in pore structure.

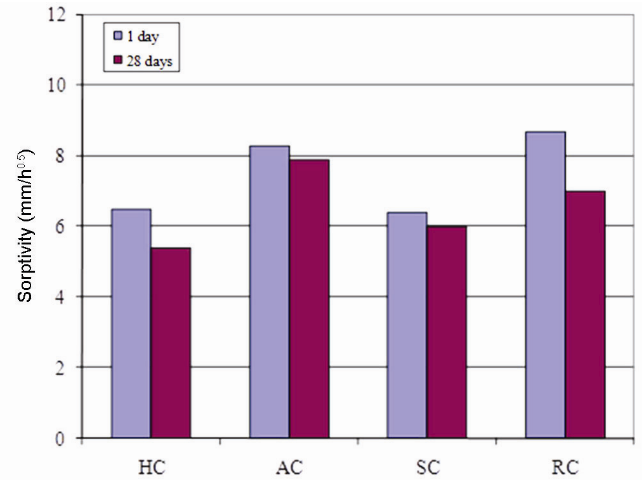

Figure 3. Sorptivity values of concretes containing cement C1 on days 1 and 28.

The sorptivity values of the concretes with cement C2 on days 1 and 28 are presented in Figure 4. Similar to C1 series, RC was found to have the highest sorptivity on day 1. The steam-cured concrete showed only half of the sorptivity value of RC on day 1. HC and AC were found to have approximately 36% and 16% lower sorptivity values than RC on day 1. On day 28, AC showed 23% higher sorptivity than RC, HC showed 20% lower sorptivity values than RC, while SC showed only 12% lower sorptivity values than RC. RC showed tremendous decrease in sorptivity value with respect to age. It was found to be reduced by a margin of approximately 42% compared to the value on day 1.

Comparing the sorptivity values of both cements, the order of sorptivity values (decreasing order) for mixtures was RC, AC, HC and SC. Steam-cured concrete showed least sorptivity values in case of both cements. This could be due to high early strength obtained with steam curing for concretes with both cements on day 1.

Apparent porosity

The apparent porosity results of concretes with both cements on days 1 and 28 are shown in Figures 5 and 6. The day 1 porosity results indicate that RC had the highest porosity among all concretes in both cements. With cement C1, the porosity of RC and AC was found to be equal on day 1, whereas in case of cement C2, the porosity of AC was nearly 3% less than RC. The porosities of C1HC and C1SC on day 1 were found to be approximately 16% and 12% lower than the reference concrete mixture C1RC. In case of C2 series on day 1, C2HC was also found to be 16% lower than the C2RC, whereas SC showed nearly 23% lower porosity values than RC.

The 28 days porosity values were considerably lower compared to day 1, in line with the expected increase of

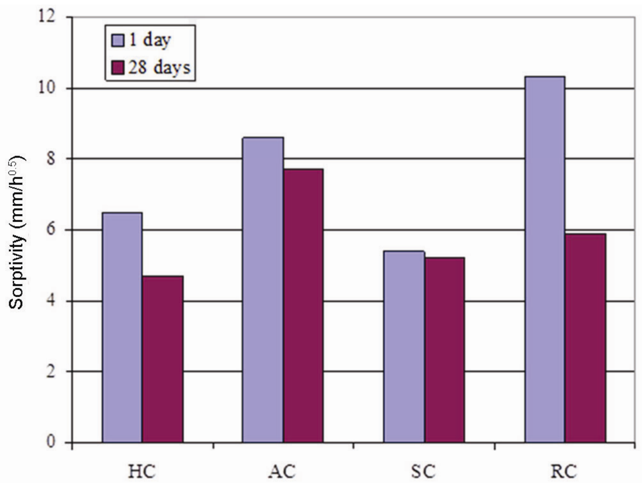

Figure 4. Sorptivity values of concretes containing cement C2 on days 1 and 28.

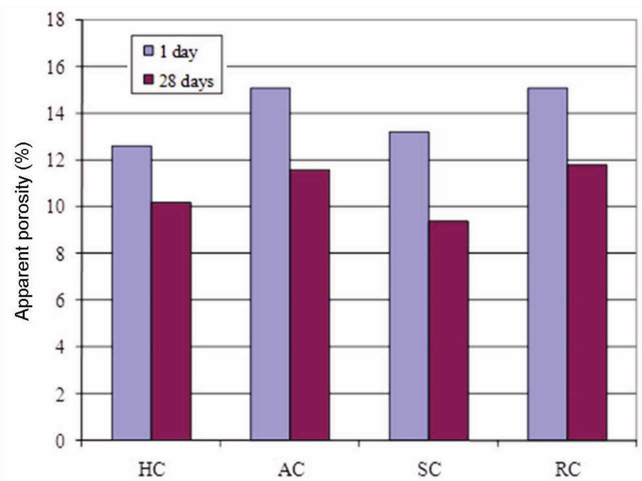

Figure 5. Apparent porosity of HESC containing cement C1 on days 1 and 28.

hydration. The porosity values on day 28 were found to decrease by a margin of approximately 20% in case of C1HC and C1RC from day 1 porosity. C1AC and C1SC showed a decline of nearly 23% and 28% from 1 day values. In case of C2 series, both HC and RC showed more than 30% reduction in porosity on day 28 compared to day 1, whereas AC and SC showed nearly 16% and 26% lower porosity values on day 28. The porosity values of C1AC, C1HC and C1SC on day 28 were approximately 2%, 14% and 20% lower than the reference concrete mixture C1RC. In case of C2 series, AC showed approximately 19% higher porosity than RC on day 28. C2SC and C2HC on day 28 were found to have 14–20% lower porosity than C2RC.

Comparing the two cements, on day 1, C2 series showed higher porosity values than C1 series except for steam-cured concrete mixture. On day 28, a reverse trend was observed, in that the C2 series showed lower porosity values than C1 series except for AC. The difference in margin on day 28 was greater in case of HC mixtures (approximately 20% between the two cements). This was supported by the compressive strength results, in which C2HC showed lesser strength on day 1 than C1HC, but thereafter the strength of C2HC was ahead of the strength of C1HC.

Rapid chloride permeability

Figures 7 and 8 show the results of rapid chloride permeability test (in terms of charge passed) for concrete mixtures containing cement C1 and C2 on days 1 and 28 respectively. The concrete mixtures containing accelerator (C1AC and C2AC) were observed to have a lower resistance to chloride ion penetration as shown by the higher charge passed during the test. As shown in Figures 7 and 8, the high cement (HC) content mixture was found to have the highest resistance to chloride ion penetration with both cements – this can be attributed to the lower w/c of the mix. The chloride permeability values of steam-cured concrete were marginally lower than the reference concrete mixtures with both cements on day one. All concrete mixtures except the concrete containing accelerators were found to be in the moderate permeability range based on the classification provided by ASTM C 1202-12 (ref. 23). AC was in the high permeability range at both ages (total charge passed exceeded 4000 Coulombs).

Oxygen permeability

Table 4 lists the coefficients of permeability and Figures 9 and 10 show the oxygen permeability indices of concrete mixtures containing cements C1 and C2 on days 1 and 28 respectively. As expected, the OPI value decreases with low w/c ratio. This behaviour was also reported by other researchers[9,11]. The results clearly indicate that HC, AC and SC had significantly lower permeability than RC. The coefficient of permeability of

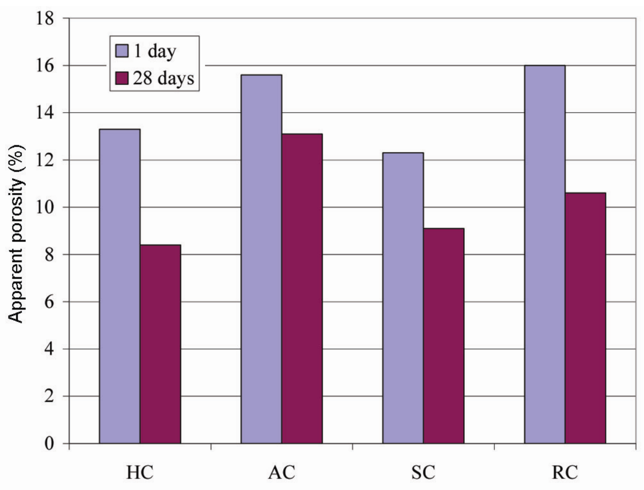

Figure 6. Apparent porosity of HESC containing cement C2 on days 1 and 28.

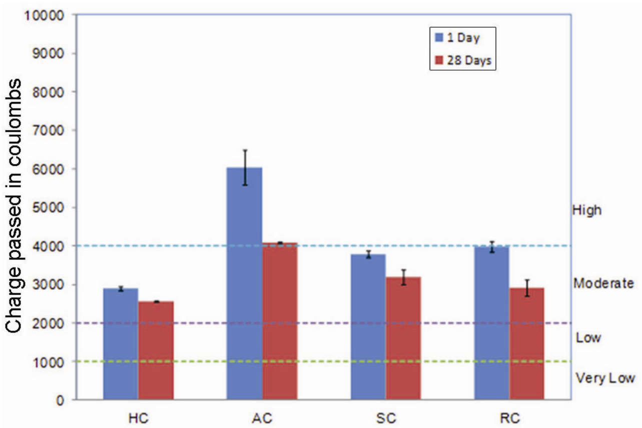

Figure 7. Chloride permeability values of concretes with cement C1.

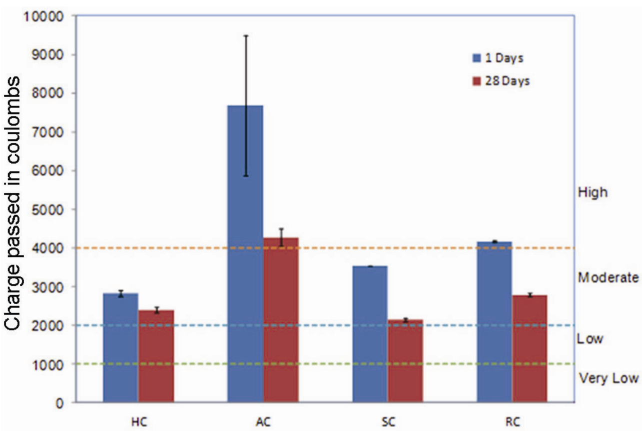

Figure 8. Chloride permeability values of concretes with cement C2.

SC, HC and AC mixtures on day 1 was in the range of 20–56% of the level for the reference concrete mixture RC. SC showed the lowest coefficient of permeability among the group. On day 28, the trend appeared to be the same as that of day 1, with steam cured concrete showing the lowest permeability. The difference between the reference concrete and the other mixtures was reduced at the age of 28 days. SC and HC mixtures were in the range of 39% and 49% of the level for the reference concrete mixture (RC), while AC showed 17% lower coefficient of permeability than RC on day 28. Comparing day 1 and day 28 results, it was observed that RC showed tremendous decrease in the coefficient of permeability than other concrete mixtures with respect to age. The coefficient of permeability (k) at 28 days was reduced by a margin of 56% from the first day k value in case of RC, whereas the corresponding decrease was only 17% in case of SC. The reduction of k values from day 1 in case of AC and HC mixtures were within the range of 30% to 40% respectively. The reduction in permeability values indicated that the resistance to oxygen permeability increased with respect to age, as expected.

The coefficient of permeability values of HESC mixtures with cement C2 also follow the same pattern as that of HESC containing cement C1. HC, SC mixtures had significantly lower permeability than RC mixtures at the age of one day. The coefficient of permeability of SC was 88% lower than the reference concrete mixture. Similar to cement C1, here also SC showed the lowest coefficient of permeability among the group. On day 28, the trend appeared to be the same as that of day 1 with steam-cured concrete showing the lowest permeability. The difference between reference concrete and other mixtures was reduced at 28 days. SC and HC mixtures were approximately 60% to 65% lower than the reference concrete mixture (RC), whereas AC had only 12% lower coefficient of permeability than RC at 28 days. Comparing day 1 and day 28 results, it was observed that RC and AC showed tremendous decrease in the coefficient of permeability than other concrete mixtures with respect to age. The coefficient of permeability (k) at 28 days was reduced by a margin of 76% from day 1 k values in case of RC, 71% in case of AC, whereas only 24% in case of SC. Similar to C1, SC mixtures with C2 also showed less decrease in permeability with respect to age.

Comparing the OPI results of two cements, C1 series showed lower k values than C2 series at the end of day 1. The difference between RC and AC mixtures of the two series was approximately 44% and 57% respectively. SC was found to have nearly equal k values with both cements. The k value of C2HC was 24% lower than that of C1HC. At 28 days, the difference between the cements reduced drastically.

Table 4. Oxygen permeability results of HESC mixtures on days 1 and 28

	$k \times 10^{-10}$ m/s	
Mixture ID	1 day	28 days
C1HC	0.91	0.54
C1AC	1.40	0.92
C1SC	0.52	0.43
C1RC	2.50	1.10
C2HC	1.20	0.44
C2AC	3.30	0.96
C2SC	0.53	0.40
C2RC	4.50	1.10

Water absorption

Figure 11 shows the water absorption results of concretes made from cement C1 on days 1 and 28. On day 1, HESC mixture AC was found to have higher water absorption than other concrete mixtures in the C1 series. AC had 11% higher water absorption than reference concrete mixture RC, whereas HC and SC showed nearly 11% to

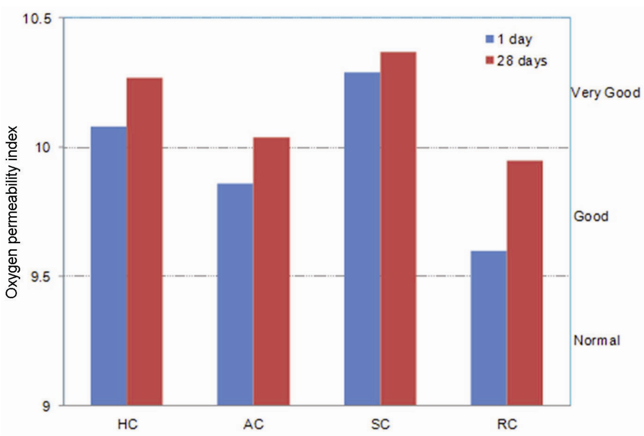

Figure 9. Oxygen permeability index results of HESC with cement C1.

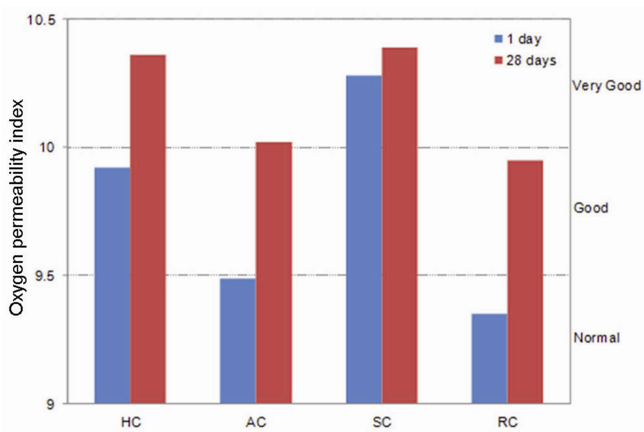

Figure 10. Oxygen permeability index results of HESC with cement C2.

24% lower water absorption than RC at day one, which was expected since both HC and SC possess a higher strength (implying lower porosity) at day 1 compared to RC. However, in case of AC, although the strength was higher than RC, it showed higher water absorption, which could be because of increased pore connectivity resulting from the formation of a more porous structure as reported by Rixom and Mailvaganam[22].

The water absorption showed the same pattern on day 28 also, with AC having the highest water absorption. SC had 34% lesser water absorption than RC, whereas HC showed only 9% lower water absorption than RC on day 28. The water absorption on day 28 was reduced approximately by a margin of 50% to 60% compared to day 1 water absorption values.

Figure 12 shows the water absorption results of HESC made from cement C2 at days 1 and 28. Similar to the case with cement C1, AC showed nearly 10% higher water absorption than RC at day 1. SC showed the lowest water absorption at day 1 (approximately 10% lower than RC), whereas HC showed 6% lower water absorption than RC.

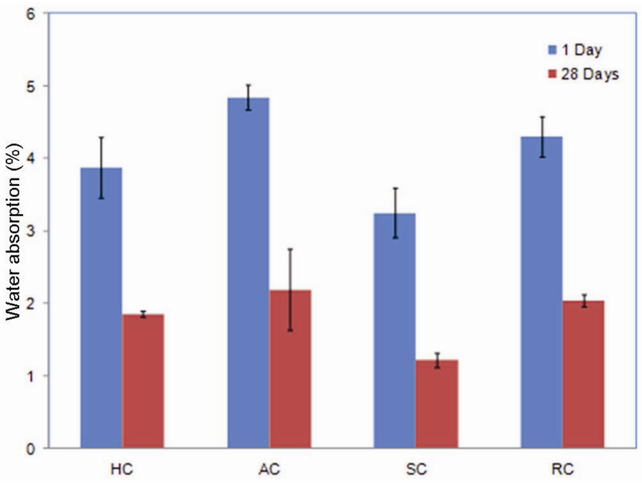

Figure 11. Water absorption of concretes with cement C1 on days 1 and 28.

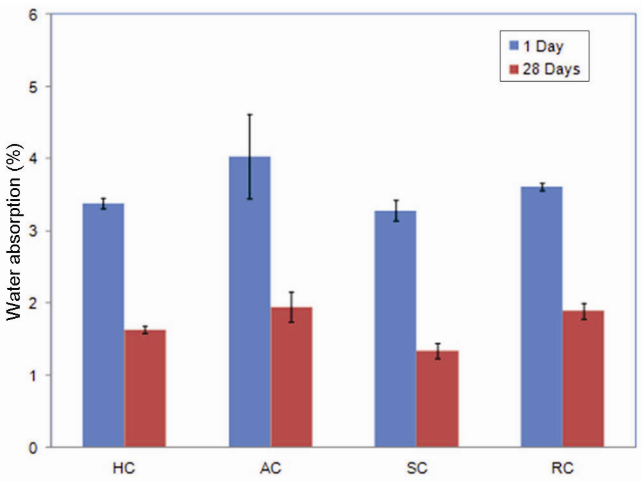

Figure 12. Water absorption of concretes with cement C2 on days 1 and 28.

On day 28, AC was found to have higher water absorption compared to other concrete mixtures. Steam cured concrete showed nearly 35% less water absorption compared to RC, while HC showed 13% less absorption than RC on day 28. The overall trend for concretes with either cement was the same. With cement C2 also, the reduction in water absorption from days 1 to 28 was in the range of 40% to 50% approximately.

Comparing the water absorption results of the two cements, water absorption is less in concrete mixtures containing cement C2 on days 1 and 28 than C1. On day 1, the difference in water absorption between the two cements was found to be higher than on day 28 except for steam-cured mixtures. Only steam-cured mixtures showed negligible difference in water absorption between the two cements. C1AC on day 1 was found to have water absorption of nearly 5%, whereas C2AC showed only 4% absorption. This indicates that the composition of the cement played a significant role in the absorption characteristics of high early strength concrete.

Microstructural characterization by scanning electron microscopy

Figures 13 to 20 show the backscattered images of concretes made with cement C1 after 1 and 28 days of hydration. Microstructural observations using SEM brought out the differences in porosity of the hydrated paste formed in the different concretes. With the aid of thresholding and segmentation methods, the porosities of all HESC

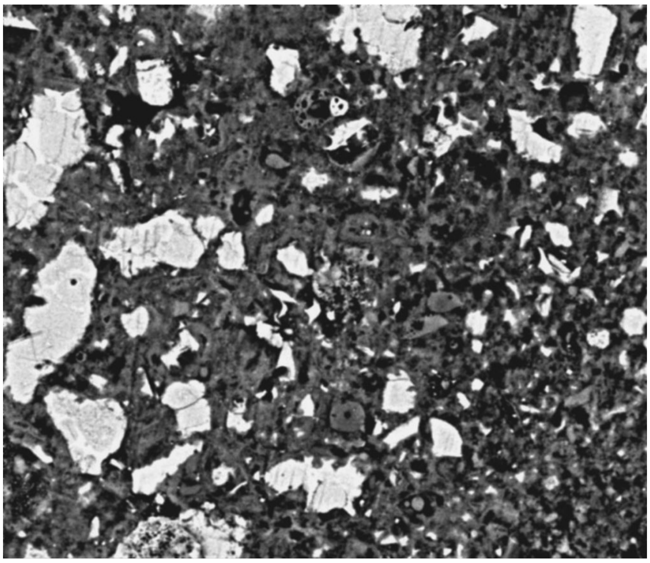

Figure 13. BSE image of C1RC after 1 day of hydration showing high porosity and unhydrated cement grains (width of field ≈ 275 μm).

were obtained and presented as shown in Table 5. The pore area fractions presented in this table can only be used for comparison, as they do not include gel porosity and small capillary porosity, which are not visible at this level of magnification. However, these values give some idea about pore distribution and amount of pores present in different concrete mixtures. It can be seen from Table 5 that at the end of day one, RC showed higher porosity than other concrete mixtures (for either cement). The order of porosity for concretes with both cements was RC, AC, SC and HC (from highest to lowest). High cement content mixtures showed the lowest porosity among the group. It was also noticed that with the addition of accelerator, the concrete was found to be more porous comparatively to other high early strength concrete mixtures, except reference concrete mixtures. C1AC, C1SC and C1HC were 20%, 39% and 68% lower than the porosity of C1RC on day one. But at the age of 28 days, C1AC was found to be slightly more porous than C1RC. Other mixtures C1SC and C1HC were approximately 10% and 60% lower than the C1RC on day 28. The porosity at 28 days was nearly half of the one day porosity. Similar pattern was found in case of cement C2. The only difference in cement C2 was that C2AC at 28 days had lower porosity than C2RC.

The apparent porosity measured using vacuum saturation method and pore area fraction measured using image analysis followed the same pattern, even though both

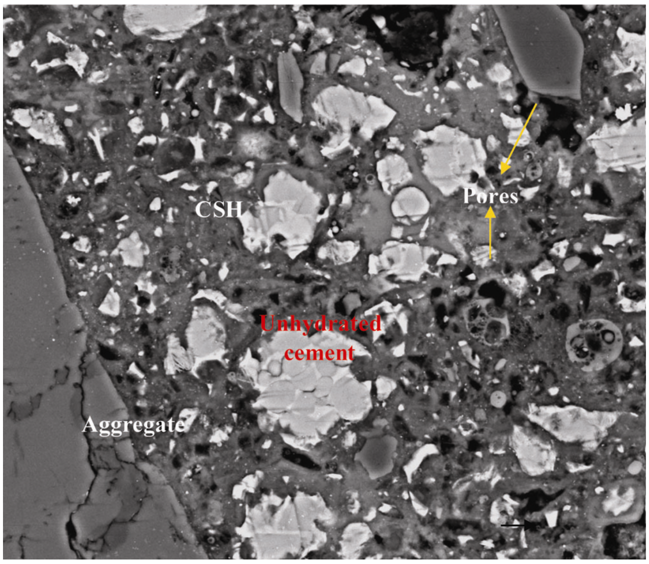

Figure 14. BSE image of C1RC after 28 days of hydration (width of field ≈ 275 μm).

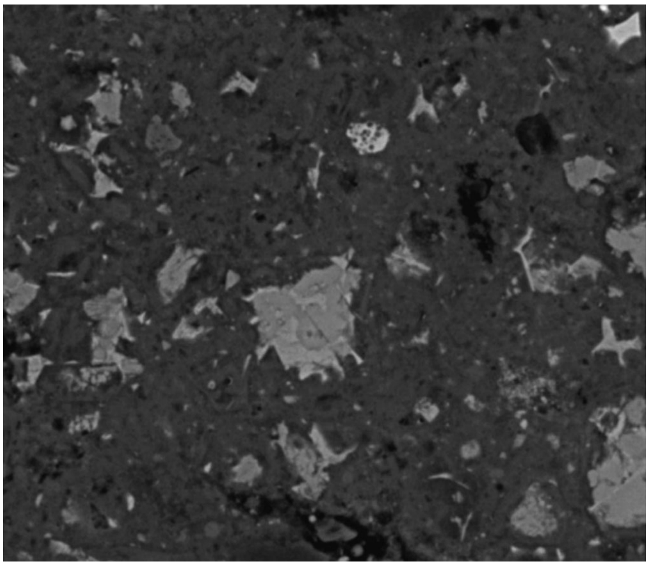

Figure 15. BSE image of C1HC after 1 day of hydration (width of field ≈ 275 μm).

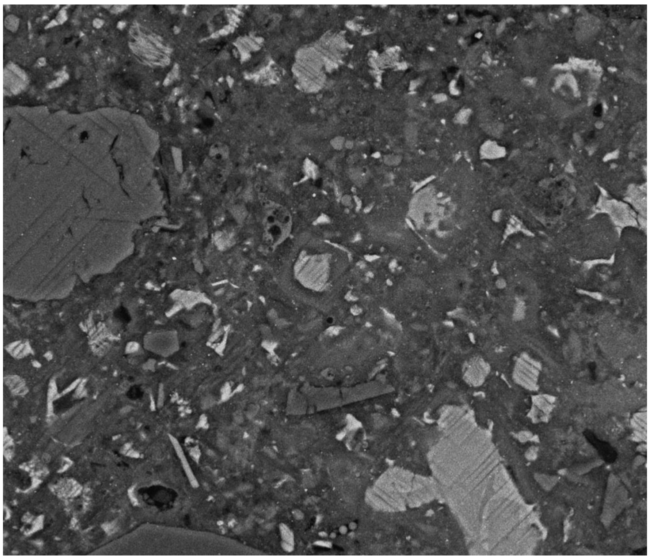

Figure 16. BSE image of C1HC after 28 days of hydration (width of field ≈ 275 μm).

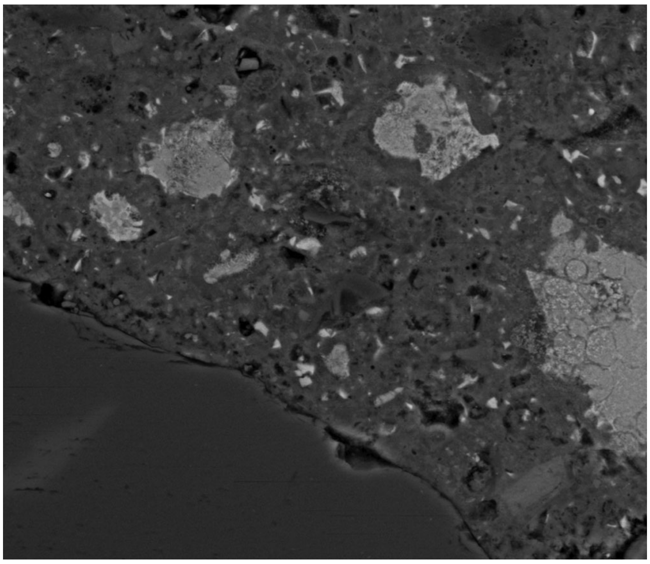

Figure 17. BSE image of C1SC after 1 day of hydration (width of field ≈ 275 μm).

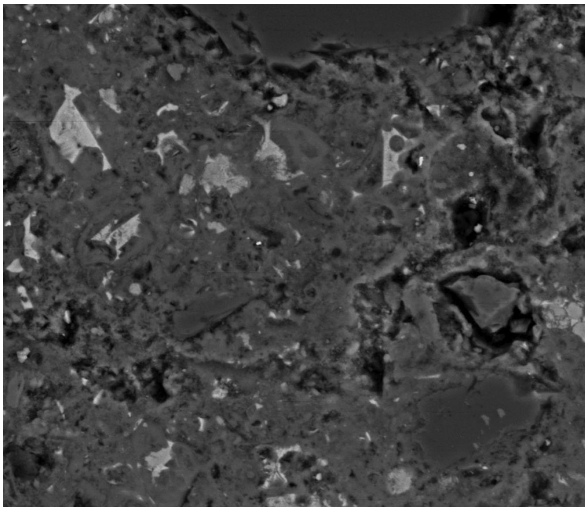

Figure 18. BSE image of C1SC after 28 days of hydration (width of field ≈ 275 μm).

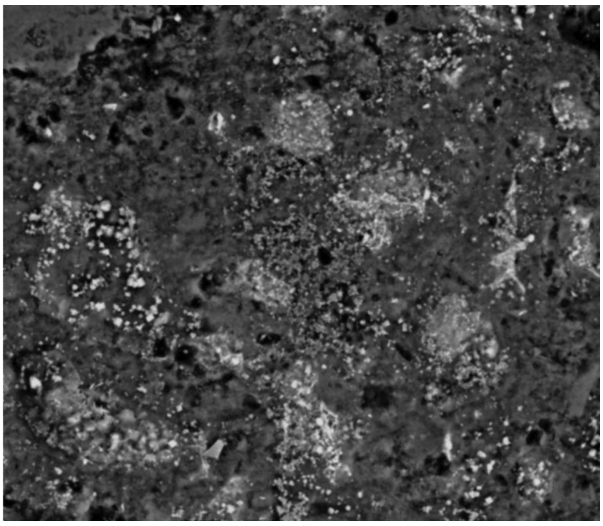

Figure 19. BSE image of C1AC after 1 day of hydration (width of field ≈ 275 μm).

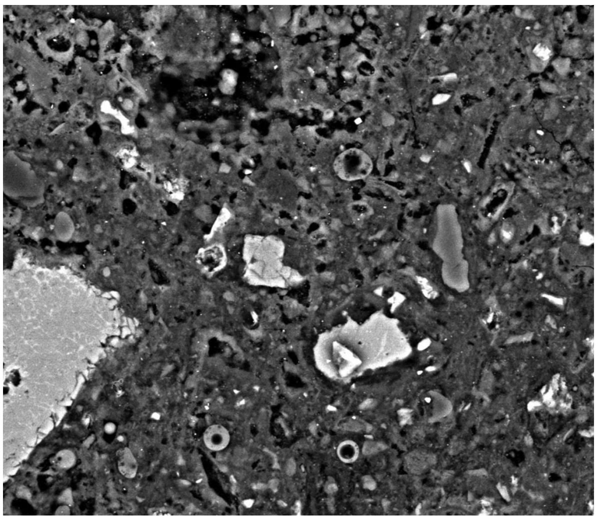

Figure 20. BSE image of C1AC after 28 days of hydration (width of field ≈ 275 μm).

Table 5. Pore area fractions of HESC

Mixture ID	Porosity @ 1 day (%)	Porosity @ 28 days (%)
C1HC	3.40	1.92
C1AC	8.56	4.63
C1SC	6.40	3.85
C1RC	10.48	4.29
C2HC	2.97	1.82
C2AC	7.91	2.24
C2SC	3.12	2.07
C2RC	10.03	2.79

values were not exactly comparable. Porosity was found to be higher for the concrete with accelerator as compared to the other HESC mixtures, which confirms the results obtained in the durability investigations.

Conclusions

The conclusions drawn from this study related to durability index characteristics of high early strength concrete mixtures are summarized as follows:

- Cement composition played a vital role in the strength development of high early strength concrete. The differences in the C_3S and C_3A contents caused a variation in the strength development pattern in accelerating conditions.
- Water absorption of concrete with cement C1 was found to be higher than that of concrete with cement C2 on days 1 and 28.
- Sorptivity values of all concrete mixtures were in the range 'good to excellent' at both ages (except for C2RC on day 1), according to the characterization provided by Ronne and Alexander[7].
- Rapid chloride permeability results showed that all concrete mixtures except the concrete containing accelerators (AC) were in the moderate permeability range based on the classification provided by ASTM C 1202-12 (ref. 23).
- According to the characterization of concrete based on OPI values, all concrete mixtures were in the range 'good to very good' at both ages, according to the characterization provided by Alexander *et al.*[24], except C2RC and C2AC at day one which were in the 'normal' category.
- Microstructural investigations support the durability index properties by giving a clear picture about the porosities of the concrete tested.

1. Zia, P., Ahmad, S. H., Leming, M. L., Schemmel, J. J. and Elliott, R. P., Mechanical behaviour of high performance concretes. High early strength concrete Volume 4, *Strategic Highway Research Program,* National Research Council, Washington, DC, 1993, **xi**, p. 179.

2. Khurana, R., Heat curing in precast concrete. *Master Build. Technol.*, Treviso, Italy, 1998.
3. Mehta, P. K. and Monteiro, P. J., *Concrete, Microstructure, Properties and Materials*, New York, 3rd edn, 2005.
4. Neville, A. M., *Properties of Concrete*, Fourth and Final Edn, Longman Publication, 2000.
5. Radjy, F. and Richards, C. W., Effect of curing and heat treatment history on the dynamic mechanical response and the pore structure of hardened cement paste. *Cement Concrete Res.*, 1973, **3**, 7–21.
6. Kelham, S., A water absorption test for concrete, *Mag. Concrete Res.*, **40**, 1988, 143, 106–110.
7. Ronne, P. D. and Alexander, M. G., Quantifying the effects of steam curing on concrete durability. Proceedings, Concrete for the 21st Century, Progress through Innovation, Midrand, South Africa, 2002, p. 13.
8. Ho, D. W. S., Chua, C. W. and Tam, C. T., Steam-cured concrete incorporating mineral admixtures. *Cement Concr. Res.*, 2003, **33**, 595–601.
9. Alexander, M. G., Ballim, Y. and Mackechnie, J. R., Concrete durability index testing manual. *Res. Monogr. No. 4*, Cape Town, South Africa, 1999.
10. Hooton, R. D. and Titherington, M. P., Chloride resistance of high performance concrete subjected to accelerated curing. *Cem. Concrete Res.*, 2004, **34**, 1561–1567.
11. Githachuri, K. and Alexander, M. G., Durability performance potential and strength of blended Portland limestone cement concrete. *Cement Concr. Comp.*, 2013, **39**, 115–121.
12. San Nicolas, R., Cyr, M. and Escadeillas, G., Performance-based approach to durability of flash-calcined metakaolin as cement replacement. *Constr. Build. Mater.*, 2014, **55**, 313–322.
13. IS 12269 Specifications for 53 grade ordinary Portland cement. *Bureau of Indian Standards*, New Delhi, 1987.
14. IS 2386 Methods of test for aggregate concrete. *Bureau of Indian Standards*, New Delhi, 1968.
15. ASTM C 494/C 494M, Standard specification for chemical admixtures for concrete. *Am. Soc. Testing Mater.*, Philadelphia, 1999.
16. Chokkalingam, R. B., Santhanam, M., Ballim, Y. and Graham, P. C., A comparative assessment of selected Indian and South African cement clinkers. *Indian Concr. J.*, 2010, **86**, 9–16.
17. ACI 211.4R, Guidelines for selecting proportions for high strength concrete with Portland cement and fly ash. *ACI Manual of Concrete Practice*, 1999.
18. Ramesh Babu, C. and Santhanam, M., Optimization of high early strength steam cured concrete mixtures using central composite design, *Indian Concr. J.*, 2006, **80**(6), 11–15.
19. Ballim, Y., A low cost falling head permeameter for measuring concrete gas permeability. *Concrete/Beton, J. Concr. Soc., Southern Africa*, 1991, **61**, 13–18.
20. Durability Index Testing Procedure Manual, Concrete durability index testing, South Africa, 2009.
21. Chan, S. Y. N. and Ji, X., Water sorptivity and chloride diffusivity of oil shale ash concrete. *Constr. Build. Mater.*, 1998, **12**, 177–183.
22. Rixom, R. and Mailvaganam, N., *Chem. Admixtures Concrete*, E&FN SPON, London, 3rd edn, 1999.
23. ASTM C 1202–12 Standard test method for electrical indication of concrete's ability to resist chloride ion penetration. *Am. Soc. Testing Mater.*, Philadelphia, 1999.
24. Alexander, M. G., Ballim, Y. and Mackechnie, J. R., Guide to the use of durability indexes for achieving durability in concrete structures. Industry/FRD collaborative research programme: achieving durable and economic concrete construction in the South African context. Research Monograph, 1999.

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