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Performance of fly ash concretes containing lightweight EPS aggregates

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Abstract

Non-absorbent man-made aggregates like expanded polystyrene (EPS) do not suffer with the disadvantage of water absorption, which makes production of the normal lightweight aggregate concrete difficult. The present investigation is directed towards the development and performance evaluation of the concrete composites containing EPS aggregates. Lightweight EPS concrete composites were produced by replacing the normal aggregate, either partially or fully, with EPS aggregates depending upon the density and strength required. The study covers the use of EPS beads as lightweight aggregate both in concrete and mortar, containing a fly ash replacement of 50% in the cementitious material. The concretes were designed to cover a wide range of densities (550–2200 kg/m^3), through EPS replacements ranging from 95% to 0%. The results were compared with similar concrete composites, essentially having OPC as the binder, from the literature. The study indicates that the EPS mixes produced with fly ash show lower absorption values compared to the mixes with OPC reported earlier. These concretes were also found to have a better chemical resistance. The chloride permeability of these concretes was seen to be 50–65% lower compared to that of normal concretes having similar water cement ratios. The corrosion rates of these concretes were also lower compared to the normal concretes.

Keywords: Expanded polystyrene; Fly ash; Density; Permeability; Absorption; Chemical attack; Chloride permeability; Corrosion

1. Introduction

Lightweight aggregate concrete, popular through the ages, was reported to have a comparable or some times better durability even in severe exposure conditions [1]. One of the main problems associated with the use of conventional lightweight aggregates produced from clay, slate and shale in concrete is that these porous aggregates absorb a very large quantity of the mixing water. This is known to affect the performance of the concrete, apart from the fact that it is difficult to maintain specific water content during the casting. Also, this absorption of water by the aggregate will mean that additional water will be required to maintain the slump at acceptable levels. These increased water contents necessitate higher cement contents, even without the benefit of higher strength. Also, the durability of any concrete is primarily controlled by the permeability and a better understanding of moisture transfer can therefore reduce or prevent the damage in building materials [2]. Concrete is also affected by the aggressive action of deleterious substances presents in industrial liquids and gases or in marine environment through chemical attack. This deterioration of concrete also leads to the corrosion of the reinforcement resulting in the spalling of concrete.

In view of the above it is essential to improve the matrix characteristics to ensure that the absorption is restricted to acceptable limits without the associated higher cement contents. Non-absorbent, hydrophobic and closed cellular aggregates like expanded polystyrene (EPS) beads do not suffer with this disadvantage [3–5]. To improve the performance further a part of the cement phase can also be replaced with fly ash incorporated as a supplementary cementitious material through the efficiency concept developed earlier [6].

Earlier researchers reported that the hydrophobic nature of the EPS in concrete necessitated the use of either bonding additives [4] or should be chemically

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treated [5]. However, in the present investigation all the mixes were designed to have adequate paste content with small quantity of superplasticizer to avoid this problem. The concretes thus produced were studied for their performance in terms of their durability and corrosion resistance.

The addition of EPS in place of normal aggregate not only reduces the weight of the concrete but could also reduce the permeability and increase the resistance to chemical attack, because of the closed cellular and inert nature of these aggregates. However, information on these parameters particularly for EPS concretes is scanty. Also, the effect of fly ash as a supplementary cementitious material on the performance of EPS concretes was not available in literature. Thus it was felt necessary to study the durability of these concretes, over a wide range of densities, to qualify them as concretes of high performance.

2. Experimental investigation

2.1. Materials

Cement conforming to both IS:12269 (C53 grade) [7] and ASTM type I [8], and Class F fly ash were used as cementitious materials in the concrete mixes. The chemical characteristics of the cement and fly ash are given in Table 1. Sand finer than 2.36 mm, with a fineness modulus of 2.8, was used. The aggregates were either sand alone or a combination of sand and normal coarse aggregate (crushed blue granite) of maximum size 8 mm, apart from the EPS. Two types of commercially available spherical EPS beads that are essentially single sized (types A and B) were used. The grading shows that type A (8–4.75 mm) has mostly (90%) 6.3 mm size beads and type B (4.75–2.36 mm) has mostly (98%) 4.75 mm size. The bulk density and relative density of these beads were 9.5 kg/m^3 and 0.014 for type A and 20 kg/m^3 and 0.029 for type B, respectively. A naphthalene-based superplasticizer and an air-entraining admixture were used to produce mixes of flowable or flexible nature suitable for the hand compaction adopted.

Table 1
Chemical composition of cement and fly ash

Chemical composition	Cement	Fly ash (Class F)
Silica (SiO_2)	21.78	58.29
Alumina (Al_2O_3)	6.56	31.74
Ferric oxide (Fe_2O_3)	4.13	5.86
Calcium oxide (CaO)	60.12	1.97
Magnesium oxide (MgO)	2.08	0.14
Sodium oxide (Na_2O)	0.36	0.76
Potassium oxide (K_2O)	0.42	0.76
Sulphuric anhydride (SO_3)	2.16	0.15
Loss on ignition (LOI)	2.39	0.31

2.2. Mix proportions

Concretes were initially designed as per the recommendations of ACI-211.2 [9] and were modified for incorporating fly ash through the efficiency concept [6]. All the EPS concretes were designed with a fly ash replacement of 50% by weight of the total cementitious material. The details of the concrete mixes studied are presented in Table 2. All the mixes were containing both a superplasticizer and an air-entraining admixture at 0.25% and 0.02% by weight of the total cementitious material respectively. The concretes were designed over a wide range of densities ranging from 550 to 2200 kg/m^3 with corresponding EPS replacements of the total aggregate ranging from 95% to 0% respectively. The mixes E124 and E220 have the same mix proportions (with 50% fly ash), except for the fact that E220 has 0% EPS and is used as reference concrete with fly ash for comparison. In addition a normal concrete without fly ash (NC) made with 20 mm maximum size, graded coarse aggregate was also investigated for comparison.

2.3. Test program

The main objective of the present investigation was to study the performance of lightweight EPS aggregate concretes containing fly ash over a wide range of concrete densities of 500–2200 kg/m^3, with the corresponding compressive strengths varying between 1.5 and 24 MPa. The performance characteristics were investigated through permeability, absorption and chemical attack representing the durability of concrete. The corrosion aspects of the steel in these concretes were investigated through the chloride permeability, corrosion rates and accelerated corrosion studies. Each of the results reported for the compressive strength is an average result of two 150 mm cube specimens. However, if the variation between the two values is more than 10%, an additional specimen is tested to find this average.

2.3.1. Durability characteristics

The permeability characteristics of these concretes were assessed using Germann Water permeability Test (GWT meter, Denmark). This test, conducted on two saturated 150 mm cube specimens, basically measures the volume of water penetrating under a 5 kg/m^2 pressure over a 1-h period. The coefficient of permeability was determined with the help of Darcy's law. The test is performed on two side surfaces of each of the cubes, and it is ensured that there is no leakage at any point through the gasket.

The absorption test was carried out on two 100 mm cubes as per ASTM C 642-82 [10]. Saturated surface dry cubes were kept in a hot air oven at 60 °C (though ASTM suggests a temperature range of 100–110 °C) till a constant weight was attained. This is because at this temperature range of 100–110 °C, the EPS beads ini-

Table 2
Mix details of the concretes investigated

Name[a]	Cement (kg/m^3)	Fly ash (kg/m^3)	$w/(c+f)$ ratio	Weight distribution of aggregate			% of EPS in total volume	Max. size of CA[b] (mm)	Wet density (kg/m^3)
				Sand (%)	CA (%)	EPS (%)			
E57	142	142	0.651	5.5	–	94.5	66.5	–	582
E76	190	190	0.487	10	–	90	58	–	779
E95	224	224	0.413	20	–	80	49	–	984
E124	247	247	0.434	20	16	64	38	8	1304
E153	274	274	0.412	20	30	50	28.5	8	1484
E182	309	309	0.396	20	50	30	16.3	8	1723
E220	247	247	0.455	20	80	0	0	8	2215
NC	319	0	0.58	31	69	0	0	20	2578

[a] *Note*: All concretes (except NC) were made by hand compaction.
[b] CA—Normal coarse aggregate.

tially shrink and finally evaporate. These are then immersed in water and the weight gain was measured at regular intervals until a constant weight is reached. The absorption at 30 min (initial surface absorption) and final absorption (at a point when the difference between two consecutive weights at 12 h interval was almost negligible) is reported to assess the concrete quality. The final absorption in all cases is observed to be at 72 h.

The chemical resistance of these EPS concretes was studied through chemical attack, immersing them in a 3% H_2SO_4 solution. For this test four 100 mm cubes were immersed in the test solution after attaining the age of 28 days. The solution was replaced at regular intervals to maintain constant concentration throughout the test period. The parameters studied were the weight loss measured after 15 and 30 days and the strength loss measured after 30 days of immersion.

2.3.2. Corrosion characteristics

The chloride permeability test was conducted to assess the concrete quality as per ASTM C 1202-94 [11]. A potential difference of 60 V DC was maintained across the specimen. One of the surfaces was immersed in a sodium chloride solution and the other in a sodium hydroxide solution. The total charge passing through in 6 h was measured on at least two specimens, with the average indicating the resistance of the specimen to chloride ion penetration.

The half-cell potentials were recorded using a saturated calomel electrode (SCE). Potentiodynamic polarization technique was adopted to measure corrosion rate of an 8 mm diameter bar having an exposed length of 100 mm placed centrally in a cylinder specimen (100 diameter by 200 mm long) by using a scanning potentiostat (EG & G PAR Model 362) and an $X-\log X$, Y recorder. A potential of 250 mV was applied on either side of open circuit potential (OCP) and the corrosion current (I_{corr}) was taken from the tangents drawn at 100 mV from the potentiodynamic plot. In all the tests a scan rate of 1 mV/s was selected. The corrosion rate was calculated from this I_{corr} by using Faraday's equation.

Accelerated corrosion study was performed on the same cylinder specimen containing a central 8 mm diameter bar. The test was conducted in a 3% NaCl solution by impressing a current of 6 V for a period of 8 days. This test was performed in accordance with the method suggested by the Florida Department of Transportation [12] and the average daily resistance (ADR) was calculated. The results reported for the potentials, corrosion rate and accelerated corrosion were the average of at least two specimens.

3. Results and discussion

A comprehensive summary of the results of the durability characteristics of all the concretes are presented in Table 3. The results of the corrosion related parameters are given in Table 4.

3.1. Permeability

The volume of water penetrating with time for the different concretes was measured for evaluating the permeability values of these concretes. It was not possible to conduct the test on the concretes of lower density (E57 and E76), as the cube surface started crushing while clamping the meter. All the concretes including the normal concretes were having permeability values between 1×10^{-12} and 9×10^{-12} m/s. As per CEB guide line [13], all the EPS as well as the normal reference concretes were in the range of "average" concrete quality. It can also be seen that the EPS concretes were showing a higher permeability compared to the normal reference concretes (E220, NC). The permeability values were slightly higher for EPS concretes of lower density concretes compared to the higher density EPS concretes. The variation of permeability with percentage volume of EPS given in Fig. 1, indicates that the permeability was decreasing with increasing compressive strength (decreasing with the EPS volume). Incidentally, Zhang and Gjorv [1] reported a similar range of water permeability

Table 3
Durability characteristics of EPS concretes (after 28 day immersion curing)

Name	Compressive strength (MPa)		Permeability ($\times 10^{-12}$ m/s)	Absorption (%)		Chemical attack[a] (3% H_2SO_4)		
						Weight loss (%)		Strength loss (%)
	28 d	90 d		30 min	Final	15 d	30 d	30 d
E57	1.10	1.50	–	11.47	20.84	2.06	2.12	–
E76	2.30	3.60	–	3.79	10.69	−4.41	−3.25	−22.95
E95	3.83	5.90	9.172	3.25	8.99	−3.06	−2.82	−17.95
E124	6.00	7.40	8.626	3.07	7.11	−2.09	−1.46	0
E153	7.80	11.6	3.617	2.92	7.05	−1.86	−1.71	6.41
E182	12.5	16.0	2.638	2.22	6.71	−1.12	−1.11	9.26
E220	18.4	23.4	3.303	1.90	4.52	−0.51	−0.14	15.22
NC	43.0	44.5	1.194	1.23	4.93	0.65	5.96	36.17

[a] Negative value indicates weight gain.

Table 4
Corrosion characteristics of EPS concretes (after 90 day immersion curing)

Name	Chloride permeability (C)	Potentials with respect to SCE (−mV)	Corrosion rate (mpy)	Daily average resistance (Ω)
E57	–	602	2.713	171.43
E76	967.14	240	0.072	4536.6
E95	943.20	150	0.144	3376.4
E124	1469.34	230	0.260	2128.3
E153	1305.27	280	0.210	2001.6
E182	1371.96	295	0.222	854.88
E220	1065.15	195	0.133	3341.5
NC	2983.00	626	4.526	–

even for the lightweight high strength concretes (50–100 MPa, having densities ranging from 1600 to 1900 kg/m^3) made with expanded clay aggregates containing 9% silica fume.

3.2. Absorption

The absorption in 30 min (initial surface absorption) as well as the absorption after 72 h (final absorption) for these concretes are presented in Fig. 2. From these results, it can be seen that the initial surface absorption of all the EPS concretes (except E57) show values around 3%, the limit specified for "good" concrete by CEB [13]. The final absorption at the end of 72 h for these concretes also followed a similar trend, which was also similar to that of the permeability results. The total absorption values are decreasing from 10% to 4.5% for

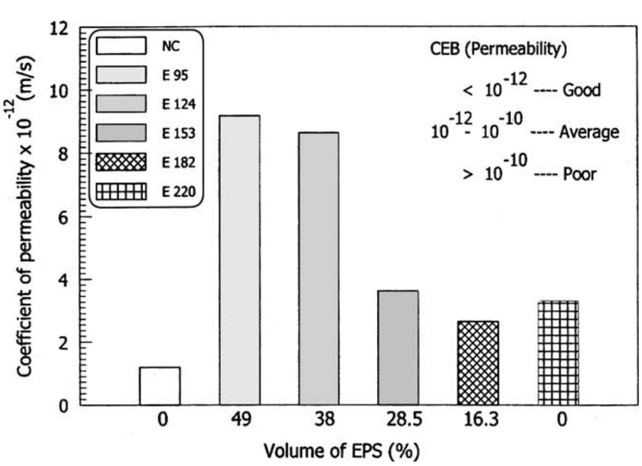

Fig. 1. Permeability characteristics of EPS concretes.

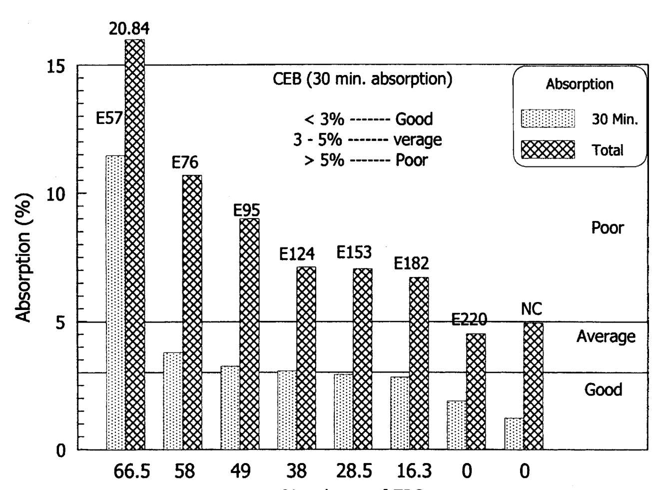

Fig. 2. Absorption characteristics of EPS concretes.

E76 to E220 concretes respectively. However, the lowest density concrete studied (E57) showed a total absorption of 20%. This is mainly due to the fact that in this mix the cementitious paste was very low. It was also observed that the concrete absorbs a lot of water, which drained off immediately on removal from water. Also the EPS may have been affected (shrunk) during drying process. In general, from the results it can be seen that, lower strength concretes were showing higher absorption compared to the higher strength concretes. The variation of total absorption with 90 day compressive strength and plastic density is shown in Fig. 3. It can be seen that the absorption values were decreasing with increasing compressive strength.

Bagon and Yannas [14] earlier reported that the EPS concretes with wet densities ranging between 815 and 980 kg/m^3 show absorption values in the range of 21–27% of dry weight. In comparison to this, in the present study a concrete of 984 kg/m^3 density shows an absorption value of 9% only. This may be attributed to the pore filling and pozzolanic effects of the additional paste, contributed by fly ash. Also, Kluge et al. [15] reported very high absorption values for the various types of lightweight aggregate concretes of corresponding density. It is observed that the absorption values of the EPS concretes of the present study (with fly ash) were much lower than both the EPS concretes (with only cement as binder) and other lightweight aggregate concretes reported in literature.

3.3. Chemical attack

The results of the weight change and strength loss studied for all concretes are presented in Table 3. The chemical attack, in terms of the weight change for all the EPS concretes, show a continuous gain up to 30 days, which can be attributed to the formation of gypsum and ettringite in the matrix. The lower density concretes, containing a lower cementitious materials content, are observed to be having higher weight gain, may be due to the higher porosity of the matrix, which allows the environment to penetrate more easily.

The strength loss at 30 days is shown in Fig. 4. From the results, it can be seen that the EPS concretes with lower cement content with corresponding lower strength (density) show strength gain even after 30 days of immersion, while the concretes with higher cement content show a strength loss. This effect of the strength variation due to chemical attack with the cement content was also shown in Fig. 4.

The resistance to chemical attack for the concretes containing chemically treated EPS was studied by Sri Ravindrarajah and Tuck [5] earlier. They reported that these concretes were unaffected by saturated calcium hydroxide, 10% sodium sulphate and 10% ammonium sulphate solutions but suffered a noticeable attack, showing a weight loss of 7.8%, 12.4% and 14.3% at the water to cement ratio of 0.4, 0.5 and 0.6 respectively, in 5% hydrochloric acid.

3.4. Chloride permeability

Accelerated chloride permeability test was conducted on all the EPS concretes (except for E57 because of the clamping difficulty already explained). The total charge passing in 6 h as a measure of the chloride permeability was presented in Fig. 5. The chloride ion penetrability limits suggested by ASTM C1202 were also superimposed. It can be seen that, all the EPS concretes show low chloride permeabilities in the range of 1000–1500 C, primarily due the fly ash in these mixes. In contrast, the normal aggregate concrete without fly ash (NC) shows a

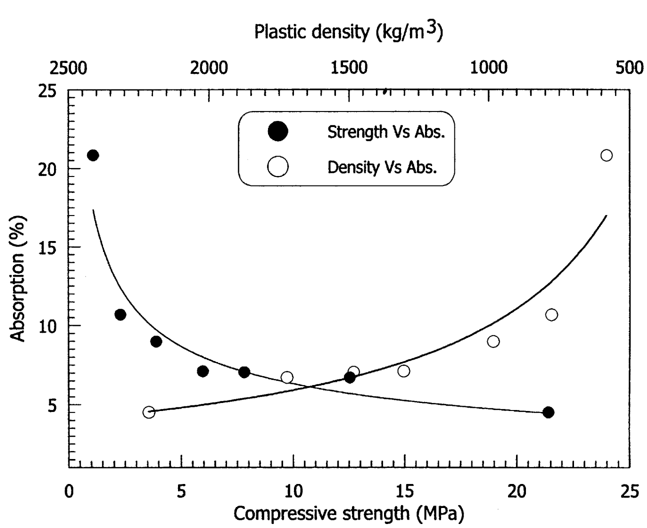

Fig. 3. Variation of absorption with strength and density.

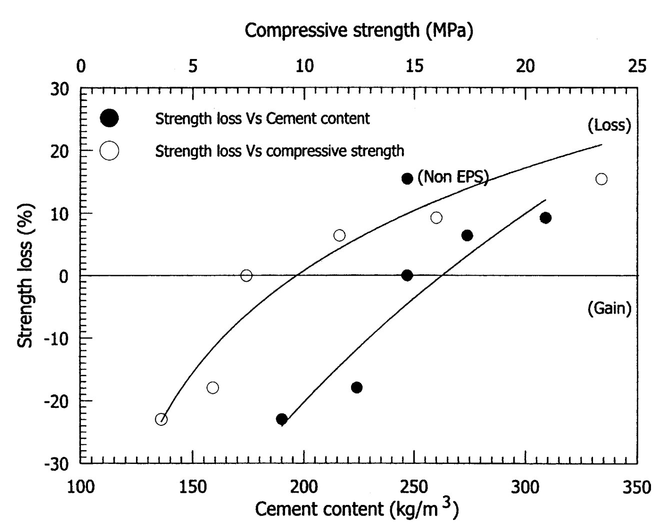

Fig. 4. Effect of cement content on strength loss.

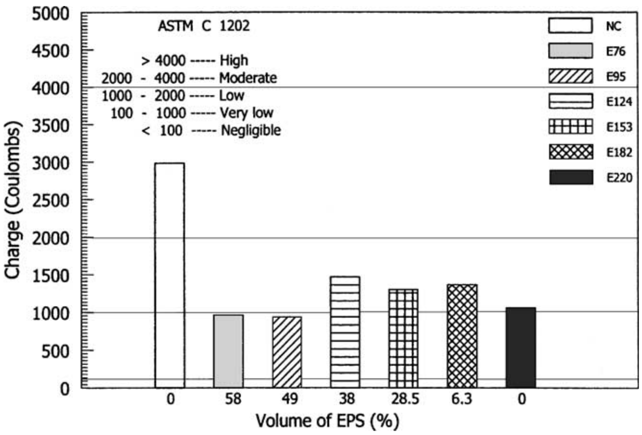

Fig. 5. Chloride permeability of EPS concretes.

chloride permeability of about 3000 C, indicating clearly that the mixes containing fly ash were behaving much better. This could be the due to the fact that the chloride ion penetration depends on the chloride binding capacity of constituent materials. The presence of C_3A in hydrated cement reacts with chloride ions and forms inert products like Friedels salt ($3CaO\,Al_2O_3\,CaCl_2 \cdot 10H_2O$). If the part of cement is replaced with pozzolanic material like fly ash, the alumina content in that further favors the binding of chloride ion [16]. Also, the addition of fly ash improves the pore structure and impermeability of concrete resulting in higher binding capacity and lowers the chloride ion permeability. Zhang and Gjorv [1] reported very low chloride permeabilities (200–950 C) for the high strength lightweight silica fume concretes (1600–1900 kg/m^3 densities) made with expanded clay aggregates.

3.5. Potentials and corrosion rate

The potentials and the corrosion rates of the steel in EPS concretes were not reported hitherto in literature, but in general, these are expected to be influenced only by the matrix phase. The OCPs and corrosion rates were measured at the age of 90 days. The potentials indicate that the steels were all in a passive state (below −270 mV with respect to SCE). The corrosion current densities (I_{corr}) of all the EPS concretes (but for E57) do not show any significant variation and the values were lower than that for the normal concrete without fly ash. From the corrosion current densities, corrosion rates of the rebars in all the concretes were calculated. It can be seen that all the EPS concretes have corrosion rates lower than that for the normal concrete without fly ash. The factors contributing to this may be the higher impermeability of EPS concretes to chloride ions and the higher chloride binding capacity of the fly ash in concrete as reflected in the chloride permeability studies.

3.6. Accelerated corrosion studies

Corrosion being a long-term process an exact evaluation of the corrosion resistance capability of the concrete composites is difficult and accelerated corrosion test methods are adopted to evaluate the relative corrosion resistance capability in a reasonably short period. The results of the accelerated corrosion studies were presented in Table 4. The variation of current with time during the test period for the different concretes cured in seawater (after a 3 day normal water curing) at the various EPS volume percentages was observed. The ADR of these concretes was observed to be decreasing with decreasing percentage of the EPS volume or with an increasing paste content, except in the case of E57. This concrete was having a very high porosity, as the cementitious paste content was very low, as discussed earlier in absorption and this concrete had the lowest ADR value. However, the average daily resistance of E76 and E95 concretes showed higher ADR values than the normal concrete containing fly ash (E220), mainly due to the lower paste contents in these concretes. The ADR values were also decreasing with increasing paste content, matching well with the variation of the total charge, which was increasing with increasing paste content as reflected in the chloride permeability studies. This indicates that a minimum paste content is required to achieve a concrete of higher performance. Also, a comparison of the mixes E124 and E220, both having the same paste content (including fly ash), show that the concrete with EPS aggregate has slightly lower ADR value. In general, these observations indicate that the corrosion properties mostly depend up on the paste content and are not so much influenced by the aggregate properties.

4. Conclusions

The permeability of EPS as well as comparable normal concrete were in the range of 1×10^{-10}–1×10^{-12} m/s and can be designated to be of "average quality" based on the assessment criteria of Concrete Society (CEB, 1989). The permeability was also decreasing with increasing density. The higher strength and higher density EPS concretes (1500 kg/m^3) behave more or less like the normal concretes in terms of permeability.

The absorption characteristics which indirectly reflect the porosity, show that the initial absorption values for the all the EPS concretes was about 3%, the limit specified for good concrete by Concrete Society (CEB, 1989). The total absorption values also show a similar decreasing trend with increasing density of the concretes.

The effect of chemical attack was assessed by weight loss and strength loss methods. The attack was found to be reducing with increasing the EPS volume, which can be attributed to the lower cement contents in these concretes. The weight and strength losses were very less in EPS mixes at 30 days compared to the normal concretes, with some mixes even gaining weight as well as strength, which can be attributed to the pore filling effects of the compounds formed.

The chloride permeability of the EPS concretes was observed to be 50–65% lower compared to normal concretes and was increasing with increasing density. All the EPS concretes showed "very low to low" chloride permeability as per the assessment criteria. It was observed that all the concretes with fly ash were behaving more efficiently, compared to the normal aggregate concretes.

The corrosion rate of steels in the concretes containing fly ash was also found to be lower (<1.0 mpy) compared to normal concrete. The concretes E57 and NC showed higher corrosion rates than the other EPS concretes. The average daily resistance was also higher for EPS concretes and was increasing with a decrease in percentage of EPS.

In general, the behaviour of EPS concretes was better than the normal concrete, because of the non-absorbent nature of the EPS aggregates and the fly ash in the matrix. The permeability and absorption results show an increase with increasing EPS volume. However the chemical attack and corrosion characteristics, which are largely influenced by the cement and paste content show a significant improvement even at the lower densities, once a minimum paste content is ensured.

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