Cement & Concrete Composites 33 (2011) 1057–1062

Contents lists available at SciVerse ScienceDirect

Cement & Concrete Composites

journal homepage: www.elsevier.com/locate/cemconcomp

Transport properties of high volume fly ash roller compacted concrete

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ARTICLE INFO

Article history:
Received 28 June 2009
Received in revised form 26 July 2011
Accepted 30 July 2011
Available online 22 August 2011

Keywords:
Concrete
Dam construction
Fly ash
Permeability
Roller compacted concrete

ABSTRACT

This paper describes research on the transport properties of high-volume fly ash roller compacted concrete (RCC). The mixes were developed through incorporating 50–260 kg/m^3 cement and high volumes of fly ash ranging from 40% to 85% by mass of the total cementitious material. The concretes were investigated for permeability, absorption, sorption and chloride diffusion. The study showed that RCCs of moderate cement and moderate fly ash contents had lower values of permeability, absorption, sorption and chloride diffusivity.

1. Introduction

Modern civil engineering projects are placing an increased emphasis on sustainable and environmentally friendly construction. As concrete is one of the predominant construction materials, it is necessary to identify cement substitutes for making concrete more cost effective and environmentally friendly. In recent years research on replacement of cement in concrete with by-products such as fly ash, silica fume and rice husk ash have established that use of these by-products can improve fresh and hardened state properties of concrete and reduce construction cost [1–4]. Every year millions of tonnes of fly ash are produced across the world, with India producing 80 million tones per year. Of the total production, however, only less than 10% is being utilized. As a result, the majority of the fly ash is finding its way to landfill [5].

As one potential means for fly ash utilization, it has been found that high volumes of fly ash (e.g., 50–80% by mass of the cementitious binder) can be used in no slump concrete, that is, roller compacted concrete (RCC) [6]. RCC is relatively new form of concrete especially for mass concreting like dams, pavements and embankments [6]. The main advantages of this concrete are: reduced cost, reduced time for construction, and rapid implementation of technology for emergency projects [6]. Use of fly ash in RCC serves as: partial replacement for cement to reduce heat of hydration; a means of reducing concrete cost; and a mineral addition to the mixture to provide fines to improve workability [6].

With rapid growth, India has created a large demand for infrastructure construction like dams, pavements, bridges, airports, embankments and water channels for years to come. However, such development should be achieved in a sustainable and environmentally friendly mode. Use of RCC with high volumes of fly ash could be a prudent option for the infrastructure development. However, information on the transport parameters such as permeability, water absorption, sorption and chloride diffusion, which are of significant practical importance for durability of concrete, is scarce for RCC with fly ash. Although some data on permeability of RCC have been presented by Banthia et al. [7], understanding of these vital properties of RCC remains far from adequate. Therefore, better understanding of transport properties when incorporating high volumes of fly ash in RCC is required. Thus, this experimental study concentrates on the transport properties of RCC produced with high volumes of fly ash.

2. Materials and test specimens

2.1. Materials

The constituent materials used in this investigation were procured from local sources. Ordinary Portland cement of C53 grade conforming to both the requirements of IS: 12269 [8] and ASTM C 642-82 type I [9] was used. Class F fly ash was used, which was conforming to the ASTM C 618 [10]. Physical characteristics and chemical compositions of the materials were found to satisfy the requirements of both ASTM C 618 and IS: 3812–1981 [11], and are given in the Table 1. Well-graded river sand finer than 2.36 mm was used. Normal course aggregate, that is, crushed blue granite of maximum size 20 mm was chosen as coarse aggregate.

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doi:10.1016/j.cemconcomp.2011.07.010

Table 1
Chemical composition and physical characteristics of cement and fly ash.

	Cement	Fly ash
Chemical composition (%)		
Silica (SiO_2)	21.8	58.3
Alumina (Al_2O_3)	6.6	31.7
Ferric oxide (Fe_2O_3)	4.1	5.9
Calcium oxide (CaO)	60.1	2.0
Magnesium oxide (MgO)	2.1	0.1
Sodium oxide (Na_2O)	0.4	0.8
Potassium oxide (K_2O)	0.4	0.8
Sulphuric anhydride (SO_3)	2.2	0.2
Loss on ignition (LOI)	2.4	0.3
Physical characteristics		
Fineness (Blaine) (m^2/kg)	307	350
Standard consistency (%)	33	NA
Normal consistency (%)	28	NA
Specific gravity	3.15	2.06
Initial setting time (min)	205	NA
Final setting time (min)	287	NA
Compressive strength (N/mm^2)		
1 day	24	NA
3 days	37.5	NA
7 days	49.5	NA
28 days	65	NA
Lime reactivity	NA	9.87

Coarse aggregate passing through sieve sizes of 20 mm, 12.5 mm and 6 mm and fine aggregate finer than 2.36 mm were combined in different fractions to match with a desirable grading that is described in the literature [12]. Combined aggregate grading is shown in Fig. 1. Locally available potable water was used for mixing and curing.

2.2. Mix proportions

To investigate transport properties of high-volume fly ash RCC, six mixes were employed. Proportions of cement and water were determined after conducting few trial experiments. Out of the six mixes, two were created with low cement and high fly ash content (RCC1 and RCC2); two of moderate cement and moderate fly ash content (RCC3 and RCC4); and the remaining two of high cement and low fly ash content (RCC5 and RCC6). Cement in the mixes was between 50 and 260 kg/m^3 and fly ash percentage ranged between 40% and 85% on a mass basis. Details of the concrete mixes are presented in Table 2.

2.3. Mixing, compaction, specimen preparation and curing

The concretes were mixed in a planetary mixer of 100 l capacity. The mixing time was kept to about 3–4 min. Mixing of the materials

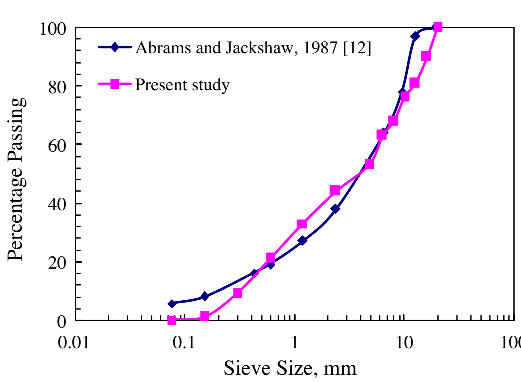

Fig. 1. Combined aggregate grading used for the mixes.

Table 2
Mixture proportions.

Concrete name	c (kg/m^3)	f/(c + f) (%)	w/(c + f)	CA (kg/m^3)	FA (kg/m^3)
RCC1	50	85	0.51	1024	750
RCC2	90	75	0.45	1024	750
RCC3	150	70	0.31	996	729
RCC4	190	60	0.36	1111	813
RCC5	250	40	0.38	1114	816
RCC6	260	50	0.35	1003	735

c – cement, f – fly ash, w – water, CA – coarse aggregate and FA – fine aggregate.

was in a sequence: (i) a portion of design water was poured into mixture drum; (ii) coarse aggregate was placed and spread to the boundaries of the mixture drum; (iii) cement and fly ash were gently placed over the aggregate; and (iv) sand was spread over the powder after which mixing commenced. During mixing, the remaining design water was poured into the mixture so that the concrete ingredients could combine thoroughly. Specimens were then prepared in accordance with ASTM C1176 [13]. They were compacted in three equal layers and each layer was compacted with top surcharge of 5 kPa. Compaction was continued until a paste ring was observed between the periphery of the surcharge and the cylinder or cube. The compaction time for each layer for the concretes was found to be between 15 and 20 s. The moulds were then covered with wet gunny bags until demoulding. The specimens were demoulded after 24 h and immersed in normal water for curing until the test age. The hardened properties of the concretes discussed in this paper are for 90 days of water curing.

2.4. Properties of fresh concrete

In the present study, Vebe compaction test was used for evaluating the workability of the concrete. Broken split tensile test specimens was used for evaluating the segregation, uniformity in the aggregates and layer joint behaviour of the concretes.

3. Test program

The main objective of the present investigation was to study the performance of high-volume fly ash RCC with relatively low cement content and with no chemical admixtures in the mixes. Performance of the concretes was assessed through: water permeability, water absorption, moisture migration and chloride permeability. Cube compressive strengths of the concretes were between 20 and 60 MPa.

3.1. Water permeability test

The Germann Water permeation Test (GWT) was used for testing water permeation of the skin-concrete. It consists of a water-tight pressure chamber. Many researchers have used GWT to assess water permeability of the concrete [14–16]. As mentioned in Section 2.3, the permeability test was conducted on 150 × 150 mm cubes after 90 days of water curing. The specimens were placed on the stand and fixed to GWT with the help of clamping pliers. Care was taken to arrest water leakage between the pressure chamber and sample surface with the help of gasket. The water chamber was then filled with water and the desired pressure applied on the specimen. The pressure was maintained for 10 min before starting the measurements at different time intervals. Once the test was initialized, the micrometre gauge reading was noted for every 2 min interval for 20 min and later for every 5 min until 1 h. Thus, with the help of the data obtained the relationship between micrometre readings with square root of time was determined (Fig. 2). The coefficient of permeability was calculated with Darcy's law as:

$$k = q * l / p * t \quad (1)$$

where the time t was considered only from the linear region of the relationship (Fig. 2).

$$q = B * (g_1 - g_2)/A \quad (2)$$

where k is the coefficient of water permeability in mm/s; q is the flux of water penetrating the surface for a given water pressure in mm; B is the area of the micrometre pin being pressed into the chamber, which is 78.6 mm^2 for the instrument adopted; g_1 and g_2 are the gauge readings in mm at the start and end of the linear regression considered (Fig. 2); A is the water pressure surface area, which is 3018 mm^2 for the instrument adopted; t is the time between the gauge readings g_1 and g_2 in sec; l is the length the pressure is applied over (15 mm, equal to the thickness of the pressure gasket); and p is the gauge pressure in terms of water head in mm.

3.2. Permeable voids and water absorption studies

An absorption study was conducted to understand the relative porosity permeable void space of the concretes, in according to ASTM C 642-82 [9]. The absorption and permeable voids test was conducted on two 100 × 200 mm cylinders. Saturated surface dry specimens were kept in a hot air oven at 105 °C until a constant weight was attained. The ratio of the difference between the mass of saturated surface dry specimen and the mass of the oven dried specimen at 105 °C to the volume of the specimen gives the permeable voids in percentage as:

$$\text{Permeable voids} = [(A - B)/V] \times 100 \quad (3)$$

where A is the weight of surface dried saturated sample after 90 days immersion period. B is the weight of oven dried sample in air. V is the volume of sample.

The specimens removed from the oven were allowed to cool to room temperature. These specimens were then completely immersed in water and weight gain was measured until a constant weight was reached. The absorption at 30 min (initial surface absorption) and final absorption (at a point when the difference between two consecutive weights was almost negligible) were reported to assess the concrete quality. The final absorption for all the concretes was observed to be at 72 h.

3.3. Sorption test

The sorption test was conducted on the concretes in order to characterize the rate of moisture migration of water into the concrete pores. One hundred millimetre cube specimens were marked on all four sides at 10 mm interval to measure the moisture migration. As explained in the water absorption test, the specimens were oven-dried. They were then allowed to cool down to the room temperature. After cooling, the cubes were placed in water on the wedge supports to make sure that only the bottom surface of the specimens was in contact with the water. A cotton cloth was covered on top of the wedge supports to ensure the specimens are in contact with water throughout the test period. Moisture rise in the cubes was measured at regular intervals. The readings were taken on all four sides of the cubes and average values were reported.

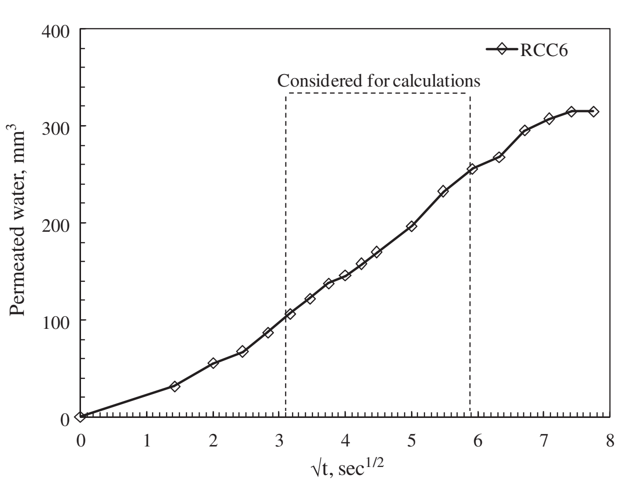

Fig. 2. Typical relationship between micrometre reading with square root of time.

3.4. Chloride diffusivity test

The chloride permeability test was conducted to assess the concrete quality as per ASTM C 1202-94 [17]. A potential difference of 60 V DC was measured across the 100 × 50 mm discs. 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 the two test specimens. The average of the two values was indicated as chloride ion penetration resistance of the specimen.

4. Results and discussion

4.1. Fresh properties

Visual observations during mixing, placing and compaction suggested that all the mixes were cohesive and there was no segregation. Furthermore, sufficient workability is necessary for RCC for easy compaction, uniform density, bonding with previously placed layer and for support of compaction equipment. The workability of RCC is most affected by the paste portion of RCC mixture [18]. In the present investigation, although there was a lack of fines in combined aggregate grading (Fig. 1), sufficient paste was observed in all the mixes even for very low cement concrete mixes. High volumes of fly ash helped to generate sufficient paste in the mixes. The Vebe time for the concrete mixes was between 15 and 20 s, indicating that the RCC mixes are sufficiently workable as per ACI [18]. Further, in RCC bonding with previously placed lifts is important to arrest permeability at lift joints [18]. In the concretes investigated, no joint separation was observed during split tensile test and there was uniform aggregate distribution in the broken specimens.

4.2. Water permeability

The volume of water permeating with time was measured to evaluate permeability of the concretes. The average coefficient of water permeability, obtained from two replicate specimens is shown in Fig. 3. As shown, the result indicated that the coefficient of permeability of the concretes was between 6.9×10^{-12} and 106×10^{-12} m/s. On comparing the values of permeability coefficients for RCC obtained in this study with those reported in the literature, it may be said that they are in the same range (1.5–150×10^{-12} m/s) [7,18]. From Fig. 3 it can also be observed that low cement and high fly ash concretes had shown higher permeability (RCC1 and RCC2). Further, permeability of high cement and low fly ash concretes (RCC5 and RCC6) was slightly higher than moderate cement and moderate fly ash concretes (RCC3 and RCC4). Increased cement content did not help to decrease permeability. This could be attributed to variation in cement, fly ash percentage and w/(c + f) ratios in the mixes. Porosity and pore system which influences permeability depends on hydrated paste phase of the concrete. This observation suggests that moderate cement (150–190 kg/m^3) and moderate fly ash percentage (60–70%) in RCC

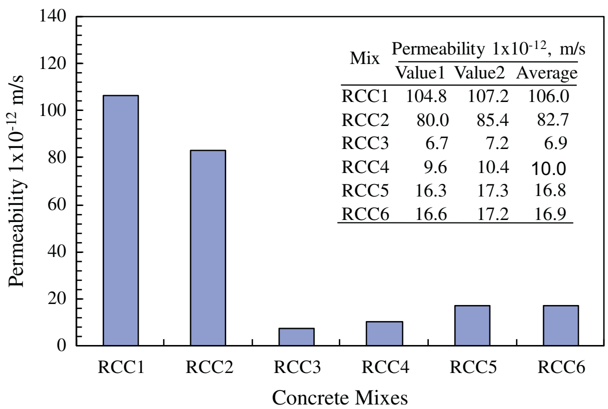

Fig. 3. Water permeability for the concretes.

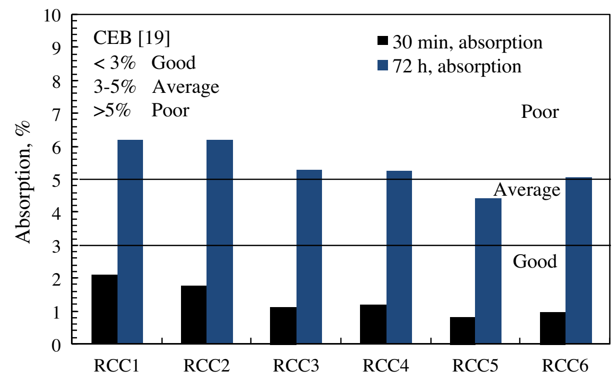

Fig. 5. Water absorption of the concretes at 30 min and 72 h.

mix might lead to less permeable hardened paste phase and there by lower permeability. Further, from Fig. 4 it is clear that for a given compaction w/(c + f) decreased with increase in total cementitious material for full compaction. Thus, it can be understood that optimum w/(c + f) ratio which influences permeability depends on total cementitious material than either on cement or on fly ash quantities in RCC. Therefore, it can be concluded that on one hand, low cement and high fly ash percentage in RCC leads to more permeable concrete and on the other hand, high cement and low fly ash in RCC mix is un-economical in terms of permeability.

4.3. Permeable voids and water absorption

The absorption in 30 min (initial surface absorption) and the absorption after 72 h (final absorption) for the concretes are presented in Fig. 5. It can be seen that the initial surface absorption of all the concretes shows values lower than 3%, the limit specified for "good" concrete by CEB [19]. The final absorption at the end of 72 h for these concretes also followed a similar trend. The variation of water absorption with time for the concretes is shown in Fig. 6. It shows that similar to permeability, the absorption results of low cement and high fly ash concretes (RCC1 and RCC2) were higher than other concretes. It can also be observed that absorption of high cement and low fly ash RCCs (RCC5 and RCC6) was nearly same as that of moderate cement and moderate fly ash RCCs (RCC3 and RCC4). As in permeability, increase in cement content did not show any appreciable decrease in absorption in RCC5 and RCC6. This can be attributed to pore volume and pore system. A relation between percentage of permeable voids and absorption was observed (Fig. 7). There exists a good correlation between the percentage of permeable voids and absorption. As the permeable voids increased, the absorption also increased correspondingly. This observation suggests that for an economical and low absorption concrete selecting appropriate quantities of cement and fly ash is more important than simply increasing cement in RCC mixes.

4.4. Sorptivity – capillary water absorption

Sorptivity of the concretes is presented in Fig. 8. Sorptivity of the low cement and high fly ash RCCs (RCC1 and RCC2) was higher than other concretes. Further, it can also be observed that sorptivity of high cement and low fly ash RCCs (RCC5 and RCC6) was nearly same as that of moderate cement and moderate fly ash RCCs (RCC3 and RCC4). As for permeability and absorption, increase in cement content did not show any appreciable decrease in sorptivity in RCC5 and RCC6.

Fig. 9 gives comparison between sorptivity and permeability of the concretes, regardless of amount of cement, fly ash percentage, total cementitious material and w/(c + f). In general, very good correlation is observed between the sorptivity and the permeability values. As both the parameters are functions of porosity and pore system, permeability increased with sorptivity.

4.5. Chloride diffusivity

The total charge passing in 6 h as a measure of the chloride permeability is presented in Fig. 10. The chloride ion penetrability limits

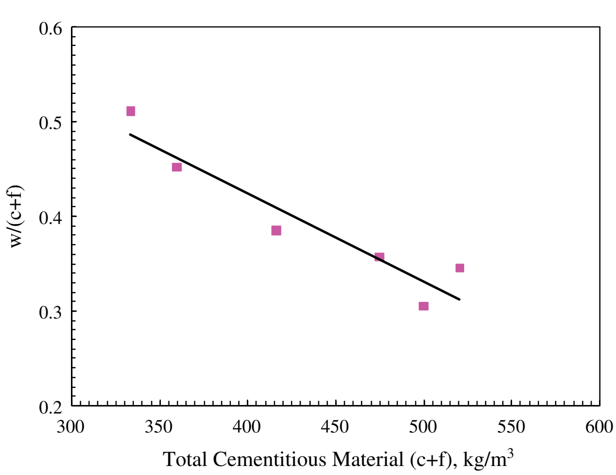

Fig. 4. Relationship between water to total cementitious materials ratio and total cementitious material.

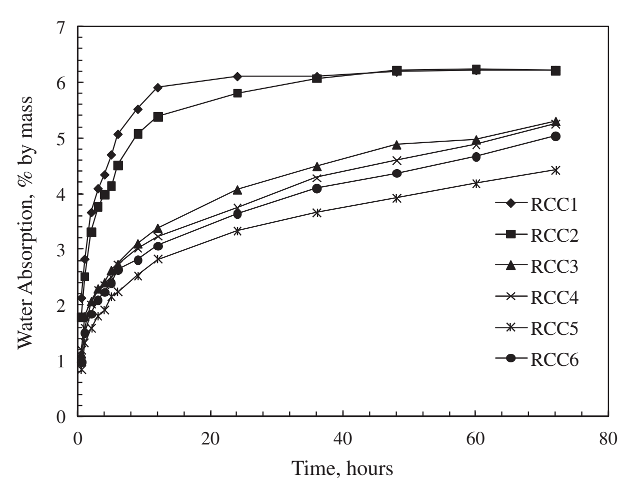

Fig. 6. Variation of water absorption with time.

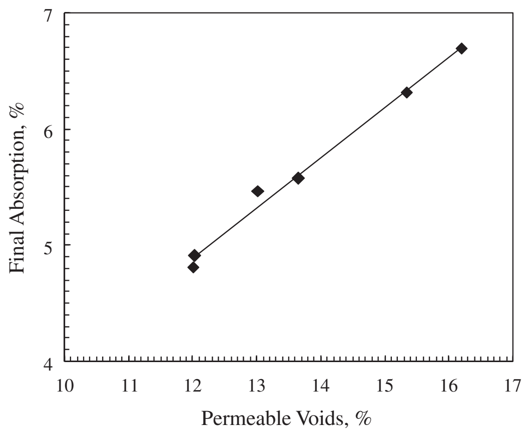

Fig. 7. Variation of final absorption with permeable voids.

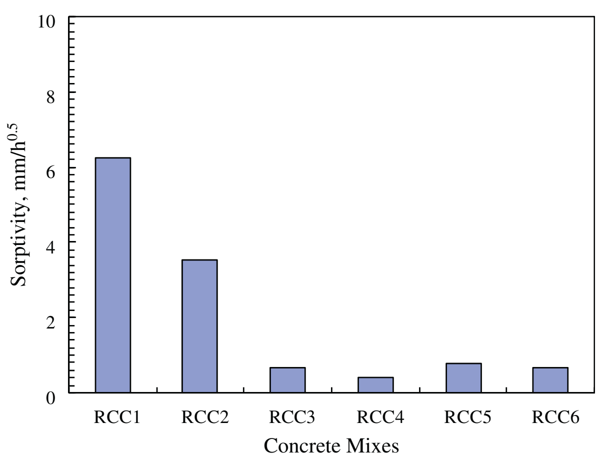

Fig. 8. Sorption characteristics of the concretes.

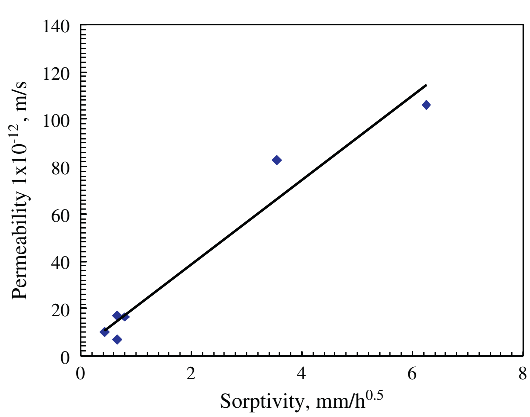

Fig. 9. Relationship between permeability and sorptivity.

suggested by ASTM C1202-94 [17] were compared with the results. It can be seen that all the concretes showed far less than 1000 C total charge passing and these were assessed as "very low" chloride permeability concretes as per ASTM C1202-94 [17] assessment criteria. The reduced chloride permeability vales in all the concretes could be attributed to presence of high volumes of fly ash. However, presences of the highest fly ash percentage in RCC1 did not help to reduce chloride permeability than other concretes. The chloride permeability obtained for RCC2 was nearly 48% lesser than RCC1. Increased cement content and reduced w/(c + f) ratio could have helped to

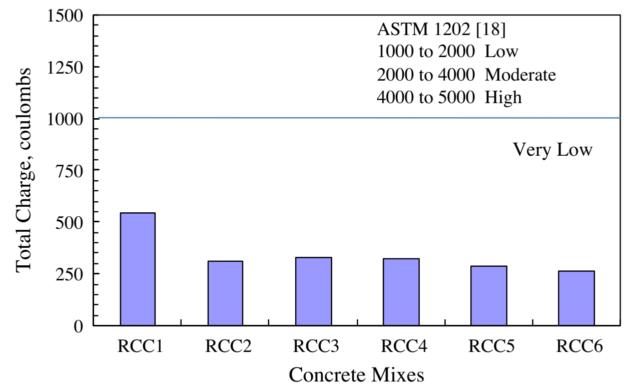

Fig. 10. Chloride permeability values of the concretes investigated.

reduce chloride permeability. Contrary, increased cement content in moderate cement and moderate fly ash RCCs (RCC3 and RCC4) and high cement and low fly ash RCCs (RCC5 and RCC6) did not show any appreciable decrease in chloride permeability when compared to RCC2.

There was some variation in chloride permeability results when compared with other transport parameters. RCC2 showed higher permeability, higher absorption and higher sorptivity to other concretes. However, the same concrete, in the chloride permeability test, showed better performance. This could be due to the fact that the chloride ion penetration depends on the chloride binding capacity of the constituent materials. Usually chlorides penetrate in concrete by diffusion along water paths or open pores. Some of these chlorides can react with the cement compounds, mainly tricalcium-aluminates (C_3A), forming stable chloro complexes. The presence of fly ash leads to an increase in the amount of C_3A due to the higher amount of alumina present in the mix and to an increase in the content of calcium silicate hydrate that is formed in the pozzolanic reactions. Thus, the chloride binding capacity of concrete tends to increase with fly ash addition and consequently less free chloride is available [20].

5. General discussion

In this study it is important to note that the laboratory investigations were conducted under different conditions, that is, moisture cured for 90 days and 105 °C oven dried which could be different from routine concrete in practice. In addition, in order to identify and measure the fundamental parameters involved in practical exposure conditions, different transport mechanisms are usually dealt with separately. However, different transport mechanisms may act simultaneously or they may prevail in sequence during consecutive periods. Therefore, when dealing with real transport problems, different transport mechanisms and their interactions and relative importance, as well as reactions between the transport media and cement matrix, have to be considered.

6. Conclusions

The data shows that high volumes of fly ash can be incorporated in RCC. However, the quantities of constituent materials in RCC mix influences transport properties of high-volume fly ash RCC. Based on the result presented in this paper the following conclusions can be drawn.

1. All the concretes have satisfied the basic fresh properties requirements of RCC. The concretes were cohesive and there was no segregation even at very low cement content. Vebe time of the concretes was between 15 and 20 s and there was sufficient paste in all the mixtures.

2. For a given compaction, high (c + f) content is beneficial to decrease w/(c + f) ratio for the formation of a paste ring around the periphery of the surcharge, that is, full compaction of the concrete mixture.
3. From the above investigations it can be concluded that less permeable fly ash RCC (7–10 $\times$ 10^{-12} m/s) can be produced with cement ranging from 150 to 190 kg/m^3 and fly ash percentage ranging from 60% to 70%, with Vebe compaction of 15–20 s.
4. The absorption characteristics show that the initial 30 min absorption values for all the concretes were lower than limits commonly associated with good quality concrete [19]. The maximum absorption observed was 2.11% for 85% fly ash RCC. The absorption decreased with decrease in permeable voids.
5. A good positive correlation was observed between the permeability and the sorptivity values. As the permeability increased sorptivity also increased indicating both the properties depend on the porosity and pore system.
6. Chloride penetration results showed that the chloride permeabilities of all the concretes were below 1000 C, indicating that the concretes have very low chloride permeability as per ASTM C1202 criteria. The highest total charge passed was 541 C for 85% fly ash RCC.

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