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Performance evaluation of concretes having different supplementary cementitious material dosages belonging to different strength ranges

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HIGHLIGHTS

- Incorporation of SCMs affect strength and durability properties of concrete.
- *Performance indicators*, combining both strength and durability criteria, are developed.
- Limiting values of *Performance Indicators* are also suggested.
- Many options are available to get different levels of durability within a strength range.
- Within the same strength range, SCM mixes are more durable compared to pure OPC mixes.
- Database generated in this study can act as a guideline for material selection.

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ABSTRACT

Production of durable concrete at lower strength levels is always a challenge for concrete technologists. One way to achieve this objective is by the use of Supplementary Cementitious Materials (SCMs). An attempt has been made in this paper to develop indicators called performance indicators, which combine both strength and durability criteria. Limiting values of these indicators are also suggested. Different mixes in the same strength range are classified into different performance classes based on these performance indicators. The durability parameters evaluated here include surface resistivity, charge passed, sorptivity index and oxygen permeability index. The database generated can act as a guideline for material selection and it demonstrates the potential of SCMs to improve durability.

1. Introduction

Concrete is the largest consumed man-made material. According to Richardson [1], the challenge before the engineering community is to produce sustainable concrete by combining different aspects such as strength, cost effectiveness and environment-friendliness. One way to achieve this goal is to make the structures more durable. Durability of concrete structures in a particular service environment depends mainly on three factors – the aggressiveness of the environment, the material used for construction and the construction practices. Control of the first factor is not possible. Thus, the plan for achieving durability in concrete construction should focus on material selection as well as on construction practice [2].

Traditionally, compressive strength is considered as the only crucial parameter to select a particular concrete. However, both research and practical experiences show clearly that strength and durability are not necessarily related [3–5]. Strength depends on the total porosity of the concrete, whereas durability depends on the pore interconnectivity [3].

Achievement of durability in high strength and high performance concrete is not that difficult as the microstructure in these types of concretes is well developed. Producing durable concrete at lower and medium strength levels is still a challenge. There is a distinct need to address durability in such concretes, as these are used for a variety of projects ranging from residential to infrastructure. The goal of achieving durability in low strength grade

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concretes can only be realized by the use of Supplementary Cementitious Materials (SCMs). However, there is lack of clarity on how much is the extent of improvement in each of the durability parameters when SCMs are used. Thus, a combined study of all the durability parameters along with strength in the same concrete is highly essential.

Many researchers have attempted to study the above aspect. Ramezanianpour et al. [6] did a comparative study on the relationship between concrete resistivity, water penetration, charge passed in rapid chloride permeability test (RCPT), and compressive strength. The authors were able to get good correlation between resistivity and water penetration as well as resistivity and charge passed. However, they were not able to achieve any correlation between compressive strength and surface resistivity. The study by Burden [7], on concrete mixtures with different water to binder ratios and fly ash replacement levels, drew the conclusion that fly ash had greater influence on durability parameters than on strength. The tests conducted included compressive strength, RCPT and accelerated carbonation test. The author re-emphasized that strength is not a good indicator of durability. By contrast, in a correlation study between compressive strength and certain durability indices of plain and blended cement concretes, Al-Amoudi et al. [8] obtained good correlation between compressive strength and certain selected durability indices corresponding to chloride permeability and coefficient of chloride diffusion irrespective of the mix design parameters. This observation differs with other available literature. The binders used in the study included Type I cement, silica fume and fly ash. Indeed, most of the literature agrees to the fact that SCMs influence the durability parameters more compared to strength. The reasons for the same are due to the filler effect as well as pozzolanic reaction, which eventually leads to more tortuous pore structure and alterations in the pore solution chemistry [9,10].

Baroghel-Bouny [11] presented a performance based approach to evaluate and predict the durability of reinforced concrete structures. In this approach, the durability indicators (DIs) were classified into two, viz., universal indicators and complementary parameters. The universal indicators are basic physical and chemical properties that are directly related to transport properties and microstructural characteristics such as initial $Ca(OH)_2$ content, porosity, chloride diffusion coefficient, gas/liquid permeability etc. The complementary or optional parameters need to be evaluated many a times because they appear in many predictive models. Examples of such parameters include the surface chloride concentration, chloride-binding capacity etc. Potential durability classes corresponding to each durability indicator, such as very low, low, medium, high and very high were developed, which can be used as a tool for mixture comparison. Based on the above framework, a multi-level modelling concept by combining the durability indicators and physical/chemical models was proposed, which can be applied at four levels of sophistication [12]. The DIs were determined at different ages (28, 90, 120 and 180 days) on saturated concretes along with 28 day characteristic compressive strength values. Even though an overall correlation between chloride diffusion coefficients and 28 day compressive strength was reported, it was shown that mineral additives like fly ash can produce durable concrete at lower strength level, which violates the correlation.

Fig. 1 indicates the implementation of the performance approach based upon durability indicators, as proposed by Baroghel-Bouny [11].

However, this approach seems to be very complicated for practicing engineers as the evaluation of both universal indicators and complementary parameters suggested by the authors require sophisticated laboratory facilities. Further, combining the DIs measured at different ages (28, 90, 120 and 180 days) with 28 day compressive strength seems to be illogical. For engineering purposes, simple qualitative tables are more suitable rather than complicated models on quantification.

The current paper focuses on the influence of SCMs on the durability parameters of concrete belonging to different strength classes. The performance of 38 different concretes with 28 day mean strengths from 20 to 70 MPa was evaluated using compressive strength and four different durability tests. Initially, the mixes having the same strength range were classified based on their performance in durability tests. Later on, performance indicators were developed combining parameters such as strength, durability and mix design aspects.

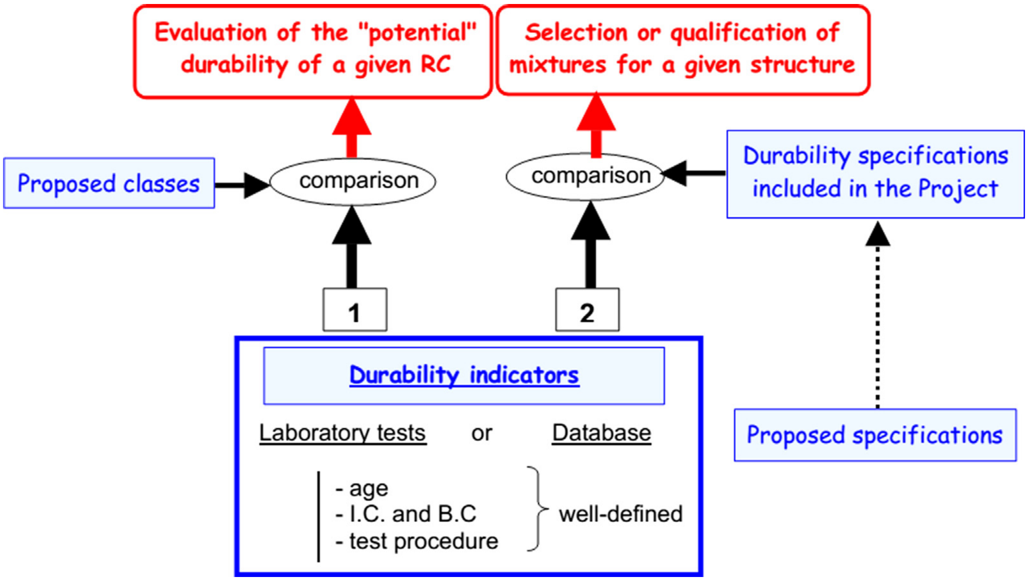


Fig. 1. Implementation of the performance approach based upon durability indicators proposed by Baroghel-Bouny [11].

2. Experimental investigation

2.1. Materials used

A total of 38 mixtures having different binder contents and water to binder ratios were included in this study. The cement conformed to OPC 53 grade, as per IS 12269:1987 [13]. Supplementary Cementitious Materials such as slag (from two sources), Class C fly ash and Class F fly ash were used at different replacement levels of 15, 30 and 50%. The oxide analysis of the binders used is given in Table 1. The total binder contents for the concretes were 280, 300, 310, 320, 340, 360, 380 and 400 kg/m^3 whereas the w/b ratios were 0.65, 0.6, 0.55, 0.5, 0.45 and 0.4. Table 2 provides the mixture design details. A Sulphonated Naphthalene Formaldehyde (SNF) based superplasticizer was used to obtain slump value between 80 and 150 mm. The specimens were cured in a moist room, for two ages – 28 and 90 days. All the concretes were prepared with a fine (river sand) to coarse aggregate ratio of 40:60. The coarse aggregates used were combinations of 20 mm down and 10 mm down crushed granite, in a proportion of 60:40.

Table 1
Oxide analysis of the binders used in the study.

Compound	Concentration (%)				
	OPC	Slag A	Slag B	Class F fly ash	Class C fly ash
Al_2O_3	4.73	17.38	21.06	29.95	31.46
CaO	65.11	35.61	31.46	1.28	13.76
Fe_2O_3	3.86	1.04	1.87	4.32	6.17
K_2O	0.54	0.58	0.88	1.44	0.12
MgO	1.20	8.03	8.57	0.61	2.28
Na_2O	0.5	0.36	0.36	0.16	0.59
SiO_2	19.44	33.82	32.38	59.32	39.89
SO_3				0.16	3.19

2.2. Experimental methods

The present experimental investigation used four durability tests, along with concrete compressive strength determination as per IS 516:1999 [14] on 100 mm cubes. The durability tests involved in the study are (a) Wenner 4 – probe resistivity test, (b) rapid chloride permeability test (ASTM C 1202) [15], (c) water sorptivity test (Durability index testing procedure manual, South Africa) and (d) oxygen permeability index test (Durability Index testing procedure manual, South Africa) [16]. The Wenner 4-Probe resistivity test measures surface resistivity of concrete whereas rapid chloride permeability test assesses the resistance of concrete against chloride ion migration. The water sorptivity test is a measure of the unidirectional water sorption whereas oxygen permeability index test measures the resistance against gas penetrability. This combination of tests was selected to represent major transport mechanisms involved in concrete durability issues. A summary of these test methods, in terms of the standard followed, the type of specimen and the conditioning of the specimen, along with the qualitative classification criteria for concretes

Table 2
Mixture proportions.

Mix No.	w/b	Binder content (kg/m^3)	SCM content	Sand (kg/m^3)	10 mm aggregate (kg/m^3)	20 mm aggregate (kg/m^3)	Water (kg/m^3)	Super Plasticizer (kg/m^3)
1	0.65	280	0	760	499	749	182	0.50
2	0.65	280	30% Slag A	760	499	749	182	0.40
3	0.65	280	30% Slag B	760	499	749	182	0.54
4	0.65	280	30% Class F fly ash	760	499	749	182	0.67
5	0.55	340	0	735	483	725	187	0.00
6	0.55	340	15% Slag A	735	483	725	187	0.24
7	0.55	340	15% Slag B	735	483	725	187	0.98
8	0.55	340	15% Class F fly ash	735	483	725	187	0.01
9	0.55	340	15% Class C fly ash	735	483	725	187	0.04
10	0.6	310	0	747	491	736	186	0.07
11	0.6	310	15% Slag A	747	491	736	186	0.37
12	0.6	310	15% Slag B	747	491	736	186	0.26
13	0.6	310	15% Class F fly ash	747	491	736	186	0.13
14	0.6	310	15% Class C fly ash	747	491	736	186	0.20
15	0.5	310	0	759	498	748	155	2.97
16	0.5	310	15% Slag A	759	498	748	155	3.35
17	0.5	310	15% Slag B	759	498	748	155	3.57
18	0.5	310	30% Slag B	759	498	748	155	3.83
19	0.5	310	50% Slag B	759	498	748	155	4.39
20	0.5	310	15% Class F fly ash	759	498	748	155	0.37
21	0.5	310	30% Class F fly ash	759	498	748	155	3.75
22	0.5	310	50% Class F fly ash	759	498	748	155	2.38
23	0.5	310	15% Class C fly ash	759	498	748	155	0.34
24	0.5	310	30% Class C fly ash	759	498	748	155	0.50
25	0.4	380	0	733	482	723	152	2.28
26	0.4	380	15% Slag B	733	482	723	152	2.10
27	0.4	380	30% Slag B	733	482	723	152	2.00
28	0.4	380	50% Slag B	733	482	723	152	2.28
29	0.4	380	15% Class F fly ash	733	482	723	152	2.10
30	0.4	380	30% Class F fly ash	733	482	723	152	1.50
31	0.4	380	50% Class F fly ash	733	482	723	152	2.28
32	0.5	300	0	764	502	753	150	2.52
33	0.55	300	0	759	498	748	165	1.58
34	0.45	320	0	759	499	748	144	3.30
35	0.45	340	0	748	492	737	153	2.45
36	0.4	340	0	755	496	744	136	5.71
37	0.4	360	0	744	489	733	144	2.16
38	0.4	400	0	723	475	712	160	2.88

Table 3
Details of test methods [17,15,18].

<table>
<tr><th>Test</th><th>Standard</th><th>Property measured</th><th>Concrete Specimen details</th><th>Conditioning</th><th>Classification criteria</th></tr>
<tr><td>Compressive strength</td><td>IS 516-1959</td><td>Compressive strength</td><td>Cube of size 100 mm</td><td>Saturated Surface Dry Specimens</td><td></td></tr>
<tr><td>Wenner 4-Probe resistivity</td><td></td><td>Surface resistivity</td><td>Cube of size 150 mm</td><td>Saturated condition</td><td>ACI 222 R [17]
<table>
<tr><td>Resistivity (kΩ.cm)</td><td>Corrosion rate</td></tr>
<tr><td>> 20</td><td>Low</td></tr>
<tr><td>10 to 20</td><td>Low to moderate</td></tr>
<tr><td>5 to 10</td><td>High</td></tr>
<tr><td>< 5</td><td>Very high</td></tr>
</table></td></tr>
<tr><td>Rapid chloride permeability</td><td>ASTM C 1202</td><td>Total charge passed</td><td>Discs of 100 mm diameter and 50 mm thickness prepared from cylinder of 100 mm diameter and 200 mm height</td><td>Vacuum saturation with saturated Ca(OH)₂ solution</td><td>ASTM C 1202 [15]
<table>
<tr><td>Charge passed (Coulombs)</td><td>Chloride ion penetrability</td></tr>
<tr><td>>4000</td><td>High</td></tr>
<tr><td>2000 - 4000</td><td>Moderate</td></tr>
<tr><td>1000 - 2000</td><td>Low</td></tr>
<tr><td>100 - 1000</td><td>Very Low</td></tr>
<tr><td><100</td><td>Negligible</td></tr>
</table></td></tr>
<tr><td>Water sorptivity</td><td>DI Testing Procedure Manual, South Africa</td><td>Sorptivity Index</td><td>Discs of 70 mm diameter and 30 mm thickness prepared from cube of size 150 mm</td><td>Oven drying for 7 days. Test is followed by vacuum saturation with saturated Ca(OH)₂ solution</td><td>Alexander et al.,1999 [18]
<table>
<tr><td>Sorptivity Index (mm/√hr)</td><td>Concrete quality</td></tr>
<tr><td>< 6</td><td>Very good</td></tr>
<tr><td>6 - 10</td><td>Good</td></tr>
<tr><td>10 - 15</td><td>Poor</td></tr>
<tr><td>> 15</td><td>Very poor</td></tr>
</table></td></tr>
<tr><td>Oxygen permeability index</td><td>DI Testing Procedure Manual, South Africa</td><td>Oxygen permeability index</td><td>Discs of 70 mm diameter and 30 mm thickness prepared from cube of size 150 mm</td><td>Oven drying for 7 days</td><td>Alexander et al.,1999 [18]
<table>
<tr><td>Oxygen permeability index (OPI)</td><td>Concrete quality</td></tr>
<tr><td>> 10</td><td>Very good</td></tr>
<tr><td>9.5 - 10</td><td>Good</td></tr>
<tr><td>9.0 – 9.5</td><td>Poor</td></tr>
<tr><td>< 9</td><td>Very poor</td></tr>
</table></td></tr>
</table>

tested by these methods, is presented in Table 3. Fig. 2 shows the schematic diagrams of the durability test set ups.

3. Results and discussion

3.1. Influence of supplementary cementitious materials on durability parameters

Fig. 3(a) to (d) show the influence of SCMs on the durability parameters for all the concretes at 28 days of curing duration. OPC mixtures are represented as mixtures having 0% replacement with SCMs.

From the results presented in Fig. 3(a) and (b), it is clear that SCM mixes show better resistance against chloride ion penetration (as measured by the surface resistivity and charge passed) than OPC mixes. As the SCM dosage increases, concrete quality increases. The best performance is exhibited by mixtures having 50% replacement with SCMs. It is to be noted that, in order to achieve higher levels of durability, the replacement levels need to be higher (in this case, 30% and 50%). In the case of mixes having a replacement level of 15%, even though the durability parameters got improved, the enhancement is not much significant. Slag and Class F fly ash give better durability performance.

Fig. 3(c) represents the influence of SCMs on Oxygen Permeability Index test result. From the results, it is difficult to identify a clear difference between different concretes selected for the study. All the results fall either in the good or very good category.

From Fig. 3(d), it can be concluded that SCMs positively influence the water sorptivity test results. Mixes with SCMs perform better than OPC mixes; however, the influence is not as significant as in the case of surface resistivity and charge passed.

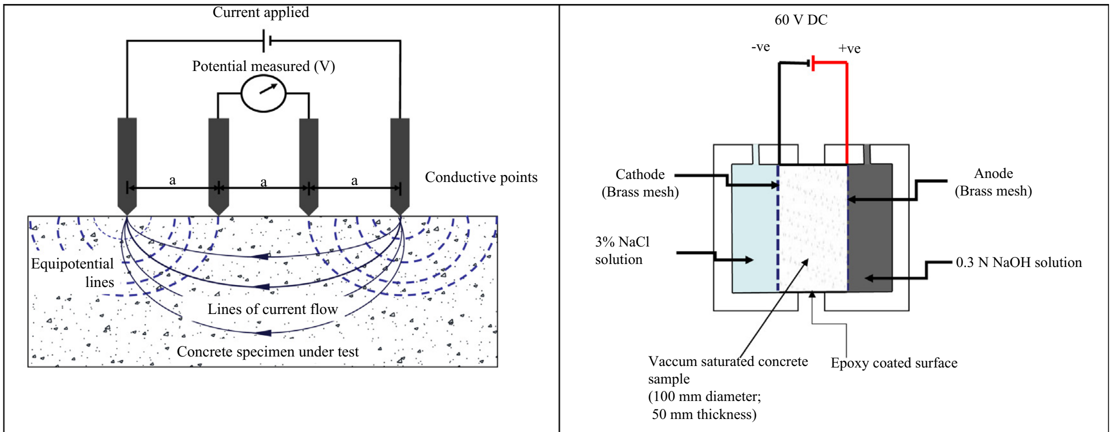
In general, the improved performance of SCM mixes in durability tests may be attributed to the development of pore structure caused by the pozzolanic reaction as well as modification in the pore solution chemistry [9,10].

3.2. Is compressive strength a good predictor of durability?

The plots in Fig. 4(a) to (d) explore the relationships between the durability parameters (surface resistivity, total charge passed, sorptivity index and Oxygen Permeability Index respectively) and compressive strength.

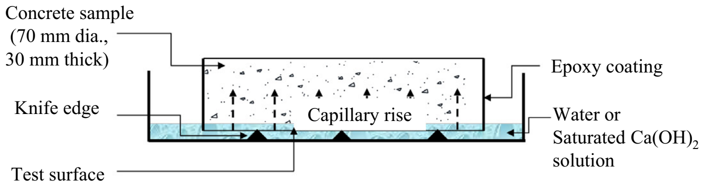
The figures clearly show the extent of scatter in the data, and no semblance of a correlation can be picked out. This conclusion is in agreement with most of the available literature [6,7], but disagrees with the observations of Al-Amoudi et al. [8], which were described earlier.

From the figures presented above, it is clear that for the current set of data, there is no direct correlation between compressive strength and the durability parameters. Thus, an alternative strategy is required to provide an engineering perspective to the

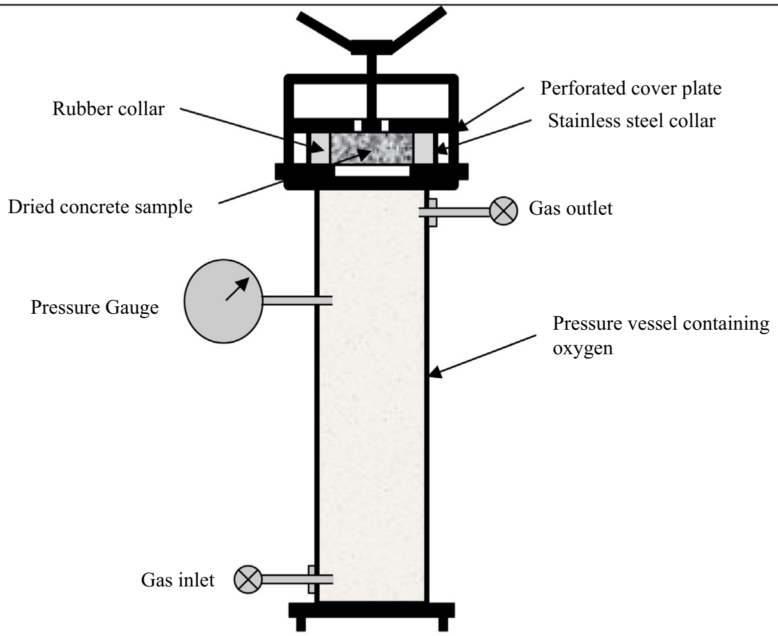


(a) Wenner 4-probe resistivity test set up (Adapted from Bjegović et al. [19])

(b) Rapid chloride permeability test

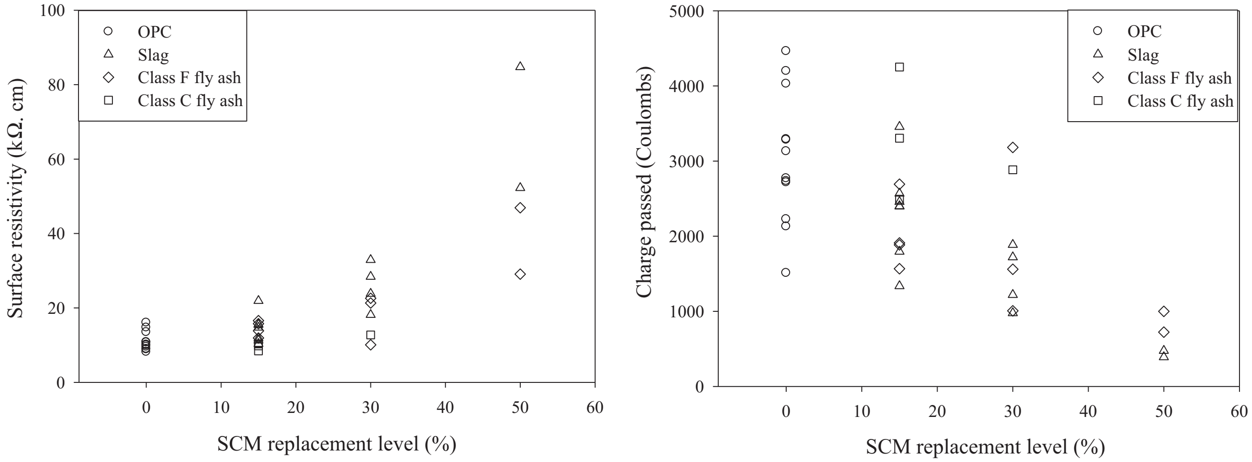


(c) Water sorptivity test



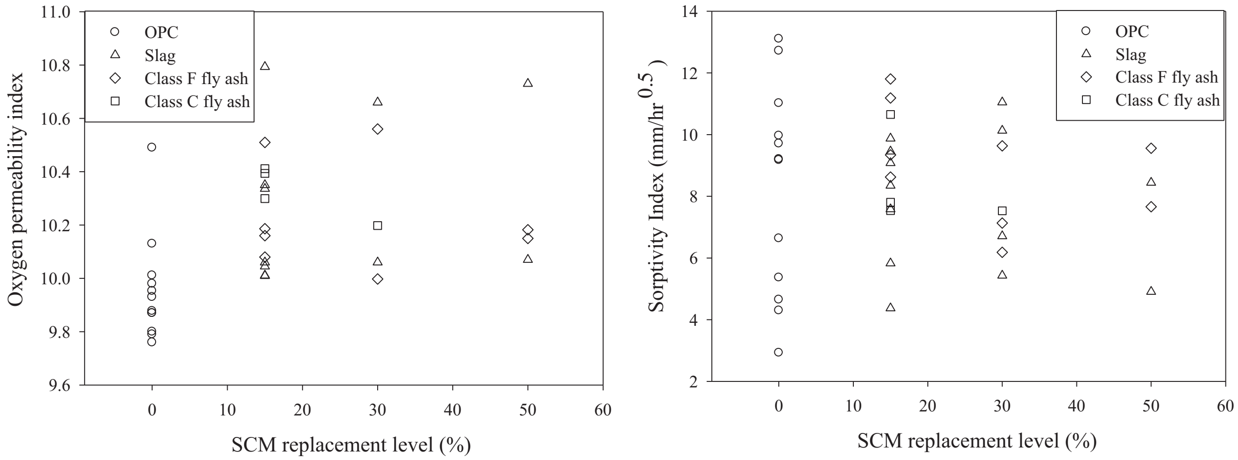
(d) Oxygen Permeability Index Test

Fig. 2. Schematic diagram of durability tests [19].



(a) Influence of SCMs on surface resistivity of all concretes at 28 days

(b) Influence of SCMs on charge passed of all concretes at 28 days



(c) Influence of SCMs on Oxygen Permeability Index of all concretes at 28 days

(d) Influence of SCMs on sorptivity index of all concretes at 28 days

Fig. 3. Influence of SCMs on the selected durability parameters.

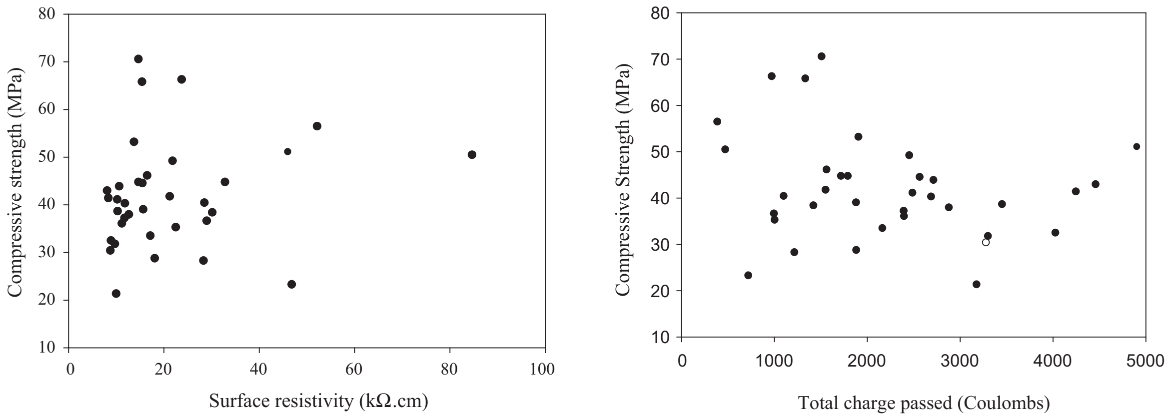
database. This is attempted in the following section, which explores the use of a durability class within specific strength range.

3.3. Durability classes within a strength range

Table 4 presents all the experimental results, clubbed in terms of the compressive strength range.

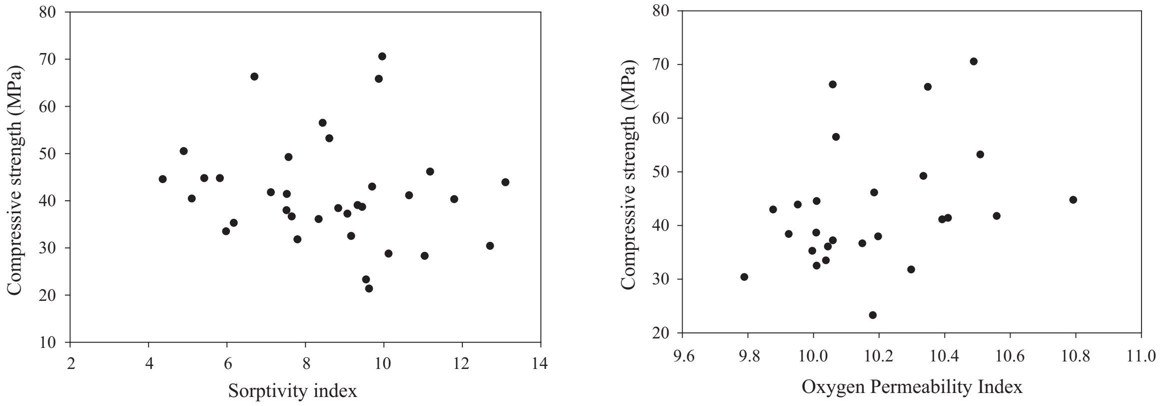
The mixes are categorized into 5 strength ranges such as 20–30, 30–40, 40–50, 50–60, and >60 MPa. Concrete mixes having mean compressive strength between 20 and 30 MPa fall under the strength range 20–30. Typically this category would include mixes having characteristic compressive strength of 20 MPa. It must be understood, of course, that only the absolute numbers are being used here, and not the statistical deviations. For instance, concrete with a compressive strength of 29 MPa may even fall in the strength range of 30–40 if the statistical variation is considered. In a similar way, the entire matrix involves low to medium strength concretes that are used for general purposes, i.e., from 20 to 60 MPa.

Table 4 gives an assessment of durability at an equivalent strength level. It can be seen that, within a strength range, different levels of durability are possible. For example, in order to design a concrete mix having a mean strength between 30 and 40 MPa (typically M30 grade concrete according to Indian Standard IS456), as per the 28 day results matrix, 10 options are available. If the binder chosen is OPC alone, the mix having a binder content of 310 kg/m^3 and w/b 0.60 is an option. However, the durability performance of this mix is not good. The corrosion rate from surface resistivity measurements and chloride ion penetrability from RCPT are both in the ‘High’ category. The concrete quality from sorptivity results is in the ‘Good’ range whereas that from OPI is in ‘Very good’ category. If in the same mix, the binder proportion is slightly altered, i.e., when 15% slag is added, then the corrosion rate and the chloride ion penetrability get improved by one level, i.e. they get classified into the ‘Low’ and ‘Moderate’ categories respectively. The classes for sorptivity index and OPI remain at the same level. When the replacement is with 15% Class F fly ash, similar trends are obtained with an exception that the category for chloride ion penetrability gets improved by two levels (new category is ‘Low’). With 30% Class F fly ash and w/b of 0.5, corrosion rate and chloride ion penetrability get classified as ‘Low’. OPI results are classified in the ‘Excellent’ category whereas sorptivity index is in the ‘Good’ category. When the option is total binder content 380 kg/m^3 and w/b 0.4 with 50% Class F fly ash replacement, all the durability



(a) Compressive strength and surface resistivity

(b) Compressive strength and charge passed



(c) Compressive strength and sorptivity index

(d) Compressive strength and Oxygen Permeability Index

Fig. 4. Compressive strength plotted against specific durability parameters.

parameters are classified towards the best category except the sorptivity index. Another thing to be noticed is that the mixture having a binder content of 310 kg/m^3 and water binder ratio 0.5, having 50% fly ash replacement, satisfies all the requirements for the best durability category except sorptivity index. However, this is not a good option for the current group because the strength is 23.2 MPa, which is in the strength category 20–30.

3.4. Proposed methodology for performance classification

In general, it can be concluded that within a strength range, as the replacement level increases, durability gets improved. Furthermore, performance of the mixes (both strength and durability) is influenced by other mix design parameters such as water to binder ratio, total binder content, and type of SCM. Thus, an attempt is made in this section to calculate indicators, which reflect the effect of mix proportioning parameters, strength and durability. At first, the parameter 'cement content' is calculated as the product of total binder content and (1-SCM replacement fraction), as per equation (1). Using 'cement content', performance indicators in terms of surface resistivity, charge passed, sorptivity index and oxygen permeability index are calculated as shown below in equations (2) to (5). Water to binder ratio and type of SCM used are indirectly reflected in both strength and durability parameters.

$$Cement\ content,\ C = Total\ binder\ content \times (1 - SCM\ replacement\ level) \quad (1)$$

$$PI_{SR} = \frac{SR \times 100}{f_{ck} \times C} \quad (2)$$

$$PI_{CP} = \frac{10^7}{TC \times f_{ck} \times C} \quad (3)$$

$$PI_{OPI} = \frac{OPI \times 100}{f_{ck} \times C} \quad (4)$$

$$PI_{SI} = \frac{10^5}{SI \times f_{ck} \times C} \quad (5)$$

Where,

PI_{SR} – Performance Indicator in terms of surface resistivity and compressive strength
PI_{CP} – Performance Indicator in terms of charge passed and compressive strength
PI_{OPI} – Performance Indicator in terms of Oxygen permeability index and compressive strength
PI_{SI} – Performance Indicator in terms of sorptivity index and compressive strength
f_{ck} – compressive strength in N/mm^2
SR – Surface resistivity in kΩ. cm
CP – Charge passed in Coulombs
SI – Sorptivity index in in mm/$\sqrt{}$h
OPI – Oxygen permeability index

Table 4
Details of durability parameters and mix proportions arranged in terms of different strength levels at 28 days.

Strength range (MPa)	w/b	Binder content (kg/m^3)	SCM content and type	Tests results								
				Cube Compressive strength Test	Surface Resistivity Test		Rapid chloride permeability test		Oxygen permeability index test		Sorptivity index test	
				Compressive strength (MPa)	Surface Resistivity (kΩ.cm)	Corrosion rate	Charge passed (Coulombs)	Chloride ion penetrability	Oxygen permeability index	Concrete quality	Sorptivity index (mm/$\sqrt{}$h)	Concrete quality
20–30	0.65	280	30% Class F fly ash	21.3	10.08	Low to moderate	3180	moderate			9.63	Good
	0.5	310	50% Class F fly ash	23.2	46.92	low	720	Very low	10.18	Very good	9.56	Good
	0.65	280	30% Slag A	28.2	28.42	low	1220	Low			11.05	Good
	0.65	280	30% Slag B	28.7	18.17	Low to moderate	1885	Low			10.13	Good
	0.65	280	0	29.9	8.88	high	3285	moderate			12.72	
30–40	0.6	310	15% Class C fly ash	31.7	9.80	high	3305	moderate	10.30	Very good	7.81	Good
	0.6	310	0	32.4	9.02	high	4030	High	10.01	Very good	9.18	Good
	0.5	310	30% Class F fly ash	35.2	22.58	low	1010	Low	10.01	Very good	6.18	Good
	0.6	310	15% Slag A	36.0	11.27	Low to moderate	2400	moderate	10.05	Very good	8.35	Good
	0.4	380	50% Class F fly ash	36.6	29.08	low	1000	Very low	10.15	Very good	7.66	Good
	0.55	340	15% Slag A	37.2	11.83	Low to moderate	2400	moderate	10.06	Very good	9.08	Good
	0.5	310	30% Class C fly ash	37.9	12.75	Low to moderate	2885	moderate	10.20	Very good	7.53	Good
	0.6	310	15% Slag B	38.6	10.38	Low to moderate	3460	moderate	10.01	Very good	9.45	Good
	0.6	310	15% Class F fly ash	38.9	15.75	Low to moderate	1885	Low	10.08	Very good	9.34	Good
	0.55	340	15% Class F fly ash	39.9	11.92	Low to moderate	2690	moderate	10.16	Very good	11.80	Good
40–50	00.5	310	15% Class C fly ash	41.1	10.31	Low to moderate	2490	moderate	10.39	Very good	10.65	Good
	0.55	340	15% Class C fly ash	41.3	8.45	high	4250	high	10.41	Very good	7.54	Good
	0.4	380	30% Class F fly ash	41.7	21.33	low	1555	low	10.56	Very good	7.13	Good
	0.55	340	0	42.9	8.19	high	4465	high	9.88	Good	9.71	Good
	0.5	310	0	43.8	10.73	Low to moderate	2720	moderate	9.95	Good	13.11	Poor
	0.55	340	15% Slag B	44.5	15.58	Low to moderate	2570	moderate	10.01	Very good	4.37	Very good
	0.5	310	15% Slag A	44.7	14.75	Low to moderate	1795	low	10.79	Very good	5.83	Very good
	0.5	310	30% Slag B	44.7	32.92	low	1720	low	10.66	Very good	5.43	Very good
	0.5	310	15% Class F fly ash	46.1	16.58	Low to moderate	1570	Low	10.19	Very good	11.19	Good
	0.5	300	0	46.1	10.86	Low to moderate	3295	Moderate	10.13	Very good	9.21	Good
	0.4	340	0	47.5	16.08	Low to moderate	2225	Moderate	9.98	Good	2.93	Very good
	0.45	340	0	47.8	9.96	high	3130	Moderate	9.76	Good	4.65	Very good
	0.45	320	0	48.4	10.81	Low to moderate	2735	Moderate	9.93	Good	4.30	Very good
	0.4	400	0	48.9	9.58	high	2135	Moderate	9.87	Good	6.64	Good
	0.5	310	15% Slag B	49.2	21.92	low	2460	Moderate	10.34	Very good	7.58	Good
50–60	0.5	310	50% Slag B	50.4	84.75	low	475	Very low	10.73	Very good	4.91	Very good
	0.55	300	0	50.8	10.17	Low to moderate	4200	Very high	9.80	Good	11.02	Poor
	0.4	380	15% Class F fly ash	53.1	13.83	Low to moderate	1910	low	10.51	Very good	8.62	Good
	0.4	360	0	54.1	13.5	Low to moderate	2770	moderate	9.87	Good	5.37	Very good
	0.4	380	50% Slag B	59.1	52.25	low	390	Very low	10.07	Very good	8.45	Good
>60	0.4	380	15% Slag B	65.7	15.50	Low to moderate	1340	low	10.35	Very good	9.88	Good
	0.4	380	30% Slag B	66.2	23.83	low	975	Very low	10.06	Very good	6.71	Good
	0.4	380	0	70.5	14.75	Low to moderate	1515	low	10.49	Very good	9.97	Good

Table 5
Definition of performance classes.

Performance class	Performance Indicator			
	PI_{SR}	PI_{CP}	PI_{OPI}	PI_{SI}
Excellent	>0.4	>1	> 0.1	>1.5
Good	0.2 – 0.4	0.5 – 1	0.1 – 0.08	1 – 1.5
Moderate	0.1 – 0.2	0.3 – 0.5	0.05 – 0.08	0.5 – 1
Poor	< 0.1	< 0.3	< 0.05	< 0.5

By calculating the above performance indicators for all the mixes in this study, criteria are proposed for classifying concretes, as presented in Table 5. The mixes are divided into four performance classes such as Excellent, Good, Moderate, and Poor based on the different performance indicators under consideration. The limiting values of each performance indicator are also given in Table 5.

Table 6 provides the mix design parameters and performance indicators calculated for all the concrete mixtures at the age of

Table 6
Performance classification for all the concretes at 28 days.

Strength range (MPa)	w/b	Binder content (kg/m^3)	SCM content and type	Cement content	PI_{SR}	PI_{CP}	PI_{OPI}	PI_{SI}
20-30	0.5	310	50% Class F fly ash	155	1.30	3.86	0.28	2.91
	0.65	280	30% Slag A	196	0.51	1.48		1.64
	0.65	280	30% Slag B	196	0.32	0.94		1.75
	0.65	280	30% Class F fly ash	196	0.24	0.75		2.49
	0.65	280	0	280	0.11	0.36		0.94
30-40	0.4	380	50% Class F fly ash	190	0.42	1.44	0.15	1.88
	0.5	310	30% Class F fly ash	217	0.30	1.30	0.13	2.12
	0.5	310	30% Class C fly ash	217	0.16	0.42	0.12	1.61
	0.6	310	15% Class C fly ash	263.5	0.12	0.36	0.12	1.53
	0.6	310	15% Class F fly ash	263.5	0.15	0.52	0.10	1.04
	0.6	310	15% Slag A	263.5	0.12	0.44	0.11	1.26
	0.6	310	15% Slag B	263.5	0.10	0.28	0.10	1.04
	0.55	340	15% Slag A	289	0.11	0.39	0.09	1.02
	0.55	340	15% Class F fly ash	289	0.10	0.32	0.09	0.73
	0.6	310	0	310	0.09	0.25	0.10	1.08
40-50	0.5	310	30% Slag B	217	0.34	0.60	0.11	1.90
	0.4	380	30% Class F fly ash	266	0.19	0.58	0.10	1.26
	0.5	310	15% Slag B	263.5	0.17	0.31	0.08	1.02
	0.5	310	15% Class F fly ash	263.5	0.14	0.52	0.08	0.74
	0.5	310	15% Slag A	263.5	0.13	0.47	0.09	1.46
	0.5	310	15% Class C fly ash	263.5	0.10	0.37	0.10	0.87
	0.55	340	15% Slag B	289	0.12	0.30	0.08	1.78
	0.55	340	15% Class C fly ash	289	0.07	0.20	0.09	1.11
	0.5	300	0	300	0.08	0.22	0.07	0.79
	0.5	310	0	310	0.08	0.27	0.07	0.56
	0.45	320	0	320	0.07	0.24	0.06	1.50
	0.4	340	0	340	0.10	0.28	0.06	2.11
	0.45	340	0	340	0.06	0.20	0.06	1.32
	0.55	340	0	340	0.06	0.15	0.07	0.71
	0.4	400	0	400	0.05	0.24	0.05	0.77
50-60	0.5	310	50% Slag B	155	1.08	2.69	0.14	2.61
	0.4	380	50% Slag B	190	0.47	2.28	0.09	1.05
	0.4	380	15% Class F fly ash	323	0.08	0.31	0.06	0.68
	0.55	300	0	300	0.07	0.16	0.06	0.60
	0.4	360	0	360	0.07	0.19	0.05	0.96
>60	0.4	380	30% Slag B	266	0.14	0.58	0.06	0.85
	0.4	380	15% Slag B	323	0.07	0.35	0.05	0.48
	0.4	380	0	380	0.06	0.25	0.04	0.37

Table 7
Total charge passed and mix details in different strength ranges – data from literature [8,20–24].

Strength grade	Mix details (w/b; Total binder content, SCM type and replacement level)	Mean 28 day strength (MPa)	Durability parameter (Total Charge Passed)	Cement content	PI_{CP}	Reference
20-30	(0.45, 300; 20% FA)	29.9	2219	240	0.6	Al-Amoudi et al., 2009 [8]
	(0.5, 350, 20% FA)	23.7	3548	280	0.4	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.5, 400, 20% FA)	25	2750	320	0.4	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
30-40	(0.4, 400, 80% slag)	34.2	1580	80	2.3	Guneyisi and Gesoglu, 2008 [23]
	(0.4, 400, 70% slag)	37.1	1600	120	1.4	Guneyisi and Gesoglu, 2008 [23]
	(0.51, 300, 40% FA)	35.5	2145	180	0.7	Mathur et al., 2005 [22]
	(0.54, 280, 30% FA)	34.5	2560	196	0.5	Mathur et al., 2005 [22]
	(0.4, 350, 20% FA)	36.2	1769	280	0.5	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.4, 400, 20% FA)	36.5	1630	320	0.5	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.35, 350, 20% FA)	36.7	1603	280	0.6	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.35, 400, 20% FA)	37.6	1477	320	0.5	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.45, 400, 20% FA)	32.9	2220	320	0.4	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.45, 350, 20% FA)	31.6	2510	280	0.4	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.61, 235, OPC)	34	3480	235	0.3	Mathur et al., 2005 [22]
	(0.5, 400, OPC)	33.9	4150	400	0.1	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.45, 400, OPC)	35.9	3593	400	0.1	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.5, 350, OPC)	31.6	5614	350	0.1	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.45, 350, OPC)	34.9	3820	350	0.2	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.4, 350, OPC)	39.5	3639	350	0.2	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.55, 300, OPC)	31.76	3650	300	0.2	Das et al., 2012 [21]
	(0.45, 300, OPC)	34.4	3984	300	0.2	Al-Amoudi et al., 2009 [8]
40-50	(0.4, 400, 60% slag)	43.1	1870	160	0.7	Guneyisi and Gesoglu, 2008 [23]
	(0.37, 360, 50%FA)	43	775	180	1.6	Mathur et al., 2005 [22]
	(0.4, 400, 50% slag)	49	2050	200	0.5	Guneyisi and Gesoglu, 2008 [23]
	(0.43, 300, 40%FA)	42.5	890	180	1.4	Mathur et al., 2005 [22]
	(0.47, 275, 30%FA)	43	995	192.5	1.2	Mathur et al., 2005 [22]
	(0.55, 300, PPC)	40.94	1195	210	0.9	Das et al., 2012 [21]
	(0.4, 400, OPC)	41	3271	400	0.1	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.35, 400, OPC)	45.3	2445	400	0.2	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.55, 400, OPC)	42.8	5445	400	0.1	Chia and Zhang, 2002 [24]
	(0.35, 350, OPC)	43.1	2875	350	0.2	Ahmed et al., 2008 [20], Al-Amoudi et al., 2009 [8]
	(0.45, 320, OPC)	42.81	3325	320	0.2	Das et al., 2012 [21]
	(0.52, 260, OPC)	44	1351	260	0.6	Mathur et al., 2005 [22]
50-60	(0.33, 470, 50% FA)	53	761	235	1	Mathur et al., 2005 [22]
	(0.35, 420, 40% FA)	53	812	252	0.9	Mathur et al., 2005 [22]
	(0.38, 360, 30% FA)	55	990	252	0.7	Mathur et al., 2005 [22]
	(0.4, 360, PPC)	58.02	870	252	0.7	Das et al., 2012 [21]
	(0.45, 320, PPC)	54.88	1078	224	0.7	Das et al., 2012 [21]
	(0.4, 400, OPC)	56.2	4250	400	0.1	Guneyisi and Gesoglu, 2008 [23]
	(0.4, 360, OPC)	51.2	3020	360	0.1	Das et al., 2012 [21]
	(0.43, 300, OPC)	57	1295	300	0.4	Mathur et al., 2005 [22]
>60	(0.35, 470, OPC)	78.2	2290	470	0.1	Chia and Zhang, 2002 [24]

28 days. The mixes are divided into 5 strength ranges such as 20–30, 30–40, 40–50, 50–60, and >60 MPa. Within a strength range, the mixes are presented in the order of % replacement with SCM. The colour codes for the different performance classes specified in Table 5 are also used in Table 6.

The priority of arrangement of Table 6 is SCM replacement level, followed by cement content in the decreasing order. From Table 6, it is clear that within a particular strength range, it is possible to get different levels of performance by varying the parameters such as the binder content, water to binder ratio, SCM type and SCM replacement level. Within a strength range, SCM mixes are seen to perform better compared to OPC mixes. As SCM replacement level increases, the performance of the mixes increases. Mixes having 50% replacement fall within the excellent performance category in the three strength ranges 20–30, 30–40, and 50–60. There are no mixes with 50% level of replacement in other strength ranges. In strength ranges 40–50 and >60, mixes having 30% SCM content occupy the better performance category. Another noticeable point is that the mixes having lower cement content show better performance. This is a good sign to reduce clinker content in the mixes, a move towards sustainability. Further, as water to binder ratio increases, the performance indicators decrease, as expected. These general trends are obtained for all the performance indicators, calculated using different durability parameters. It is worthwhile to point here that these durability parameters point towards penetrability of different deteriorating agents.

Further, this performance classification supports the concept of performance specification. The concrete producer can have flexibility on the type and dosage of SCMs as well as other mixture parameters.

The data from literature is also compiled to see the level of durability parameters obtained for various strength grades and is presented in Table 7. It is to be noted that data for both compressive strength and durability parameters along with mix details were available in very few publications. Here, compilation is made only for the one durability parameter, namely the total charge passed in RCPT. For Portland Pozzolana Cement (PPC), a replacement level of 30% is assumed with fly ash.

It can be seen that the data from literature agrees with the conclusions made from the present study. It is possible to get different levels of durability in same strength concretes by adequately varying the mixture parameters such as type of binder, binder content and water to binder ratio.

4. Conclusions

An attempt has been made in this paper to develop indicators called performance indicators, which combine both strength and durability criteria. Limiting values of these indicators are also suggested. Different mixes in the same strength range are classified into different performance classes based on qualitative criteria developed based on the above performance indicators. The durability parameters used here to classify concrete include surface resistivity, charge passed, sorptivity index and oxygen permeability index.

From the result matrix, it can be concluded that within the same strength range, mixes with SCMs are better compared to their OPC counterparts. As the replacement level increases, the durability parameters get improved. As the strength range increases, the mixes attain higher durability categories. Furthermore, as water binder ratio decreases, more mixes are qualifying in the higher durability classes, which is expected. In addition, there is no correlation obtained between strength and durability parameters.

The results show that different options are available to make concrete at a particular strength grade, which can result in different levels of durability. It is clear that use of SCMs can result in high levels of durability even in mixes having high w/b and low binder content. The data from literature are also in agreement. The performance classification developed will be useful for concrete technologists for choosing the right blend of materials depending on their requirement at site. Depending on the service requirement (i.e., level of durability required), the mixture proportion can be tailor made.

It is recommended that the construction specifications should specify both strength and durability parameters, pointing towards the correct deterioration mechanism prevailing in that service environment. On the contrary, the performance indicators presented in Table 5 can be specified. This can be considered as a stepping stone towards "performance based specifications".

Conflict of interest

There is no conflict of interest.

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