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Steam-cured concrete incorporating mineral admixtures

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Abstract

This paper explores the potential benefits of steam-cured concrete, particularly on mixes incorporating mineral admixtures. Twenty mixes with various combinations of Portland cement, fly ash (FA), slag and silica fume (SF) were investigated. For each mix, specimens were either standard-cured in a water bath of 27 °C or steam-cured at 55 °C maximum temperature over 8 h. For the materials and test conditions reported in this study, it was found that steam-cured concretes were more porous as indicated by the much higher sorptivity values compared with standard-cured specimens. Mixes with SF have the best performance and hold promise in precast manufacturing due to their high early strength development and low sorptivity values.

Keywords: Heat curing; Fly ash; Slag; Silica fume; Durability; Sorptivity

1. Introduction

Precast concrete elements are used increasingly in construction to improve the quality of concrete production and to reduce the construction time. Various techniques can be employed for heating concrete with low pressure steam curing being commonly used in practice. Despite heat curing being used widely in the precast industry to speed up production, investigations on heat-cured products focused mainly on their strength development. Research on durability of heat-cured products, particularly on mixes incorporating mineral admixtures, is somewhat limited.

Research in Australia [1,2] found that for heat-cured products, the quality of the concrete cover, as indicated by water sorptivity, was poor and was equivalent to that achieved with only 2–3 days of standard curing (i.e., 23 °C, 100% RH). Their 1-day steam curing cycle included a delay period of 2 h followed by a temperature rise of about 20 °C/h. A maximum temperature of 70 °C was maintained over 8.5 h.

This above finding was based on mixes incorporating ordinary Portland cement (OPC). However, by using fly ash (FA) at 20% replacement, it was reported [3] that the quality of concrete achieved was better than that obtained with 28 days of standard curing. This research pointed to the potential benefits in the utilization of mineral admixtures in heat curing.

In a subsequent study [4], the maximum temperature was reduced slightly to 65 °C due to the industry concern over delayed ettringite formation. By comparing the 7-day quality of standard curing, the paper confirmed the earlier finding that, for OPC concrete, heat curing produced a vastly inferior product. Similar results were obtained for blended cement containing 35% blast furnace slag (BFS). However, the situation was reversed when high slag content of 65% was used and, in this case, heat curing resulted in a significantly improved quality when compared to 7 days of standard curing.

Note that the above comparisons were based on concretes with standard curing at 23 °C and conditioned in laboratory under 50% RH. This is appropriate for concrete to be used in temperate climates. However, for countries like Singapore and those in the tropical region, daily temperature ranges from 25 to 32 °C with an average humidity around 75% RH all the year round. Thus, for concretes to be used in the tropics, standard curing and conditioning of specimens take on a different meaning, providing concrete with a higher maturity compared to those used in temperate climates.

It is obvious from the above discussion that the influence of heat curing on the quality of concrete depends on the type

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Table 1
Chemical (%) and physical properties of binders

	OPC	FA	BFS	SF
CaO	62.3	2.50	41.8	0.90
SiO_2	20.7	52.5	31.4	93.6
Fe_2O_3	3.40	10.5	–	1.50
Al_2O_3	5.50	28.2	–	0.50
MgO	2.10	1.60	4.40	0.60
SO_3	2.10	0.20	2.00	0.30
Na_2O	0.42	0.04	–	0.04
K_2O	0.46	0.90	–	0.54
LOI	0.70	1.70	1.80	2.00
Fineness (m^2/kg)	357	410	500	2600
Density (kg/m^3)	3150	2380	2900	2000

and amount of binder used. This paper explores the potential benefits of steam-cured products to be used under hot or tropical climatic conditions.

2. Criterion for concrete durability

It is generally accepted that the permeability of concrete to liquids and gases is of direct relevance to durable concrete. Although the term 'permeability' is strictly related to the flow that occurs under an applied pressure differential, it is also frequently used in a general sense to cover other transport mechanisms including absorption and diffusion. It was pointed out [5] that 'in most practical situations the test method should be chosen to be appropriate to the predominant mechanism acting on the concrete under consideration.'

In studying the aspect of reinforcement corrosion relating to above-ground structures, the quality of concrete cover has been discussed in terms of water sorptivity. The concept and its application to durability issues have been reported in numerous publications [6–9]. Note that water sorptivity relates to the 'rate' at which water is absorbed into concrete through capillary action. This property is determined by measuring the depths of water penetration at various time intervals. By measuring depth rather than volume of water absorbed, it was found that test results are less sensitive to the initial moisture condition of concrete provided that specimens were conditioned under ambient conditions (23 °C, 50% RH) for about 21 days prior to testing [6].

A similar approach has been considered by other workers [10,11]. However, their measurements were based on the volume or weight of water absorbed and this necessitated the removal of evaporable water prior to testing, usually by heating specimens at elevated temperatures. This severe drying condition may cause internal microcracking of the concrete and the resulting predamage is expected to be more severe with high-quality concretes.

In 1989, RILEM technical committee, TC 116-PCD was formed to evaluate the use of permeability as a criterion of concrete durability. Test methods were evaluated and reported with regard to their suitability for routine testing of concrete transport parameters [12–14]. One of the recommendations was to precondition specimens slowly under ambient conditions of 75% RH at 20 °C prior to testing. This procedure overcomes one of the main concerns over heating at elevated temperatures and the resulting predamage.

In 1990, the Roads and Transport Authority (RTA) of New South Wales in Australia adopted the water sorptivity concept as an additional durability requirement for concrete to be used in bridge construction. For practicality, RTA simplified the test by determining only the depth of water penetration after 24 h of wetting and referred to as the sorptivity depth in their Part B80 document [15]. To assist measurement in practice, a special dry mixture of 10-part glucose and 1-part methylene blue was formulated and by sprinkling the mixture onto the fractured surface, enhances the perception of the water front and provides a permanent record.

3. Experimental details

One OPC and three mineral admixtures, namely FA, ground granulated BFS and silica fume (SF), commonly available in Singapore were used. Chemical and physical properties of the materials given by the suppliers are presented in Table 1. The coarse and fine aggregates were crushed granite and natural sand, respectively. Five series of concrete mixes were prepared for testing of water sorptivity and compressive strength. In practice, grade 30–50 MPa concretes are often specified and used in precast products. In this study, four strength levels were considered and mixes were proportioned to have a target 28-day compressive

Table 2
Summary of mix details

Binder (wt.%)				W/B	Aggregates (kg/m^3)		Slump (mm)	F28 (MPa)
OPC	FA	BFS	SF		Fine	Coarse		
100	–	–	–	0.65	595	1230	35	32.0
				0.57	580	1200	37	43.0
				0.50	565	1170	48	50.5
				0.42	525	1095	55	59.5
70	30	–	–	0.65	585	1210	50	26.0
				0.56	585	1215	55	42.5
				0.45	565	1170	53	50.0
				0.32	455	960	85	68.5
35	–	65	–	0.65	590	1225	45	36.0
				0.56	590	1225	30	47.5
				0.49	560	1175	67	50.0
				0.33	465	965	37	64.5
90	–	–	10	0.80	655	1180	40	31.5
				0.65	590	1225	35	44.5
				0.49	535	1110	40	61.5
				0.37	450	950	33	69.0
70	20	–	10	0.81	645	1160	40	25.5
				0.60	575	1195	40	41.5
				0.49	530	1095	85	53.5
				0.34	450	945	30	76.5

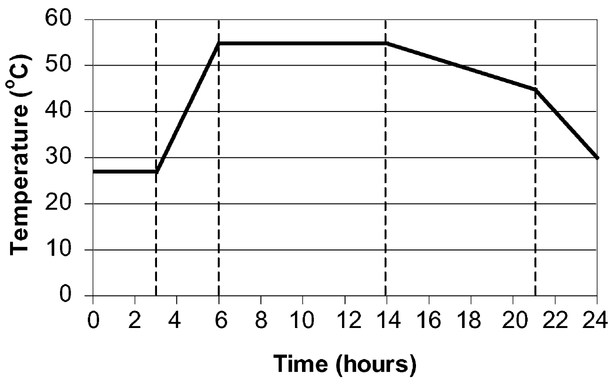

Fig. 1. One-day steam cycle.

strength of 30, 40, 50 or 60 MPa. The target slump was 50 mm since low slump values are often specified for precast concrete. A summary of mix details is presented in Table 2.

Precast concrete products are used widely in Singapore, but generally not heat cured. This may be due to the already high ambient temperatures encountered locally. However, for special projects where the turnaround time is critical, a 24-h heating cycle similar to that illustrated in Fig. 1 is generally adopted. This heating cycle, featuring a 3-h delay period and a maximum temperature of 55 °C maintained over 8 h, was used in this investigation.

For the determination of compressive strengths, six specimens (100 mm cubes) from each mix were tested either after 28 days of standard curing (F28) or at the end of the 1-day steam cycle referred to as the 'ex-steam' strength. In this research, 'standard curing' is referred to as curing under standard laboratory conditions of 27 °C in a fog room maintained at 100% RH. The achieved 28-day strengths of the mixes are also reported in Table 2.

A total of 16 specimens (100 × 100 × 150 mm) of each mix were produced for sorptivity tests. The experimental set-up is shown in Fig. 2. Two coats of epoxy paint were applied to the ends and two opposite sides of specimens. In this paper, water sorptivity were determined based on both the depth of water penetration and weight gained over 24 h of wetting. There were four curing regimes as described in Table 3. After curing, specimens were conditioned under ambient conditions of 27 °C and 75% RH. For depth measurements, the preconditioning period of the specimens was 28 days. For measurements of weight gained, the aim was to condition specimens until a constant weight was obtained and this was usually achieved over 28 days of conditioning.

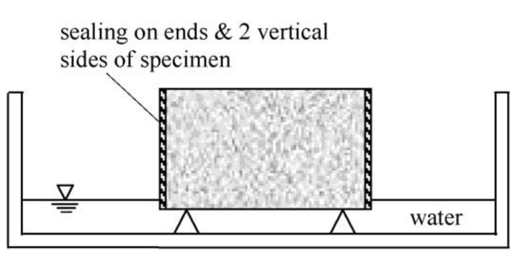

Fig. 2. Experimental set-up for sorptivity tests.

Table 3
Curing regime of specimens for sorptivity tests

Regime	Description
3-d Sd	1 day in mould + 2 days in 27 °C water bath
7-d Sd	1 day in mould + 6 days in 27 °C water bath
3-d HE	1 day of steam cycle + 2 days wrapped in plastic envelope
7-d HE	1 day of steam cycle + 6 days wrapped in plastic envelope

4. Results and discussions

4.1. Ex-steam compressive strength

The ex-steam compressive cube strength of all mixes after being subjected to 1 day of steam curing cycle is presented in Fig. 3. For the range of materials considered in this study, it was observed that the ex-steam strengths of FA concretes were low compared to OPC concretes, particularly at high F28 strength levels. BFS concretes showed the opposite trend with their ex-steam strengths approaching those of OPC concretes at about 60 MPa. It was also observed that the ex-steam strengths of SF and FA + SF concretes were similar to those of OPC concretes. At common 28-day strength of, say, 50 MPa, the strength ratios of ex-steam to F28 are:

0.58 for OPC and SF concretes
0.44 for FA concrete
0.47 for BFS concrete
0.62 for triple bended concrete (OPC/FA/SF)

In general and for standard-cured specimens, the 1-day strength is about 0.35–0.40 of the 28-day value for OPC concrete and 0.25–0.35 for blended cement mixes [16,17]. Thus, steam curing at 55 °C used in this study has the effect of increasing the 1-day strength by about 40%, which can lead to the efficient use of molds and increase the production rate. The benefit is found to be more significant with mixes incorporating SF.

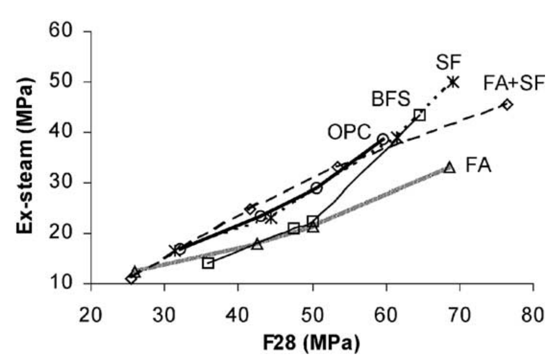

Fig. 3. Ex-steam compressive strength of mixes.

4.2. Sorptivity by weight gained

Water sorptivity results based on measurements on weight of water absorbed over 24 h, WA, are illustrated in Fig. 4. As indicated in the OPC, FA and BFS mixes, steam curing produced very porous concrete. Their WA values were generally about twice those for specimens obtained with 3 days of standard curing. The performance of BFS concrete improved rapidly at high strength levels and this finding was consistent with the trend on its ex-steam strengths presented earlier in Fig. 3. For mixes incorporating SF (Fig. 4d and e), steam curing produced only slightly more porous concrete as indicated by the marginal increase in WA values compared to concrete with standard curing. In this study, the benefit of FA and BFS in heat curing was not realized as reported earlier [3,4]. This could be due to a combination of factors including differences in the materials, mix proportions, heating and environmental conditions.

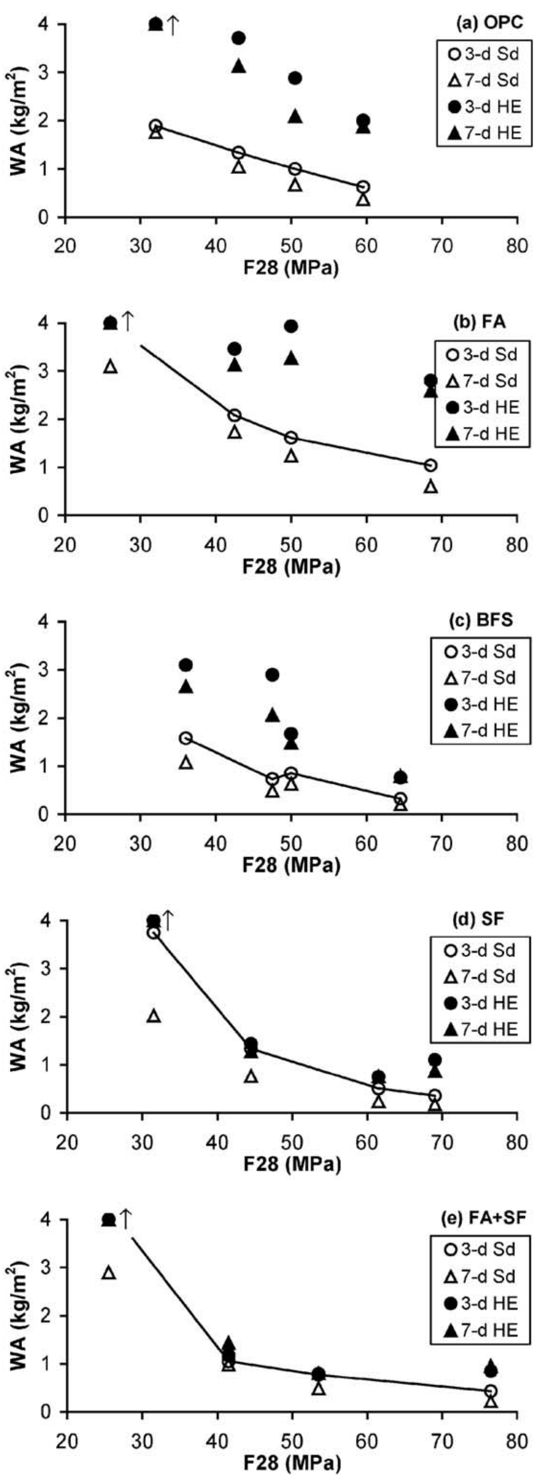

Fig. 4. Sorptivity results, WA, based on weight of water absorbed for (a) OPC, (b) OPC/FA, (c) OPC/BFS, (d) OPC/SF and (e) OPC/FA/SF mixes.

In general, sorptivity values increased gradually with decreases in the 28-day strengths. However, the values increased sharply as strengths fell below 40 MPa. In some cases, specimens reached near saturated conditions in less than 24 h and were recorded as >4 kg/m^2 of water absorption. Such a result was represented by an arrow next to the 4 kg/m^2 data point. For external reinforced concrete elements, a minimum of 40 MPa concrete should be specified, particularly for steam-cured precast products. Obviously, in aggressive environments such as those near the coast or in polluted areas, grade 50–60 MPa concrete should be specified. The use of SF mixes could be considered as an added advantage.

4.3. Sorptivity by depth of water penetration

Since the depth of water penetration, *D*, and weight gained were derived from the same transport mechanism of capillary absorption, observations on results of sorptivity depth were expected to be similar to those of weight gained reported earlier. Indeed, results presented in Fig. 5 confirmed the earlier findings on steam-cured concretes and that:

sorptivity depths increased rapidly for strengths below 40 MPa;

steam-cured concretes from OPC, FA and BFS mixes were more porous with sorptivity depths about twice those of specimens having 3 days of standard curing;

there were obvious benefits in the use of SF in improving the pore structure of concrete under steam or standard curing conditions.

4.4. Water-to-binder ratio

It is generally recognized that durability is more related to water to binder ratio, W/B, than compressive strength. A close examination of results would reveal also that water sorptivity values increased slowly with increases in W/B, but increased sharply when W/B was greater than about 0.55. For the ease of comparison, water sorptivity values at a common W/B of, say, 0.45 were obtained by interpolation using results presented in Table 2 and Figs. 4 and 5. These

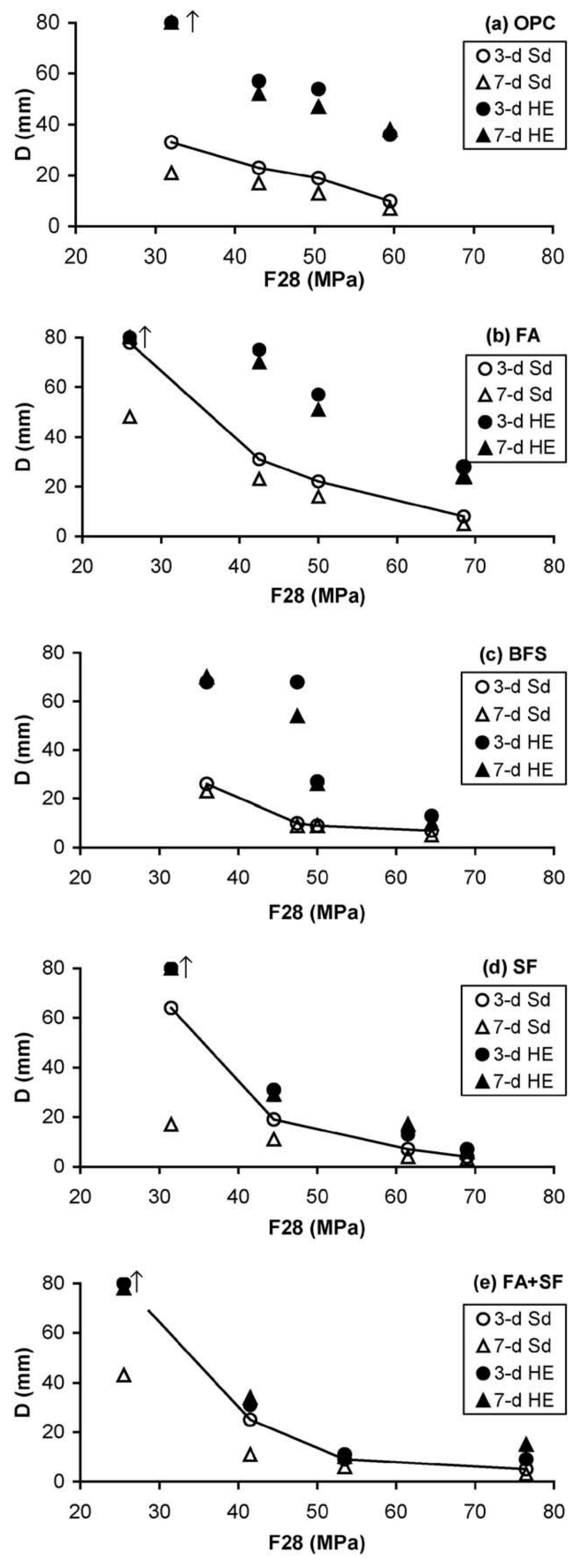

Fig. 5. Sorptivity results, *D*, based on depth of water penetration for (a) OPC, (b) OPC/FA, (c) OPC/BFS, (d) OPC/SF and (e) OPC/FA/SF mixes.

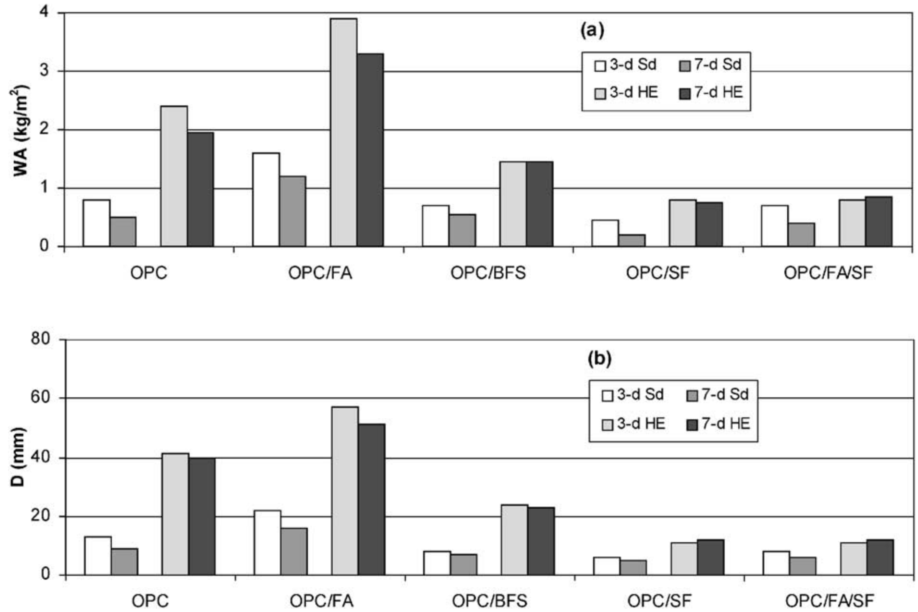

Fig. 6. Comparison of mixes at common W/B of 0.45 on sorptivity results from (a) weight of water absorbed per unit surface area, WA and (b) depth of water penetration, *D*.

interpolated values are presented in Fig. 6 and, as indicated, the quality of steam-cured concretes from OPC, FA and BFS was inferior compared to those of corresponding standard-cured specimens. Good quality concrete was achieved with mixes incorporating SF as indicated by the low values of water sorptivity. These findings were similar to those obtained earlier from comparisons basing on the 28-day strengths.

5. Practical considerations

Results and conclusions obtained in this study on FA and BFS mixes were somewhat different to those obtained in other research [3,4]. More research is needed to clear up this confusion. This highlights the danger of adopting overseas findings without taking into consideration of differences in local construction practices and environmental conditions.

As expected, results demonstrated that the quality of concrete varied over a wide range depending on many factors. The use of strength or W/B alone is not adequate in specifying concrete for durable structures. One way to overcome this problem is to specify directly the quality required for the concrete under consideration [18–20]. Although permeability is considered as an important parameter, there has not been any general agreement on the definition of 'quality.' Furthermore, measuring techniques and testing procedures on the permeability of concrete varied depending on the researcher. Therefore, the work of RILEM TC-PCD [13] is a significant contribution and a step in the right direction in recommending standard test methods and procedures in measuring transport properties of concrete. Once accepted, the next development would be proposals on acceptance levels based on these tests for concrete to be used under various service and exposure environments.

In this respect, RTA [21] has led the way in using sorptivity depth as a performance criterion in the durability design of bridges. For the 100-year service life, the maximum permissible sorptivity depths for concrete to be used under different exposure conditions are reproduced in Table 4. Obviously, these acceptance levels and testing procedures should be considered as interim and are expected to be fine tuned when more information becomes available. If this performance criterion were to be adopted locally in Singapore, bridge structures should be specified with a maximum sorptivity depth of 17 mm. That means, precast concrete of grade 50 SF mixes are deemed to comply. For other mixes, concrete of grade greater than 70 MPa should be specified.

For any test methods to be accepted in practice, they have to be simple and can be performed in most testing laboratories. For tests on water sorptivity, it was found that the measurements on weight of water absorbed were simpler and produced less scattered results compared to depth measurements. However, for weight measurements, the preconditioning of specimens to constant initial moisture content, such as

Table 4
RTA durability requirement on sorptivity

Exposure classification	Maximum sorptivity depth (mm)
Dry climate, no industry, nonaggressive	45
Industrial area, inland	35
Close to coast or permanently in sea water	17
Tidal/splash zone	8

that at 75% RH cannot be overemphasized. With the industry moving towards performance specifications and the extensive effort put in by many research organizations around the world, it is expected that in the near future, simpler and more reliable test methods would be developed.

6. Conclusions

Five series of mixes with various combinations of Portland cement, FA, ground granulated BFS and SF were investigated. For each mix, specimens were either steam-cured at 55 °C maximum temperature over 8 h or cured in a water bath of 27 °C to represent local climatic conditions. For the materials and testing procedures used in this study, it was found that steam-cured concretes from OPC, FA and BFS mixes were more porous as indicated by the much higher sorptivity values compared to the 3-day standard-cured specimens at 27 °C. Mixes incorporating SF have the best performance and showed excellent promise in precast manufacturing due their high ex-steam compressive strength and low sorptivity values.

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