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# Near surface characteristics of concrete: prediction of freeze/thaw resistance

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**Abstract.** The durability of concrete is related to the permeation characteristics of its near surface. An attempt was made to use the permeation characteristics namely, absorptivity, permeability and diffusivity, to predict the freeze/thaw resistance of concrete. Test results indicate that in general, there was a trend that freeze/thaw resistance of concrete was enhanced with improved absorptivity and diffusivity whilst the freeze/thaw resistance of normal concrete was found to have the best relationship with its intrinsic permeability. The latter method is therefore proposed to be adopted to predict freeze/thaw resistance of normal concrete. Since Figg air test is an inexpensive and simple test method that measures indirectly the intrinsic permeability of concrete, it is further proposed that it could be used as a quality control tool to assess, non-destructively, the freeze/thaw durability potential of in-situ concrete.

**Key words:** Intrinsic permeability; Figg air test; freeze/thaw resistance; concrete.

## 1. Introduction

Freezing and thawing is a serious problem for concrete structures in cold regions. This is particularly the case with highways and bridges where the structures are sited in exposed aggressive environments and damage can be greatly accelerated by the additional influence of applied deicing salts.

Direct measurement of durability of concrete in general can be very time consuming and in most cases not practical. Thus it is not surprising that in common practice, provision is made in specifications for the durability potential of concrete in the form of strength. However, it has been shown that strength alone can not be employed to assess the potential durability of concrete, instead permeation characteristics (absorptivity, permeability and diffusivity) could be used (Dhir, Hewlett and Chan 1985). Work carried out by the authors has established that intrinsic permeability and initial surface absorptivity can be used respectively to quantitatively measure the carbonation resistance and abrasion resistance of concrete (Dhir, Hewlett and Chan 1989, 1991).

For freeze/thaw durability of concrete, there have been reports by various research workers advocating a similar route to the specification and assessment (Levitt 1971, Valenta 1970 and Weston 1981). However, only very limited amount of concretes have been investigated in these studies and contradicting observations have been reported. This study was undertaken to establish

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Table 1 Concrete mix proportions used

| Mix | Cement ($kg \cdot m^{-3}$) | Water/ cement ratio | Slump (mm) | Maximum aggregate size (mm) | Additives or admixtures | Design strength ($N \cdot mm^{-2}$) |
|---|---|---|---|---|---|---|
| Series 1: Variable water/cement ratio | | | | | | |
| N1 | 490 | 0.40 | 75 | 20 | – | 65 |
| N2 | 400 | 0.47 | 75 | 20 | – | 55 |
| N3 | 340 | 0.55 | 75 | 20 | – | 45 |
| N4 | 300 | 0.62 | 75 | 20 | – | 35 |
| N5 | 265 | 0.70 | 75 | 20 | – | 30 |
| Series 2: Variable workability | | | | | | |
| NW1 | 300 | 0.55 | 25 | 20 | – | 45 |
| N3 | 340 | 0.55 | 75 | 20 | – | 45 |
| NW3 | 350 | 0.55 | 125 | 20 | – | 45 |
| NW4 | 365 | 0.55 | Collapse | 20 | – | 45 |
| NW5 | 300 | 0.55 | 75 | 20 | Superplasticizer | 45 |
| NW6 | 300 | 0.55 | 125 | 20 | Superplasticizer | 45 |
| NW7 | 300 | 0.55 | Collapse | 20 | Superplasticizer | 45 |
| Series 3: Variable maximum aggregate size | | | | | | |
| NA1 | 500 | 0.55 | 75 | 5 | – | 45 |
| NA2 | 370 | 0.55 | 75 | 10 | – | 45 |
| N3 | 340 | 0.55 | 75 | 20 | – | 45 |
| NA4 | 300 | 0.55 | 75 | 40 | – | 45 |
| Series 4: Variable constituent materials | | | | | | |
| NC | 340 | 0.55 | 75 | 20 | Normal concrete | 45 |
| RHC | 335 | 0.56 | 75 | 20 | Rapid-hardening portland cement* | 45 |
| PFAC | 285 | 0.44+ | 75 | 20 | Pulverized-fuel ash (105 $kgm^{-3}$) | 45 |
| MSC | 305 | 0.59+ | 75 | 20 | Microsilica (25 $kgm^{-3}$) | 45 |
| SAC | 300 | 0.55 | 75 | 20 | Superplasticizer | 45 |
| AEC | 375 | 0.47 | 75 | 20 | Air-entraining agent | 45 |
| LWC | 420 | 0.47 | 75 | 12 | Coarse lightweight aggregate | 45 |

*Fully replaced OPC
+Water/total cementitious material ratio

the specific permeation characteristic that can be used for determining non-destructively the freeze/thaw durability potential of in-situ concrete.

## 2. Experimental details

Four series of concrete mixes covering a range of water/cement ratio from 0.7 to 0.4, workability from 25 mm to collapse slump with and without water-reducing admixture, maximum aggregate size from 5 mm to 40 mm and a variety of mineral and chemical admixtures, see Table 1. The curing conditions employed are shown in Table 2. Parallel series of tests were carried out for freeze/thaw resistance, initial surface absorptivity (ISA), Figg air index (Dhir, Hewlett and Chan 1985), intrinsic permeability (Dhir, Hewlett and Chan 1989) and vapour diffusivity (Dhir, Hewlett and Chan 1991).

Table 2 Curing after demoulding (until age of 28 days)

| Curing | Conditions |
|---|---|
| E1 | Water at 20℃ |
| E2 | 6 days water, then in air at 20℃, 55% RH |
| E3 | 3 days water, then in air at 20℃, 55% RH |
| E4 | Air at 20℃, 55% RH |

## 3. Freeze/thaw resistance

Fig. 1 shows that the resistance of concrete to freezing and thawing, signifies by the number of freeze/thaw cycles to failure, increases with (a) period of moist curing and (b) decreasing water/cement ratio. It is also clear that strength of concrete alone could not be used as a measure of its freeze/thaw durability.

The freeze/thaw durability of the various types of concrete with different constituent materials are illustrated in Fig. 2. It can be seen that although these concretes had similar strength, they had significantly different behaviour under freeze/thaw environment.

Freeze/thaw durability of concrete was also found to be affected by its workability and the maximum aggregate size (Table 3 and Fig. 3). An increase in workability (increase in water) reduces the freeze/thaw durability of concrete. This trend however does not apply to the superplasticized concrete. The poorer durability of high workability concrete is believed to be caused by the higher water content in the mix, bleeding and the reduced air content in the high slump concrete (Table 4). The better performance of the superplasticized high workability concrete was probably due to its favorable bubble size and distribution of air in the superplasticized concrete (Edmeades and Hewlett 1976) and the fact that no water was added to the concrete.

For a given water/cement ratio and workability, the results (Table 3 and Fig. 4) show greater susceptibility to freeze/thaw attack of concrete containing larger size aggregates. The difference

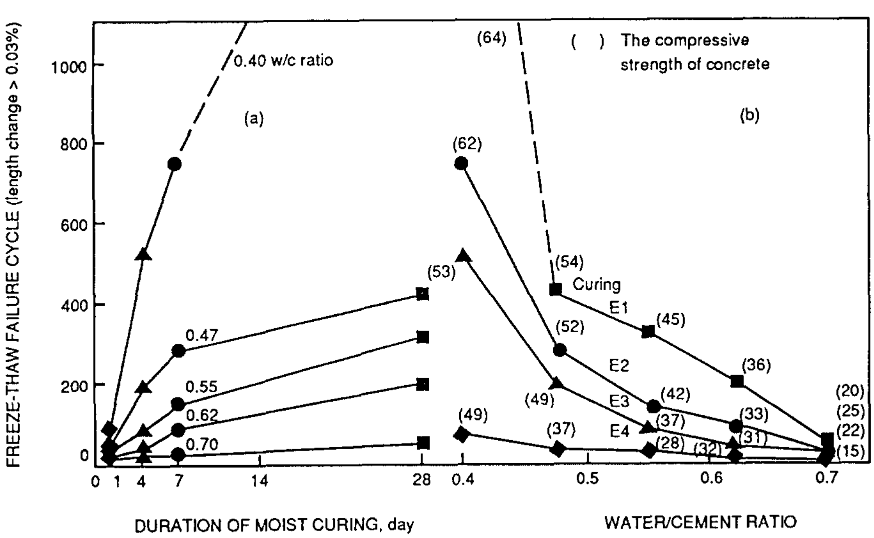


Fig. 1 Freeze/thaw durability of concretes with varied W/C ratio and period of moist curing.

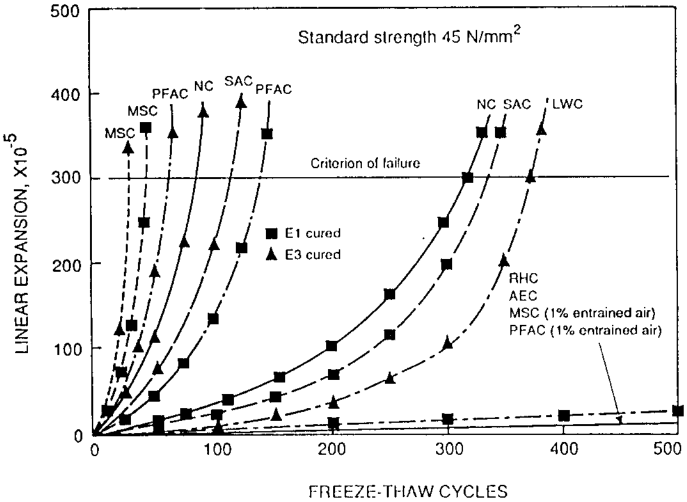


Fig. 2 Linear expansion of concretes with various special constituent materials in relation to number of freeze-thaw cycles.

Table 3 Freeze/thaw durability of concrete with 0.55 w/c ratio

| Concrete mix | Nominal workability (mm·slump) | Maximum aggregate size (mm) | Compressive strength ($N/mm^2$) | | Freeze/thaw durability (cycles) | |
|---|---|---|---|---|---|---|
| | | | E1 cured | E3 cured | E1 cured | E3 cured |
| Variable workability series | | | | | | |
| NW1 | 25 | 20 | 45 | 38 | 390 | 170 |
| N3 | 75 | 20 | 45 | 37 | 322 | 85 |
| NW3 | 125 | 20 | 44 | 37 | 210 | 68 |
| NW4 | Collapse | 20 | 43 | 37 | 182 | 65 |
| NW5 | 75* | 20 | 44 | 37 | 336 | 114 |
| NW6 | 125* | 20 | 45 | 38 | 327 | 118 |
| NW7 | Collapse | 20 | 43 | 36 | 239 | 87 |
| Variable maximum aggregate size | | | | | | |
| NA1 | 75 | 5 | 41 | 35 | >1000 | >1000 |
| NA2 | 75 | 10 | 44 | 36 | 350 | 95 |
| N3 | 75 | 20 | 45 | 37 | 322 | 85 |
| NA4 | 75 | 40 | 43 | 37 | 274 | 69 |
| N3A+ | 75 | 20 | 41 | 36 | >1000 | >1000 |

*Superplasticized concrete; +With addition of 1% entrained air

was marginal between concrete made with 10, 20 and 40 mm maximum size aggregates. On the other hand, 5 mm aggregate concrete suffered no significant damage after 1000 freeze/thaw cycles. This is believed to be due to its higher air content (Table 4). The entrapment of a higher quantity of air into the matrix during the mixing/casting process in the case of the 5 mm aggregate concrete was due to the floatation of a large proportion of fine particles. These particles, which have a high surface energy, attracting air bubbles towards their surface. Since water has a low surface tension, these bubbles were stably retained by the fine particles. These entrapped air

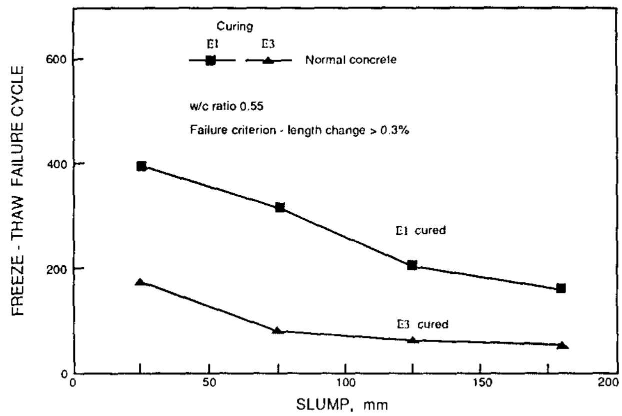


Fig. 3 Effect of workability on freeze-thaw durability of concrete.

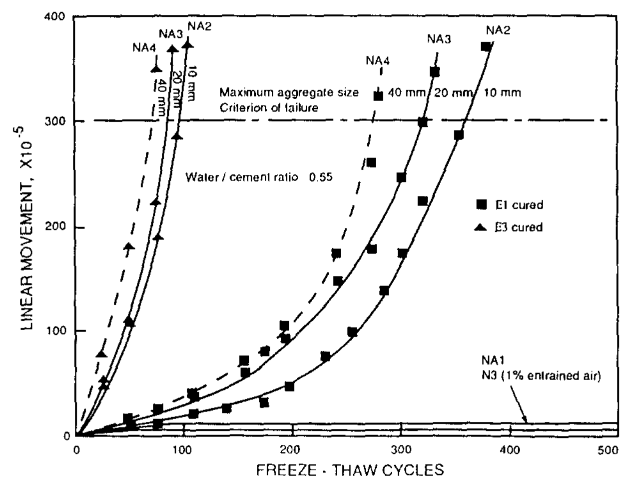


Fig. 4 Linear expansion of concretes with various maximum aggregate size in relation to the number of freeze-thaw cycles.

Table 4 Air content of various types of concrete mix

| Concrete mix | *w/c* ratio | Nominal workability (mm) | Maximum aggregate size (mm) | Air content (%) |
|---|---|---|---|---|
| N1 | 0.4 | 75 | 20 | 1.3 |
| N3 | 0.55 | 75 | 20 | 1.3 |
| N5 | 0.7 | 75 | 20 | 1.4 |
| NW1 | 0.55 | 25 | 20 | 1.4 |
| NW4 | 0.55 | Collapse slump | 20 | 0.8 |
| NW5* | 0.55 | 75 | 20 | 1.7 |
| NW7* | 0.55 | Collapse slump | 20 | 0.9 |
| PFAC | 0.44+ | 75 | 20 | 1.0 |
| NA1 | 0.55 | 75 | 5 | 2.4 |
| N3A | 0.55 | 75 | 20 | 2.4 |

N3A-N3 with 1% entrained air; *Superplasticized concrete; + Water/total cementitious materials ratio

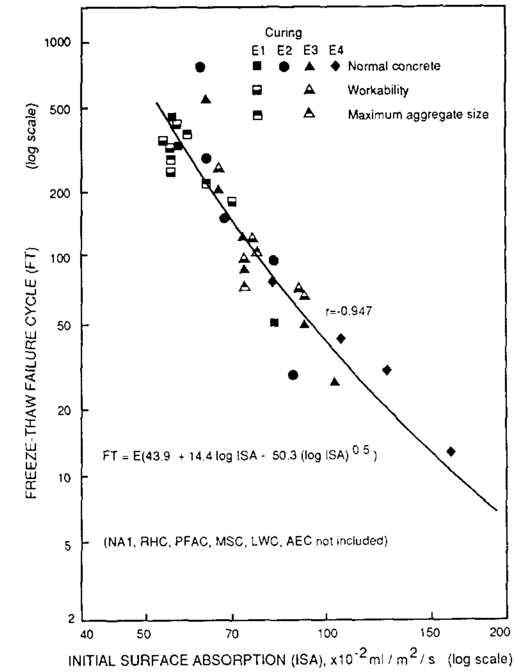


Fig. 5 Relationship between freeze-thaw durability and initial surface absorption.

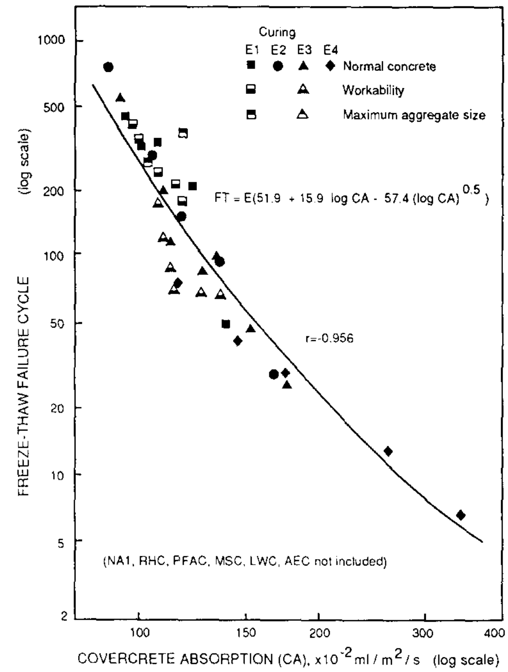


Fig. 6 Relationship between freeze-thaw durability and covercrete absorption.

bubbles act as buffers for the advancing ice front.

The freeze/thaw resistance of concrete is affected by its air content, air void size, distribution and spacing factor. Furthermore, BS8110 (1985) recommends that where freezing/thawing actions exist, an average air content of 5% should be provided for concrete with 20 mm maximum size aggregates, it was not expected that a 2.4% air content in the 5 mm aggregate concrete, 1% higher than the 20 mm aggregate concrete, could have such a dramatic effect on its freeze/thaw durability. To verify this, a 20 mm aggregate concrete (N3) was cast with 1% extra air in the mix, using air entraining admixture, without altering the original mix proportion. This concrete did not show any sign of deterioration after 1000 cycles, which shows the significance of even a small increase in the air content on the freeze/thaw resistance of concrete.

## 4. Freeze/thaw resistance and permeation characteristics

The results of the freeze/thaw tests were compared with the various permeation tests conducted on the corresponding specimens for normal and superplasticized concretes, see Figs. 5~8. All permeation measurements were found to reflect to a varying degree, the freeze/thaw resistance of concrete and the best relationship was found with the intrinsic permeability (Fig. 7). However, it was also clear that apart from superplasticizers, other additives and admixtures which have affected the air content of concrete specimens had significant effect on their freeze/thaw resistance. It is believed that for normal concrete and perhaps for concretes with similar air content, there is a close relationship between the intrinsic permeability and the freeze/thaw resistance.

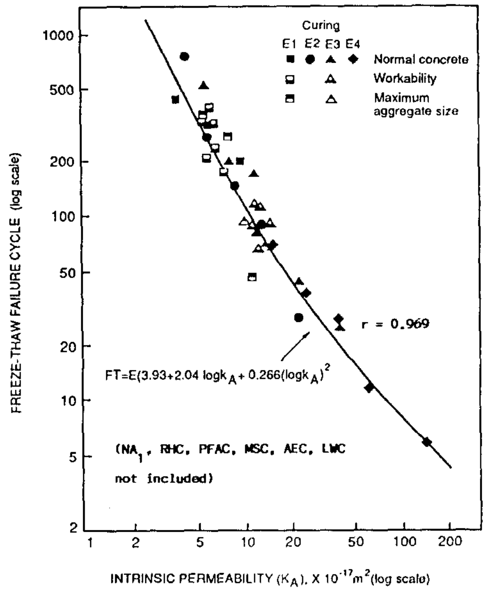


Fig. 7 Relationship between freeze-thaw failure cycle and intrinsic permeability of concrete.

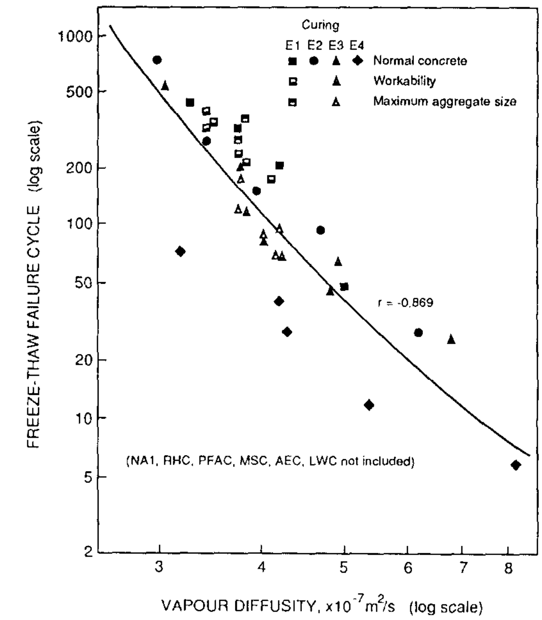


Fig. 8 Relationship between freeze-thaw durability and vapour diffusivity.

## 5. Figg air index

Figg air test, which was originally developed by J. Figg (1973), involved drilling a hole into the concrete surface and measuring the rate of pressure drop inside the hole. A number of versions of this test method have subsequently been developed in various countries.

In this study, the test hole was increased to 13 mm diameter $\times 50$ mm depth and a vacuum ranged from 0.055 to 0.045 N/mm$^2$ below atmospheric pressure was adopted. The drying method adopted was oven drying at 105℃ until constant weight. These changes improved the reliability of the test significantly (Dhir, Hewlett and Chan 1985). The diagrametric arrangement of the equipment is shown in Fig. 9.

It was observed that the experimental results obtained for the Figg air index and intrinsic permeability in test series 1 to 4 showed a close relationship in every case. This suggested that the Figg air index may be used to derive the intrinsic permeability of concrete. The results plotted in Fig. 10 clearly show a good correlation of the form

$$k = \exp[(2.55 - \log F)/0.64] \tag{1}$$

where $k$ is the intrinsic permeability (m$^2$) and $F$ is the Dundee modified Figg air index (sec).

The practical significance of this is that the Figg air test, which is simple to use and cheap, has the potential to be used to measure the intrinsic permeability of concrete in-situ.

## 6. Prediction of freeze/thaw resistance

To monitor the freeze/thaw resistance of in-situ concrete, a performance/quality control method

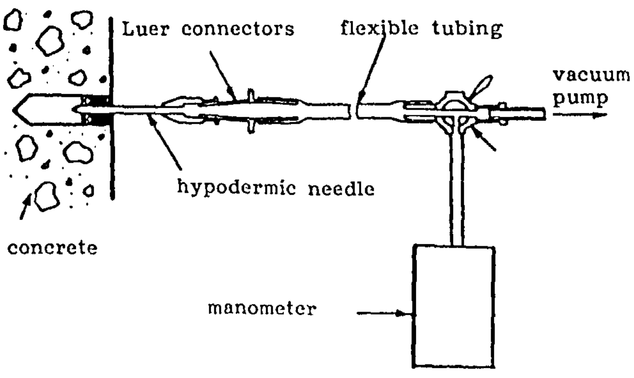


Fig. 9 Figg apparatus for determining the air permeability index of concrete.

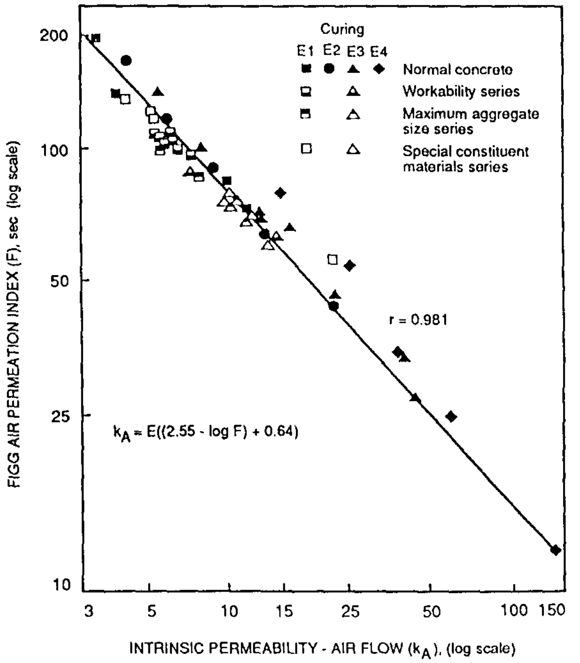


Fig. 10 Relationship between Figg air permeation index and intrinsic permeability (air flow).

would be essential. Test results indicate that, for normal concrete, there is a close relationship between the intrinsic permeability and freeze/thaw resistance. The Figg air index which have been shown to correlate closely with the intrinsic permeability, also correlates closely with the freeze/thaw data (Fig. 11). It could be a new approach to the performance specification and assessment of freeze/thaw resistance potential of in-situ normal concrete.

For concrete with additives or admixtures (apart from superplasticizers), pilot tests carried out indicated that for a given air content, there was a close relationship between the intrinsic permeability and freeze/thaw resistance. Further detail study is now underway to verify this. The ultimate aim is to predict the freeze/thaw resistance of a wide variety of concrete by the combination of air content and intrinsic permeability measurements.

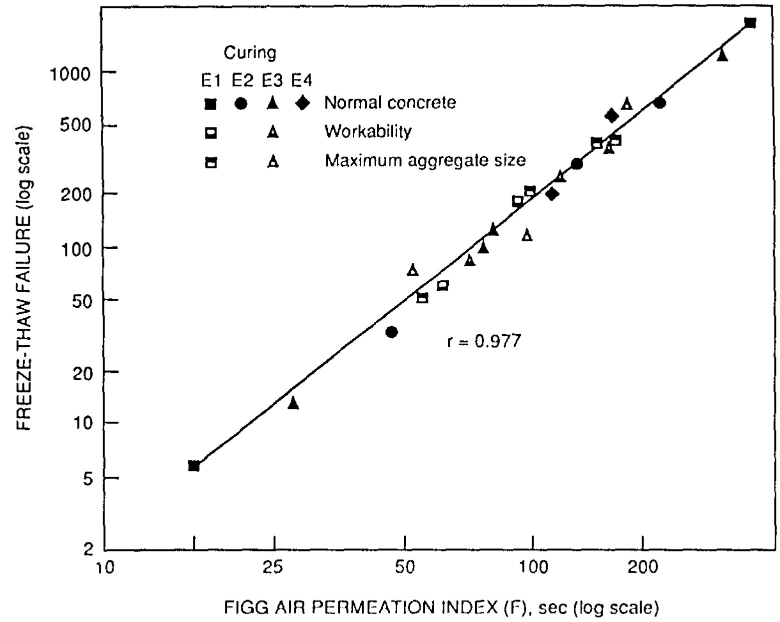


Fig. 11 Relationship between freeze-thaw failure cycle and Figg air permeation index of concrete.

## 7. Conclusions

(1) The freeze/thaw resistance of concrete is most significantly influenced by the air content, water/cement ratio and period of moist curing.
(2) Variable workability, variable maximum aggregate size or the use of superplasticizer (non air-entraining) appears to have less/insignificant influence on the freeze/thaw durability of concrete.
(3) For normal concrete, the permeation characteristics and in particular, the intrinsic permeability are shown to have a good relationship with its freeze/thaw resistance.
(4) The limited results obtained indicate that for practical purposes, the freeze/thaw resistance of concrete could be predicted by its intrinsic permeability and air content.
(5) Figg air test, which is an inexpensive and simple test could be used as a quality control method to assess the freeze/thaw durability potential of in-situ concrete.

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