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Effect of compressive stress on the intrinsic permeability of concrete

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ABSTRACT

Intrinsic permeability of concrete is a fundamental material property governing its durability and the development of pore pressure during fire exposure. Qualitative studies reported in literature suggest a slight decrease in effective permeability under typical service loading levels. However, the extent of this reduction has not been studied quantitatively in relation to typical observational variance. Moreover, no such results are reported for intrinsic permeability. This study shows that, under typical service compressive stress levels, the reduction in intrinsic permeability can be considered negligible.

1. Introduction

No matter how dense, concrete always contains a measure of interconnected pores, making it an inherently permeable material. Numerous parameters influence the permeability of concrete. These can be grouped into (i) parameters related to concrete mix proportions, (ii) factors related to the placement and curing of concrete, and (iii) properties of concrete or the concrete element in its hardened state. An extensive overview of these parameters can be found in [9].

Damage to concrete in the form of cracks typically increase the interconnectivity of pores. Such damage due to high levels of applied compressive load can therefore be expected to increase the permeability of concrete. Sugiyama et al. [7] observed a significant increase in permeability at axial compressive stress levels exceeding 75% of concrete compressive strength, whilst Heam and Lok [3] observed a similar increase at stress levels exceeding 71% of concrete compressive strength. Zhou et al. [10] reported such an increase beyond a stress level of 70%, although an inspection of their results seems to suggest that a stress level of 80% would be more appropriate. Bošnjak et al. [1] reported a negligible effect of moderate load levels on permeability. Performing permeability tests at various stress levels and after unloading, Choinska et al. [2] observed that the permeability recorded at low and intermediate load levels were slightly lower than after unloading, but that the opposite was observed for stress levels exceeding 80% of concrete compressive strength. Fig. 1 shows their results. They conclude that, up to intermediate stress levels, concrete remains in a quasi-elastic state ensuring a reversible response to load. As such, these load levels seem to slightly compress the concrete microstructure, thereby reducing the overall pore volume and, subsequently, permeability. High load levels resulting in crack formation tend to increase permeability. Upon unloading, some cracks close and result in a slightly lower permeability than during load application. Overall, they conclude that under load levels between 40% and 60% of concrete compressive strength, the permeability of concrete is slightly reduced. As applied load increases further, the permeability tends to increase slightly at first, but rapidly once the load exceeds 80% of concrete compressive strength.

In addition to the observed quasi-elastic effect of intermediate loads on concrete permeability, Choinska et al. [2] mentioned that time dependent effects, such as creep, do not have a substantial influence on permeability under normal service loading conditions.

2. Research significance

In addition to its relevance to the durability of concrete, intrinsic permeability is a fundamental material property governing pore pressure development in concrete during fire. Numerical models have been proposed in the past to assess the risk of explosive spalling of concrete (e.g. [4]). The practical relevance of such precise models depends, however, on the accurate and appropriate estimation of input parameters such as intrinsic permeability.

Although the effect of compressive stress on effective permeability has been studied qualitatively in the past, its effect has not been quantitatively compared with the extent of influence of other relevant parameters. Moreover, such a study has not been performed in relation to intrinsic permeability. Previous studies have shown a decrease in permeability under low to moderate compressive loading. It is, however, not clear if the level of reduction is significant when considering the typical scatter of recorded values.

This study aims to investigate and quantify the influence of typical
service compressive loads on the intrinsic permeability of concrete.

3. Experimental investigation and validation database

Given the limited intrinsic permeability observations reported in literature, this study is based on own experimental results from tests performed between 90 and 110 days. Intrinsic permeability was recorded in an unloaded state as well as during the application of compressive load levels deemed to be representative of practical service load levels for structural concrete elements. Load levels were defined as fractions of the mean 28-day concrete compressive strength, as this is the concrete material property that is most often considered in structural design. Tests were conducted to load levels of 10%, 20%, 30%, 40% and 50%.

4. Reference concrete mixes

Six reference concrete mixes were considered in the study, covering both NSC and HSC. Table 1 summarises the mix proportions of the reference concrete mixes.

Standard cylinders (150 mm diameter × 300 mm) and standard cubes (150 × 150 × 150 mm³) were cast to record reference compressive strength. After casting, all specimens were stored in a climate-controlled room at 20 °C and 95% relative humidity. Specimens were demoulded no sooner than 24 h, and no later than 72 h, after casting. Demoulded specimens were stored in the same high-humidity conditions up to an age of 28 days. At 28 days, specimens were removed from the high-humidity environment. Reference 28-day material properties were tested at this stage. Specimens identified for testing at 90 days were subsequently stored in laboratory conditions (20 °C ± 2 °C and approximately 50% relative humidity). Table 2 summarises the reference standard cylinder compressive strengths of the six mixes.

### Table 1

<table>
<thead>
<tr>
<th>Ref. mix</th>
<th>M1</th>
<th>M2</th>
<th>M3</th>
<th>M4</th>
<th>M5</th>
<th>M6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type</td>
<td>CEM I 42.5 N</td>
<td>CEM I 42.5 N</td>
<td>CEM I 52.5 R</td>
<td>CEM I 52.5 R</td>
<td>CEM I 52.5 R</td>
<td>CEM I 52.5 R</td>
</tr>
<tr>
<td>Cement [kg/m³]</td>
<td>310</td>
<td>310</td>
<td>330</td>
<td>400</td>
<td>539</td>
<td>560</td>
</tr>
<tr>
<td>Silica fume [kg/m³]</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>32</td>
<td>44</td>
<td>59</td>
</tr>
<tr>
<td>Fine aggregate [kg/m³]</td>
<td>700</td>
<td>676</td>
<td>1260</td>
<td>596</td>
<td>464</td>
<td>933</td>
</tr>
<tr>
<td>Coarse aggregate [kg/m³]</td>
<td>1156</td>
<td>1202</td>
<td>678</td>
<td>1105</td>
<td>1105</td>
<td>638</td>
</tr>
<tr>
<td>Water [kg/m³]</td>
<td>186</td>
<td>170</td>
<td>173</td>
<td>190</td>
<td>190</td>
<td>192</td>
</tr>
<tr>
<td>Water-binder ratio</td>
<td>0.60</td>
<td>0.55</td>
<td>0.52</td>
<td>0.44</td>
<td>0.33</td>
<td>0.31</td>
</tr>
<tr>
<td>Superplasticizer [kg/m³]</td>
<td>0</td>
<td>0</td>
<td>4.40</td>
<td>2.20</td>
<td>3.95</td>
<td>6.82</td>
</tr>
</tbody>
</table>

*a* Microsilica by BASF.

*b* Siliceous aggregate, 0–4 mm.

*c* Siliceous aggregate, 4–8 mm.

*d* BASF MasterGlenium ACE 30.

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**Fig. 1.** Results reported by Choinska et al. [2] shown as (a) Absolute values, and (b) relative development. A slight initial decrease in permeability at low and intermediate load levels is followed by a rapidly increase at high load levels.
4.1. Intrinsic permeability measurements

Six standard concrete cubes (150 × 150 × 150 mm$^3$) of each reference mix were produced to record intrinsic permeability. Of each batch, three cubes were used to determine the 28-day compressive strength, whilst the remaining three cubes were moved to a laboratory environment up to the age of 90 days. Cubes were demoulded and cured in a similar manner as described above. At an age of 90 days, the specimens were dried at 105 °C in an electric oven. Specimen mass was measured before starting the drying process and daily thereafter until the mass loss was no more than 0.1% over a 24-h period. Once a constant mass was achieved, specimens were allowed to cool naturally inside the electrical oven after it was switched off. Specimens were subsequently sealed to minimise moisture absorption from ambient conditions during laboratory storage when not tested immediately.

Gas permeability was measured using a Torrent Permeability Tester by Proceq [8] (shown in Fig. 2a), which has been accepted as a standard method for site testing in Switzerland [6]. The apparatus relies on a two-chamber vacuum cell system: an inner chamber for permeability measurement, and an outer guard-ring chamber. A regulator balances the pressure in the two chambers. Fig. 2b provides a schematic detail of the suction head. After placing the suction head against a concrete surface, a pump generates a vacuum. Rubber rings effectively seal the two chambers. The guard ring prevents air from areas surrounding the vacuum cell from entering the measurement chamber. Concrete permeability is calculated from the measured pressure increase in the inner chamber during the test.

After ensuring that the vacuum pump has been warmed up as recommended in relevant product literature, a permeability calibration test was performed before using the apparatus for each testing sequence (i.e., for each new cube or at the start of each testing day). Measurements were recorded on concrete cube specimens in an unloaded condition as well as during the application of compressive load using a Walter and Bai Universal Testing Machine as shown in Fig. 3. All tests were performed between the concrete ages of 90 and 110 days.

For each concrete cube, permeability measurements were taken on two opposing faces. This ensured a total of six measurements per reference mix at each level of loading. Based on the interquartile range (IQR) of each set of recorded values, statistical outliers were identified and omitted from the database. Such outliers typically occurred in isolated cases towards the upper range of recorded intrinsic permeability results.

Table 3 summarises recorded intrinsic permeability results. Generally, intrinsic permeability shows a slight initial reduction when a compressive load is applied, suggesting a slight compaction of the cement matrix. This reduction is followed by a slight increase as the compressive load increases further, suggesting damage to the cement matrix. This trend can be seen in Fig. 4, showing the scatter plot of relative intrinsic permeability development with an LOESS data smoother fitted to each reference concrete mix. It should be noted that, given the small scale of untransformed intrinsic permeability results, relative scatter will, although small on an absolute scale, show a greater percentage variation. Log-transformation of this parameter in subsequent analyses resolves this to a large extent. Considering the variation within each reference mix, the various smoothers seem to compare well. In most cases, the smoothers indicate a slight initial reduction in intrinsic permeability within the range of typical service stress levels, followed by a slight increase at higher load levels. The smoother generated for M2 contradicts the trend due to fewer results available.
Table 3
Mean intrinsic permeability ($k_0$ [m$^2$]) measurements for each of the six reference concrete mixes (M1 to M6) at various levels of compressive stress, expressed as a percentage of its mean 28-day cube compressive strength. Values in brackets refer to standard deviation.

<table>
<thead>
<tr>
<th>Ref. mix</th>
<th>$k_0$ [m$^2$] under compressive stress levels.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0%</td>
</tr>
<tr>
<td>M1</td>
<td>1.080 x 10^{-15}</td>
</tr>
<tr>
<td></td>
<td>(3.266 x 10^{-16})</td>
</tr>
<tr>
<td>M2</td>
<td>1.186 x 10^{-15}</td>
</tr>
<tr>
<td></td>
<td>(6.248 x 10^{-17})</td>
</tr>
<tr>
<td>M3</td>
<td>1.787 x 10^{-16}</td>
</tr>
<tr>
<td></td>
<td>(7.903 x 10^{-18})</td>
</tr>
<tr>
<td>M4</td>
<td>2.224 x 10^{-16}</td>
</tr>
<tr>
<td></td>
<td>(9.869 x 10^{-18})</td>
</tr>
<tr>
<td>M5</td>
<td>9.448 x 10^{-17}</td>
</tr>
<tr>
<td></td>
<td>(2.587 x 10^{-17})</td>
</tr>
<tr>
<td>M6</td>
<td>2.168 x 10^{-17}</td>
</tr>
<tr>
<td></td>
<td>(9.539 x 10^{-18})</td>
</tr>
</tbody>
</table>

Fig. 4. Scatter plot of recorded intrinsic permeability normalised to the mean value of unloaded measurements for each reference concrete mix.

which limited the identification of potential statistical outliers.

5. Analysis and discussion

An analysis of variance (ANOVA) was performed considering own experimental results to quantify the contribution of moderate applied compressive load to overall observation variance. The analysis considered results from tests up to a load level of 40% to ensure appropriate predictive capability of the resulting model at a load level of 30%, as this was considered representative of typical service stress levels. Fig. 5 shows the experimental design of the ANOVA.

Variables considered for the ANOVA include:

- **MIX**: Random factor variable since the mixes are considered as random selections from a possible concrete population.
- **FACE**: Random factor variable, since the six faces per mix (three cubes x two faces per cube) were randomly selected from a potential 18 faces.
- **LOAD**: Fixed variable (specified load levels).
- **$k_0$**: Intrinsic permeability observations. Only one observation was recorded per cell, so no interaction term could be investigated. A histogram of intrinsic permeability results suggests that log-transformation should be considered for this variable.

Visualisation of data is shown in Fig. 6 and Fig. 7. A systematic reduction of intrinsic permeability is observed for all mixes with increasing concrete strength. Variation in results between mixes in Fig. 6a seems greater than the variation of observations within each mix. Moreover, the variation of observations appears quite similar for each mix. Trace lines are fitted for each of the six randomly assigned cube face numbers tested for each reference concrete mix (Fig. 6b). An overall gradual decrease of intrinsic permeability is observed for mixes with increasing concrete compressive strength. Trace lines for all faces are sufficiently parallel, suggesting that there should be no significant effect between the concrete mix and the face tested.

Observational variation within each load level (Fig. 7a) seems greater than the variation between different load levels. Trace lines fitted for each reference concrete mix in the interaction plot shown in Fig. 7b indicate a negligible variation with increasing load. The nearly parallel trace lines suggest that there should be no significant interaction effect between the reference concrete mix and the load level.

The model subsequently investigated is shown in Eq. (1).

$$Y_{ik} = \mu + \alpha_i + \beta_j + Y_{ij} + \varepsilon_{ijk}$$  \hspace{1cm} (1)

where:
- $Y_{ik}$ = Mean log-transformed intrinsic permeability;
- $\mu$ = Global mean;
- $\alpha_i$ = Random effect of concrete mix;
\[ \beta_{j(i)} = \text{Random effect of cube face, nested in reference concrete mix;} \]
\[ \gamma_k = \text{Fixed effect of load level, crossed with both concrete mix and cube face;} \]
\[ \varepsilon_{k(i)} = \text{Random error term.} \]

To estimate variance contributions of the random effects, a restricted maximum likelihood estimator (REML) was fitted in R \[ 5 \], as this method is less biased than a more classical technique, and therefore more suited for unbalanced data:

\[ \sigma^2_{\alpha} = 2.36531 \]
\[ \sigma^2_{\beta} = 0.04542 \]
\[ \sigma^2_{\varepsilon} = 0.02428 \]

The ranova command in R \[ 5 \] provides conservative p-values for the random effect variances, and shows that the null-hypothesis (H\( _0 \): \( \sigma^2_{\gamma} = 0 \)) can be rejected for both Mix and Face on a 5% significance level.

Fixed effects output suggests that the mean log-transformed intrinsic permeability under a load level factor of 0.1 is 0.27% lower than that when no load is applied. The mean values are subsequently 0.29%, 0.38%, and 0.27% lower than the unloaded mean when applying load levels 0.2, 0.3 and 0.4 respectively. This very slight reduction in intrinsic permeability is considered negligible for practical purposes. There were instances where recorded values were not possible, resulting in a database with some missing values. As such, the database compiled from own experimental results is slightly unbalanced. As such, the variance contribution from the fixed effect of applied load was investigated from the ANOVA table of Type III sum of squares obtained from model output in R \[ 5 \]:

\[ \sigma^2_{\gamma} = 0.07538 \]

The p-value of this fixed effect suggests that the null-hypothesis (i.e. H\( _0 \): \( \sigma^2_{\gamma} = 0 \)) can be rejected on a 5% significance level. Total variance was subsequently calculated as the sum of all variance contributions:

\[ \sigma^2_{\text{total}} = \sigma^2_{\alpha} + \sigma^2_{\beta} + \sigma^2_{\gamma} + \sigma^2_{\varepsilon} = 2.51039 \]

Table 4 summarises the contribution of each factor to overall variance. The contribution from the concrete mix (with its inherent proportioning parameters and compressive strength) dominates total observational variance. The contribution from both the load level and the cube face, although statistically significant, is very small. If the variance contribution from these two terms is neglected, their variance contributions would be lumped with the random error term, resulting in a contribution of 5.78%.

6. Conclusions

Variables for the face on which permeability was measured and the level of applied compressive stress contribute very little to overall variance. The increase in variance contribution of random error effects that results when these two variables are neglected is considered reasonable for practical purposes. It is therefore concluded that typical service load levels do not have a substantial influence on the intrinsic permeability of concrete. Only at stress levels exceeding 50% of concrete compressive strength can the development of microcracks be expected to increase intrinsic permeability. Where concrete elements are highly stressed, resulting in potential damage to the concrete matrix, models for the estimation of concrete intrinsic permeability (e.g. \[ 9 \]) can be expected to underestimate intrinsic permeability. It is recommended that, in such cases, intrinsic permeability be determined by representative experimental tests only.
7. Outlook

This study considered only normal concrete types and should be extended to concretes with steel and/or polypropylene fibres.

Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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