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Factors affecting measurement of hydraulic conductivity in low strength cementitious materials

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Abstract

The hydraulic conductivity (permeability) is one of the most significant transport properties of concrete and measuring it is a key step in predicting the performance of concrete as a barrier to the movement of fluids and ions. The transport properties are critical for the performance of the cover layer in protecting embedded reinforcement as waste containments barriers (which are considered in this paper) and other applications such as dams. The measurements are difficult to interpret due to experimental effects of sample size and changes of flow with time and the chemistry of the fluid used.

The intrinsic permeability to water and synthetic leachate was determined and the relationship between the eluted volume passing and permeability was established for mortar mixes having compressive strengths ranging from 5 to 20 MPa. Two mortar mixes containing Portland cement and one with no Portland cement and incorporating Cement Kiln Dust, Lagoon ash and Ferrosilicate slag were tested. The effects of sample size were also investigated.

The results indicate a decrease in hydraulic conductivity for lower strength mixes and a slight increase in permeability coefficient for the higher strength mixes with increasing permeating volumes. Increasing the testing specimen size also slightly increases the coefficient of permeability in lower strength mixes and decreases the coefficient in higher strength mixes. The permeability coefficient does not change significantly with pore solution pressure.

Keywords: Permeability; Transport Properties; Physical Properties; Concrete; Mortar.

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1. Introduction

The cementitious chemical barrier is one of the main engineering features of the current research on novel composite landfill liners [1 and 2]. The novel multi-layer barrier concept is based on the theory that the pollution of soils and watercourses by the release of leachate may be prevented by adoption of a composite-barrier liner, which not only chemically conditions the waste, but is designed to be self-sealing through secondary mineralisation and will retain heavy metal ions through ion exchange, surface sorption, filtration and precipitation.

A landfill liner (barrier) must be physically strong enough to allow vehicular access during the operational phase, and provide adequate containment of leachate during the post-closure period. In order to satisfy both these operational and long-term requirements, a range of composite barrier materials have been evaluated. These include: low cost, chemically conditioning, cementitious media (like concretes containing metallurgical slags, spent foundry sands and/or demolition waste as an aggregate, blended cements containing waste materials such as fly ash, cement kiln dust and slag) and non-swelling clays.

The properties of an ideal barrier system are:

- Low permeability. This must be less than 10^{-9} ms^{-1}.
- High cation exchange capacity
- The ability to chemically condition leachate through sacrificial action
- Construction from inexpensive materials
- Tolerance of deformation during service without barrier failure through brittle cracking
- The ability to promote self-sealing of cracks
- Ease of construction
- Sufficient strength to support a refuse vehicle during operation. A cube strength of 5 N/mm^2 is adequate.

In the design considered in this work, three layers are envisaged such that the clay-based hydraulic barrier is sandwiched between two layers of cementitious materials. These concretes for the liners are made with a range of waste materials which would otherwise have to be disposed of in the landfill [1 and 2].

The basic principles of physical containment with concrete are well understood and documented [3, 4 & 5]. The degree of containment will depend on the transport properties of the barrier. The properties considered for modelling purposes are the permeability, diffusion coefficient and capacity factor. The capacity factor is used to give an approximation for the chemical containment, the diffusion coefficient measures ion transport but the most significant property has been found to be the permeability which measures fluid transport. The permeability of concrete and mortar must be measured in a cell which prevents flow around the sides of the sample and for this work a modified Hoek cell [6] has been used.

Containment has been studied in detail for nuclear waste [7]. For a nuclear waste repository in which a cementitious barrier is used the main mechanism of loss of radionuclides is caused by flowing groundwater. This flow may be present in the area before the repository is built or it may be caused by the heat generated in the repository. In order to operate for a long time the chemical barrier depends on other barriers to limit the flow of groundwater through it. This is normally achieved by positioning the repository in a geology with a very low permeability. In this situation the permeability of the repository itself can be shown not to have a significant effect on the flow of water through it. In the non-nuclear landfills which are considered in this paper the hydraulic head on the barrier is caused by standing leachate in the bottom of the cell. European guidelines require leachate extraction in order to limit this to a depth of 1m above the liner but, in order to guarantee effective containment, a possible head of 10m has been considered in the design.

In the literature limited research has been carried out into effect of confining pressure, pore pressure and specimen dimension on permeability of rocks and heterogeneous soil mixtures [8-12] but no works have been found on cementitious mixes carried in this work.

The work reported here forms part of a major industry-based project on a novel composite barrier system, which uses the metallurgical waste materials for the cementitious liners in the landfill barriers [1, 2, 13 & 14]. This work includes carrying out large-scale site trials to demonstrate the construction of the system. The trials consist of cells approximately 8 m wide, which are designed to contain leachate to a depth of 1 m maximum allowable leachate level in current landfill practice and are made with the candidate barriers [2]. In this paper the results of an extensive laboratory investigation into the intrinsic coefficient of permeability of potential multi-layer barrier mixes using various mineral wastes are presented and discussed.

The permeability is one of the most significant transport properties of concrete and measuring it is a key step in predicting the movement of fluids and ions in the cover layer for protecting embedded reinforcement in structures and calculating pore pressures in dams in addition to the waste containments barriers which are considered in this paper.

2. Experimental programme

The broad objectives of the experiments were to establish a permeability for the different concretes and mortars to provide a result which could be used in calculations of the performance of barriers in which they are used. In order to do this an investigation has been carried out into the evolution of bulk permeability with increased sample volume and different pore pressure and specimen size. In all tests the confining to pore pressure ratio was kept constant.

The specific objectives were to measure the following:

1. The permeability of the specimens to water.
2. The change in permeability in the presence of leachate.
3. The relationship between numbers of sample volumes passing and changes in permeability.
4. The effect of different residence times in the sample by running the test at different pressures and/or sample thicknesses. This determines the sensitivity of the observed permeability to changes in pressure.
5. The effect of sample size and boundary effects by testing samples in a larger cell.

2.1 Eluted liquids

Both deionised water and a synthetic (acetogenic) leachate have been eluted through the materials to examine their effects on permeability evolution of the mixes. The composition of the synthetic leachate used in this work was obtained by comparing the composition of various natural and synthetic leachates and is given in table 1. This solution was chosen as it represents a leachate from the early (acetogenic) phase of a landfill and is therefore the most aggressive solution to which a cementitious barrier would be likely to be exposed. The evolution of leachate chemistry during the service life of a landfill, normally shows a decrease both in acidity and ionic strength as the landfill matures, so experiments using this solution are thought to be conservative.

Mix designs

The mixes were designed with consideration for requirements for strength, permeability, chemical conditioning capacity (“through pH”) and cost benefit analysis. The results of a screening programme on a large number of mixes [1 and 2] lead to the selection of three candidate mixes which satisfied the criteria. Two samples from each selected mix design were tested with leachate and two more were tested with water to give a programme of over 200 permeability tests.

The designs of the three mixes are given in Table 2. Two of these mixes were Portland cement mortar mixes with different strengths and permeability coefficients and one other mix was one of the several trial cell mixes used for site trials. For one of the mixes a low strength of about 5 MPa was deliberately engineered to find the effect of applied pore pressure and number of sample volumes eluted on the coefficient of permeability.

2.2 High pressure test

The permeabilities of the specimens were determined using a continuous high-pressure flow experiment in which solution is eluted through the cylindrical specimens at pressures up to 10 MPa depending on the compressive strength of the particular specimen. These high pressures were chosen in order to give results in a practical timescale and measurements of the effect of pressure on the results were made to relate them to the site application.

The confined leach test cells [6] are a modification of the Hoek cell, in which a solution is eluted through a sample of barrier material under a pressure gradient. To maintain the structural integrity of the sample, and prevent flow past its sides, a confining (triaxial) pressure is applied around an impermeable sleeve surrounding the sample. By maintaining the pore solution pressure below that of the confining pressure, the internal structure of the barrier material is maintained.

The apparatus is shown schematically in figure 1. The high pressures (up to 10MPa, i.e. 100 bar) are provided by a pump driven from the compressed air supply. The pressure is controlled by adjusting a pressure relief valve which re-circulates fluid back to the reservoir. This method was chosen because the pump maintained a more constant pressure when some flow was permitted and also it ensured safe operation. All of the components and pipework were made with stainless steel to permit the use of corrosive leachates in the experiments.

Details of the modifications to the Hoek cells are shown in Figure 3. The cell itself simply provides radial containment to samples and is intended for use in a compression frame for measurement of mechanical properties of rocks under tri-axial containment. The modifications are designed to provide a fluid supply to and drain from the sample and to contain the axial load to permit use without a compression frame. On the downstream (top) face of the sample this load could have caused spalling from the surface of the sample due to the high pressure in the pores so it was carried through a thick perforated disc. A porous (sinter) disc was placed against the sample to permit free flow across the face. From the perforated disc the load was carried by the end pieces and then through load bearing spacers to a substantial (20mm thick) end plate with tie bars around the circumference.

Measurements were normally made after one sample volume of liquid had passed through the mortar specimens. Assuming an average permeability of 10^{-9} and a maximum leachate head of 1m above the liner, this corresponds to 16 years of exposure in service.

The specimens were cylindrical with either 54 mm diameter and about 30 mm thickness or 100 mm diameter and 55 mm thickness and were cured for one month before testing.

3. Results

The effect of eluted volume on the coefficient of permeability at different pore solution pressures is shown in figures 4 to 6. The effect of permeating a volume of liquid equal to seven times the sample volumes are shown in these figures. One sample volume shown on the graph represents a volume of fluid passing through the sample equal to the total overall volume of the sample itself, not just its porosity. For low strength materials such as materials being used in the novel liner mixes i.e. compressive strength of up to 5 MPa, increased eluted sample volumes slightly decrease the coefficient of permeability but this is contrary to higher strength materials in which the permeability increases. The authors suggest that the reason for this is that high strength materials are rigid whereas low strength materials are compliant and weak bonding fine particles cause blockage of the pore routes in these types of materials by “silting”. Claisse and Unworth [15] have found a slight decrease in intrinsic permeability coefficient after permeating 30 times the sample volumes for higher strength OPC mixes. This may be due to using concrete, which contains coarse aggregate, however they had not determined the permeabilities for intermediate number of sample volumes passing so that a more detailed comparison can be made. In this investigation the results clearly indicate a decrease in hydraulic conductivity for lower strength mixes and a slight increase in permeability coefficient for the higher strength mixes with increasing number of permeating sample volumes.

The effect of specimen size on the coefficient of permeability at different pore solution pressures is shown in figures 7 to 9. Increasing the specimen size slightly increases the coefficient of permeability in lower strength mixes and decreases the coefficient in higher strength mixes. This trend is in agreement with findings from figures 4 to 7 and as high strength materials are rigid bigger volumes would reduce the permeability. From the figures 4 to 9, it can also be seen that the permeability coefficient does not change significantly with pore solution pressure.

Discussion

The following differences between the test conditions may make the test results conservative:

1. The samples were tested at early ages (normally 28 day). It is well known (Neville) that the permeability of concrete reduces substantially with age as the hydration progresses.
2. The simulated leachate used for the experiments was free of all particulate matter. A typical leachate on site contains a large fraction of material with the potential for siltation in pores.

The following may make the conclusions unsafe:

1. The results are to be used in a system with a leachate head up to 10m. The applied pressure of up to 10MPa in the testing represents a head of up to 1000m. The calculations automatically assume that the flow will reduce linearly with pressure (i.e. the permeability will not change). While the present results do not prove that it will not change they do not indicate any trend to show that it would.
2. The area of a typical disposal cell is 1-2 Hectares while the experimental samples are six orders of magnitude smaller. The possibility of defects (which are a main consideration when modelling HDPE) must therefore be considered. The main defect in a concrete liner will be a crack and this problem is addressed with the use of a clay layer which will extrude into and seal the cracks. The reason why larger laboratory samples appeared more permeable is not clear but it is not indicated that this trend would be likely to continue up to site scale samples.

And the following appear to be well represented in the experiments:

1. Each sample volume of fluid passing through the liner corresponds to at least 16 years of operation. The test have been run for up to 7 sample volumes, i.e. the equivalent of just

over 100 years. Nuclear repositories are designed for very much longer periods but for normal landfill design this is currently typical. Most current designs are based on a High Density Polyethylene (HDPE) membrane with a design life no greater than this. The membrane is used with a mineral barrier (e.g. bentonite enhanced sand) but most modelling relies substantially on the membrane itself.

2. The temperature of the trial cells has been monitored and did not deviate by more than a few degrees from typical room temperatures which were measured during laboratory testing.

In addition to all of the above Neville states “it is important to note that the scatter of permeability test results made on similar concrete at the same age and using the same equipment is large. Differences between, say, 2×10^{-12} and 6×10^{-12} are not significant”. While laboratory trials are a necessary first step in work of this kind (in particular for mix selection) these results indicate that large site trials are a necessary second step.

4. Conclusions

- Depending on the strength, the cementitious mortar mixes behave differently with permeating number of sample volumes at the same pore pressure and age. For low strength materials such as Controlled Low Strength Materials, which are increasingly being used nowadays, increased eluted sample volumes slightly decrease the coefficient of permeability but this is contrary to higher strength materials in which the coefficient of permeability increases.
- Increasing the testing specimen volume slightly increases the coefficient of permeability in lower strength mixes and decreases the coefficient in higher strength mixes.
- Variation in pore solution pressure during high-pressure permeability test does not significantly affect the permeability coefficients in low strength cementitious mixes.
- Large site trials are a necessary step in establishing the performance of concrete barriers.

Acknowledgements

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Table 1: Composition of synthetic leachate, per litre of solution (pH=5.1)

2.043g	Concentrated Sulphuric acid
4.48g	Acetic acid
1.897g	Potassium chloride
7.755g	Calcium acetate
1.186g	Ammonium chloride
0.91g	Sodium chloride
2.588g	Sodium hydroxide

Table 2: Mix proportions and strength of the mortar mixes used for hydraulic conductivity study.

Mortar mix	**Cementitous material**	**% by mass**	**Pozzolanic ash**	**% by mass**	**Fine aggregate (<5mm)**	**% by mass**	**W/C**	**28 days Str. (Mpa)**
Cement/ Quartz	OPC	11.8	_	_	Quartz	88.2	0.92	15
Cement/ Quartz	OPC	16.7	_	_	Quartz	83.3	0.75	20
Typical site trial mix	CKD	20.7	Lagoon ash	13.6	Ferrosilicate slag	65.9	0.39	5

Figure captions:

Figure 1: Schematic view of high-pressure permeability apparatus.

Figure 2: High-pressure apparatus at Coventry, showing two small cells (for 54 mm diameter samples) and one big cell (for 100 mm diameter samples) together with liquid pump and pressure gauge.

Figure. 3 Modifications to Hoek Cell for Concrete Permeability Measurements

Figure 4: Permeability Vs. eluted sample volume for 5 MPa. Mix.

Figure 5: Permeability Vs. eluted sample volume for 15 MPa. Cement mortar mix.

Figure 6: Permeability Vs. eluted sample volume for 20 MPa. Cement mortar mix.

Figure 7: Coefficient of permeability Vs. Sample size for 5 MPa. mix.

Figure 8: Coefficient of permeability Vs. Sample size for 15 MPa cement mortar mix.

Figure 9: Coefficient of permeability vs. sample size for 20 MPa cement mortar mix.

Fig. 1: Schematic view of high-pressure permeability apparatus.

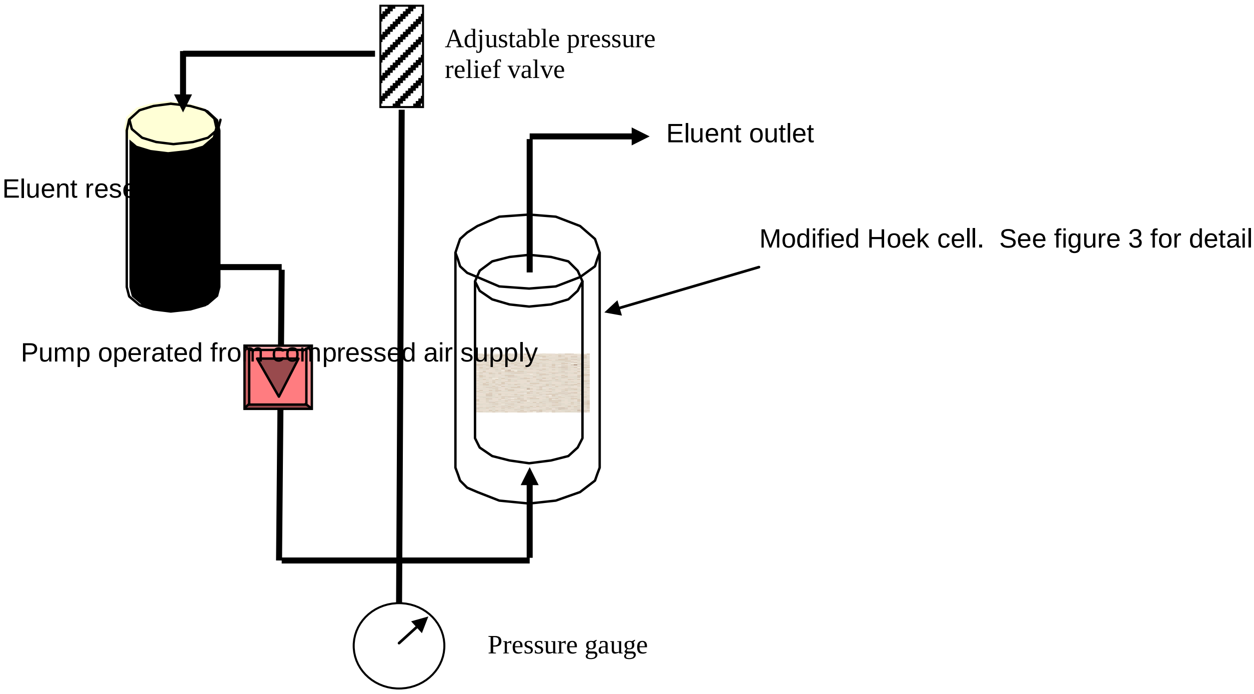

Fig. 2: High-pressure apparatus at Coventry, showing two small cells (for 54 mm diameter samples) and one big cell (for 100 mm diameter samples) together with liquid pump and pressure gauge.

Fig. 3 **Modifications to Hoek Cell for Concrete Permeability Measurements**

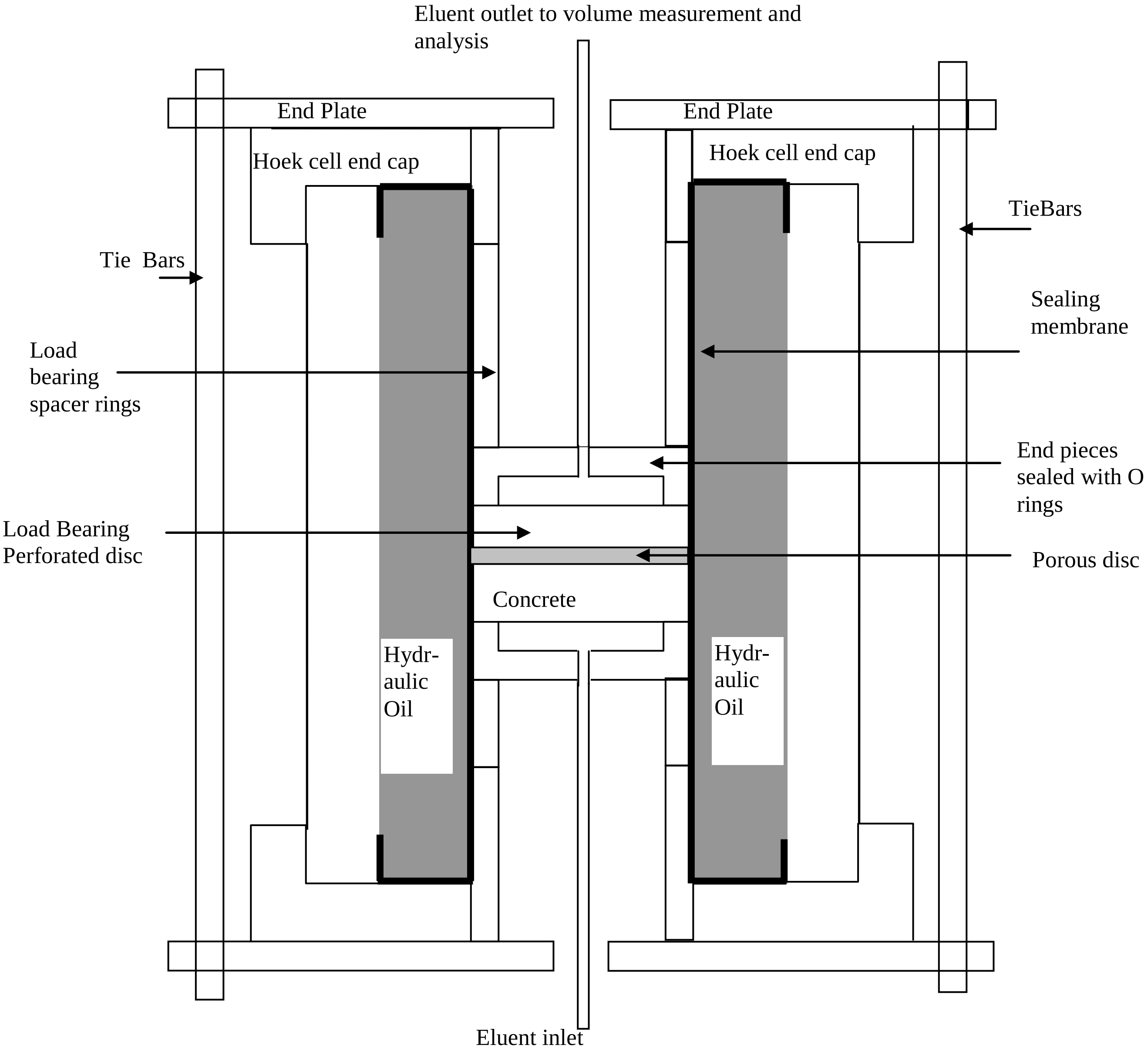

Fig. 4: Permeability Vs. eluted sample volume for 5 MPa. Mix.

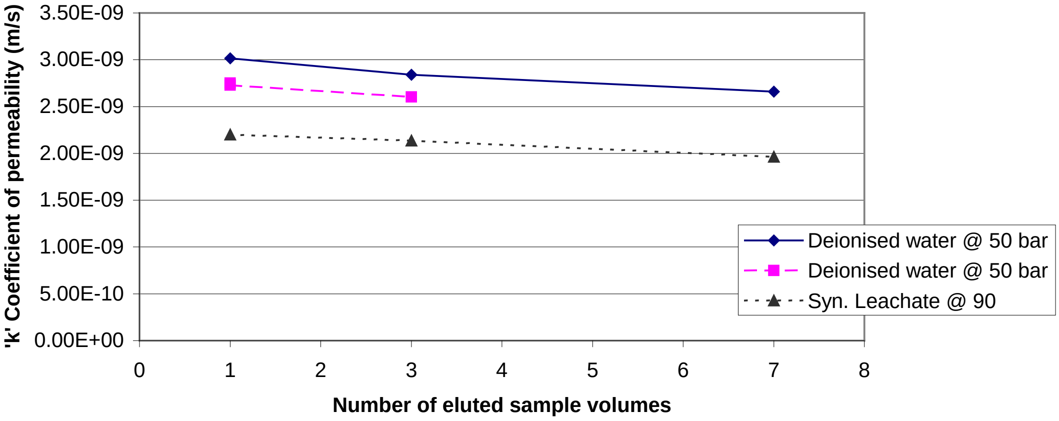

Fig. 5: Permeability Vs. eluted sample volume for 15 MPa. Cement mortar mix.

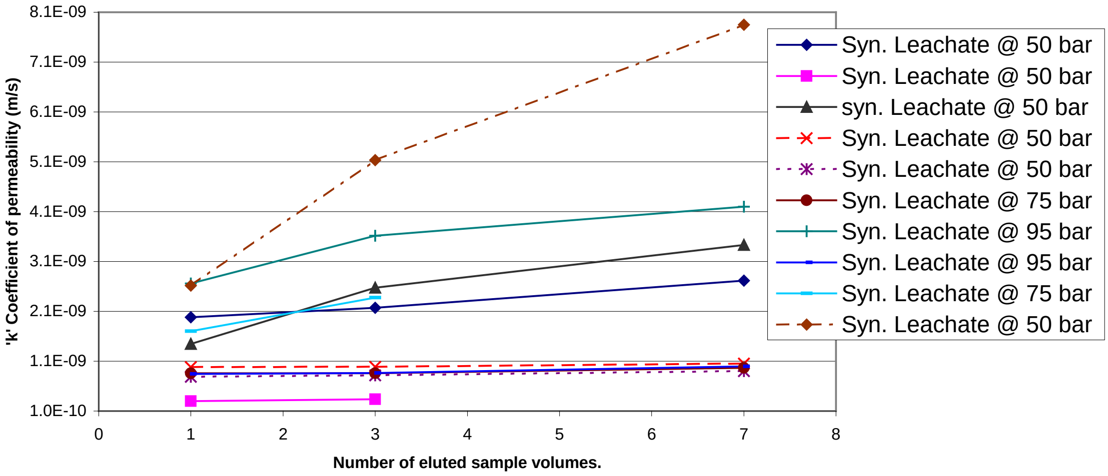

Fig. 6: Permeability Vs. eluted sample volume for 20 MPa. Cement mortar mix.

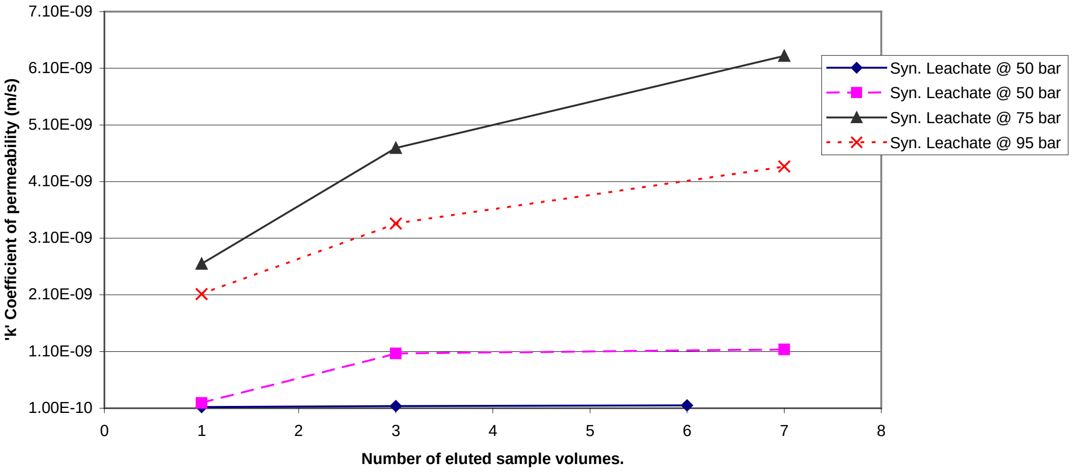

Fig. 7: Coefficient of permeability Vs. Sample size for 5 MPa. mix.

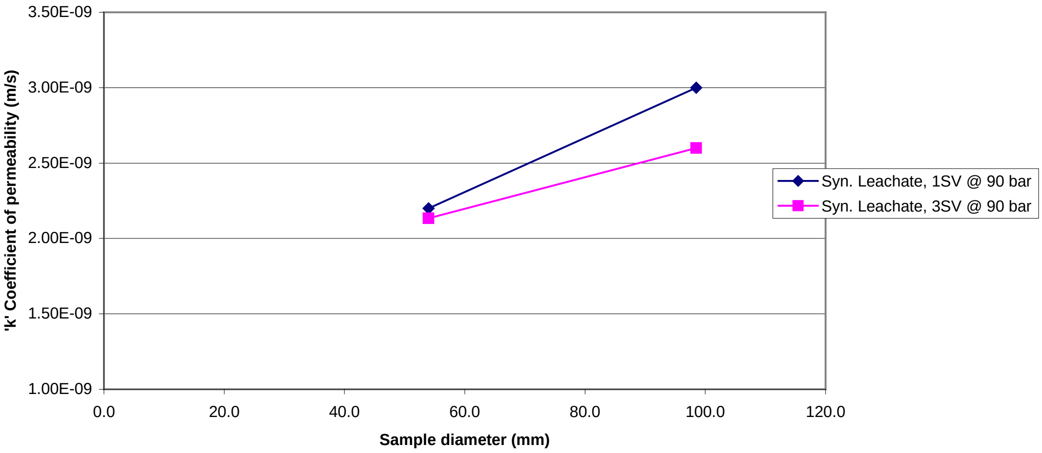

Fig. 8: Coefficient of permeability Vs. Sample size for 15 MPa cement mortar mix.

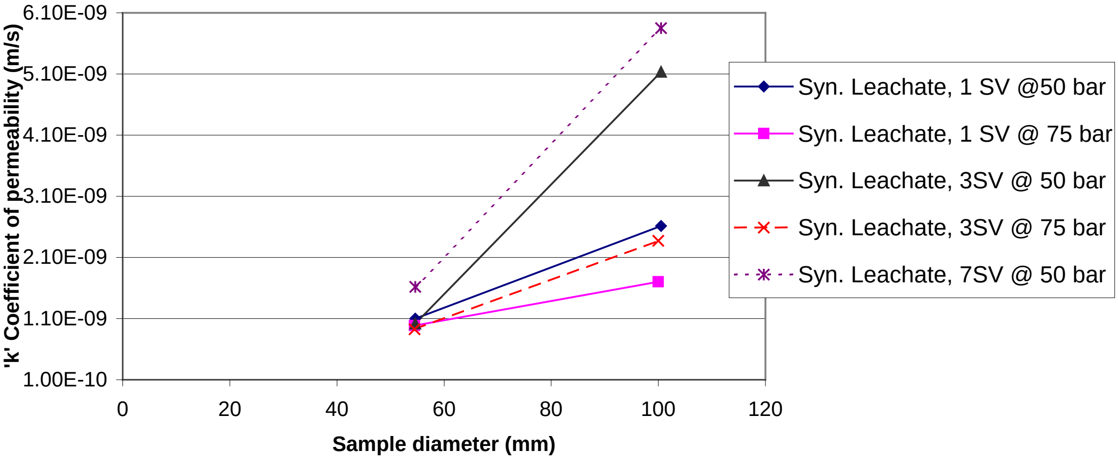

Fig. 9: Coefficient of permeability vs. sample size for 20 MPa cement mortar mix.