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Factors affecting measurement of hydraulic conductivity in low-strength cementitious materials

Eshmaiel Ganjian [a,*], Peter Claisse [a], Mark Tyrer [b], Alan Atkinson [b]

[a] Department of Built Environment, University of Coventry, Sir John Laing Building, Priory St., Coventry CV1 5FB, UK
[b] Department of Materials, Royal School of Mines, Imperial college, Prince Consort Road, London SW7 2BP, UK

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Abstract

The hydraulic conductivity (water 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 mixtures having compressive strengths ranging from 5 to 20 MPa. Two mortar mixtures containing portland cement and one without portland cement and incorporating cement kiln dust, lagoon ash, and Ferrosilicate slag were tested. The effects of the sample size were also investigated.

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

Keywords: Concrete; Mortar; Permeability; Physical properties; Transport properties

1. Introduction

The cementitious chemical barrier is one of the main engineering features of the current research on novel composite landfill liners [1,2]. The novel multi-layer barrier concept is based on the theory that the pollution of soils and water 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 capture and 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 of these operational and long-term requirements, a range of composite barrier materials were evaluated. These include: low cost, chemically conditioning, cementitious media (such as concretes containing metallurgical slags, spent foundry sands, and/or demolition waste as an aggregate, blended cements containing by-product 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} in UK [3].
- High cation exchange capacity (a minimum capacity factor of 5.0).
- The ability to chemically condition leachate through sacrificial action.
- Construction from low cost materials.

* Corresponding author. Tel.: +44 24 7688 7625; fax: +44 24 7688 8296.
E-mail address: E.Ganjian@Coventry.ac.uk (E. Ganjian).

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

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

- Ease of construction.
- Sufficient strength to support a refuse vehicle during operation. A cube strength of 5 N/mm^2 is considered to be adequate.
- Tolerance of deformation during service without barrier failure through brittle cracking.
- The ability to promote self-sealing of cracks.

In the design evaluated in this work, three layers were 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 discarded materials, which would otherwise have to be disposed off in a landfill [1,2].

The basic principles of physical containment with concrete are well understood and documented [4–6]. 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 [7] has been used.

Containment has been studied in detail for nuclear waste [8]. 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 (over 100 years) 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 [9] require leachate extraction in order to limit this to a depth of 1 m above the liner but, in order to guarantee effective containment, a possible head of 10 m has been considered in the design.

In the literature, limited research information is available into effect of confining pressure, pore pressure, and specimen dimension on permeability of rocks and heterogeneous soil mixtures [10–14]. However, no literature has been found on cementitious mixtures that are studied in this manuscript.

The work reported here forms part of a major industry-based project on a novel composite barrier system, which uses the metallurgical discarded materials for the cementitious liners in the landfill barriers [1,2,15,16]. 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 proposed-candidate barriers [2]. In this paper the results of an extensive laboratory investigation into the intrinsic coefficient of permeability of potential multi-layer barrier mixtures using various discarded mineral sources are presented and discussed.

2. Experimental programme

The broad objectives of the experiments were to establish the hydraulic permeability for 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, different pore pressure, and specimen size. In all tests the confining to pore pressure ratio were 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.

Table 2
Mixture proportions and strength of the mortar mixtures used for hydraulic conductivity study

Mortar mixture	Cementitious material	% by mass	Pozzolanic coal ash	% by mass	Fine aggregate (<5 mm)	% by mass	W/C and W/Cm	28 days compressive strength (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 mixture	CKD [a]	20.7	Lagoon ash	13.6	Ferrosilicate slag	65.9	0.39	5

[a] Cement Kiln Dust.

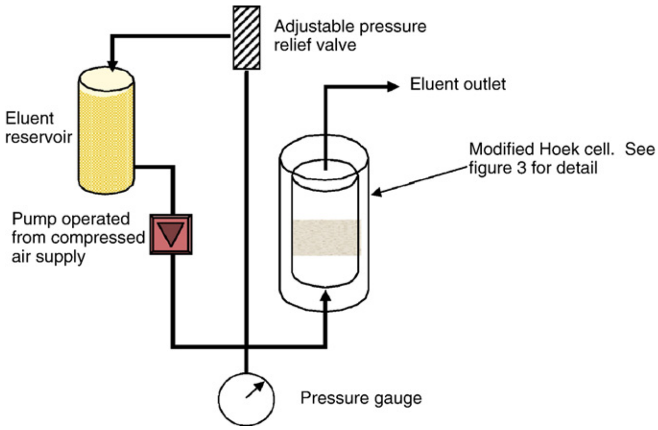

Fig. 1. Schematic view of high-pressure permeability apparatus.

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 mixtures. The composition of the synthetic leachate used in this work was obtained by comparing the composition of various natural and synthetic leachates 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 (i.e., more aggressive on its effects on the barriers).

2.2. Mixture proportions

The mixtures were proportioned 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 mixtures [1,2] lead to the selection of three candidate mixtures which satisfied the criteria. Two samples from each selected mixture proportion were tested with leachate and two more were tested with water to give a programme of over 200 permeability tests.

The proportions of the three mixtures are given in Table 2. Two of these mixtures were portland cement mortar mixtures with different strengths and permeability coefficients, and one other mixture was one of the several trial cell mixtures used for site trials. For one of the mixtures 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.

2.3. 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.

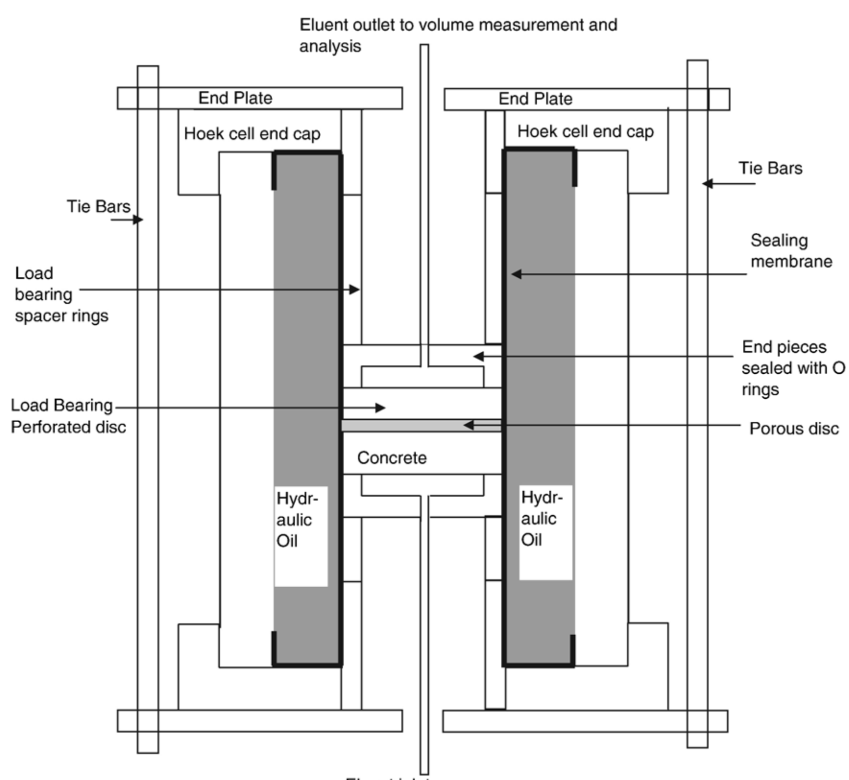

Fig. 2. Modifications to Hoek Cell for Concrete Permeability Measurements.

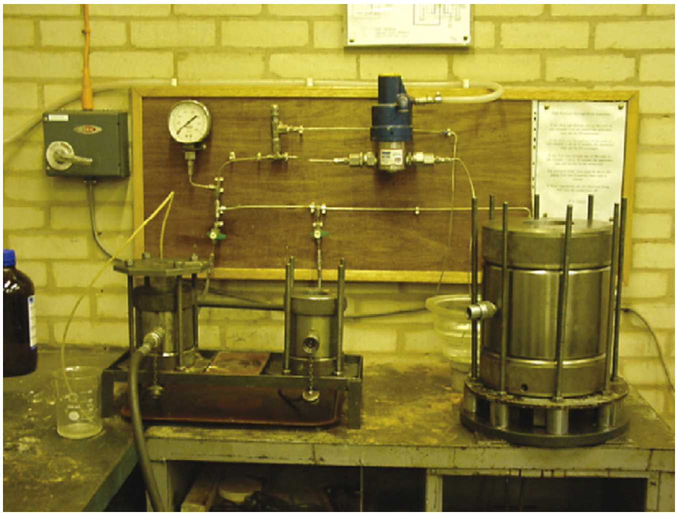

Fig. 3. High-pressure apparatus at Coventry, showing two small cells (for 54 mm diameter samples) and one big cell (for 100 mm diameter samples) together with liquid pump and pressure gauge.

These high pressures were chosen in order to produce results in a practical timescale. Measurements of the effect of pressure on the results were made to relate them to the site application.

The confined leach test cells [7] 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 Fig. 1. High pressures (up to 10 MPa, 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 that 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 Fig. 2. The cell itself simply provides radial containment to test samples. It is intended for use in a compression frame for

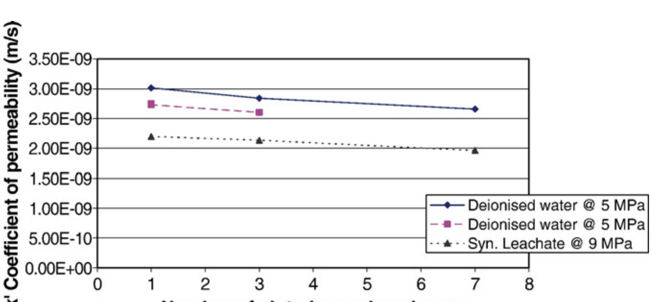

Fig. 4. Permeability vs. eluted sample volume for 5 MPa. Mixture.

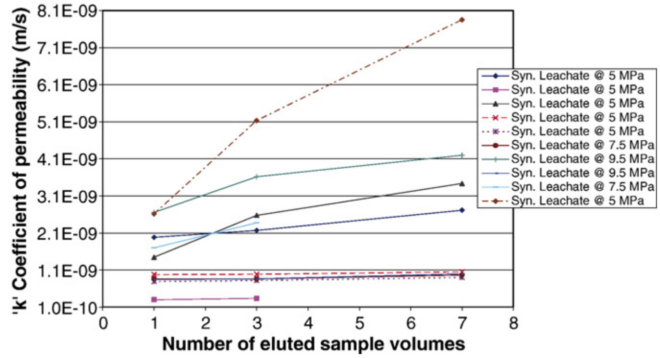

Fig. 5. Permeability vs. eluted sample volume for 15 MPa. Cement mortar mixture.

measurement of mechanical properties of rocks under tri-axial containment. The modifications were 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 (20 mm thick) end plate with tie bars around the circumference. Fig. 3 shows the cells and liquid pump used in this work.

Measurements were normally made after one sample volume of liquid had passed through the mortar test specimens. Assuming an average permeability of 10^{-9} and a maximum leachate head of 1 m 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. The specimens were cured for 28 days before testing. This was to ensure that majority of hydration process has taken place for the cementitious mixtures before testing. The time taken to complete seven sample volume hydraulic permeability tests was about 46 h for the 20 MPa strength portland cement

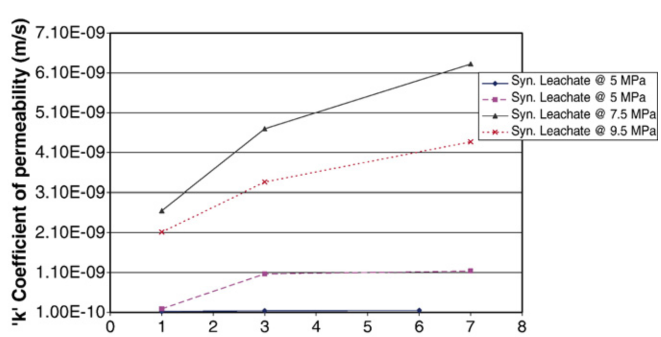

Fig. 6. Permeability vs. eluted sample volume for 20 MPa. Cement mortar mixture.

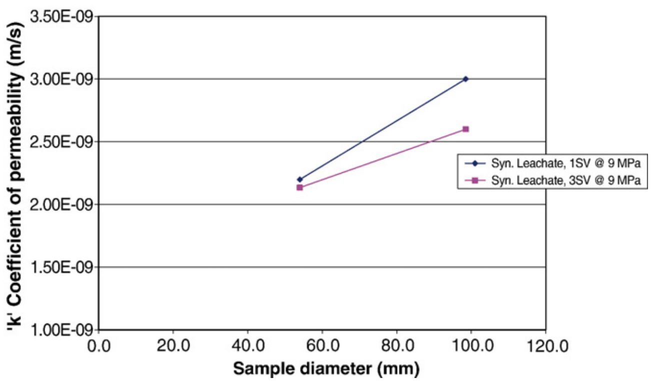

Fig. 7. Coefficient of permeability vs. sample size for 5 MPa. Mixture.

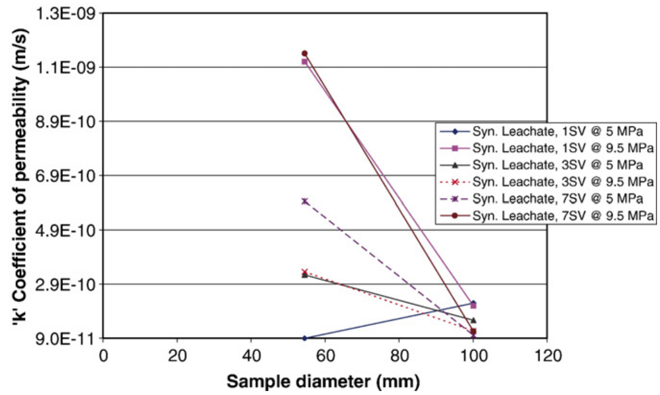

Fig. 9. Coefficient of permeability vs. sample size for 20 MPa cement mortar mixture.

mortar mixture at 5 MPa pressure, and about 1 h for the 5 MPa strength cement kiln dust mortar mixture at 9.5 MPa pressure.

3. Results

The effect of eluted volume on the coefficient of permeability at different pore solution pressures is shown in Figs. 4–6. The effect of permeating a volume of liquid up to seven times the sample volumes (i.e., 7 SV) are shown in Figs. 7–9. One sample volume (1 SV) 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 these proposed novel liner mixtures, i.e., compressive strength of up to 5 MPa, increased eluted sample volumes slightly decreased coefficient of permeability, but this was contrary to higher strength materials in which the permeability increased. It is suggested 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 [17] have found a slight decrease in intrinsic permeability coefficient after permeating 30 times the sample volumes for higher strength ordinary portland cement mixtures. 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 mixtures and a slight increase in permeability coefficient for the higher strength mixtures with increasing number of permeating sample volumes.

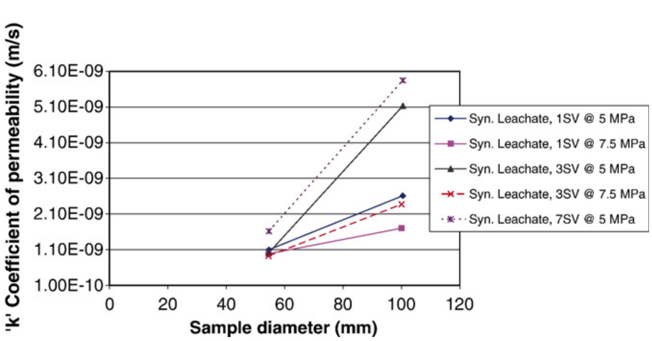

Fig. 8. Coefficient of permeability vs. sample size for 15 MPa cement mortar mixture.

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

4. Discussion

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

1. The samples were tested at early ages (normally 28 days). It is well known [18] 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 10 m. The applied pressure of up to 10 MPa in the testing represents a head of up to 1000 m. 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 ha while the experimental samples are six orders of magnitude smaller. The possibility of defects (which are a main consideration when modelling High Density Polyethylene, 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 tests 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 [18] 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.

5. Conclusions and observations

- Depending on the strength, the cementitious mortar mixtures 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, 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 test specimen volume slightly increases the coefficient of permeability in lower strength mixtures and decreases the coefficient in higher strength mixtures.
- Variation in pore solution pressure during high-pressure permeability test does not significantly affect the permeability coefficients in low strength cementitious mixtures.
- Large site trials are a necessary step in establishing the performance of the tested cementitious barriers.

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References

[1] E. Ganjian, P. Claisse, M. Tyrer, A. Atkinson, Preliminary Investigations into the Use of Secondary Waste Minerals as a Novel Cementitious Landfill Liner, Construction and Building Materials, vol. 18 (9), Elsevier, London, U.K., 2004, pp. 689–699.

[2] E. Ganjian, P. Claisse, M. Tyrer, A. Atkinson, Selection of Cementitious Mixes as a Barrier for Landfill Leachate Containment, ASCE Journal of Materials in Civil Engineering, Reston, VA, USA, vol. 16 (5), 2004, pp. 111–119.

[3] J.K. Mitchell, Physical Barriers for Waste Containment, International Congress on Environmental Geotechnics, 1994, pp. 951–962.

[4] U.S. Environmental Protection Agency, Technical Background Document on the Efficiency and Effectiveness of CKD Landfill Design Elements, Prepared by: Science Applications International Corporation, McLean, VA, EPA Contract 68-W4-0030, Work Assignment 215 SAIC Project 01-0857-07-7389-160, 1997.

[5] A.W. Harris, A. Atkinson, A.K. Nickerson, N.M. Everitt, Mass transfer in water saturated concretes, Nirex Safety Studies Report NSS/R125, UK Nirex Ltd., Didcot, Oxon, U.K., 1988.

[6] A. Atkinson, P.A. Claisse, The use of cement in a repository for the disposal of spent fuel, Harwell Report AERE R 13479, AEA Technology Ltd., Didcot, Oxon, U.K., 1989.

[7] Anon, Technical literature on Hoek cell and drainage platens, Robertson Geologging, Conwy, Gwynedd, LL31 9PX, 1994.

[8] UK Nirex, Report No 525, Scientific Update, United Kingdom Nirex Ltd., Harwell, Didcot, OXON, UK, 1993, p. 25.

[9] Guidance on Good Practice for Landfill Engineering, Report No. CWM 106/94c, Dept. of the Environment, London, UK, 1996, pp. 49–54.

[10] Shi-Ping Li, Da-Xin Wu, Wei-Hong Xie, Yu-Shou Li, Zhen-Ye Wu, Gang Zhou, Hai-Yun Zhao, Effect of confining pressure, pore pressure and specimen dimension on permeability of Yinzhuang sandstone, International Journal of Rock Mechanics and Mining Sciences 34 (3–4) (1997) 432–440.

[11] A.J. Bolton, Some measurements of permeability and effective stress on a heterogeneous soil mixture: implications for recovery of inelastic strains, Engineering Geology 57 (2000) 95–104.

[12] N.H. Kilmer, N.R. Morrow, J.K. Pitman, Pressure sensitivity of low permeability sandstones, Journal of Petroleum Science and Engineering 1 (1) (1987) 65–81.

[13] G. Brighenti, Effect of Confining Pressure on Gas Permeability of Tight Sandstones, Proc. International Symposium on Rock at Great Depth, vol. 1, Pau, Publ, Rotterdam, 1989, pp. 187–194.

[14] S. Fukushima, T. Ishii, Experimental study of the influence of confining pressure on permeability coefficients of fill dam core material, International Journal of Rock Mechanics and Mining Science & Geomechanics Abstracts 24 (4) (1987) 136–143.

[15] M. Tyrer, A. Atkinson, P.A. Claisse, E. Ganjian, Novel composite landfill liners, Proc. “Green3”, 3rd International Symposium on Geotechnics Related to the European Environment, Berlin 21–24 June, 2000.

[16] P.A. Claisse, E. Ganjian, A. Atkinson, M. Tyrer, Site trials of concrete barriers for landfill liners, Research in Progress, ACI Spring Convention, Detroit, USA, 2002.

[17] P.A. Claisse, H.P. Unworth, The engineering of a cementitious barrier, Geological Society Engineering Geology Special Publication, No. 11, 1995, pp. 267–272.

[18] A.M. Neville, Properties of Concrete, Forth edition, Longman Group Ltd., Essex, England, 1995, p. 494.