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Cracking in a cementitious backfill and its implications for flow and chemistry

B. T. Swift[1,]*, P. B. Bamforth[2] and G. M. N. Baston[1]

[1] AMEC, Building 150, Thomson Avenue, Harwell Oxford, Didcot, Oxfordshire OX11 0QB, UK
[2] 8 Hamilton Court, Hamilton Road, Ealing, London W5 2EJ, UK

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ABSTRACT

In the UK, disposal of packaged intermediate-level radioactive waste may involve waste packages being placed in a geological disposal facility (GDF) and surrounded by a cementitious backfill. Cracking of the backfill could occur due to a number of mechanisms, and this could affect the post-closure performance of the GDF.

This work has assessed potential cracking in the backfill during the backfilling and early post-closure period of GDF vaults with an open crown space in a higher strength rock. From the comprehensive range of processes considered, three were identified as potentially causing cracking: (1) during backfilling, plastic settlement under solid horizontal surfaces could result in horizontal gaps beneath waste packages; (2) within days of backfilling, early-age thermal contraction of the backfill could result in primarily vertical cracks; (3) over a number of years, expansion of waste packages could result in large horizontal cracks.

A groundwater flow model incorporating a representation of the cracks was used to calculate flows through a backfilled GDF vault, and through the cracks themselves. Including cracks increased the flow rate significantly. A reactive transport model was used to estimate the evolution of the pore water chemistry as groundwater flows through the cracked backfill. Calcite and brucite were predicted to precipitate, with brucite subsequently dissolving. Calcite build-up could seal some cracks.

Keywords: waste, geological disposal, cementitious backfill, cracking, groundwater flow, pH, brucite, calcite, armouring.

Introduction

A range of potential concepts for the geological disposal of radioactive wastes are being considered in the UK. These include concepts that use a cementitious backfill in the vaults or tunnels containing intermediate-level waste (ILW) packages. The backfill provides a high pH environment and a high sorption capacity for many radionuclides. It is one of a number of components of a GDF design that are important in helping to retard radionuclide migration.

Assessments of the post-closure performance of geological disposal facility (GDF) concepts (e.g. Nuclear Decommissioning Authority, 2010*a*) generally have assumed that immediately after closure the radionuclides will be distributed evenly throughout an undamaged backfill. However, in reality, the radionuclides will be released over a period of time from waste packages that are surrounded by a backfill that may have undergone cracking. A number of mechanisms could lead to cracking of the backfill, and there is uncertainty as to whether this could affect post-closure performance with respect to radionuclide release via the groundwater pathway.

* E-mail: ben.swift@amec.com
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This study aims to understand the significance of backfill cracking by considering the following questions:

(1) Where are cracks likely to form in the backfill? What will the apertures of the cracks be, and how will the apertures change with time?

(2) How will the presence of cracks affect groundwater flow through the GDF?

(3) How will the presence of cracks affect groundwater chemistry in the near-field of the GDF?

In combination, the answers to these questions provide the understanding required to determine the implications of cracking of the backfill for the post-closure performance of the GDF. To answer the questions fully would require a large programme of work, which was not possible for this study. This study therefore aims to provide initial answers to the questions by considering them only for key scenarios with some simplification.

This paper provides an overview of the work performed, and includes some of the main findings, but does not include all the details of the work undertaken, particularly for the reactive transport modelling. Full details of the study are given in Swift *et al.* (2010).

Crack formation and crack patterns

Cracking assessment methodology

An assessment was undertaken to describe where the backfill is likely to crack, what the probable range of crack apertures will be, and how the cracks might evolve. This was achieved by considering the following five aspects of the technical specification for an ILW vault (Nuclear Decommissioning Authority, 2010*b*; Nirex, 2007; Francis *et al.*, 1997):

(1) The vault dimensions and operating environment.

(2) The waste package design and stacking arrangements.

(3) The backfilling strategy.

(4) The performance of the waste packages with regard to heat generation, their rate of corrosion and resulting gas evolution.

(5) The properties of the backfill together with a broad understanding of the behaviour of cementitious systems.

Within each of these specifications simplifying assumptions were, necessarily, made to enable a first order prediction of strains and stresses to be made. These values were then compared with the

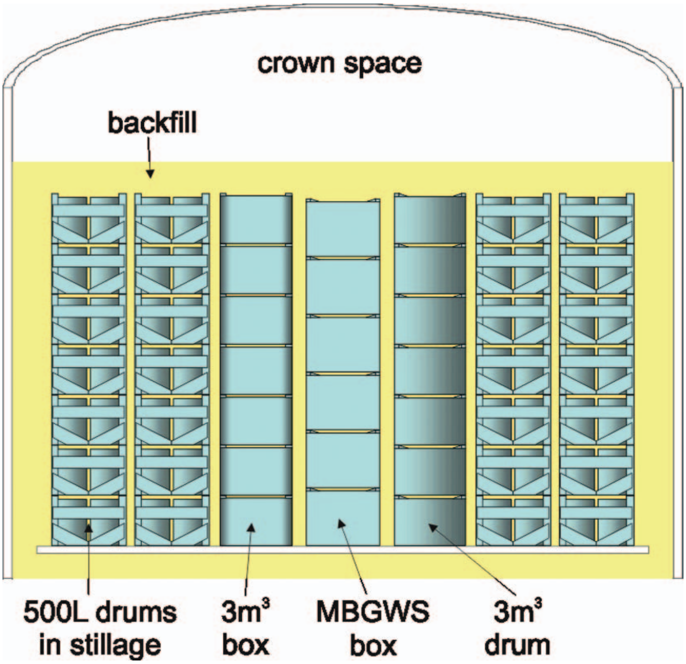

FIG. 1. Cross-section of a GDF vault for ILW showing stacks of waste packages surrounded by a backfill with an open crown space at the top of the vault.

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strain capacity of the backfill to enable crack locations to be determined and crack apertures to be estimated. In particular, Fig. 1 shows some of the features of a vault assumed, including the stacking arrangement of different types of waste packages. For the purposes of this study it was assumed that the crown space at the top of the vault is not backfilled prior to closure.

Cracking mechanisms

Cracking in the backfill will be caused either by restraint to deformations or by imposed loading. Contraction of the backfill, if unrestrained, will result in a dimensional change. However, if the contraction is restrained (fully or partially) the restrained component of strain leads to tensile stresses, and if the restrained (stress-inducing) strain exceeds the tensile strain capacity of the backfill, cracking will occur. Similarly, if loads are induced in the backfill, cracking will occur if the tensile stresses generated exceed the tensile strength.

For NRVB, a cementitious material formulated to be used as a possible backfill, the tensile strain capacity (i.e. the tensile strain at which a crack will occur) was measured as part of its development (Francis *et al.*, 1997). A value of 100 microstrain was assumed for this cracking assessment. By comparison, the magnitude of strains that can potentially develop are substantially higher and the risk of cracking is very high.

The process by which the risk and extent of cracking has been estimated is described by Swift *et al.* (2010), who also define the properties of the backfill (assumed to be NRVB) used in the assessment. Initially, the various crack-forming mechanisms were considered independently. The development and propagation of cracking was then considered, with existing cracks being taken into account in relation to new crack formation.

The main mechanisms that can cause strains in the backfill, and the relative magnitudes of the potential strains associated with these, at different stages of the GDF, are shown in Fig. 2. However, the assessment found that only four of these mechanisms were likely to lead to the development of cracks in the backfill. These mechanisms are discussed below.

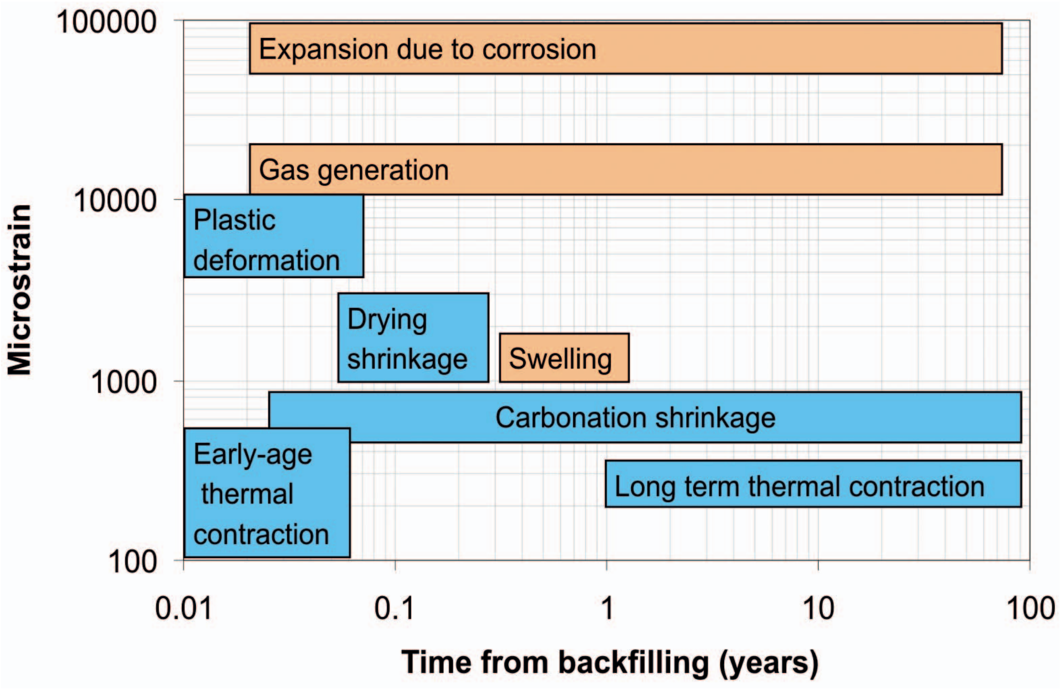

FIG. 2. Potential strains developed at various stages in the GDF. Orange shading indicates a size-increasing strain and blue shading indicates a size-reducing strain.

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Plastic deformation

Plastic deformation and settlement of the fluid backfill will occur during backfilling (i.e. when left to settle the solids will consolidate under gravity leaving a layer of bleed water on the top surface, which is reabsorbed when the backfill hardens and hydration proceeds). For NRVB, bleed was measured to be 1.7% (Worthington *et al.*, 1991). Therefore, in the horizontal space (100 mm) between stacked packages for example, the consequence of bleed and settlement prior to setting is to leave a gap of up to about 2 mm below the upper package, as shown in Fig. 3.

Early-age thermal deformation due to heat of hydration of cement

Heat is generated very rapidly during the early period of cement hydration. For NRVB, within the first two days about 150 MJ m^{-3} is generated (Francis *et al.*, 1997). This leads to a rise in temperature and thermal expansion, followed by cooling and contraction. During the heating phase, the backfill is relatively soft (low modulus of elasticity) and the compressive stresses that are generated, if the expansion is restrained, are therefore low and are largely relieved by creep. Cooling occurs when the backfill is stiffer (with a higher modulus of elasticity and less creep) and the tensile stresses generated under restraint are higher than those generated during the heating period. This leads to a residual tensile stress being generated in the backfill after cooling. For estimating the risk and extent of cracking, this is expressed as a restrained-tensile strain.

Estimated early-age temperature changes are up to about 34ºC (Swift *et al.*, 2010). With a coefficient of thermal expansion of 10.5 microstrain $^{\circ}C^{-1}$ (Francis *et al.*, 1997), the thermal deformation may be up to about 357 microstrain. Hence, only about 30% restraint is needed to exceed a restrained tensile strain of 100 microstrain. This is easily achieved by the stiffness of the waste packages in relation to the backfill, and cracking is predicted with an aperture size up to about 0.2 mm.

Corrosion of waste package contents

The free expansions caused by the corrosion of metals within some waste packages are much greater than any other form of deformation (Chambers *et al.*, 2007). There are two distinct groups of ILW packages: ‘reactive’ packages that may expand rapidly (i.e. within a few years or tens of years) and ‘unreactive’ packages that expand very slowly (i.e. over thousands of years)

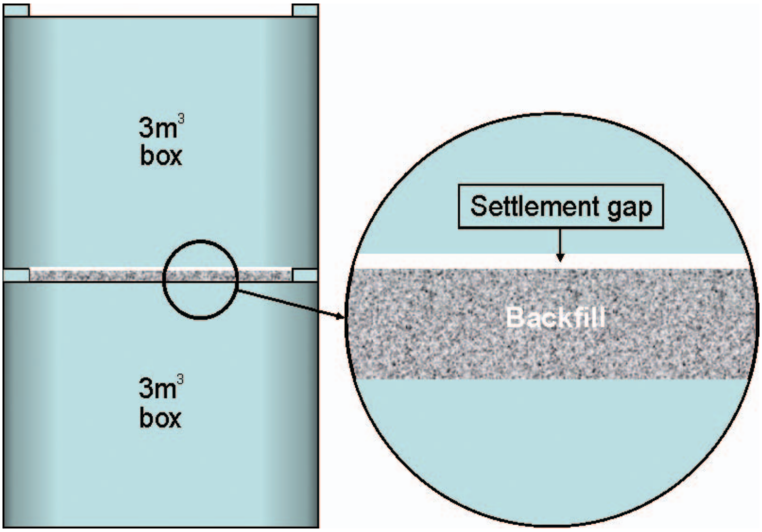

FIG. 3. Gap below a waste package resulting from settlement and bleed of the backfill. The gap could be up to 2 mm deep.

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(Swift *et al.*, 2010). For the rapidly expanding packages, expansion due to corrosion occurs in three stages: pre-backfilling (up to 100 years; not relevant for this study); from backfilling to closure (100 to 110 years; about 0.4%); and post-closure (from 110 years; up to 3.5%).

Taking account of the ullage spaces in the packages and the distribution of reactive packages within a GDF vault (reactive packages occupy about 10% of the vault volume), the estimated linear strain during the backfilling period is about 0.007%. This expansion may initially cause existing cracks to close but restraint may ultimately lead to compressive stresses in the horizontal direction and associated tensile stresses in the vertical direction due to Poisson's effects. This in turn could result in fine horizontal cracks (about 0.1 mm wide) forming across the full width of a vault, as shown in Fig. 4.

In the post closure phase, when the magnitude of expansion due to corrosion could be substantially higher, the horizontal cracks could be up to 5 mm wide. If reactive packages are close to the top of a stack, significant local disruption could also occur at this stage in the absence of a filled crown space, as shown in Fig. 4.

Internal pressures arising from gas generation

Most gas is generated by the corrosion of metals in the waste and is vented through a filter in the top of containers. Gas generation occurs prior to backfilling and continues during and after the backfilling process. For the reactive packages, significant increases in gas generation rate occur at two stages: immediately after backfilling, due to the increase in temperature; and post closure, due to resaturation of the packages with groundwater (Swift *et al.*, 2010). Rates of gas generation in the worst case may be in excess of 100 $m^3\ a^{-1}$ per package for several years. For this rapid rate of generation, even for the relatively permeable NRVB, this can lead to gas pressures of up to 2.5 MPa (Hoch, 2008), which would exceed the tensile strength of the backfill (0.6 MPa).

In considering the effect of gas pressure on cracking, the following factors must be taken into account: (1) disturbance of the backfill by gas flow during emplacement, providing leakage paths for subsequent pressure relief; (2) cracking due to other mechanisms providing paths for pressure relief; (3) location of gas generation sources in relation to cracks and open void spaces

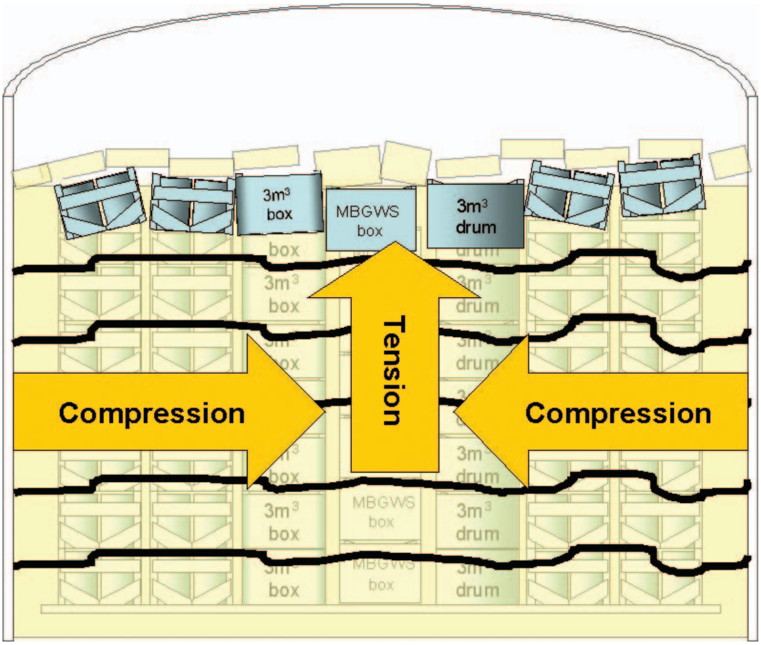

FIG. 4. Cross-section of a GDF vault with an open crown space showing (exaggerated for clarity) development of horizontal cracking and disruption of backfill near its top surface due to restrained lateral expansion.

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(i.e. the crown space in the vault and void space within waste containers); (4) degree to which the backfill may deform or is restrained; (5) degree of saturation of the backfill with water, affecting its permeability. However, as rapid gas generation is due to corrosion, which could induce significant cracking, gas generation is not expected to cause any additional cracking. Nonetheless, it could affect the rate at which cracks develop.

Summary of estimated cracking

The processes identified as potentially causing cracking, and the cracks likely to be formed, were as follows:

(1) During placing of the backfill, plastic settlement under solid horizontal waste package surfaces is expected to result in horizontal gaps (i.e. cracks) of up to 2 mm under the base of each package. These would extend only as far as the edge of the packages, so would not be connected. Gaps are less likely to occur under the stillages in which 500 litre drum waste packages are placed to allow stacking, as these have holes in the base plate that allow flow of backfill and bleed water.

(2) Within days of backfilling, early-age thermal contraction of the backfill will result in primarily vertical cracks of up to 0.2 mm. These would extend between waste packages at the locations where the backfill is thinnest. Some of these cracks may connect the gaps previously formed under packages (Fig. 5).

(3) Later, expansion of reactive packages (and associated gas generation) could result in horizontal cracks of up to 5 mm (cracks of up to 0.1 mm may occur before closure). These could extend across the full width of the vault between each layer of waste packages (i.e. expanding the gaps under packages generated due to settlement of the backfill and connecting adjacent gaps). This cracking pattern assumes a uniform distribution of packages undergoing significant expansion and an open crown space. Much more significant damage may occur if reactive packages occur in a group, with local openings developing in proportion to the linear expansion (which could be a substantial fraction of the package dimensions). As a possible consequence, in the absence of a filled crown space, the layer of backfill above the topmost waste packages may delaminate. Under these conditions, estimation of crack widths would be largely meaningless.

The crack widths given are maximum values, assuming one crack forms in each relevant volume of backfill. In the latter two cases it is possible that a number of smaller cracks, with the same total width, could form in each volume. Assuming maximum crack widths provides cautious conclusions in terms of the impact on post-closure performance of the GDF.

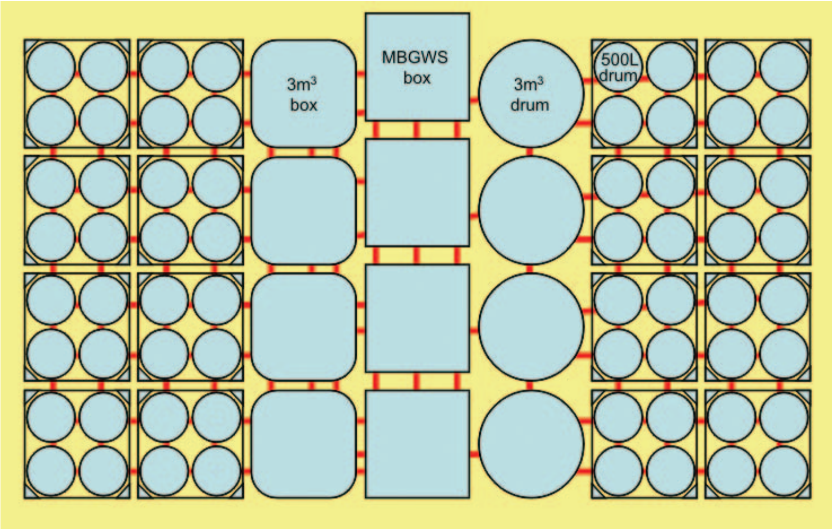

FIG. 5. Plan view of a section of a GDF vault showing probable pattern of vertical cracks in the backfill (red lines) due to early-age thermal contraction.

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Effect of cracking on flow

Modelling methodology

To determine the effect of cracking of the backfill in a GDF vault on the flow through the vault, a model was developed using the *CONNECTFLOW* groundwater flow program (Serco, 2007). This program allows porous medium and fracture network sub-models to be combined within a single model. To provide a simplified representation of the cracked backfill, a fracture network sub-model of a section of the vault was constructed using a repeating pattern of fractures, based on the locations, orientations and apertures of the potential cracks described above. The occurrence and description of cracks due to expansion of the waste packages are somewhat less certain than for the other mechanisms, so these cracks were not included. The remainder of the vault and its surroundings were represented using a sub-model containing porous media representing each of the components. Properties and geometric data for the porous media were based on data from previous modelling experience, and are described in detail by Swift *et al.* (2010). The boundary conditions were set such that in the undisturbed host rock there would be a pressure gradient of 250 Pa m^{-1} across the model, in the direction parallel to the long axis of the vault, providing a background groundwater flow. To provide a comparison, an additional model (using only porous media) was constructed representing the case in which the backfill was not cracked.

Results

Both the overall flow through the vault and the flows through the individual fractures were examined. The latter were determined by examining the velocities of an array of particles released into the fracture network as they passed through different fractures.

For the cracked backfill case, the calculated flow rate through the vault centre (across the full cross-section including the backfilled region and the crown space) was 4.5 $m^3\ a^{-1}$. This was almost 3 times the flow calculated for the case with no cracking (1.6 $m^3\ a^{-1}$). This is consistent with the region of higher permeability increasing in extent in the cracked backfill case from the crown space above the waste only (~6 m high) to the crown space plus the backfilled region (~16 m high).

The medians of the sampled flow velocities in the cracks were 0.9 μm s^{-1} for the 2 mm cracks, and 3 μm s^{-1} for the 0.2 mm cracks. The range of velocities for the 2 mm cracks was quite small (between 0.7 μm s^{-1} and 3 μm s^{-1}) whereas the range of velocities for the 0.2 mm cracks was large (between 0.2 μm s^{-1} and 300 μm s^{-1}) (although over 90% of the sampled velocities were less than 7 μm s^{-1}). It is noted that the model includes a vault lining material that has a relatively low permeability, so significantly reduces the flow through the vault. Without this, the flow velocities through the cracks would be expected to be significantly higher than for the model presented. In addition, the idealized arrangement of the cracks assumed will have some effect on the velocities.

Effect of cracking on groundwater chemistry

Modelling methodology

A reactive transport model was developed to estimate the evolution of the groundwater chemistry and its effects on the backfill as it flows through the cracks. A range of crack sizes, flow rates and groundwater compositions were used.

To simplify the problem, flow was modelled through a single crack, with diffusion of dissolved components between the crack and the backfill porosity. The *PHREEQC* program offers two methods for modelling transport within dual porosity media: a first order exchange approximation; and finite differences for diffusion in the stagnant zone (Parkhurst and Appelo, 1999).

The latter approach was chosen, as this method allows more than one layer of stagnant cells in the model. For the finite difference method, a grid is superimposed over the area, dividing it into cells. To keep the geometry as simple as possible, each cell was rectangular in shape on a plane sheet, forming a regular grid. The crack is represented by a row of mobile layer cells, with each mobile layer cell in contact with one adjacent stagnant cell. One layer of stagnant cells is in contact with the mobile layer cells, with more layers of stagnant cells deeper in the backfill. At each time step the entire contents of cells in the mobile layers are shifted to the adjacent cell in the direction of flow. Exchange of water and solutes between the stagnant and mobile layer cells is by diffusion across the boundaries between the cells. Two-dimensional diffusion between cells in the stagnant layers is also incorporated into the model. The *PHREEQC* program does not have the capability to model dual flow, but because the

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TABLE 1. Parameters used in reactive transport model of groundwater in crack.

Parameter	Value
Effective diffusion coefficient for backfill	4×10^{-10} m^2 s^{-1}
Porosity of backfill	0.44
f_{bc} (for plane sheet)	0.533
Portlandite content of backfill	2771 mol m^{-3}
CSH (with Ca:Si = 1.8) content of backfill	758 mol m^{-3}
Ettringite content of backfill	311 mol m^{-3}
Calcite content of backfill	4950 mol m^{-3}

flow in the crack is expected to be high relative to that in the backfill, representing the backfill as a stagnant zone is a reasonable approximation.

Thermodynamic data from the *HATCHES* database version NEA.18 (Baston *et al.*, 2008) was used, with additional data from the literature, including a solid solution model for calcium silicate hydrate (C-S-H) dissolution (Walker *et al.*, 2007).

The changes in concentration due to diffusion between adjacent cells were approximated using mixing factors, which need to be defined in the input file for each cell of the grid. The mixing factors were calculated using the formulae given in the *PHREEQC* user's manual (Parkhurst and Appelo, 1999).

Values for the effective diffusion coefficient and the porosity were taken from experimental measurements (Harris and Nickerson, 1995). The value of the effective diffusion coefficient used was that of tritiated water. The cement mineral composition was taken from a review of a backfill (NRVB) mineralogy (Holland and Tearle, 2003). The values are given in Table 1. The pore volume was taken as the product of the porosity and the standard cell volume, with the crack having a porosity of 1. As the geometry for the model is a plane sheet, for the purpose of calculating mixing factor values, the cell dimension perpendicular to the plane may be set to any suitable value as long as it is consistent across all cells. In the model it was set to give a standard 1 dm^3 volume in the mobile phase cells. The values for flow in the crack were the median values obtained by the modelling of groundwater flow through a vault containing the cracked backfill described above.

Values for the cell layout and flow rate used in the reference case are shown in Table 2. For the reference case, the composition of groundwater flowing into the crack was that of Sellafield groundwater RCF3 DET5, a saline water from fractured hard rock (Bond and Tweed, 1995), with some minor constituents omitted (Table 3). A number of variant calculations were also performed, that considered: the configuration of the crack (i.e. backfill both sides or backfill one side with an impermeable barrier on the opposite side); the width of the crack; the flow rate of fluid in the crack; and the composition of groundwater entering the crack (an alternative composition considered is also shown in Table 3). Full details are given by Swift *et al.* (2010).

The assumptions made in modelling are summarized as: (1) calcite ($Ca(CO)_3$), brucite ($Mg(OH)_2$) and ettringite ($Ca_6Al_2(SO_4)_3(OH)_{12}\cdot 26H_2O$) formation is incorporated, but the potential for formation of other minerals is excluded; (2) the kinetics of mineral precipitation and dissolution are not considered (i.e. these reactions are assumed to be instantaneous); and (3) the only chemical interactions considered are between the backfill

TABLE 2. Parameters for *PHREEQC* model, reference case.

Item	Value
Number of cells along crack	20
Cell length	0.05 m
Crack aperture	0.002 m
Stagnant cell depth	0.015 m
Flow rate	9×10^{-7} m s^{-1}
Time step†	5.56×10^4 s

† The time step is calculated as the ratio of cell length to flow rate.

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TABLE 3. Compositions of groundwaters.

Component	Concentration (mol dm^{-3}) Sellafield RCF3 DET5	Dounreay BH1 DET6
Na	3.7×10^{-1}	8.3×10^{-3}
K	4.4×10^{-3}	3.8×10^{-5}
Mg	5.7×10^{-3}	3.3×10^{-5}
Ca	2.9×10^{-2}	2.1×10^{-4}
Al	7.4×10^{-7}	–
C	1.0×10^{-3}	2.9×10^{-3}
Si	1.1×10^{-4}	–
SO_4^{2-}	1.2×10^{-2}	2.8×10^{-4}
Cl	4.2×10^{-1}	5.2×10^{-3}
Fe	1.0×10^{-5}	–
pH	7.22	8.75

and groundwater, for example metal corrosion products and waste materials are excluded.

It is recognized that in limiting the number of minerals used, some potential reaction pathways are not considered. For example, under some conditions magnesium may be incorporated in hydrotalcite rather than brucite, and at elevated temperatures the formation of monosulphate phases could be thermodynamically favoured over ettringite. Exposure of cement systems to chloride is known to lead to the formation of Friedel's salt, $3CaO{\cdot}Al_2O_3{\cdot}CaCl_2{\cdot}10H_2O$, from reaction with aluminate phases (Glasser *et al.*, 2008).

Results and discussion for the reference case

In the initial stages, the pH of water along most of the crack is predicted to be above 12 (Fig. 6), due to the diffusion of hydroxyl ions from the backfill. At the inflow, the pH is rapidly brought to a value of ~10, controlled by precipitation of brucite. After a period of time, the pH drops to <10 because the backfill adjacent to the crack has become depleted in the components producing hydroxyl ions and the brucite dissolves. This results in a brucite front that moves through the crack in the direction of groundwater flow, as illustrated in Fig. 7, reaching over 0.3 m along the crack after 500 years.

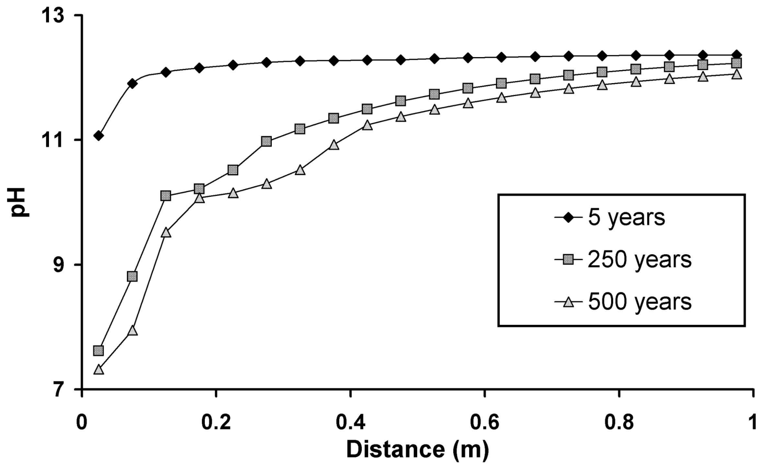

FIG. 6. Variation of pH within the crack with distance along the crack from the point of groundwater inflow and time for the reference case.

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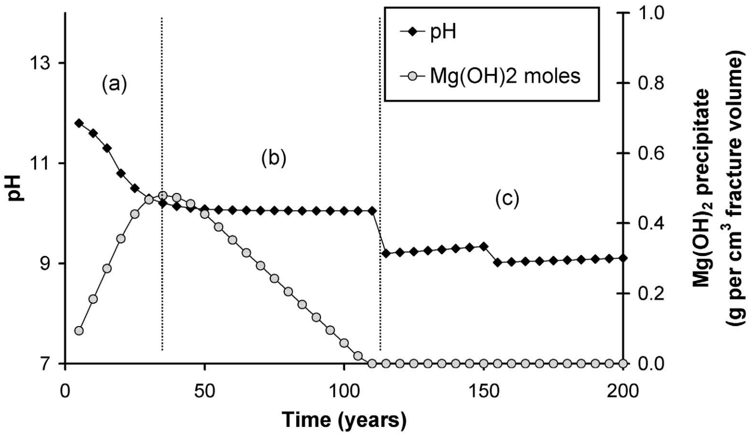

FIG. 7. Effects of brucite precipitation on pH of groundwater flowing in a crack in the backfill for the reference case. Period (a): the OH^- from backfill reacts with Mg^{2+} in the groundwater to precipitate $Mg(OH)_2$. Period (b): a layer of backfill adjacent to crack is depleted in OH^--generating minerals; diffusion of OH^- from lower layers of backfill is slow relative to the groundwater flow; the $Mg(OH)_2$ is dissolving. Period (c): all the $Mg(OH)_2$ has dissolved; the diffusion of OH^- from lower layers of backfill is not sufficient to precipitate $Mg(OH)_2$; the pH is marginally above that of the groundwater.

Calcite precipitation occurs at the inflow end of the crack and in the adjacent backfill. The calcite front moves slowly relative to that of brucite, and calcite is not predicted to dissolve on the timescales considered (Fig. 8). After 500 years the volume of calcite precipitated in the crack was sufficient to completely seal the crack at the inflow. As calcite precipitates on the surface of the crack and fills pore space in the surrounding backfill, it is likely to have the effect of 'armouring' the crack and reducing the rate of diffusion of Ca^{2+} and OH^- ions from the backfill porewater into the crack. As a consequence, it is probable that, as the calcite builds up on the surfaces of the crack, the rate of deposition would be reduced. This effect is not considered in the

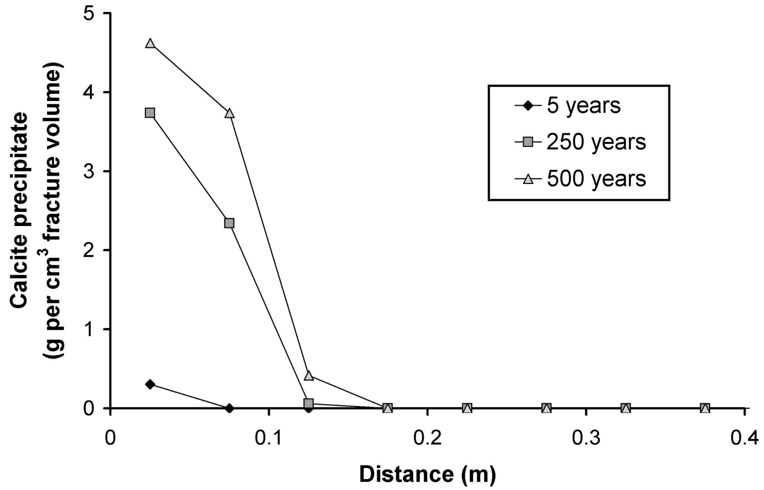

FIG. 8. Predicted calcite deposition within the crack with distance along the crack from the point of groundwater inflow and time for the reference case.

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model, so the predicted thickness of the calcite layer may be an overestimate. Experiments investigating the deposition of calcite in cements have concluded that crack filling tends to occur with narrower cracks (<0.1 mm), but that wider cracks (>0.2 mm) tend to develop impervious layers of calcium carbonate that slow considerably the rate of crack filling (Brodersen and Nilsson, 1992). It is recognized that to model the 'armouring' process correctly would require the use of a coupled reactive transport model that links the precipitation and dissolution reactions to changes in porosity, permeability and groundwater flow (e.g. Benbow *et al.*, 2005; Baston *et al.*, 2011).

Results and discussion for the variant cases

For the crack bordered on both sides with backfill, the quantities of calcite and brucite precipitated were similar to those predicted in the reference case, but concentrated over a smaller distance along the crack. With the narrower 0.2 mm crack, the flow velocity (3 $\mu m\ s^{-1}$, derived in the flow modelling) was higher than that in the 2 mm crack of the reference case. However, as the cross-section of the crack was smaller, the volumetric flow rate was one third of that for the reference case. As a result, conditioning of the water in the crack was predicted to occur for a longer period of time. Doubling the flow in the 0.2 mm crack caused the rate of leaching of components from the backfill to increase and reduced the predicted time taken for the pH to drop.

Using a non-saline groundwater composition based on Dounreay Borehole 1 DET6 water (Nirex, 1994), the strong buffering to pH 10 in the region of brucite precipitation (as seen in the reference case) was not predicted. Instead, there was a gradual drop in pH with time over all regions of the crack. The main reason for this difference seems to be the lower magnesium concentration in this groundwater (Table 3). With smaller quantities of brucite precipitated, fewer hydroxyl ions are consumed in the reaction, giving a higher pH compared to the reference case. The quantities of calcite precipitated were higher than in the reference case. This reflects the concentration of carbonate being higher in this groundwater and shows that calcite precipitation in the reference case was limited by the carbonate concentration in the groundwater, rather than the calcium generated by the backfill.

It is important to note that all the modelling was performed on a 1 m length of crack. Within a GDF vault, groundwater may flow through a number of metres of cracked backfill from the point at which it enters the backfill. For example, if the groundwater flow through a vault was vertical, it would flow through 10 m or more of backfill (depending on how well the cracks were aligned with the flow) but, if the groundwater flow was parallel to the long axis of the vault, the pathway through the cracked backfill could be more than 100 m. Therefore, for some parts of the backfill, the timescale for changes in conditions would be substantially longer than given by the results presented.

Conclusions

An assessment of cracking of cementitious backfill in a GDF vault with an open crown space identified three mechanisms that may lead to cracking. First, during backfilling, plastic settlement under solid horizontal surfaces could result in horizontal gaps of up to 2 mm beneath waste packages. Next, within days of backfilling, early-age thermal contraction of the backfill could result in primarily vertical cracks of up to 0.2 mm. Finally, over a number of years, expansion of waste packages could result in horizontal cracks of up to 5 mm.

The significance of these cracks to groundwater flow and chemistry has been assessed for selected scenarios. Groundwater flow modelling showed that cracking could enhance the flow through a vault. Results from the flow modelling were used in a simple reactive transport model of a crack and surrounding backfill. This found that significant quantities of calcite and brucite may be precipitated in the crack and in backfill bordering the crack. Calcite precipitation is expected to extend further along the crack with time. In some cases this may seal the crack, but it is possible that, on reaching a certain thickness, further deposition of calcite will be stopped or greatly reduced, because the calcite armouring will prevent interaction between calcium from the backfill and carbonate in the groundwater. Brucite can dissolve if the pH of groundwater in the crack reduces sufficiently, resulting in a brucite front moving along the crack. Water in contact with brucite was predicted to have a pH of ~10, with water behind the brucite front having a pH and magnesium concentration closer to that of the groundwater entering the crack. The period of

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conditioning depends on the volumetric groundwater flow rate.

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