ORIGINAL ARTICLE



Database for validation of thermo-hydro-chemo-mechanical behaviour in bentonites

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Abstract

This paper presents a database of thermo-hydro-chemo-mechanical tests on bentonites, which has been named "Bento_DB4THCM". After a comprehensive literature review, a set of experimental tests have been compiled. The experimental data are used to perform validation exercises for numerical codes to simulate the coupled thermo-hydro-mechanical and geochemical behaviour of bentonites. The database contains the information required for the simulation of each experimental test solving a boundary value problem. The validation exercises cover a wide range of clays, including the best-known bentonites (MX-80, FEBEX, GMZ) as well as others. The results collected in this database are from free swelling, swelling under load, swelling pressure and squeezing tests. The database is attached as Supplementary material.

Keywords Bentonite · Experimental tests · Database · Swelling · Salinity

Introduction

The sole objective of radioactive waste management is to protect the environment and all living beings in it from the harmful effects of the radiation they generate (IAEA 2006, 2014). To this end, it has been agreed that the best available option for long-term management is the deep geological disposal of high-level radioactive wastes (IAEA 2011). This strategy is, in most cases, of a definitive nature, as no further re-use of the waste is foreseen.

The main goal of deep geological disposal is to safely store waste for extended periods, reducing its potential danger to safety levels. To this end, the design of passive safety solutions based on a multi-barrier system has been chosen. Multiple layers of both man-made and natural barriers work together to prevent the release of harmful substances or slow their movement into the environment to levels that are considered safe according to regulatory standards. The bedrock where the disposal site is located serves as a natural barrier.

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Geoenvironmental Group, Civil Engineering School, University of Castilla-La Mancha, Avda. Camilo José Cela s/n, 13071 Ciudad Real, Spain In addition, engineered barriers include the ceramic nature of the nuclear fuel, the final disposal container (canister) and the buffer and backfill materials used, mainly compacted bentonites or bentonite mixtures (Bennett and Gens 2008). These clayey materials allow for sealing the gaps between the canister and the host rock (Pusch 1992, 2006; Sellin and Leupin 2014) thanks to their high swelling capacity, high water retention and low hydraulic permeability.

There are different types of bentonites with different fractions of montmorillonite (the mineral that provides the advantageous properties sought in bentonites), depending on their location and/or geological origin. The most commonly studied for the deep geological disposal of radiactive waste are: (i) the MX-80 bentonite, considered as reference material for engineered barriers in countries such as Sweden (Jönsson et al. 2009) and Finland (Kumpulainen and Kiviranta 2010), (ii) the FEBEX bentonite, which is the reference material in Spain (Huertas et al. 2006) and, (iii) the GMZ bentonite, studied in China, the world's largest producer of spent nuclear fuel (Sun et al. 2013). Other clayey materials such as Opalinus Clay (Appelo and Wersin 2007; Mäder 2004) from Mont Terri (Switzerland), the Callovo-Oxfordian Clay (Gaucher et al. 2004) from Meuse/Haute-Marne Underground Research Laboratory (URL) located at Bure (France) and the Boom Clay (Maes et al. 2002; Romero et al. 1999) of Mol (Belgium) are also being currently studied as potential

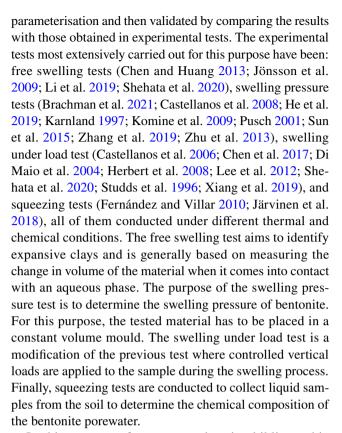


host formations for deep nuclear waste disposal for these countries.

After the installation at the disposal site, the bentonite evolves mechanically (due to its ability to swell when saturating), hydraulically (due to the interaction with natural groundwater) and thermally (due to the heating by the canister). Thus, it is essential to understand the behaviour of these materials under different conditions. During the last few years, a significant effort has been made to characterise the hydro-mechanical (HM) and thermo-hydro-mechanical (THM) behaviour of bentonites (Pintado et al. 2018). However, both buffer and backfill elements will be exposed to the surrounding groundwaters, which can have complex chemical compositions (Hellä et al. 2014; Wersin et al. 2016) that influences directly their hydro-mechanical behaviour (Di Maio et al. 1996; Karnland et al. 2005; Studds et al. 1998; Zhu et al. 2013). Therefore, only a thermo-hydro-mechanical perspective is not enough, but it is also needed to couple chemical effects to provide useful information to simulate the behaviour of bentonites realistically (Sedighi et al. 2018; Steefel et al. 2015). The great variety of couple phenomena that can occur, together with the complex geochemical system of bentonites (Kiviranta and Kumpulainen 2011), requires the use of numerical tools to facilitate the understanding of the behaviour of these materials and to help in the interpretation of experimental results.

The best known codes in the field of deep geological repository spent nuclear fuel are: FADES-CORE from University of A Coruña (Spain) developed in FORTRAN (Mon et al. 2017; Navarro and Alonso 2000; Samper et al. 2018a, b; Zheng et al. 2010, 2011b, 2015; Zheng and Samper 2008), AALTO-THEBES from Aalto University (Finland) developed in NUMERRIN (Abed et al. 2016, 2018; Abed and Solowski 2018; Abed and Sołowski 2017), TOUGH-REACT-FLAC from Lawrence Berkeley National Laboratory (USA) developed in FORTRAN / FLAC (Pruess et al. 1999; Rutqvist et al. 2011; Xu et al. 2004, 2006; Zheng et al. 2011a, 2014, 2015, 2017), COMPASS – PHREEQC from Cardiff University/ University of Manchester and developed in FORTRAN/PHREEQC (Sedighi 2011; Sedighi and Thomas 2014; Sedighi et al. 2016; Seetharam et al. 2007; Thomas and He 1997a, b; Thomas et al. 2012), CODE BRIGHT/BExCM from the Polytechnic University of Catalonia (Spain) developed in FORTRAN (Guimarães et al. 2007, 2013; Guimarães 2002), the VTT-UCLM model from the University of Castilla-La Mancha (Spain) developed in COMSOL (Navarro et al. 2013, 2014a, 2014b, 2015, 2017a, 2017b, 2018) and the model based in iCP (coupling interface of COMSOL and PHREEQC developed by AMPHOS21) presented by (Idiart et al. 2020).

These numerical models alone should not be the only element available to characterise the behaviour of bentonite. They must first be calibrated to obtain an accurate



In this context, after a comprehensive bibliographic search to obtain a significant amount of information about experimental tests, a database on bentonite swelling under different conditions of confinement, temperature and salinity has been developed. The resulting database has been named "Bento_DB4THCM". and is provided as Supplementary Material. It has been implemented in the well-known Microsoft Excel environment and it is composed of several worksheets for each validation exercise. Each worksheet is prepared to indicate the bibliographic reference of the test, the initial and boundary conditions, the time evolution curves of different variables, as well as the bentonite used in the test and its properties. Therefore, the database contains the necessary information for experimental tests to be simulated by solving a boundary value problem, so that they can be used as validation exercises. The bibliographical sources for developing the database are analysed in "Bibliometric analyses" and the use and content of the database are described in "Research distribution analysis".

Bibliometric analyses

Data source

Following a comprehensive literature review, laboratory test data has been collected from a total of 42 documents (Table 1) including 5 reports from organisations such as



 Table 1
 References list of the documents analysed in the database

Reference	Publication type	Journal	Institution	Country	
Brachman et al. (2021)	Journal article	Canadian Geotechnical Journal	Queen's University	Canada	
			Canadian Nuclear Safety Commission	Canada	
Castellanos et al. (2006)	Conference paper	-	Universitat Politècnica de Cata- lunya	Spain	
Castellanos et al. (2008)	Journal article	Physics and Chemistry of the Earth	Universitat Politècnica de Cata- lunya	Spain	
			CIEMAT—Centro de Investiga- ciones Energéticas, Medioambi- entales y Tecnológicas	Spain	
Chen and Huang (2013)	Journal article	Physics and Chemistry of the	Atomic Energy Council	Taiwan	
		Earth	National Central University	Taiwan	
Chen et al. (2017)	Journal article	Applied Clay Science	Tongji University	China	
			Changsha University of Sciences and Technology	China	
			Ecole des Ponts-Paristech	France	
Chen et al. (2018)	Journal article	Applied Clay Science	Tongji University	China	
			Anhui Transport Consulting and Design Institute	China	
			Ecole des Ponts-ParisTech	France	
Chen et al. (2019)	Journal article	Engineering Geology	Tongji University	China	
			Anhui Transport Consulting and Design Institute	China	
			Ecole des Ponts-ParisTech	France	
Chen et al. (2021)	Journal article	Geomechanics for Energy and the	Tongji University	China	
		Environment	Anhui Transport Consulting and Design Institute	China	
			Ecole des Ponts-ParisTech	France	
Cuevas et al. (2002)	Journal article	Applied Clay Science	Universidad Autónoma de Madrid	Spain	
			CIEMAT—Centro de Investiga- ciones Energéticas, Medioambi- entales y Tecnológicas	Spain	
Di Maio et al. (1996)	Journal article	Géotechnique	Università della Basilicata	Italy	
Di Maio et al. (2004)	Journal article	Mechanics of Materials	Università della Basilicata	Italy	
Dixon (2000)	Report	_	Posiva OY	Finland	
Dueck et al. (2011)	Journal article	Clays and Clay Minerals	Clay Technology AB	Sweden	
			SKB—Swedish Nuclear Fuel and Waste Management	Sweden	
Fernández and Villar (2010)	Journal article	Applied Geochemistry	CIEMAT—Centro de Investiga- ciones Energéticas, Medioambi- entales y Tecnológicas	Spain	
Gómez-Espina and Villar (2010)	Journal article	Applied Clay Science	CIEMAT—Centro de Investiga- ciones Energéticas, Medioambi- entales y Tecnológicas	Spain	
He et al. (2016)	Journal article	Applied Clay Science	Tongji University	China	
			United Research Center for Urban Environment and Sustainable Development	China	
			Ecole des Ponts-ParisTech	France	



Table	າ 1	(continu	ned)

Reference	Publication type	Journal	Institution	Country
He et al. (2019)	Journal article	Engineering Geology	Tongji University	China
			Central South University	China
			United Research Center for Urban Environment and Sustainable Development	China
			Ecole des Ponts-ParisTech	France
Herbert et al. (2008)	Journal article	Physics and Chemistry of the Earth	GRS—Gesellschaft für Anlagen- und Reaktorsicherheit	Germany
			University of Greifswald	Germany
			CIEMAT—Centro de Investiga- ciones Energéticas, Medioambi- entales y Tecnológicas	Spain
Järvinen et al. (2018)	Journal article	Clay Minerals	VTT Technical Research Centre	Finland
Jönsson et al. (2009)	Report	-	SKB—Swedish Nuclear Fuel and Waste Management	Sweden
Karnland (1997)	Report	_	Clay Technology AB	Sweden
Karnland and Muurinen (2002)	Conference paper	_	Clay Technology AB	Sweden
			VTT Technical Research Centre	Finland
Karnland et al. (2006)	Report	_	Clay Technology AB	Sweden
Karnland et al. (2007)	Journal article	Physics and Chemistry of the	Clay Technology AB	Sweden
		Earth	Lund University	Sweden
			SKB—Swedish Nuclear Fuel and Waste Management	Sweden
Komine et al. (2009)	Journal article	Canadian Geotechnical Journal	Ibaraki University	Japan
Lee et al. (2012)	Journal article	Engineering Geology	Korea Atomic Energy Research Institute	South Korea
			Korea Institute of Geoscience and Mineral Resources	South Korea
			Inha University	South Korea
Li et al. (2019)	Journal article	Acta Geotechnica	Shanghai Jiao Tong University	China
Navarro et al. (2017b)	Journal article	Engineering Geology	University of Castilla-La Mancha	Spain
			B+Tech Oy	Finland
Pusch (2001)	Report	-	SKB—Swedish Nuclear Fuel and Waste Management	Sweden
Shehata et al. (2020)	Journal article	Bulletin of Engineering Geology and the Environment	University of Ottawa	Canada
Studds et al. (1996)	Conference paper	_	University of Leeds	United Kingdom
Studds et al. (1998)	Journal article	Clay Minerals	University of Leeds	United Kingdom
Sun et al. (2015)	Journal article	Applied Clay Science	Shanghai University	China
			RMIT University	Australia
Sun et al. (2018)	Journal article	Engineering Geology	Tongji University	China
			Ecole des Ponts-ParisTech	France
			China National Offshore Oil Corporation Research Institute	China
Sun et al. (2020)	Journal article	Engineering Geology	Tongji University	China
			Charles University in Prague	Czech Republic
			Ecole des Ponts ParisTech	France
Wang et al. (2012)	Journal article	Engineering Geology	Ecole des Ponts ParisTech	France
			ANDRA—Agence nationale pour la gestion des déchets radioactifs	France



Table 1	(Lacuttural)
Table I	(continued)

Reference	Publication type	Journal	Institution	Country
Xiang et al. (2019)	Journal article	Clays and Clay Minerals	Anhui University of Technology	China
			Shanghai Jiao Tong University	China
Xiang et al. (2020)	Journal article	Engineering Geology	Anhui University of Technology	China
			Tongji University	China
			Shanghai Jiao Tong University	China
Zhang et al. (2016)	Journal article	Engineering Geology	Tongji University	China
			Ecole des Ponts ParisTech	France
Zhang et al. (2019)	Journal article	Engineering Geology	Tongji University	China
Zhang et al. (2020)	Journal article	Acta Geotechnica	Tongji University	China
Zhu et al. (2013)	Journal article	Engineering Geology	Tongji University	China
			United Research Center for Urban Environment and Sustainable Development	China
			Ecole des Ponts ParisTech	France

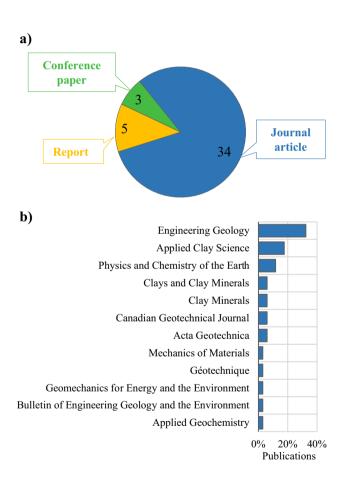


Fig. 1 a Distribution of document type. b Source of the journal arti-

SKB or CIEMAT, 3 conference papers, as well as research articles from 12 internationally leading journals (Fig. 1a). The 50% of the journal articles used in the database come from Engineering Geology (IF=6.755, 2020 JCR) together with Applied Clay Science (IF=5.467, 2020 JCR), with the 32% and the 18%, respectively (Fig. 1b). The review covers the period from 1996 to 2021. Figure SI1 shows how the number of publications increases in the last few years, being the 2019 and 2020 the years with the highest number of publications. The selected research papers involve 36 organisations including universities, scientific-technical companies, and research centres from 14 countries. The collaborative relationships between them are discussed in the next section.

Research distribution analysis

Analytical tool

VOSviewer was the tool used to present the bibliometric analysis. It was developed in the Java programming language and the version used (VOSviewer 1.6.17) was released on July 22, 2021 (van Eck and Waltman 2021). VOSviewer allow the construction of node-link maps based on bibliographic data to visualize the networks, and to identify the structure of the study field (van Eck and Waltman 2010). VOS stands for visualization of similarities, which is a mapping technique based on a co-occurrence matrix adopted by the computer program to map research trends of studies (van



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Eck et al. 2010). Each node-link map created by VOSviewer represents a co-authorship or co-occurrence network of one type of item, which can be researchers, countries, research institutions, journals, and keywords. Besides, based on the bibliographic database files such as Scopus, VOSviewer connects these items in the networks through bibliographic coupling, citation, or co-citation links (van Eck and Waltman 2017). Therefore, these maps can be used to visually analyse the research trends.

Co-authorship analysis

The co-authorship maps analyse researchers' connections, to reveal their collaborations, as well as collaborative behaviour between institutions and countries. The relatedness of item is

 Table 2
 The ten researchers with the highest participation in the database.

Author	Document	Co-authorship link strength
Ye, W. M	13	53
Chen, Y. G	12	50
Cui, Y. J	11	46
Chen, B	6	26
Villar, M. V	6	12
Karnland, O	5	6
Wang, Q	4	16
Dong, X. X	3	12
Zhang, F	3	12
Zhang, X. D	3	12

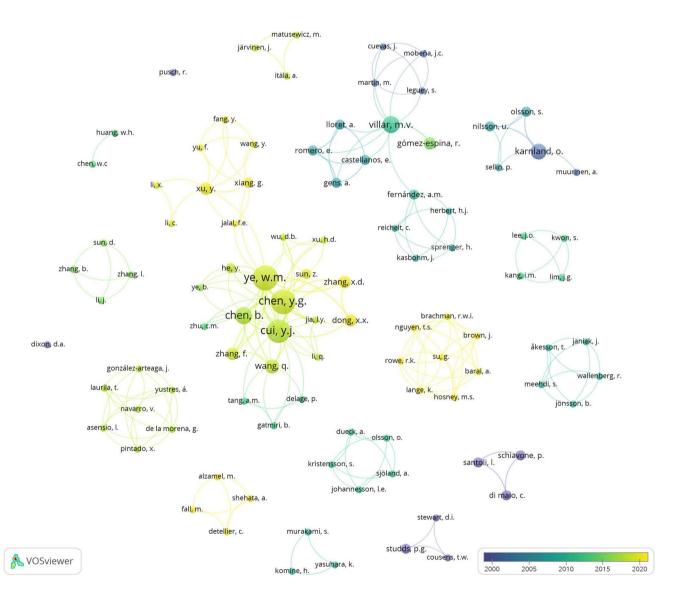


Fig. 2 Overlay map of the co-authorship network between researchers



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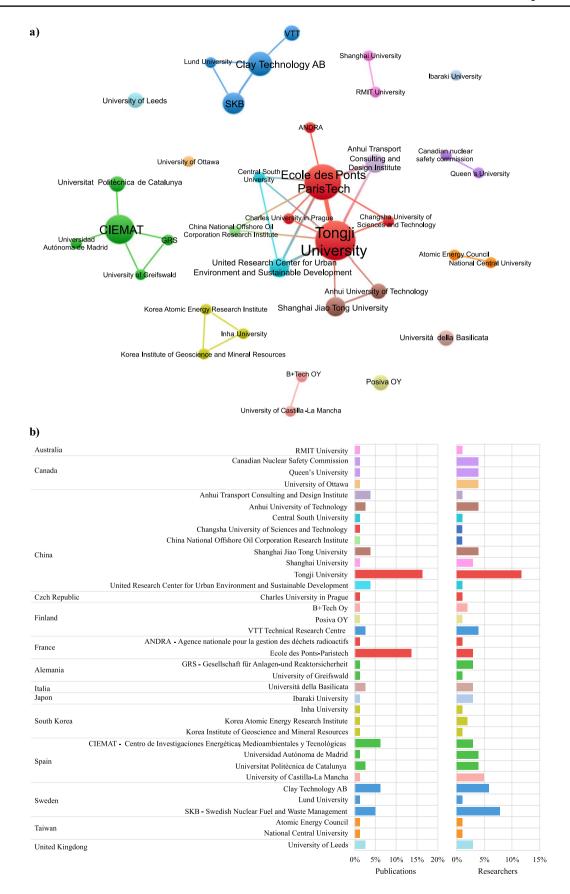


Fig. 3 a Co-authorship network between research institutions. b Distribution of research institutions participation of documents and researcher in the database

 Table 3
 The five researcher institions with the highest participation in the database

Researcher institutions	Documents	Co-authorship link strength
Tongji University (China)	13	22
Ecole des Ponts-Paristech (France)	11	21
CIEMAT (Spain)	5	4
Clay Technology AB (Finland)	5	4
SKB (Sweden)	4	3

Table 4 The five journal articles of the database with the highest number of cites

Journal article	Citations	Citing and cited links
Di Maio et al. (1996)	291	6
Di Maio et al. (2004)	177	5
Wang et al. (2012)	147	4
Castellanos et al. (2008)	118	10
Zhu et al. (2013)	108	14

determined based on their number of co-occurrences in the documents that have been chosen to develop the database. The first analysis shows the co-authorship links between researchers (Fig. 2). Altogeter, 100 authors are involved, grouped into

19 clusters. The colour of the clusters shows the chronological distribution of the publication of documents. Table 2 shows that W. M. Ye is the researcher with the highest participation in the database with 13 papers, followed by Y. G. Chen (12 papers) and Y. J. Cui (11 papers). Moreover, these researchers are the most colaborative authors as they have the highest co-authorship link strength, which indicate the number of co-ocurrences that a given researcher has with other colleagues.

Figure 3 shows well-defined groups, although the coauthorship analysis between institutions shows how these clusters are formed by researchers from different research organizations (Fig. 3a). Only five of the 36 institutions involved in the documents of the database has no coauthored interrelationships. The first position in terms of the volume of publications correspond to Tongji University, which has participated in 13 papers, and in second place is Ecole des Ponts-ParisTech, which has participated 11 papers (Table 3). These two institutions also have the strongest coauthorship linking, showing their researcher are the most colaborative authors of the document analysed in the database. Besides, Tongji University is the institution with the highest numbers of researchers (Fig. 3b).

The co-authorship analysis between countries (Fig. SI2a) shows two clusters and six countries without co-authorship links. The size of the circles and labels indicates the number of documents in which the country has participated. Therefore, Fig. SI2a show that most of the papers studied in the database was done by researchers from Chinese and French



Fig. 4 Bento_DB4THCM home interface



Table 5 Sheet design for a validation exercise of Bento_DB4THCM

· ·	
Bentonite name	
Bentonite type	
Mineralogical composition of bentonite	Montmorillonite
	Calcite
	Quartz
	Feldspar
	Gypsum
Properties	Grain density
	Liquid limit
	Plastic limit
	Cation exchange capacity
	Specific surface area
Exchangeable cations	Na
	Ca
	Mg
	K
Type of test	
Initial conditions	
Thermal	Temperature
Hydraulic	Water content
Mechanical	Dry density
	Vertical stress
Chemical	Porewater
Boundary conditions	
Thermal	Top boundary
	Bottom boundary
	Lateral boundary
Hydraulic	Top boundary
	Bottom boundary
	Lateral boundary
Mechanical	Top boundary
	Bottom boundary
	Lateral boundary
Chemical	Infiltration water
Geometry	
Cylindrical specimen	Height
	Diameter
Results	
Observations	
Reference	
Link	

institutions. Figure SI2b shows that the countries with the highest number of institutions are China (25%), following by Spain (11%).

Citation analysis

The citation map analyses the links of citing and cited of each document, and thus, can help in identifying the main works. In this study, the document type was restricted to journal articles and conference papers due to the citation data was obtained from the Scopus citation database, in which reports are not included. Therefore, the citation analysis considered 36 of the 42 documents collected for the database. Figure SI3 shows most of the document has citation links in just one cluster and only three documents have not citation links. The size of the circles and labels is determined based on the number of citations each paper has. To know whether they are cited or citing works, take into account the years of publication of each one. The works with the highest number of citations are Di Maio et al. (2004), with 291 and 177 citations as shown in Table 4.

Database

Interface

Bento_DB4THCM has been developed in Microsoft Excel[®], thus making the information accessible in a user-friendly environment. The database has been structured in a home sheet (Fig. 4) and a series of validation exercises sheets (Table 5). The home sheet has a dashboard with three blocks: "Bentonite", "Test" and "Reference". The first block, "Bentonite", is used to select the bentonite type. The next block, "Test", is developed to select the test according to its confining conditions (free swelling, swelling pressure, swelling, or squeezing tests). In addition, the temperature and the infiltrating water can be chosen also. Finally, the third block, "Reference", is designed to search a case by its first author and the publication year of the reference document. According to the selection made, a list of exercises is displayed in the section "Validation exercises" with a link to the corresponding sheet. Each validation sheet contains information on the bentonite being tested, the initial and boundary thermal, hydraulic, mechanical and chemical conditions, results which have been digitised from the figures in the published documents. Table 6 shows a summary of the validation exercises obtained from each document. Altogether, 357 validation exercises are obtained from this review.



Table 6 Summary of validation exercises in the database

Reference	Bentonite						Test				Infiltration water	Temperature (°C)	Validation
	FEBEX (GMZ	GMZ MX-80 Others	1	Calcium	Sodium	Free swelling	Squeezing	Swelling pressure	Swelling under load			exercises
Brachman et al. (2021)			×	×		×			×	×	Hypersaline	22	10
Castellanos et al. (2006)	×				×					×	CaCl ₂ NaCl	20	12
Castellanos et al. (2008)	×				×				×	×	Saline Granitic CaCl ₂ NaCl	20	22
Chen and Huang (2013)				×	×		×				Na ₂ SO ₄ CaCl ₂ NaCl	30	36
Chen et al. (2017)	,	×				×				×	NaCl-CaCl ₂ NaCl- DW-CaCl ₂	20	2
Chen et al. (2018)		×				×				×	CaCl ₂ NaCl	20160	24
Chen et al. (2019)	, ,	×				×			×		NaCl	20160120—401 20—60	14
Chen et al. (2021)		×				×				×	NaCl	20—60	12
Cuevas et al. (2002)	×				×				×	×	Saline Granitic	20 100-60 60-35	10
Di Maio et al. (1996)				×		×				×	CaCl ₂ NaCl KCl	20	4
Di Maio et al. (2004)				×		×				×	NaCl Natural—DW	20	15
Dixon (2000)		. 1	×			×				×	Brackish Brine Fresh Saline	20	4
Dueck et al. (2011)			×			×				×	Natural Na-Ca-Cl	14—95 17—25	2
Fernández and Villar (2010)	×				×			×			Granitic	100—20	
Gómez-Espina and Villar (2010)											Deionized Water	140—30	П
He et al. (2016)		×				×				×	NaCl	20	2
He et al. (2019)		×				×			×	×	NaCl KCl KOH	20	6
Herbert et al. (2008)			×			×				×	Aspo IP21 NaCl IP21c NaClc Opalinus YPC	20	7
Järvinen et al. (2018)			×			×		×			Ca-rich solution	20	4
Jönsson et al. (2009)			×		×	×	×				NaCl	25	9
Karnland (1997)		. 1	×			×			X		NaCl	22	1
Karnland and Muurinen (2002)		. ,	×			×			×		NaCl	20	4
Karnland et al. (2006)				×	×	×			×		CaCl ₂ NaCl	20	15
Karnland et al. (2007)			×		×	×			×		CaCl ₂ —Ca(OH) ₂ NaCl—NaOH NaCl—NaOH — DW	20	12
											NaOH I NaCi		



Reference	Bentonite					Test				Infiltration water	Temperature (°C)	Validation
	FEBEX GMZ MX-80 Others Calcium Sodium Free swelling Squeezing Swelling pressure	MX-80	Others	Calcium	Sodium	Free swelling	Squeezing	Swelling Swell: pressure under load	Swelling under load			exercises
Komine et al. (2009)		×	×		×			×	×	Seawater	20	15
Lee et al. (2012)			×	×					×	NaCl	20	_
Li et al. (2019)			×		×	×				CaCl ₂ Na ₂ SO ₄ NaCl	25	12
Navarro et al. (2017b)		×			×	×				Brackish Saline Saline Highly Saline	20	3
Pusch (2001)		×			×			×		CaCl ₂ NaCl	20	2
Shehata et al. (2020)		×			×	×			×	Guelph Trenton	23 40 80	~
Studds et al. (1996)		×			×				×	AICl ₃ CaCl ₂ CsCl KCl MgCl ₂ NaCl	20	17
Studds et al. (1998)		×			×				×	Chloride salts	20	3
Sun et al. (2015)	×			×	×			×		NaCl-Na ₂ SO ₄	25	10
Sun et al. (2018)	×				×			×		BSW ECW YCW	20	9
Sun et al. (2020)	×				×			×		BSW ECW YCW BSW—ECW—YCW	20160	9
Wang et al. (2012)		×			×			×	×	Synthetic	20	5
Xiang et al. (2019)	X				×				×	$CaCl_2 \mid NaCl$	25	9
Xiang et al. (2020)	×				×				×	$CaCl_2 \mid KCl \mid NaCl$	25	9
Zhang et al. (2016)	×				×				×	NaCl	20	6
Zhang et al. (2019)	×				×			×		NaCl	20	9
Zhang et al. (2020)	×				×				×	NaCl	20	9
Zhu et al. (2013)	×				×			×		CaCl ₂ NaCl	20	~

Table 6 (continued)

YPC young portland cement, BSW Beishan site water, YCW young cement water, ECW evolved cement water



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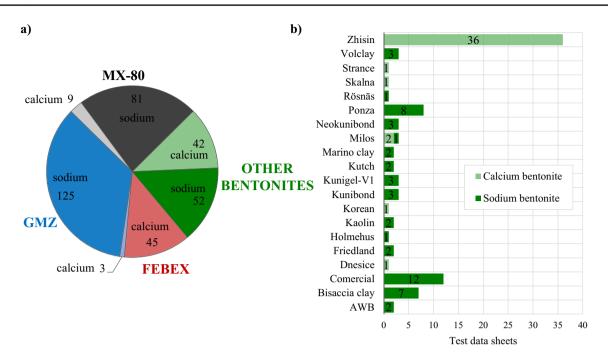


Fig. 5 Distribution of validation exercises in calcium or sodium bentonite of a main bentonites and b other bentonites (AWB alternate Wyoming bentonite)

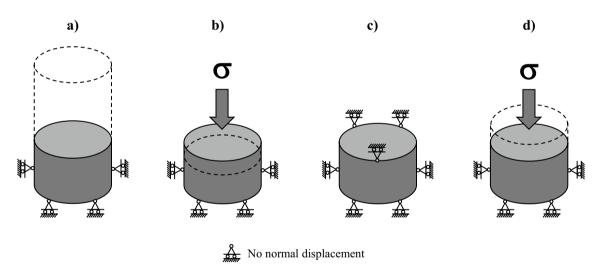


Fig. 6 a Free swelling test, b squeezing test, c swelling pressure test and d swelling test

Materials

Most of the laboratory tests collected for this database have been carried out on extensively studied bentonites: GMZ (128 validation exercises), MX-80 (90 validation exercises) and FEBEX (45 validation exercises). However, the database also includes tests carried out on other bentonites (94 validation exercises). Figure 5 shows the distribution of validation exercises in each bentonite and whether it is calcium or sodium bentonite. As a result, almost three quarters of the validation exercises are carried out on sodium bentonites

Table 7 Validation exercises distribution according to bentonite and test in the database

	FEBEX	GMZ	MX-80	Others	Total
Free swelling test	0	0	15	48	63
Swelling pressure test	10	51	28	18	107
Swelling under load test	34	77	42	28	181
Squeezing test	1	0	5	0	6
Total	45	128	90	94	357



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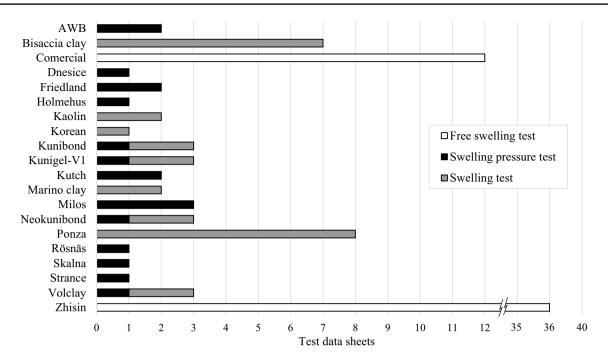


Fig. 7 Validation exercises distribution according to other bentonites and test in the database (AWB alternate Wyoming bentonite)

(258 validation exercises) and just over a quarter on calcium bentonites (99 validation exercises). The information about the tested bentonite included in each validation sheet is the mineralogical composition and some additional properties such as the grain density, liquid limit, plastic limit, cation exchange capacity, specific surface area and exchangeable cations (Table 5).

Tests

In the database, the tests have been classified according to the mechanical boundary conditions in free swelling test, swelling pressure test, swelling test, and squeezing tests (Fig. 6). Table 7 summarises the number of validation exercises in the database for each type of test performed on each type of bentonite. For other bentonites, Fig. 7 shows the distribution of validation exercises. These tests are carried out under different thermal and chemical conditions. Although the most common tests are carried out with chloride salts (NaCl and CaCl₂), a wide selection of infiltrating waters has been collected in the database as Fig. 8 shows. Note that squeezing tests are performed to obtain liquid

samples from soil to characterise the chemical composition of the aqueous saline solution in its pores.

Conclusions

The database published herein aims to help validate new codes for modelling the thermo-hydro-chemo-mechanical behaviour of bentonites. A substantial amount of validation exercises was included in the database. From a mechanical point of view, the results included correspond to free swelling, swelling under load, swelling pressure and squeezing tests. The infiltration water used in these tests ranges from NaCl or CaCl₂ solutions to groundwaters of complex composition. Besides, the database not only cover the most known bentonites (MX-80, FEBEX and GMZ) but also includes other bentonites that might be of interest for use as engineered barriers in deep geological repositories for nuclear fuel. The database should always be in a continuous review and update process to include new developments in experimental testing.



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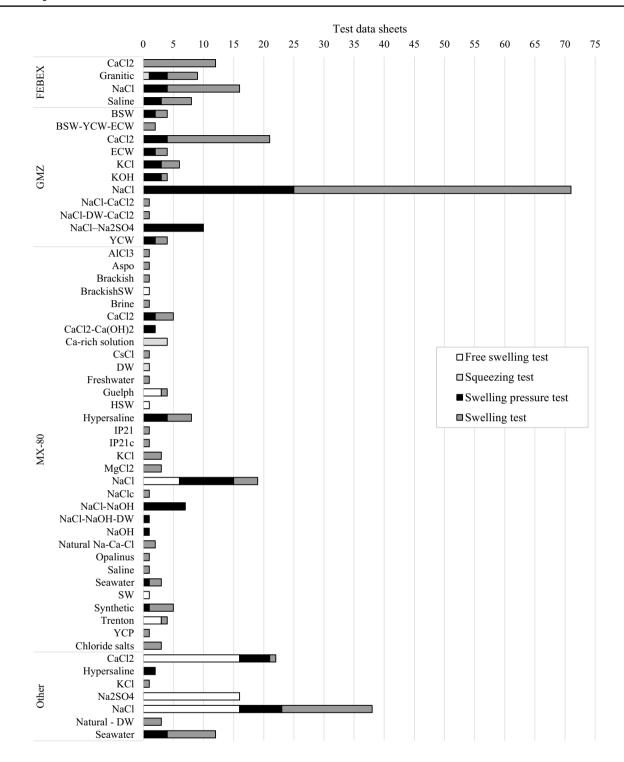


Fig. 8 Validation exercises distribution of experimental tests according to infiltration water and bentonite type in the database (BSW Beishan site water, YCW young cement water, ECW evolved cement water)

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Availability of data and materials The data for the experimental tests are available in the database provided in the supplementary material. Data supporting the tables and figures are available on request.

Declarations

Conflict of interest The authors have no relevant financial or non-financial interests to disclose.

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