FORGE

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European Commission FP7

Review of Boom Clay and Opalinus Clay parameters

FORGE Report D4.6 – VER 1.0

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Euratom 7th Framework Programme Project: FORGE

EURATOM

Fate of repository gases (FORGE)

The multiple barrier concept is the cornerstone of all proposed schemes for underground disposal of radioactive wastes. The concept invokes a series of barriers, both engineered and natural, between the waste and the surface. Achieving this concept is the primary objective of all disposal programmes, from site appraisal and characterisation to repository design and construction. However, the performance of the repository as a whole (waste, buffer, engineering disturbed zone, host rock), and in particular its gas transport properties, are still poorly understood. Issues still to be adequately examined that relate to understanding basic processes include: dilational versus visco-capillary flow mechanisms; long-term integrity of seals, in particular gas flow along contacts; role of the EDZ as a conduit for preferential flow; laboratory to field up-scaling. Understanding gas generation and migration is thus vital in the quantitative assessment of repositories and is the focus of the research in this integrated, multi-disciplinary project. The FORGE project is a pan-European project with links to international radioactive waste management organisations, regulators and academia, specifically designed to tackle the key research issues associated with the generation and movement of repository gasses. Of particular importance are the long-term performance of bentonite buffers, plastic clays, indurated mudrocks and crystalline formations. Further experimental data are required to reduce uncertainty relating to the quantitative treatment of gas in performance assessment. FORGE will address these issues through a series of laboratory and field-scale experiments, including the development of new methods for up-scaling allowing the optimisation of concepts through detailed scenario analysis. The FORGE partners are committed to training and CPD through a broad portfolio of training opportunities and initiatives which form a significant part of the project.

Further details on the FORGE project and its outcomes can be accessed at www.FORGEproject.org.

D4.6 (WP4)

Progress report – review of Boom Clay and Opalinus Clay parameters

Introduction

The FORGE project contains a number or laboratory and in situ tests carried out involving a Boom Clay and Opalinus Clay host rocks. The Boom Clay is the claystone in which the Mol laboratory (Belgium) was constructed. The Opalinus Clay is the claystone in which the Mon Terri laboratory (Switzerland) was constructed. The two are considered indurated clays so they are more a rock than a soil. Probably the most important properties, in regard to radioactive waste disposal, are their low permeability and their ductile deformability.

This deliverable contains a summary of properties of Boom Clay and Opalinus Clay that has been compiled from the literature.

Boom Clay

Bertrand et al (2009) has carried out a literature review of Boom Clay properties (Table 1). The bulk and dry density indicate the moderate degree of compaction of the material. Actually, this is consistent with porosity in the range of 35-40%. The water content corresponds normally with the saturated condition of the rock. The permeability given by the different authors is quite consistent in the range of $2\text{-}5\times10^{-12}$ m/s and no anisotropy has been found. The friction angle is of the order of 18° and as a clay cohesion has been measured, with a value above 0.3 MPa. The elastic modulus varies between 200 and 400 MPa, which is consistent with the relatively high porosity and low strength of this claystone.

Table 1. Boom Clay properties (compiled by Bertrand et al 2009)

Parameter	Symbol	Units	Bernier et al. (2007)	Bastiaens et al. (2006)	Mertens et al. (2004)	Belanteur et al. (1997)	Dehandschutter et al. (2005)	Delage et al. (2000)	Gens et al. (2007)	Laloui (1993)	Baldi et al. (1987;1991)	SCK-CEN (1997)	TIMODAZ (2007)
Bulk density	ρ_{sat}	t/m^3			1.9 - 2.1							1.9 - 2.1	
Dry skeleton density	ρ_{dry}	t/m^3					1.9		1.61 - 1.78		1.9		
Porosity	n	%	39	39	36 - 40		35	40	>30		37.5	33 - 40	
Solid density	ρ_s	t/m^3				2.67							
Natural water content	w_{nat}	%		30 - 40	19 - 24		25 - 30	24 - 30	>9.5			22 - 27	
Natural degree of saturation	S_r	%										95 - 100	
Liquid limit	w_L	%				59-76	70				66.6	70 - 83	
Plastic limit	w_P	%				22-26	25					25 - 28	
Horizontal permeability	k_H	10^{-12} m/s	2.0 - 4.0	1				2.5 - 3.5	2.0 - 5.0			4	
Vertical permeability	k_v	10^{-12} m/s	2.0 - 4.0	1				2.5 - 3.5	2.0 - 5.0			2	
Internal friction angle	Φ'	º	18		11		18			19.5			18 - 25
Cohesion	c'	MPa	0.3	0.5-1	0.396							0.6 - 1.2	0.3
Dilatancy angle	ψ	º	0 - 10							23			
Unconfined compression stre	UCS	MPa	2	2	2.2-28				2				
Young's Modulus	E	MPa	300	200 - 400	200 - 400				200 - 400	330			300
Poisson ratio	υ	-	0.125	0.4 - 0.45	0.4		0.4			0.134			

The strength and deformation parameters compiled in table 1 correspond to the classical approach of linear elasticity combined with a failure criterion, in this case the Mohr Coulomb. But this is insufficient when dealing with the mechanical problem coupled to flow of water and energy under saturated/unsaturated conditions.

In this case it is important to know the compressibility and the strength of the rock under elastic and plastic deformation proceses, and under saturated/unsaturated conditions. In this situation, the response of the clays can be better described with more comprehensive elastoplastic models for unsaturated materials as for instance the BBM model. Table 2 shows the parameters of the BBM model (Alonso et al., 1990) for Boom Clay given by Delahaye & Alonso (2002). The values compiled in TIMODAZ (2007) for the non-linear elasticity and elastoplasticity parameters, as well as the initial preconsolidation pressure in saturated conditions, are also included. Table 3 shows the hydro-mechanical in situ state of Boom Clay formation at depth of 223m, corresponding to the URL (Underground Research Laboratory) at Mol.

The parameters indicate a relatively high degree of compaction as the preconsolidation stress reaches 6 MPa. So, although the vertical effective stress is of the order of 2.2 MPa, the rock has experienced a higher value in the past. This is consistent with the value of the OverConsolidationRatio (OCR) that indicates that the Boom Clay has been unloaded from a higher effective stress.

Table 4 shows the values of the Van Genutchen model for the retention curve given by Delahaye & Alonso (2002) after fitting the experimental curve obtained by Volckaert et al. (1995).

Table 2. Elastoplastic constitutive model parameters for Boom Clay (Delahaye & Alonso, 2002)

Parameter	Symbol	Units	Delahaye & Alonso (2002)	TIMODAZ (2007)
Elastic volumetric compressibility agaist mean stress changes	κ	-	0.0265	0.013-0.046
Elastic volumetric compressibility agaist suction changes	κ_s	-	0.0322	
Poisson's ratio	υ	-	0.333	
Elastoplastic volumetric compressibility	$\lambda(0)$	-	0.26	0.13-0.178
Parameters to define LC yield curve	r	MPa^{-1}	0.564	
	β	-	54.4	
Parameters to define increase in strength with suction	k	-	0.1	
Reference stress	p_c	MPa	0.06	
Slope of critical state	M	-	1	
Parameter for the plastic potential	α	-	0.395	
Initial preconsolidation stress for saturated conditions	P_0*	MPa	6	5.0-6.0
Initial void ratio	e_0	-	0.588	

Table 3. In situ conditions of Boom Clay formation at Mol URL

Parameter	Symbol	Units	Bernier et al. (2007)	Bastiaens et al. (2006)	Bernier et al. (2002)	Horseman et al. (1987)	Mertens et al. (2004)	Horseman et al. (1993)	Delage et al. (2000)	SCK-CEN (1997)	Delahaye et al.(2002)	TIMODAZ (2007)
Coeff. of earth pressure at rest	K_0	-	1	0.9	0.3 - 0.9	0.5 - 0.8	1	0.8	0.8 - 1			
Overconsolidation ratio	OCR	-	2.4	2.4		2.4						2.05 - 2.64
Total vertical stress	σ_V	MPa	4.5	4.5			4.6			4.6		
Effective vertical stress	σ'_V	MPa	2.25	2.3		2.5	2.4		2.45			
Pore water pressure	p_w	MPa	2.25	2.2			2.2					
Preconsolidation pressure	p'_0	MPa	5.4			6					6	5.0 - 6.0

Table 4. Van Genuchten model parameters for retention curve (Delahaye & Alonso, 2002).

Parameter	Symbol	Units	Value
Parameter related to air entry value	P	MPa	3.44
Shape fuction	λ	-	0.3

Opalinus Clay

As indicated above, the Opalinus Clay is the rock where the Mont Terri laboratory was constructed. Tables 5 to 8 show a compilation of parameters given by Bock (2001), which is a recommendation for the selection of the rock mechanical parameters for Opalinus Clay at the region of Mont Terri (ambient conditions with an overburden of 250m).

The density of the order of 2.45 for the value under natural conditions and the value of the order of 2.34 for the value under dry conditions indicate a low pore volume (considering that the density of the particles is 2.71. These values are consistent with the low porosity given close to 10%, and the low water content. This is therefore a dense claystone.

Table 5. Opalinus Clay properties as given by Bock (2001)

Parameter	Symbol	Units	Value	Range (+-)
Bulk density	ρ	t/m^3	2.45	30
Dry bulk density	ρ_d	t/m^3	2.34	60
Grain density	ρ_s	t/m^3	2.71	30
Water content	w	%	6.1	1.9
Porosity	n	%	13.7	3.1
Liquid limit	w_L	%	38	5
Plastic limit	w_P	%	23	2
Plasticity Index	$P.I.$	%	15	3
Carbonate content	C_{RCO3}	%	9.4	5.9
$CaSO_4$ content	C_{CaSO4}	%	0.26	0.05

Table 6. Opalinus Clay deformation parameters for isotropic linear elastic model as given by Bock (2001)

Parameter	Symbol	Units	Recommended value
Tangent modulus	$E_{t\text{-}50}$	MPa	5000
Young's modulus	E	MPa	6000
Poisson's ratio	υ	-	0.27

Table 7. Opalinus Clay deformation parameters for transverse isotropic linear elastic model as given by Bock (2001)

Parameter	Symbol	Orientation to bedding	Units	Recommended value
Tangent modulus	$E_{t\text{-}50\ 1}$	Perpendicular	MPa	3000
	$E_{t\text{-}50\ 2\ and\ 3}$	Parallel	MPa	6000
Young's modulus	E_1	Perpendicular	MPa	4000
	$E_2 = E_3$	Parallel	MPa	10000
Poisson's ratio	υ_{23}	-	-	0.33
	$\upsilon_{12} = \upsilon_{13}$	-	-	0.24
Shear modulus	$G_{12} = G_{13}$	-	MPa	1200

Table 8. Opalinus Clay strength parameters as given by Bock (2001)

Parameter	Symbol	Orientation to bedding	Units	Recommended value
Uniaxial compressive strength	$UCS_{\perp}$	Perpendicular	MPa	16
	$UCS_{\parallel}$	Parallel	MPa	10
Uniaxial tensile strength	$UCS_{\perp}$	Perpendicular	MPa	1
	$UTS_{\parallel}$	Parallel	MPa	2
Shear strength of material	$c'_{\perp}$	Perpendicular	MPa	5
	$c'_{\parallel}$	Parallel	MPa	2.2
	Φ'	-	^{o}	25
Shear strength of bedding planes	$c'_{bedding}$	-	MPa	1
	$\Phi'_{bedding}$	-	^{o}	23

The very high density of the claystone leads to a quite high Young modulus with no influence of the loading/unloading conditions. The cohesion is of the material ranges from 2 to 5 MPa and the friction angle in the range of 25°. Both parameters show

sensitivity to the bedding, i.e. lower strength for shear parallel to the bedding conditions.

Table 9 shows the hydraulic properties for Opalinus Clay given by Marschall et al. (2004). The permeability of the Opalinus Clay is in the range of 10^{-12} to 10^{-14} m/s and anisotropy is expected because the existence of the bedding planes.

Table 9. Hydraulic properties of Opalinus Clay at Mont Terri (Marschall et al., 2004)

Parameter	Symbol	Units	Facies	Range
Hydraulic conductivity	*k*	*m/s*	Carbonate rich sandy facies	$4 \cdot 10^{-13}$ - $9 \cdot 10^{-13}$
		m/s	Sandy facies	$2 \cdot 10^{-14}$ - $2 \cdot 10^{-13}$
		m/s	Shaly facies	$4 \cdot 10^{-14}$ - $2 \cdot 10^{-12}$

The values given by Willeveau (2005) in Table 10 confirm similar ranges, as given above.

Table 10. Reference parameters for Opalinus Clay (Willeveau, 2005)

Parameter	Symbol	Units	Orientation to bedding	Reference value	Range
Clay content	-	%	-	62	44 - 80
Carbonate content	-	%	-	14	6 - 22
Quartz content	-	%	-	18	10 - 27
Density	ρ	t/m^3	-	2.45	+ - 0.03
Water content	*w*	%	-	6.1	+ - 1.9
Porosity	*n*	%	-	15.7	+ - 2.2
Uniaxial compression strength	R_C	MPa	Parallel	10	+ - 6
			Perpendicular	16	+ - 6
Tensile strength	R_T	MPa	Parallel	1	-
			Perpendicular	0.5	-
Cohesion	*c'*	MPa	Parallel	2.2	-
			Perpendicular	25	-
Internal friction angle	Φ'	º	Parallel	5	-
			Perpendicular	25	-
Elastic modulus	*E*	MPa	Parallel	10000	+ - 3700
			Perpendicular	4000	+ - 1000
Poisson ratio	υ	-	Parallel	0.24	-
			Perpendicular	0.33	-
Water permeability of sound clay	*k*	m/s	-	10^{-13}	10^{-13} - 10^{-12}
Biot's coefficient	*b*	-	-	0.6	0.42 - 0.78

Table 11 shows the properties considered by Gens et al. (2007) in the simulation of a heating test in Opalinus Clay at the Mont Terri underground research laboratory. The parameters of the composite mechanical constitutive model for argillaceous rocks (Vaunat & Gens, 2003; Gens et al., 2007) are indicated in table 12. The values are consistent. For instance the intrinsic permeability, should be multiplied by 10^7 to obtain the water hydraulic conductivity leading to the same range as given above.

Table 11. Opalinus Clay properties for 3D THM analysis (Gens et al., 2007)

Parameter	Symbol	Units	Orientation to bedding	Value	Comment
Young's Modulus	E	MPa	Parallel	9300	Back-analysis of borehole excavation. Anisotropic
			Perpendicular	5800	stiffness ration from Bock (2001)
Poisson's ratio	υ	-		0.295	Reference value
Intrinsic permeability	k_i	m^2	-	$5 \cdot 10^{-20}$	Back-analysis from borehole excavation
Biot coefficient	b	-	-	0.6	Reference value
Solid compressibility	β_s	MPa^{-1}	-	$2.5 \cdot 10^{-5}$	From mineral composition
Specific weight	ρ_s	t/m^3	-	2.7	Reference value
Porosity	n	-	-	0.137	Martin & Lanyon (2003)

Table 12. Composite mechanical constitutive model parameters for Opalinus Clay (Gens et al., 2007)

Parameter	Symbol	Units	Orientation to bedding	Value
Bonding Young's modulus	E_{b0}	MPa	Parallel	18150
			Perpendicular	11315
Matrix Young's modulus	E_m	MPa	Parallel	3720
			Perpendicular	2320
Bonding Poisson's ratio	υ_b	-	-	0.295
Matrix Poisson's ratio	υ_m	-	-	0.295
Structuration Parameter	χ	-	-	1.2
Bonding concentration	c_b	-	-	0.3
Damage threshold	r_0	MPa·m/m	-	10^{-3}
Damage evolution	r_1	-	-	1.8

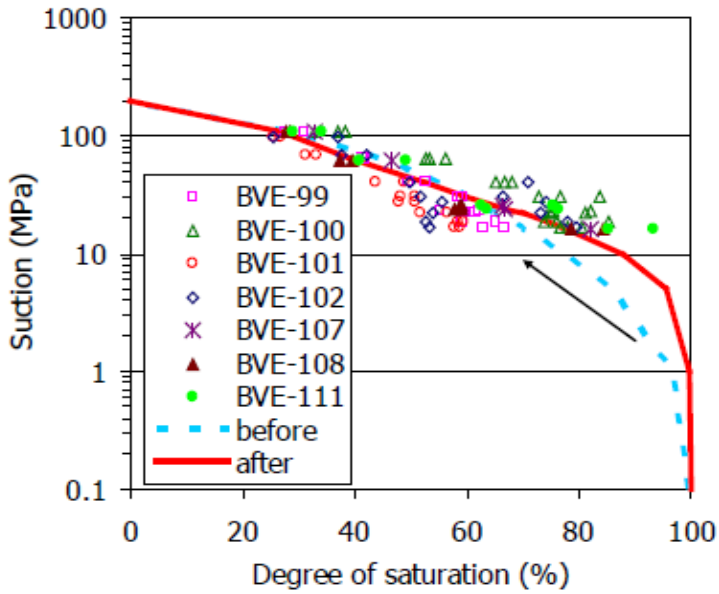

Figure 1. Water retention curves and fitting before and after a ventilation phase (Villar et al., 2009).

Figure 1 shows the retention curves obtained by Villar et al. (2009) under free volume conditions on samples taken from Mont Terri, before and after an in situ ventilation test. The experimental values were fitted using the Van Genuchten model (1980). The values of the fitted parameters appear in table 13.

Table 13. Van Genuchten model parameters for retention curve, before and after a ventilation phase (Villar et al., 2009)

Parameter	Symbol	Units	Before ventilation	After ventilation
Parameter related to air entry value	P	MPa	8.4 - 12.8	16.3 - 20.3
Shape fuction	λ	-	0.28 - 0.34	0.37 - 0.43

Figure 2 shows the retention curves obtained by Muñoz (2006) under isochoric conditions on samples taken from Mont Terri. The experimental values were fitted using the Van Genuchten model (1980). The values of the fitted parameters appear in table 14. The first values correspond to the retention curve of figure 2. The second values are given by back-analysis of a laboratory heating test under constant volume conditions (Muñoz, 2006).

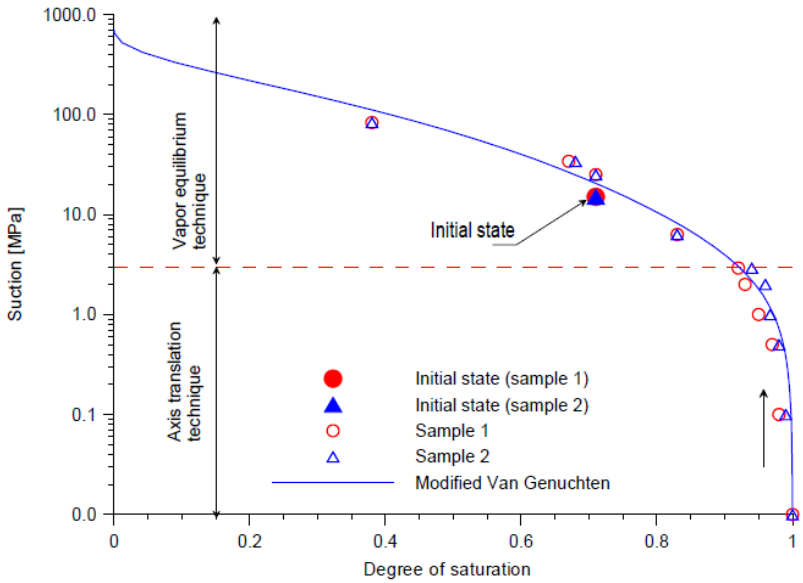

Figure 2. Water retention curve in the drying path for 2 samples under constant volume conditions (Muñoz).

Table 14. Van Genuchten model parameters for retention curve (Muñoz, 2006)

Parameter	Symbol	Units	Value 1	Value 2
Parameter related to air entry value	P	MPa	3.9	8.6
Shape fuction	λ		0.128	0.32

Concluding remarks

This report contains a summary of hydro-mechanical properties for Boom and Opalinus Clay. In both cases, the mechanical properties show the evolution of the constitutive models. Originally, the values of the three parameters of Young modulus, friction angle and cohesion were measured. The most recent parameters indicate that more elaborated constitutive models are available and applied to modelling.

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