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Investigation on Mechanical Behaviour of Coal and Overburden Rock for UCG

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SUMMARY

In recent years, the coupled UCG-CCS process has been considered as another potential CCS option, which can offer integrated energy recovery from coal and storage of CO2. However, existing potential problems may counteract its potential benefits. To develop a generic UCG-CCS site characterisation workflow, different aspects of this complex process, such as cavity progression and geomechanics, contamination of groundwater and subsidence impacts, need to be re-considered and understood. In this process, the thermo-mechanical behaviour of the roof rock and coal are the initial parameters to predict the stability and the development of the production cavity. These parameters affect heat conduction and the stability and caving of roof materials, especially under conditions of high stress and temperature. In this study, several experimental setups have been designed and built to study the thermo-mechanical properties of coal and overburden rock for UCG process. These experimental data can get an idea of elastic constants of rocks, the fracture growth mechanisms, the fracture orientations the maximum/yield stresses that the sample withstands, the conditions under which spalling occurs in overburden rock, as well as the rate which this take place. These results will be used as input for the modelling of the cavity growth of UCG.

1. Introduction

Rising greenhouse gas emissions over last decades has increased the global temperature (IPCC 2005), which consequently lead to investigation of possibilities and scenarios to get solutions for these concerns. Different options are proposed, such as reducing the consumption of carbon-based fuels, using carbon-free energy sources, e.g., solar power, wind power and geothermal energy, and capturing and storing carbon dioxide (CO_2) in geological formations (CCS). Storage strategies include CO_2 injection into deep saline aquifers (Chadwick et al. 2007), (depleted) gas and oil reservoirs (Velasquez et al. 2006), and unmineable coal seams (Bergen et al. 2009).

Moreover, in recent years, the coupled UCG-CCS process has been considered as another potential option (Barzandji et al. 2001, Blinderman and Friedmann 2006, Roddy and Younger 2010). It has been argued that a combined UCG–CCS project can offer integrated energy recovery from coal and storage of CO_2. However, existing potential problems may counteract its potential benefits (Durucan et al. 2014).

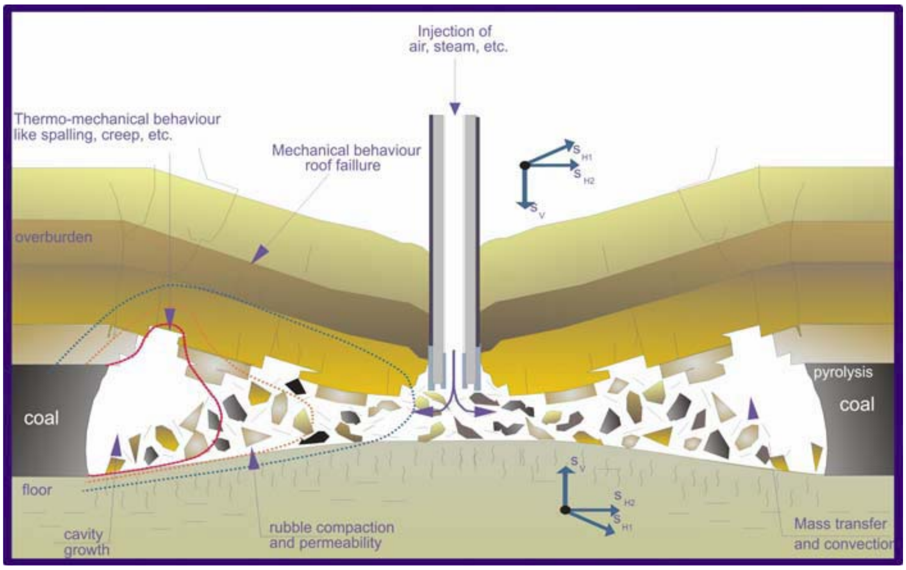

Figure 1 Cross section of a developing underground gasification cavity (after (Hettema 1996))

To develop a generic UCG-CCS site characterisation workflow, different aspects of this complex process, such as cavity progression and geomechanics, contamination of groundwater and subsidence impacts, need to be re-considered and understood. The main aspects of rock mechanics during the UCG process are the type of cavity fill from the overburden and the geometric development of cavity. Figure 1 illustrates the thermo-mechanical aspects of a developing gasifier, which is a section of a gasification cavity with a collapsed cavity, compacted rubble and isothermal lines. The creation of such a configuration is caused by gasification at the injection point. During the exothermal reactions, coal and roof rock are heated so that char and molten ash remain at the bottom and thermo-mechanically spalled roof rock (partly) fills the remaining cavity. Depending on the overburden rock type and the degree of thermal alteration, the overburden rock has an increased strength until mineral phase changes start to alter the rock (Wolf et al. 1992). This "baked" rock often gives rise to an increased roof spans and by that larger cavities. The roof span at any stage during cavity formation governs convection and associated heat and mass transfer. After collapse, the roof materials in a burning coal cavity is the major infill to be compacted and it produces a permeable rubble bed. At the start of this process, the thermo-mechanical behaviour of the roof rock (i.e. stable roof span) and coal are the initial parameters to predict the stability and the development of the production cavity. In other words, the previous mentioned parameters affect heat conduction and the stability and caving of roof materials, especially under conditions of high stress and temperature (hundreds of meters depth and temperatures over 500°C). Therefore, as a part of the TOPS program [11], the thermo-mechanical properties of coal and overburden rock need to be investigated for UCG process.

2. Methodology

2.1. Materials

In this work different type of coal samples and overburden rocks from roof rock of a coal layer from the coal mines are collected and studied (Table 1).

Table 1 *Overview to the studied sample as coal and overburden rock*

Sample	Source	Type
Velenje coal	Velenje mine, Slovenia	Lignite (as low rank coal)
Warndt Luisenthal (WL) coal	intra-mountain Saar basin in Western Germany	High volatile bituminous (hvBb) (as medium rank coal)
Pennsylvanian Coal	Corning Mine, Indiana, USA	High volatile C bituminous (as high rank coal)
Laminated carbonaceous shale	Beringen coal mine, Begium	Carboniferous sediments
Laminated (shaly) silstone	Beringen coal mine, Begium	Carboniferous sediments
Velenje roof rock	Velenje mine, Slovenia	Claystone
Whitby shale	Cliff coast north of Whitby, UK	Mudstone

For sample characterization, ultimate and proximate analysis of coal samples as well as XRD/XRF, mineral reconstruction and porosity/permeability measurements for roof rock samples were determined.

2.2. Tri-axial Compressive Strength Tests at various temperatures

To study the effect of temperature on the deformation of coal and overburden rock, triaxial compressive strength setup was improved. The dynamic and static geomechanical properties such as Young's modulus and Poisson's ratio vary greatly for different rock types and at various subsurface conditions. The compression strength test is a great method to get an idea of elastic constants of rocks, the fracture growth mechanisms, the fracture orientations the maximum/yield stresses that the sample withstands. The average size of the samples used in the measurements are 40 mm in diameter and 80 mm in length, according to the ASTM criteria. The samples were jacketed with a heat-shrink tubing for the triaxial compressive strength test in a TerraTek^{tm} steel-bodied pressure cell. The machine is capable of applying axial stress up to 400 MPa and confining stress up to 70 MPa at a constant temperature up to 200^{o}C. Before applying the axial stress in the vertical direction (and orthogonal to the bedding), the sample was confined at various constant pressures, to examine the effect of confining pressure. Afterwards, the axial stress was introduced and increased gradually until the sample breakage. During the experiment, the vertical and the radial deformations were measured by a Linear Variable Differential Transformer (LVDT). The elasticity of these rocks sample can be calculated directly from the results of these experiments. Table 2 presents the results at ambient temperature which represent the baseline data.

The experimental results of the shale compression tests in Table 2 are very different regarding the Young's modulus. This is expected from basic rock physics principles, since the elastic properties of these samples are strongly affected by their material composition and from different stratigraphic horizons.

To determine the fracture growth and breakage orientation, the CT-image of all samples were taken before and after each test. Figure 2 show the CT-images of the WL coal sample after the triaxial test.

Table 2 *Elastic properties of coal and overburden rock at various confining pressures*

Sample	Confining Pressure [bar]	E_y [Gpa]	Poisson ratio (υ_{yx}) []
WL Coal	13,71	3,34	0,37
WL Coal	28,11	3,70	0,41
WL Coal	44,32	3,83	0,44
WL Coal	62,63	3,97	0,43
Whitby Shale #22	14,40	17,69	0,14
Whitby Shale #53	9,00	2,81	0,14

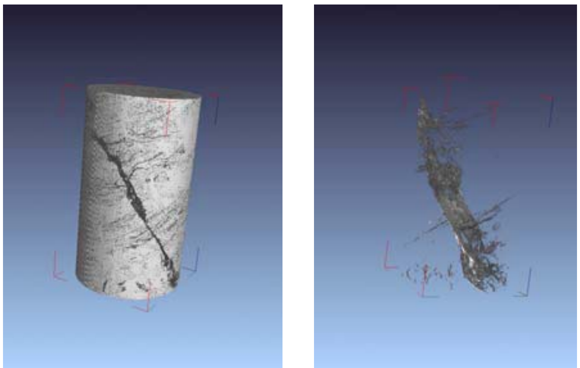

Figure 2 *CT- images of coal sample after the test which show the fracture growth and orientation of the sample; dark grey and black are the fractures and pore zones, while light grey represents the coal.*

To implement the effect of temperature and water phase change during rock heating, in next step these experiments will be conducted stepwise at higher temperatures up to 200^{o}C. The heating process during UCG causes the temperature variation in time and space in the surrounding rock. This rise in temperature is an important factor which has a considerable impact on the behaviour of cavity; it influences on the mechanical rock properties, such as strength and elasticity. In addition, the heated water and steam may result in increased pore pressures and also thermally induced stresses develop.

2.3. Thermal Spalling Experiments

To determine the conditions under which spalling occurs in overburden rock, as well as the rate which this take place, thermal spalling experiments were designed. The experiments are performed on cubic samples of 150 mm×150 mm×150 mm under bi-axial stress while heat is supplied at one side by thermal radiation from an electrical furnace. Due to the thermal shock, the samples are instantly heated up to maximum of 1200^{o}C. To measure the thermal properties and temperature distribution, five thermocouples were installed along the sample. Meanwhile, the spalling was measured against time. During the thermal expansion of the sample, the axial stress was kept constant. Figure 3 shows the digital images of the setup as well as an example of the spalled/fractured rock material of shaly siltstone after thermal-mechanical treatment.

Figure 3 *The digital images of (a) the thermal spalling setup, and (b) an example of the spalled/fractured rock material of shaly siltstone after thermal-mechanical treatment.*

Conclusions

To develop a generic UCG-CCS site characterisation workflow, different aspects of this complex process, such as cavity progression and geomechanics, contamination of groundwater and subsidence impacts, need to be re-considered and understood. In this process, the thermo-mechanical behaviour of the roof rock and coal are the initial parameters to predict the stability and the development of the production cavity. These parameters affect heat conduction and the stability and caving of roof materials, especially under conditions of high stress and temperature. In this study, several experimental setups have been designed and built to study the thermo-mechanical properties of coal and overburden rock for UCG process. These experimental data can get an idea of elastic constants of rocks, the fracture growth mechanisms, the fracture orientations the maximum/yield stresses that the sample withstands, the conditions under which spalling occurs in overburden rock, as well as the rate which this take place. These results will be used as input for the modelling of the cavity growth of UCG.

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