International Journal of Rock Mechanics and Mining Sciences 102 (2018) 15–27

Contents lists available at ScienceDirect

International Journal of Rock Mechanics and Mining Sciences

journal homepage: www.elsevier.com/locate/ijrmms

Yield envelope assessment as a preliminary screening tool to determine carbon capture and storage viability in depleted southern north-sea hydrocarbon reservoirs

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ARTICLE INFO

Keywords:
Bunter Sandstone Formation
Sherwood Sandstone Group
Carbon sequestration
Hoek-Brown
Mohr-Coulomb

ABSTRACT

This paper describes a laboratory study of the hydro-mechanical properties of samples from the Sherwood Sandstone Group (SSG), an onshore analogue of the finer grained, lower porosity portions that make up the Bunter Sandstone Formation (BSF). The study provides a yield envelope for this sandstone, and demonstrates that it is a competent sandstone at relevant reservoir depths. A theoretical yield envelope has been calculated based on the anticipated in situ stress induced by depletion and reinjection, showing that only the high porosity (35%), large grain diameter (290 μm) end-member of the BSF is likely to result in deformation of the reservoir rock. Stress analysis of four fields within the Southern North Sea suggest that depletion of 10 MPa will not result in permanent deformation of the reservoirs assuming similar porosity and grainsize characteristics to the SSG tested. Furthermore, re-inflation is unlikely to result in permanent deformation should the injection pressure not exceed the initial pre-production reservoir pore pressure.

1. Introduction

The capture of carbon dioxide (CO_2) from large point source emitters and storage in the form of a super-critical fluid within geological formations is a key technology in tackling anthropogenic climate change.[1,2] To achieve a reduction in emissions, significant quantities of CO_2 need to be injected into suitable geological formations capable of containing the fluid for thousands of years. It has been estimated that approximately 3.2 billion tonnes (Gt) of CO_2 need to be injected annually.[3] Depleted hydrocarbon reservoirs represent a significant national resource within the UK with the potential for storing gigatonnes of CO_2 and aiding UK emission reduction targets. In 2012, the then Department of Energy and Climate Change (DECC) stated that depleted gas fields represent “the most important storage type for the UK”, and “provide a significant proportion of potential future capacity for the nation”.[4] Estimates suggest up to 9.9 Gt of UK storage capacity comes from reservoirs that have previously contained hydrocarbons extracted by the oil and gas industry.[5] This form of storage site has a number of benefits, including the generally well-characterised geology and the potential for reutilisation of pre-existing infrastructure for injection activities. They also offer security of storage with an effective top-seal that previously acted as a seal to hydrocarbons, provided no deformation occurred during hydrocarbon extraction. Several demonstration projects have been conducted injecting megatonne scale CO_2 into depleted hydrocarbon reservoirs, including in the Norwegian North Sea at Sleipner.[6]

The use of a depleted reservoir will play a role in the performance of the storage facility. The process of hydrocarbon extraction, or depletion, can significantly affect both the reservoir involved and the surrounding rocks. During depletion, reservoir pore pressure will have lowered as hydrocarbon extraction occurred and as a result, the reservoir may have subsided. These activities, therefore, have the potential to cause deformation, movement on faults and/or damage to infrastructure, for example induced seismicity at Groningen in the Netherlands[7] and faulting at Ekofisk in the North Sea.[8]

The injection of super-critical fluid into a depleted reservoir will result in an increase in pore pressure, possibly resulting in heave and consequently has the potential to cause additional deformation, movement on faults and/or damage to infrastructure. The use of injection and extraction boreholes can minimise this effect, with water injected at a rate similar to the hydrocarbon extraction rate during drawdown, and extraction of aquifer water at a similar rate to CO_2 injection. Perturbations of reservoir pore-fluid pressures occur when flow out of, or into the reservoir is initiated. These changes in pore pressure, and as a result the stress state, may lead to undesired geomechanical deformation that could affect the integrity of the reservoir

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https://doi.org/10.1016/j.ijrmms.2017.11.018
Received 15 March 2017; Received in revised form 28 November 2017; Accepted 29 November 2017

and the overlying seal. The long-term impacts of such pore pressure changes, particularly when the reservoir is re-inflated during injection of CO_2, are not well understood and there is a lack of physical data for specific rock types and scenarios. Zoback & Gorelick[3] identified the risk to security from a geomechanical point of view, while Economides & Ehlig-Economides[9] showed that an upper pressure limit exists for carbon capture and storage (CCS), above which the seal is potentially compromised due to the formation of fractures. Verdon et al.[10] examined the deformation observed at pilot injection sites and noted that the geomechanical response was: complicated and non-intuitive at Weyburn (Saskatchewan Province, Canada; e.g.[11]); small at Sleipner due to the high permeability and large lateral extent of the reservoir[12]; and that uplift and microseimic activity was noted at In Salah in Algeria.[13] Therefore, reservoirs are evaluated on an individual basis, both in terms of their geometry and the properties of the geology present.

The UK's primary offshore oil and gas fields are located within the basins of the East Irish Sea, the Southern North Sea (SNS) and the Northern and Central North Sea.[5,14] Within the SNS basin, CO_2 storage potential has been estimated to be ~17 Gt,[14,15] though a broad range in theoretical capacity is generally reported for saline aquifers. However, oil and gas fields within the area may potentially provide an effective capacity of around 3.9 Gt of CO_2. The annual output of CO_2 in the UK has been calculated as 404 Mt for 2015,[16] of which 136 Mt can be attributed to energy supply and could theoretically be subject to carbon capture and storage. Additional output of CO_2 from other industrial sources could additionally be captured and stored.

Geomechanical data for the Southern North Sea is not readily available, consequently it is difficult to make a reasonable early assessment of reservoir-specific geomechanical performance. Offshore drilling for new borehole core for testing is prohibitively expensive, particularly at such an early stage of CCS development. Consequently, testing of existing borehole core is the most economical way to obtain geomechanical parameters for early reservoir viability assessment.

This paper describes a laboratory study of the mechanical and hydromechanical properties of reservoir sandstone relevant to the Southern North Sea (SNS) basin; sandstone of the Sherwood Sandstone Group (SSG) is the onshore equivalent of the Bunter Sandstone Formation (BSF) from the SNS. Testing included: porosity and density determination by the saturation and buoyancy technique; uniaxial strength and deformability; triaxial strength and deformability; sonic velocity measurements during hydrostatic compression; and transient permeability measurements during hydrostatic compression. Mohr-Coulomb, Hoek-Brown and yield envelope parameters were calculated from the results.

2. Test material and experimental protocols

2.1. Bunter Sandstone Formation and Sherwood Sandstone Group

Given its importance as a storage reservoir both in saline aquifers and depleted fields within the SNS, as well as within the East Irish Sea Basin, the Bunter Sandstone Formation (BSF) was selected as a suitable lithology for the experimental test programme. Parkes et al.[17] details the selection of candidate geologies for the current study.

The BSF is Triassic in age and is the upper part of the wider Bacton Group. Onshore in the UK the stratigraphic equivalent is the Sherwood Sandstone Group (SSG). In the North Sea Dutch Sector and the Netherlands the equivalent formation is the Main Bundsandstein Formation of the Lower Germanic Trias Group. Fig. 1 shows the stratigraphic correlation of the Triassic succession from the onshore UK across the UK and Netherland sectors of the Southern North Sea.

In the SNS the BSF is red, orange and occasionally white sandstone. It is predominately formed of an upward-coarsening sheet-sand complex, composed of mostly fine-grained sand, but with local areas of coarser-grained sands and conglomerates. The unit varies in thickness across the SNS with a maximum thickness of 600 m in the main depocentre of the Sole Pit Trough,[18] although more conservative estimates of 0–350 m (average 200 m[19];), 174–274 m (average 225 m[20];) and over 350 m[21] have been presented. Toward its northern margin the thickness gradually reduces to zero because of erosion under the Hardegsen Disconformity.[22] Typically the top of the BSF lies between 1000 and 1300 m but is variable due to salt movements.[22] The Bunter thins over highs such as the Cleaver Bank High, due to higher erosional rates and greater distance from the original source region. The source of sediment was likely to have been the London-Brabant Massif to the south or the Pennine Massif to the west. BSF was deposited in a range of basin environments during hot, arid, semi-arid climatic conditions. Marginal basin deposits represent a series of coalescing alluvial fans with braided fluvial channels formed during sheet flood events, with interbedded silt layers deposited in lower energy ephemeral lakes.[19,21] Central basin deposits have fewer conglomerates and are interpreted as large, flat plain sheet flood deposits.[19]

Generally, the SSG and BSF are composed of well-sorted, round/sub-rounded grains of quartz, feldspar and lithic fragments, with cements of calcite and other carbonates, anhydrite and quartz, as well as feldspar overgrowths, more common near the basin margins. Central basin areas have common halite cement, which can greatly reduce porosities.[23] Detrital mineralogy and grain size are not constant in the sandstones across the UK, with variability caused by the distance of the depositional environment from the original source region.

Triassic sandstones in proximal areas like south and south-western England have more abundant feldspar and rock fragments and are referred to as lithic arkoses to sub-arkosic litharenites. Some samples can have up to 30% feldspar (almost all K-spar), while the more lithic samples can have up to 50% lithic clasts including, sedimentary, igneous and metamorphic grains. Other than lithic grains and feldspars, simple and polycrystalline quartz account for a high percentage of the remaining constituents, along with minor mica, heavy minerals and opaques.[24]

In more distal regions, such as the SNS and outcrops to the north and east of Nottingham, SSG rocks are more fine-grained and are made up of sub arkoses, sub-litharenites and quartz arenites. In the sandstones, total quartz accounts for 50–65% of the whole rock, dominated by simple quartz, with lower amounts of polycrystalline quartz. Other constituents include feldspar (mostly K-spar) (5–10%), rock fragments (10–15%), minor mica, heavy minerals and opaques. Both the feldspar and rock fragments are much rarer than in the proximal sandstones.[24]

Parkes et al.[17] summarise the diagenetic alteration in the North Sea BSF. The general lithologies of the sandstones are quartz arenites, subfeldspathic arenites and sublithic arenites, composed of detrital quartz (major) and feldspar (minor - mostly K-spar, lesser albite and some perthite) and lithics (cherts, siltstones, mudstones, uncommon quartz-feldspathic rocks, rare volcanics). The sandstones are mostly angular to sub-angular grains with rare well-rounded grains restricted to coarser beds, except for at the top of Lower Volpriehausen and base and middle of Volpriehausen Clay-Siltstone in central part of Southern North Sea basin where well rounded, fine to coarse sands are interpreted as aeolian sands. The primary porosity and mineralogy has been heavily altered in parts of the North Sea. Porosity has been reduced in some areas through compaction and cementation and enhanced in others through cement and detrital framework grain-dissolution.

2.2. Test samples

Potential core material was identified within the British Geological Survey (BGS) Offshore and Onshore collections at Keyworth, UK. Extensive slabbing of core material meant that test samples of sufficient dimensions could not be produced, so no suitable material was identified within the BSF. Therefore, a suitable alternative had to be selected from the onshore equivalent, the Sherwood Sandstone Group (SSG). Potential rocks were assessed to determine their suitability based on the following criteria: (1) a reasonable degree of homogeneity within the