Summary from the RePlug project

Title:	RePlugReady: CO2-ready well and plugging cement as a preferred choice for most oil and gas reservoirs to enable early full scale CO2 storage
Project owner:	ReStone AS
Project Leader:	Astri Kvassnes
Project period:	2018-2020
Prosjektnr:	281831
Budsjett:	8 mill. kr, hvorav 5,5 mill. kr i støtte fra CLIMIT

Abstract / Summary and conclusions:

ReStone AS has developed and owns the patent-pending cement-technology RePlug®, and RePlug® is the core product in ReStone's business. The utilisation of RePlug® will ensure safe and economically sustainable operations and decommissioning of wells for the petroleum industry. The Well Barrier Acceptance Criteria (WBAC), as applied by regulators world-wide, are met by RePlug®. RePlug® works by reacting minerals with fresh-, salty water (brines), and/or CO_2 to metamorphose minerals into pores and cracks that would otherwise be pathways for leaks from petroleum reservoirs. RePlug® also withstands vibrations and earthquakes and fouling by microorganisms.

Permanent well barriers should "provide long term integrity with an eternal perspective". Use of RePlug® triggers self-healing as the material sets. Sef-healing continues until the reactive material is completely depleted, as long as 10,000 years away. RePlug® is also designed to use the same infrastructure, methods and procedures that exist for well cements today, reducing risks and adoption costs for operators.

RePlug® paves the way for Carbon-dioxide Storage in petroleum reservoirs (CCS), providing CO_2 safe well-cements. RePlug® furthermore reduces the CO_2-footprint for petroleum well cement products by 20% – 80% and will, if implemented in all clinker cements, reduce global anthropogenic CO_2-emissions by 1 - 4% or 1⁄2 - 2 Gigatonnes of CO_2.

The RePlugReady project (CLIMIT #281831) has made it possible for ReStone to develop RePlug® as a world-class high-quality well-cement. SINTEF Industry AS, Heriot Watt University in Edinburgh UK, and University of Maryland in USA are research partners and suppliers to RePlugReady. These are all professional and world-leading institutes that secure effective and experienced execution of scientific research. The industrial research performed in this project has shown that RePlug® does not only have the properties postulated in our hypotheses but the project work indicates even better performance, particularly for CO_2-resistance and self-healing.

The petroleum industry has signaled significant interest in making use of RePlug®, not only in CCS wells but also in ordinary well operations, making the NCS CCS-ready for the future. ReStone has published their work at conferences, as three patent applications and numerous publications. The ReStone team received the Fredrikke Qvam award 2020 for being the female innovators of the year.

Introduction of the innovation and underlying idea:

Underground storage of CO_2 in populated areas in continental Europe is a political impossibility. This opens incredible Carbon-dioxide Capture and Storage (CCS) market opportunities on the Norwegian Continental Shelf (NCS) for both early and commercial full-scale CO_2 value-chains.

The petroleum industry- and associated R&D ecosystems are viewed as a leading source of knowledge and resources relating to CO_2-management techniques. We are "turning the valve" on this knowledge stream. What if the CCS ecosystem were to develop technologies that improve the outcome of the petroleum industry, thereby making reservoirs CO_2-storage ready? RePlug® (REcycled well-PLUGing) is a well cement admixture developed in Norway. Replug® is part of the solution to solve the CCS-readiness challenges.

The decommissioning of oil and gas wells is an inevitable, complex and highly costly process. It is estimated that the total cost of the decommissioning activities on the NCS will exceed 160 billion NOK for the next 40 years. The majority of this funding is to come from the Norwegian government, implying that studies being carried out which aim to improve the efficiency and cost effectiveness of the process are of great interest to the country. RePlug® significantly and consistently outperforms ordinary cement for CO_2-ready well cementing, as well as the permanent plugging of CO_2 wells.

ReStone is working with SINTEF, Heriot Watt University and University of Maryland to ensure the efficient and experienced execution of tests and qualifications. If successful, ReStone's products may introduce a new CO_2-proof and -ready well cement that has the potential to be a standard product used in Petroleum well operations.

R&D activities:

The primary objective of this project is to further develop the cementitious mineral additive material RePlug® that can be applied as a new standardized cement for wells including those weathered by CO_2 storage and injection.

The project has been managed by ReStone AS, which owns the RePlug® technology, and has facilitated the development of RePlug® as a high-quality well-cement. It will ensure safe, economically sustainable and regulatory-compliant operations of wells for the petroleum industry, as the requirements set by the Well Barrier Acceptance Criteria (WBAC), applied by regulators world-wide, are well met by RePlug®.

ReStone AS's cement product RePlug® has during the last two years interacted frequently with operators, service companies and authorities, including the Petroleum Safety Authority of Norway. ReStone has in this period had a long-standing cooperation with a world leading oil service company.

Main findings:

- Physical and rheological characterization of the novel cement slurry formulation
    - The results indicate that RePlug® slurries with densities similar to Portland G slurry density exhibit similar behavior of the flow curves in terms of shear stress development.
- Mechanical properties evaluation of the admixture
    - One week of aging in carbonated brine had no observable effect on the compressive strength and Young's modulus for both Portland G and RePlug® samples. After four weeks, there was a similar reduction of the compressive strength for Portland G (by 13 %) and RePlug® (by 15 %) although RePlug® reacted much faster. Young's modulus decreased more for Portland G samples after four weeks. After two months, the UCS was reduced by about 40 % and Young's modulus by about 50 % compared to the average initial values for RePlug® samples. This could have been affected by fractures that appeared in RePlug samples after two months of aging. The cause of fracturing is uncertain. Depressurization at the end of the experiment and/or fragility of carbonation front could be some of the causes.
- Long term durability of RePlug exposed to CO2 and brines under relevant pressure and temperature
    - Comparative long term aging tests (one week, four weeks and two months) in carbonated brine at 80 °C and 100 bar were performed for neat Portland G and RePlug® samples (25 BWOC%, coarse grain). RePlug® samples reacted with the carbonated brine much faster than reference Portland G samples exposed to the same conditions. The effect of pozzolan type additives on carbonation of ordinary Portland cement is not yet well understood, but the amount of available portlandite and porosity

seems to play a crucial role. Similar assumptions are made for RePlug®. A closer investigation of the reaction fronts in the RePlug® samples showed that both precipitation of carbonates and dissolution of material occurred simultaneously. This resulted in reduction of macro-porosity (i.e. precipitation within the voids space), dissolution of calcium into the environment, formation of lower-density zones and precipitation of calcium carbonate on the surface. For Portland G, the reaction was much slower. Reduction of macro-porosity was also observed but there was no observable dissolution after four weeks of exposure.

- Testing of bonding strength for RePlug® with steel casing and sandstone
  - Specimens cured at 60°C gain strength more rapidly than those cured at 20°C. Elevated temperature does not improve nor have a detrimental impact on the maximum achievable compressive strength.
  - Due to observed variation in results, a defined relationship between the different replacement levels, type of curing condition and their influence on compressive and tensile strength is difficult to distinguish.
  - When cured in water, there appears a reduction in strength with increasing amounts of replacement level, suggesting that there is little contribution from the mineral admixture.
  - With regards to the early age response, it is shown that at 20°C the initial setting increases with increasing Replug® replacement. However, this delay effect is not observed at both 60°C and 90°C, which could be beneficial in this regard.
  - It is shown that the bond strength against steel generally decreases with increasing RePlug® replacement level.
  - The sandstone specimens exhibited similar initial bond strength behaviour to the steel specimens until peak loading.
  - The assessment of the bond strength against sandstone has proven to be much more difficult. Multiple peaks are observed which could be linked to the compressive strength of the plug rather than the bond strength. This was supported by the evidence of the failure of the top parts of the plug whereas there was no sliding movement observed at the other end suggesting the failure mode is not bond failure.
  - When cured under high temperature (60°C), a sudden splitting failure was observed on the sandstone block and therefore not offering suitable bonding resistance. Hence, this prevented the testing of the 60° specimens.

- The mechanics and micro features of a cementitious mineral admixture
  - As the volume percentage of mineral additive increases, both the stiffness and the compressive yield strength of the admixtures decrease. All of the tested samples exhibit strain softening behaviors when loaded beyond the compressive strength.
  - Post-peak failure behaviors are demonstrably different. In the cement admixture with lowest mineral additive (i.e., 20%), the failure is accompanied by a large and abrupt stress drop. At the end of the sudden stress drop, the cement mixture loses ~50% of its cohesive strength. As the amount of mineral additive increases, the stress drop becomes smaller and more gradual. The cement admixture with highest mineral additive content exhibits stable failure and loses only ~25% of its cohesive strength after failure.