Mechanical behavior of well cement cured in saline water: an application to oil and gas wells

S. Gowthaman, S. Krishnya and M. C. M. Nasvi
Department of Civil Engineering, University of Peradeniya, Sri Lanka

ABSTRACT: Geo sequestration of carbon dioxide (CO_2) has been found to be one of the best solutions to reduce greenhouse effect. The injection wells and well cement plays a vital role in well integrity. The loss of well integrity is the major issued and that may be explained by the degradation of cement as well as the down hole curing conditions. Salinity is an important factor that varies from 0-30% NaCl depending on the geological location. Therefore, aim of this research is to analyze the mechanical behaviour of cement cured in different salinity levels with various curing periods. Testings such as uniaxial compressive strength (UCS) test, X-Ray Diffraction (XRD) and Scanning Electron Microscopical (SEM) observation were conducted to obtain the behavior of the cement cured in different conditions. Based on the outcome, it was observed that the strength of the OPC based well cement decreases with increasing salinity levels and with ageing in time.

1 INTRODUCTION

The CO_2 is the gas that plays a major role in greenhouse effect that leads to environmental pollution and dispersion of sustainability of the globe. According to the report of Energy information administration 2003, annual emission of CO_2 is 6.5GT/year and it is predicted that 2000 million tons of CO_2 increment in 2030 (Nasvi et al. 2012). Therefore, it is very much important to understand how the CO_2 reaches the atmosphere. The major CO_2 emissions are due to the increasing usage of coal powered plants, petroleum usage and oil recovery. Using low carbon energy sources are eco solutions for this problem but it cannot satisfy the energy requirement in our present situation. Therefore Lecolier et al. (2007) and Bachu and Bennion (2009) concluded that storing carbon dioxide (CO_2) in underground wells is the most effective way for long-term, safe and low-cost CO_2 sequestration.

In Sri Lanka, a coal power plant (Lakvijaya coal power plant, Norochcholai) has been constructed and it is in operation from 2011. But in the future, we might go for more coal power plants to fulfil our energy requirements. However, there will be a problem related to emission of CO_2 due to the combustion of coal. Hence, carbon capture and storage will be useful in this context. Coal seams, saline aquifers and depleted oil and gas reservoirs, deep saline aquifers and unminable coals beds are used for storing captured CO_2 (Bruant et al. 2009)

Injection wells are widely used not only for CO_2 injection but also for the oil and gas extraction projects. Therefore, it is important to ensure cement integrity under various down-hole conditions. The integrity and zonal isolation of the injection wells depends on many factors and the major factor is well cement that is used as primary cement for the construction of these wells. Well cement must be carefully designed to meet demanding requirements such as predictable thickening time, high sulphate resistance, high durability, fluid loss control, consistency, low viscosity, low free fluid, and strength (Luke et al. 2012). This well cement is categorized according to the American Petroleum Institute (API) specification standards, which has identified 8 classes of cement according to the depth of the well, the temperature and pressure (Runar 2010)). Generally, API class G & H cements are commonly used for the construction of injection wells. However, class G is most preferable for construction (Runar 2010). At present, OPC based well cement is used for more than 80% of the well construction in oil & gas field (Barlet et al. 2009; Arina and Sonny 2012). This primary cement acts as a sealant and prevents fluid communication between the various underground fluid-containing layers where the salinity level (0-36%) varies in place to place and also varies with depth (Nasvi et al. 2012, Barlet et al. 2009). Therefore, the well cement in the injection/production well is exposed to different salinity level, and this issue affects the actual strength of the OPC based well cement. Hence, mechanical behaviour of the well cement depends on the curing under various salinity levels.

To date, there are few studies focusing on oil well cement behaviour in saline water. Lecolier et al. 2007) studied the strength variation of the API class G cement cured in brine for one year at 80°C. Based on the above study, the strength of the cement decreased with ageing time due to the degradation of C-S-H. Similarly, Xingshan et al.

(1996) studied the mechanical behaviour of class G cement cured in different NaCl brine concentrations at two different curing temperatures (93 °C & 160 °C) and they observed that the strength increased with curing time (up to 72 hours) at both temperatures because of the degree of hydration. In addition they also observed that the strength decreases with the brine concentrations due to the retardation in hydration process in brine. However, there are no studies relevant to the mechanical behavior of OPC based well cement in brine at average down-hole temperature (50°C). Therefore, major aim of this research is to study the mechanical behavior of OPC based well cement cured under different salinity levels for different ageing time. Uniaxial compressive strength (UCS) test, X-Ray Diffraction (XRD) test, Scanning Electron Microscopical (SEM) observation and Energy Dispersive X-ray (EDX) spectroscopy analysis were conducted and results were compared.

2 EXPERIMENTAL METHODOLOGY

Well cement samples were prepared using Ordinary Portland Cement (OPC) with sulphate resistance. OPC was purchased from Holcim Lanka (Pvt) ltd, Colombo, Sri Lanka. The composition of the OPC with sulphate resistance was obtained from X-Ray Diffraction (XRD) test and the results are given in section 3.1. The cement paste was prepared with a water/cement ratio of 0.44 as it is found to be the optimum based on Nasvi et al. (2012), Lecolier et al. (2007) and Nadine et al. (2009) . Based on the mix design, 50 mm diameter and 100 mm height samples were prepared using PVC moulds. Then they were oven cured at 50 °C and during the oven curing, top side of the samples was covered with polythene to avoid excessive moisture loss. After 24 hours of curing, the samples were allowed to cool down for another 6 hours in the atmosphere.

The samples were then transferred to the saturation containers having different brine concentrations (0, 10, 20 and 30% NaCl) except the control samples that were used to compare the results. The brine solutions were prepared by mixing NaCl salt and distilled water in due mix proportions. All the samples were saturated for 7, 14, 28 and 45 days prior to the testing. For each conditions three samples were tested to ensure reproducibility. UCS test was conducted by using the UCS testing machine shown in Fig. 1 with the stress control loading rate of 0.2 MPa/sec. Samples were machine ground both sides and top surface was capped with sulphur prior to the UCS testing to apply uniform uniaxial loading. In addition, Scanning Electron Microscopical (SEM) test was conducted by using Oxford EVO LS15 SEM apparatus at Faculty of Science, University of Peradeniya, Sri Lanka. For the SEM observation, samples were gold coated to remove the voids prior to the observation.

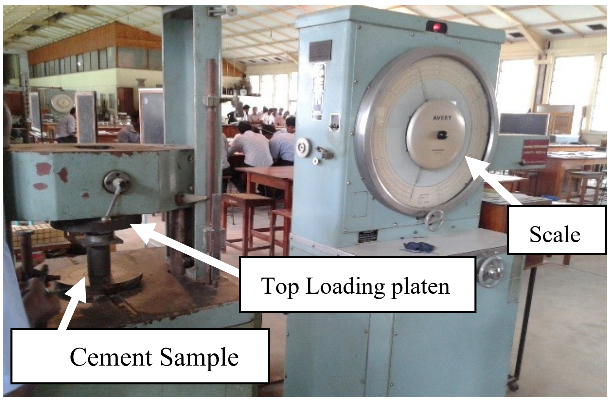


Fig. 1: UCS testing machine used for the experiment

3 RESULTS AND DISCUSSION

3.1 *XRD Test results*

The composition of the OPC based well cement (OPC with sulphate resistance) was obtained from XRD test. Table 01 shows the composition of OPC based well cement obtained from XRD test and typical composition of API class G cement. For the construction of injection wells, API class G cement is most preferable and widely used due to its suitability for high depths, high pressure/temperature conditions and high sulphate resistance.
Based on Table 1, it can be seen that the composition of OPC based well cement is similar to API class G cement. Therefore, it can be concluded that OPC can be used instead of API class G cement for the construction of injection wells.

Table 1: Composition of OPC and typical class G cement

Constituents	**Percentage (%)**	
	OPC	**Class G**
CaO	64.40	64.7
SiO_2	20.38	22.91
Fe_2O_3	3.26	4.75
Al_2O_3	4.79	3.89
MgO	0.98	1.8
SO_3	2.21	0.74
K_2O	0.04	0.64

3.2 *Variation of UCS and Young's modulus with salinity and ageing*

The variation of average UCS of OPC based well cement with curing period is shown in Fig. 2.

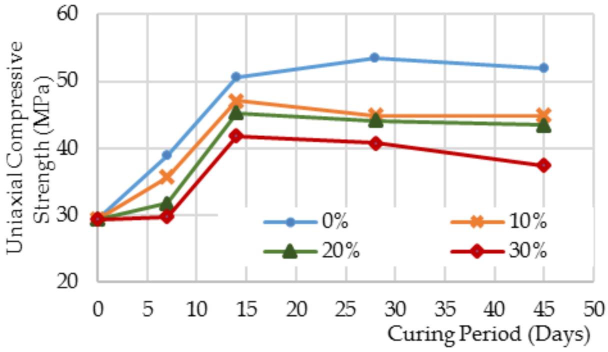


Fig. 2: Variation of Uniaxial compressive strength with curing period

It can be seen that initially the strength of the OPC cement in brine concentrations increases with the ageing period up to 14 days and then it decreases towards 45 days. The UCS of dry sample was 29.4 MPa. The increment varies from 42% - 60 % depending on the salinity up to 14 days. This initial increment is because of the dominant hydration process (Lecolier et al. 2007). However, after a certain period (approximately 14 days), continuous ageing in brine solution causes the reduction of strength and the reduction percentage varies from 4.7% - 10.6% for different salinity levels. This is because of the Ca^{2+} ions in Calcium Silica Hydrate (C-S-H) get precipitated with Cl^{-} ions i.e. in continuous aging C-S-H degrades in brine solution (Xingshan et al. 1996)**.** On the other hand, samples saturated in 0% NaCl (pure water) does not show any significant amount of decrement in compressive strength as strength variation is caused only due to hydration process.

The variation of UCS with salinity level of the samples saturated for different curing periods is shown in Fig. 3.

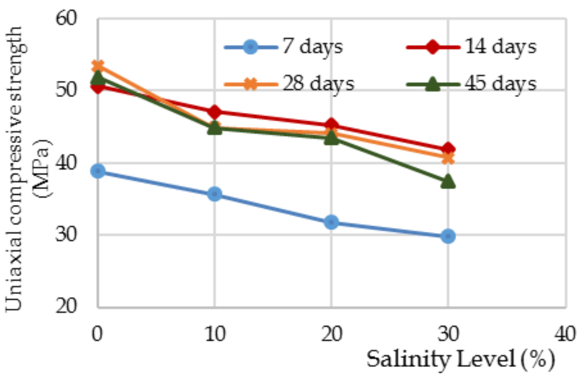


Fig. 3: Variation of Uniaxial compressive strength with salinity level

Based on Fig. 3, it is clear that the uniaxial compressive strength decreases with salinity level for all the curing periods. This strength decrement is because of the retardation in the degree of hydration. When the brine concentration increases, there is a retardation in hydration process i.e. salt content affects the $Ca(OH)_2$ formation. In addition, C-S-H absorbs the NaCl micro crystallites and Na^{+} on the surface of the fibrous structure and this affects the interface bonding between $Ca(OH)_2$ and CSH. (Lecolier et al. 2007, Xingshan et al. 1996). As a result, uniaxial compressive strength of well cement tends to reduce. In addition, it can be seen that 7 days UCS for all the brine contents (0-30%) is much lower than that of other curing periods (14, 28 & 45 days). This might be due to the partial hydration process i.e. high strength can be obtained only after the complete hydration process.

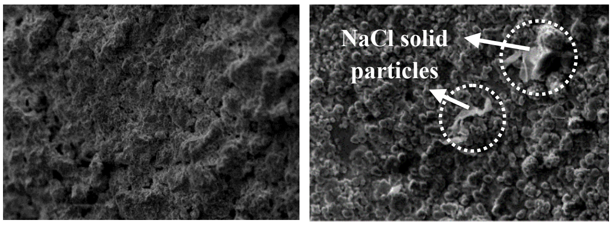
Further, average stress-strain behaviour of the brine saturated samples were obtained from UCS testing and Young's modulus of the cement samples were calculated based on these stress strain plots. Stress – strain plots were derived from the load – displacement relationship obtained from UCS test apparatus. The behavior of Young's modulus of OPC based well cement with ageing period and salinity levels are also shown the similar variation of UCS. Young's Modulus initially increases in the brine concentrations and then decreases with the saturation periods. In each duration period, Young's modulus decreases with salinity level. This means stiffness of the cement decreases with the increase of brine content and with ageing time.

3.3 *SEM Test results*

SEM observation was conducted to identify the microstructural variation and appearance of the samples cured under different curing conditions.

Fig. 4 shows the microstructural variations and appearance of the samples cured under different conditions. Samples cured under different conditions shows different microstructural characteristics. Generally, the microstructure of the samples varies due to hydration process.

Presence of NaCl affects the microstructure of the cement and behaviour of the cement as well (Fig. 4). However, the effect of NaCl is mostly dominant exposed at long term curing as can be seen from Fig. 4(b). With the help of Energy-Dispersive X-Ray Spectroscopy (EDX) analysis, it was ensured that the white colour crystal forms indicated in Fig. 4(b) are NaCl solid deposits. It shows that in continuous curing in brine solution, NaCl particles penetrates through the cement samples and get deposited in between and causes the degradation of the cement samples.



(a) (b)

Fig 4: Microstructure of the samples saturated (a) 7 days (b) 45 days in 30% NaCl brine

Because of this degradation process by NaCl, the compressive strength reduces with the increasing of brine concentration and increasing of curing time as well.

4 CONCLUSIONS

Well cement plays a vital role in the integrity of the carbon capture storages and oil and gas extraction projects. The loss of well integrity may be explained by the degradation of cement as well as the down hole curing conditions. Therefore, an experimental research conducted to analyze the mechanical behavior of OPC cured in different salinity levels. A series of uniaxial compressive strength (UCS) tests was conducted on OPC based well cement to study the effect of salinity (0% - 30% NaCl) and ageing (7 - 45 days) on the mechanical behavior of well cement.

The X-Ray Diffraction test was carried out to compare the chemical composition of the OPC samples with API Class G cement. From this test results it is ensured that OPC with sulphate resistance satisfies the requirement of API Class G cement. Therefore, OPC with sulphate resistance can be used instead of API class G cement for the construction of injection wells. Based on the findings, strength and the Young's modulus of OPC samples reduce with increase in salinity levels and this is due to the retardation in hydration process with increase in salinity. In addition, the strength and Young's modulus of the cement samples cured in brine concentrations initially increases for a short duration (14 days) but then decreases beyond 14 days. This is because initially the hydration process is dominant but in continuous ageing the samples get degraded because of the presence of NaCl and this dominant factor reduces the strength and Young's Modulus.

This result was further supported by observing the microstructural variations by using Scanning Electron Microscope (SEM) and ensured that the above behavior of OPC is due to the presence of NaCl in brine saturated samples.

Based on this research outcome, concentration of brine solution plays an important role in physical and chemical changes in well cement. Therefore, effect of saline water is a very important factor that should be considered seriously for the construction of CO_2 injection wells and oil and gas wells.Conclusion

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