Long-Term Performance of Cement-Bentonite Containment Wall

Performance a long terme d'un mur de confinement de ciment-bentonite

Kaushal Joshi & Kenichi Soga
University of Cambridge, UK.
Paul Tedd
Formerly, Building Research Establishment, UK

ABSTRACT
The paper presents hydraulic conductivity, unconfined compression strength (UCS) and triaxial test results of an 11 year old slag-cement-bentonite (CB) cut-off wall material and identifies factors affecting their long-term performance. The laboratory tests were performed on three types of CB samples ranging from contaminated block field samples to uncontaminated laboratory cast samples. The results showed that hydraulic conductivity reduces till 3 years and UCS increases till 90 days, but there after it remains constant till 11 years of age. The mean hydraulic conductivity and UCS values of block field samples are inferior and have large variability than laboratory cured samples. Such variations are mainly because of heterogeneity caused by aggressive environment and impurities within the specimen. Consolidated undrained triaxial test found that under an effective confining pressure of less than 200 kPa, tension failure occurred since the minor principal stress dropped to zero value at failure. The research outcome is useful for understanding future liability of CB wall and improving their design.

RÉSUMÉ
L'article présente la conductivité hydraulique, la résistance à la compression sans étreinte (UCS) et les résultats d'essai à trois axes d'un matériau de mur parafouille de scorie-ciment-bentonite (CB) âgé de 11 années et identifie des facteurs affectant leur exécution à long terme. Les essais en laboratoire ont été exécutés sur trois types d'échantillons de CB s'étendant des échantillons contaminés de blocs de terrain aux échantillons non contaminés de moule de laboratoire. Les résultats ont prouvé que la conductivité hydraulique réduit jusqu'à 3 ans et l'UCS augmente jusqu'à 90 jours, mais qu'il demeure après constant jusqu'à 11 ans. La conductivité hydraulique moyenne et les valeurs d'UCS des échantillons de blocs de terrain sont inférieures et ont une plus grande variabilité que les échantillons traités au laboratoire. De telles variations sont principalement en raison de l'hétérogénéité provoquée par l'environnement et les impuretés agressifs dans le spécimen. L'essai consolidé non drainé triaxial montre que sous une pression de confinement efficace de moins de 200 kPa, la rupture par traction s'est produite puisque la contrainte principale mineure a chuté à la valeur nulle à la rupture. Ces résultats de recherches sont utiles pour la compréhension de future responsabilité d'arrangement du mur de CB et d'améliorer leur conception.

Keywords : Cement-Bentonite, Cut-off wall, Hydraulic conductivity, UCS, Triaxial test

1 INTRODUCTION

Slurry trench cut-off walls constructed using self-hardening slag-cement-bentonite (CB) are the common form of in-ground vertical contaminant containment barrier in the UK, Europe and Japan. They essentially have low permeability to redirect groundwater flow and to prevent transport of contaminants. Despite their use for the last three decades, the future liability and planning restriction of the contained ground are not well understood. Since these walls are built in unmaintained ground condition and exposed to deteriorating environment during their service life, the knowledge of their long-term performance can help to estimate the risks involved with contaminants release and redeveloped of site for commercial use. The aim of this research is to assess the hydraulic and mechanical characteristic of CB wall materials exposed to contaminants at different stages of their service life through a case study.

CB cut-off walls are generally built using a single phase construction method, in which a continuous trench is excavated under the support of self-hardening CB slurry. The slurry material becomes hard as cement sets and forms a low hydraulic conductivity cut-off wall over the period of time. This method of construction invariably involves some of the surrounding soil falling into the slurry during trench construction. Due to the inherent variability of trench mixes, the UK National Specification (ICE, 1999) calls for at least 80% of laboratory cast sample should target hydraulic conductivity to be less than 1 x 10^{-9} m/s. However, these laboratory cast samples are not representative of the *in situ* CB due to the effects of the surrounding ground being mixed into the wall. The first objective of this paper is to compare the laboratory prepared samples and field samples taken from the case site. This can highlight the effect of heterogeneities and aggressive environment on the hydraulic conductivity and unconfined compression strength (UCS) in natural settings. Furthermore, the changes in these properties at different depths in CB walls and higher exposure to sulphate at the test site are examined.

In addition, the ICE (1999) specification stipulates the UCS of 100 kPa after 28 days. Since most of the specifications for CB cut-off wall only require compliance testing up to the age of 90 days, little literature reports on the evolution of CB properties during its design life. The properties of wall material may continue to change with time due to hydration of cement and slag (Opdyke & Evans, 2005; Fratalocchi et al., 2006; Jefferis, 2008). Furthermore, their long-term performance in chemically aggressive ground conditions is not known. Therefore the second objective is to examine the long term performance of CB wall materials by investigating the influence of time. This paper presents the results of the hydraulic conductivity and UCS of CB samples having their age ranging from 3 days to 11 years. Secondly, a cut-off wall is likely to experience ground movement and stresses due to excavation or

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building activity in its vicinity during regeneration of contained land. A UCS may not be sufficient to assess the mechanical performance of the wall. Triaxial compression tests were performed on 11 year old field samples to understand failure mechanisms in more realistic stress conditions, which is the third objective of the paper.

2 FIELD TEST SITE AND SAMPLES

In April 1996, a test site was established on a disused gasworks site by the UK Building Research Establishment and British Gas to study the long term hydraulic conductivity and *in situ* characterisation of CB materials. A total of 120 m of cut-off wall, 0.6 m wide by 5 m deep was constructed from CB slurry having a composition by weight of bentonite 3.4%, ordinary portland cement 2.5%, blast furnace slag 10.1% and water 84.0%. Ground conditions at the test site consist of underlying stiff clay and approximately 3 m of made ground at the top that was contaminated with spent oxide, coal residues, carbon black and foul lime. The water table was approximately 2 m below the ground level. High concentration of sulphate, total cyanide, PAHs and arsenic were the common contaminants found in the site. At some locations they were above 10,000 mg/l with a pH value between 2 and 3, which can deteriorate cement products. Further details of the test site are reported by Tedd et al. (1997).

In May 2004, the 8 years old walls were excavated down to the bottom and 'block' samples (1 m × 0.6 m × 0.25 m) were retrieved from different depths (Fig. 1a). They were then submerged in water and stored in a cold room for 3 years before conducting experiments. The 'block' samples were manually trimmed to small cylinders for laboratory tests. In addition to 'block' field samples, experiments were also conducted on two more types of CB samples, namely 'mixer-cast' and 'trench-cast'. The 'mixer-cast' samples were prepared from fresh CB slurry under laboratory conditions in plastic moulds. The slurry was prepared in a colloidal mixer by employing the same materials, mix design and procedure as used on the site. As shown in Fig 1b, the 'trench-cast' samples were prepared using slurry taken from the excavation trench during the construction of a cut-off wall at the test site in April 1996. Both 'mixer-cast' and 'trench-cast' samples were tested at the different ages ranging from 0.5 weeks to 11years to study the effect of time on the CB properties. The main differences between the three types of samples are their exposure to chemicals and mixing of impurities. Table 1 lists the mixing and curing condition along with the mineral phases, age of testing and numbers of specimen in these three varieties of samples. The 'mixer-cast' samples are uncontaminated and homogeneous as they had never been exposed to chemicals. While the 'trench-cast' samples had impurities, but they are less contaminated compared to 'block' samples as they were not exposed to chemicals. X-Ray Diffraction (XRD) tests revealed calcite and gypsum minerals phases in all three types of specimen at 11 years of age. Additional quartz minerals were detected in the 'block' samples due to the presence of stone/sand and ettringite minerals in the heavily sulphate contaminated specimens.

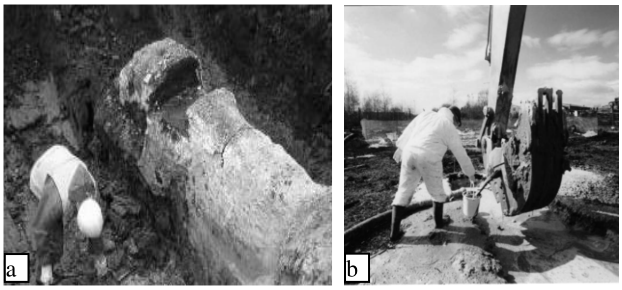

Figure 1. a) Excavation of 'block' field sample b) Slurry collection to prepare 'trench-cast' sample

3 EXPERIMENTAL PROCEDURE

Three types of laboratory tests are conducted in this study. First, the hydraulic conductivity was measured by constant flow tests carried out in a standard triaxial flexible wall permeameter cell. Specimen dimensions were 100 mm high × 100 mm diameter. The specimens were saturated by applying a back pressure of 100 kPa and consolidated at 100 kPa effective confining pressure. Syringe infusion pump was used to inject the tap water into the specimen at a slow rate. The injection flow rate was varied to measure the hydraulic conductivity at three different hydraulic gradients, ranging from 5 to 30. The cell pressure, back pressure and injection pressure were measure by pore pressure transducers and data were logged by a computer. For this experiment, 16 specimens from each 'mixer-cast' and 'trench-cast' samples were used having different ages as depicted in Table 1. Similarly 21 specimens from 'block' samples were tested out of which 19 specimens were of 11 years of age. Those 19 specimens consist of 4 specimens excavated from a wall section that was built on heavily sulphate contaminated patch on the test site to study the effect of sulfate attack on the hydraulic conductivity. Remaining 15 specimens were prepared from the five 'block' samples retrieved from 0.4, 1.1, 2.0, 2.4 and 3.55 m depths of wall to compare the change in hydraulic conductivity with the depth of wall.

The second type of laboratory experiment was UCS test. The CB specimens were 50 mm diameter by 100 mm high and compressed at the rate of 1.55 mm/minute. Both the axial deformation of the sample and the force applied were measured electronically with computerized data logging. As mentioned in Table 1, in total 37 specimens of 'mixer-cast' and 13 specimens of 'trench-cast' samples were tested at different ages. 31 'block' specimens were examined, out of which 29 specimens were prepared from the nine 'block' samples that were retrieved from 0.2, 0.4, 0.8, 1.1, 1.8, 2, 2.4, 2.8 and 3.55 m below ground surface to study the effect of depth. Remaining 2 specimens were prepared from heavily contaminated 'block' samples to investigate effect of sulphate attack on UCS.

Thirdly, consolidated undrained triaxial compression tests were carried out on 11 years 'block' field samples to determine their mechanical behaviour. All the specimens were saturated by applying back pressure of300 kPa. The specimens were then

Table 1. Properties of CB samples used for hydraulic conductivity and UCS testing.

Sample type	Slurry mixing condition	Curing/ setting condition	Nature of sample	XRD phases at 11 years of age	Age of sample (numbers of specimen tested)	
					For hydraulic conductivity test	For UCS test
'mixer-cast'	Laboratory	Laboratory in mould	Uncontaminated Homogeneous	Calcite, Gypsum	4 wk[a](2), 7/8 wk(4), 14/16 wk(3), 2 yr[b](3), 8 yr(1), 10.7 yr(3)	0.5 wk(4), 1 wk(4), 4 wk(11), 13 wk(2), 14/15 wk(7), 32 wk(2), 1 yr(3), 11 yr(4)
'trench-cast'	Field in wall	Laboratory in mould	Moderately Contaminated, Heterogeneous	Calcite, Gypsum	4 wk(1), 7/8 wk(4), 14/16 wk(7), 8 yr(1), 10.7 yr(3)	4 wk(4), 13/14 wk(4), 1 yr(1), 11yr(4)
'block' field	Field in wall	Field in wall	Contaminated, Heterogeneous	Calcite, Gypsum Quartz, Ettringite[c]	8yr(2), 11 yr(15,4[c])	11 yr(29,2[c])

[a] weeks, [b] years, [c] 'block' field samples built at heavily sulphate contaminated area.

consolidated isotropically in triaxial cell under six different effective confining pressures of 0, 50, 100, 200, 500 and 900 kPa. The B-value measured after saturation was above 0.94 in all cases. The samples were compressed at an external axial strain rate of 0.05%/minute under undrained condition.

4 RESULTS AND DISCUSSION

Figure 2 show the results of hydraulic conductivity against time for all three types of samples. Results depict that hydraulic conductivity reduces with age of the CB samples, especially till 90 days and get stabilised after 3 years. Tedd et al. (1997), Opdyke & Evans (2005), Fratalocchi et al. (2006) and Jefferis (2008) also reported such continuous slow reduction of hydraulic conductivity during initial months. Such drop of hydraulic conductivity is due to the hydration of cement and its slow reaction with pozzolanic material like slag in the slurry. The pozzolanic reaction develops denser microstructure compared to its early age and reduces hydraulic conductivity. Overall, the hydraulic conductivity of 'mixer-cast' and 'trench-cast' samples were below the ICE specified value of 1×10^{-9} m/s at the age of 90 days. At the age of 11 years, the hydraulic conductivity of 'mixer-cast' was the lowest with values 1.1×10^{-11} to 8×10^{-11} m/s, followed by the 'trench-cast' samples 5.8×10^{-11} to 1.7×10^{-10} m/s and the 'block' field samples with values 2.4×10^{-11} to 5.6×10^{-9}m/s.

Figure 3 shows UCS plotted as a function of the age of the samples. A large variation in results is observed irrespective of sample age and type of sample, but there is definite increase in strength with age. For example, the mean UCS at 28 days of uncontaminated 'mixer-cast' samples was approximately 360 kPa, whereas that at 90 days had increased to 890 kPa. After 90 days, there was relatively little increase in strength. Almost all the samples have strength above 100 kPa after age of 28 days i.e. complying ICE (1999) specification. The average strength of 'mixer-cast' and 'trench-cast' sample shows a difference of 100 kPa at age of 28 days and the difference increase more than 300 kPa at 90 days of age. The results indicate that the presence of impurities reduce the strength gain of CB. However, at a later stage, the 'trench-cast' sample exceeded the mean UCS value of 'mixer-cast' sample. At 11 years, the 'block' samples have the least average UCS with values ranging from170 to 790 kPa.

In all the cases the scatter of results for 'mixer-cast' samples was smaller than 'trench-cast' samples, followed by 'block' samples. The high variation in results of field 'block' samples is because of higher exposure to contamination and presence of impurities, which leads to more heterogeneous behaviour. Such heterogeneity can be seen in Fig. 4 where the 'block' samples have many pockets of entrapped soil/stone, air voids and contaminants. These impurities are relatively soft compared to the set CB slurry, which result in poor bonding between them causing variable UCS. It is likely that water can flow easily through these pockets that result in a higher overall hydraulic conductivity. Further level of heterogeneity is introduced by aggressive environment like chemical attack, weathering action at ground surface and wetting-drying cycles due groundwater fluctuation. This causes the behaviour of 'block' sample different than laboratory cured samples. Therefore, *in situ* testing is a way forward to characterize heterogeneity of CB cut-off wall at contaminated site (Soga et. al. 2005).

The 'block' sample exposed to high concentration of sulphates (with ettringite minerals) has their hydraulic conductivities and UCS values of similar magnitude compared to other 'block' samples. This suggests that the variation in mineralogical composition did not affect the overall CB behaviour and the wall samples resisted contaminant attack at the test site. Similarly, neither hydraulic conductivity nor UCS have specific trend with the change in depth of wall, but the scatter in results highlighted the heterogeneous nature of CB wall material. It was found that the density of 'block' samples increases with depth due to more mixing of surrounding soil. But, there does not appear to be any correlation between bulk density or moisture content with hydraulic conductivity or UCS. This implies that long term performance of field samples is not affected by a single individual parameter, but combination of many factors like impurities and aggressive environment.

Similarly for triaxial tests, the stress-strain curve and axial strain at failure for different confining pressures are inconsistent due to inherent heterogeneity in the specimen. For example, the presence of stones and micro fissures in the specimen are likely to cause zones of high stress concentration that can vary the strength-deformation pattern. Generally, the maximum deviator stress and the maximum excess pore water pressure both occurred at axial strain of approximately 1%. The peak deviator stress varied from 620 kPa to 840 kPa, which is higher than the UCS at 11 years of age. However, the undrained compressive strength did not vary much for low effective confining pressure, but increased at 500 kPa and 900 kPa pressures. Similar observation was reported by Åhnberg (2006) for stabilised soils.

The maximum excess pore water pressures developed during undrained loading is equivalent to the effective confining pressure in all tests except for the sample under confining pressure of 500 kPa and 900 kPa. This indicates that, when the deviator stress attains its maximum point, the minor principal stress approaches zero at the same time. The difference between σ_3'≤200kPa and above can better be visualised by the effective stress paths in the *q-p'* space as shown in Fig. 5. The stress paths of samples subjected to σ_3'≤200kPa first behaved elastically by moving up vertically and in an instant, they reached the tension cut-off line (1:3 slope) and failed in tension. It should be noted that this point did not necessarily correspond to the stress state when the first tensile crack happened in the specimen. This is because the pore pressure change at which the tensile crack just initiated might not be detected since the measurement was only located at the base of the specimen. The samples then mobilised the remaining strengths and travelled along the tension cut-off line. Finally, cracks are significantly

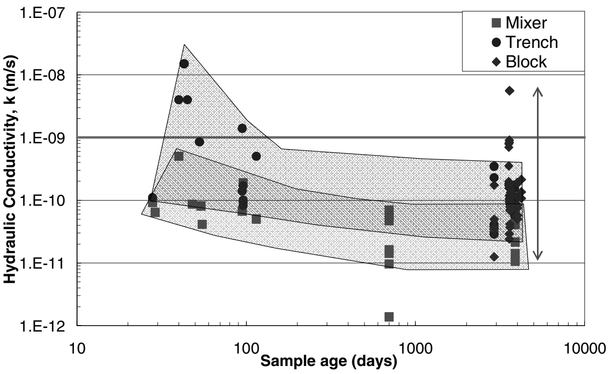

Figure 2. Hydraulic conductivity result with time for CB samples

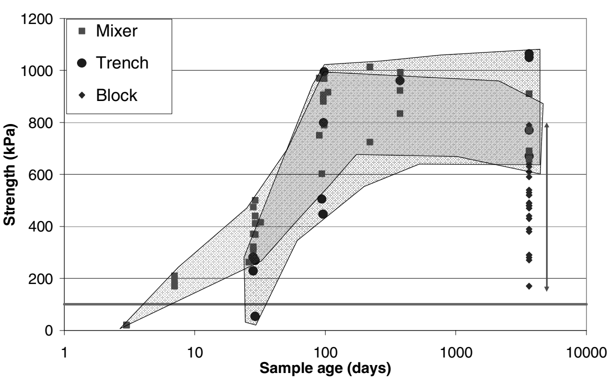

Figure 3. UCS result with time for CB samples

developed to induce large strains and the specimens reached their maximum deviator stresses. Subsequently, the stress paths of various tests fell onto the same line towards the end. The splitting cracks in failed specimen of σ_3'=50kPa test as shown in Fig. 6a confirmed the occurrence of tensile failure. Such failure patterns were also observed by Manassero et. al. (1995), where they reported low or negative pore pressure for σ_3'≤100kPa and all peak strengths lied on the tension cut-off line for low confining pressure cases.

On the other hand, stress paths of specimens subjected to σ_3'=500kPa started moving upwards and failed before hitting tension cut-off line. The pore water pressures at maximum and residual strength have not exceeded effective confining pressure as observed in the previous cases. Thus the specimen has failed under shear but not in tension. The crack pattern on the specimen after test also confirmed shear failure as shown in Fig. 6b. Beyond the peak strength, the stress-path moved towards tension cut-off line and showed residual strength similar to the other cases. Based on this observation, it is therefore recommended to perform effective stress analysis with tension criteria for any deformation and stability analysis. If the s_u (Φ=0) analysis is conducted, there is a danger that it may miss the tension (in effective stress) developed inside the wall.

5 CONCLUSION

The laboratory test showed that hydraulic conductivity of CB reduces with time up to 3 years, and remains constant until 10 years of age. The CB material gains strength by 90 days, which is much quicker than hydraulic conductivity reduction. These test indicated that the performance of CB material improves over age due slow pozzolanic reaction of slag with cement. Both 'mixer-cast' and 'trench-cast' samples achieved the target hydraulic conductivity of 1 $\times 10^{-9}$ m/s by age of 90 days and UCS more than 100 kPa by age of 28 days. Field 'block' samples were exhumed from a test site contaminated with sulphates to check their performance against laboratory cured 'mixer-cast' and 'trench-cast' samples. At the age of 11 years, the hydraulic conductivity of 'mixer-cast' was the lowest with values 1.1×10^{-11} to 8×10^{-11} m/s, followed by the 'trench-cast' samples 5.8×10^{-11} to 1.7×10^{-10} m/s and the 'block' field samples with values 2.4×10^{-11} 5.6×10^{-9} m/s. Similarly, the range of UCS values at 11 years of age were 660 to 910 kPa for 'mixer-cast', 670 to 1064 kPa for 'trench-cast' and 170 to 790 kPa for 'block' field samples. Thus, the 'block' field samples have inferior results and large variability. Such variations were mainly because of heterogeneity caused by the aggressive environment and impurities within the specimen, like stones, mud pockets, air cavities, contaminants, fissures, wet-dry cycle, and chemical attack. However, there is no co-relation between hydraulic conductivity or UCS with the depth of wall or high sulphate contamination. This implies that various parameters that cause heterogeneity do not individually affect the behaviour of CB material. Consolidated undrained triaxial experiment revealed that under realistic effective confining pressure (σ3'≤200kPa), the CB material failed in tension as the effective minor principal stress approached zero. At higher effective confining pressures, the shear failure is dominant and exhibits slightly higher peak strength compared to the specimens failed in tension. The design and interpretation based on the s_u (Φ=0) analysis should be used with caution and effective stress analysis with tension cut-off criteria is preferred.

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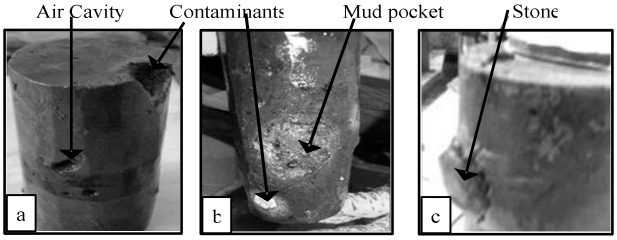

Figure 4. Presence of impurities affecting performance of CB walls

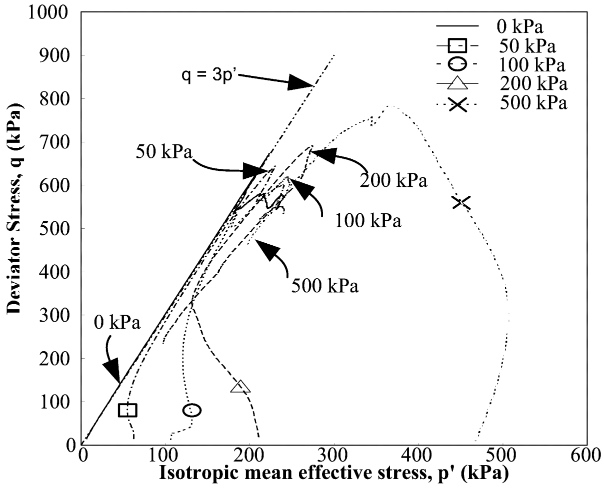

Figure 5. Stress path of triaxial test on 11 year old CB 'block' sample

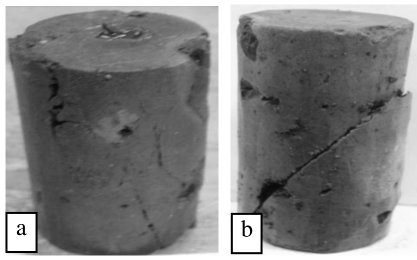

Figure 6 Triaxial specimens after test (a) σ3'=50 kPa (b) σ3'=500 kPa

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