Time-Dependent Strength Behavior of Soil-Bentonite Slurry Wall Backfill

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Abstract

Soil-bentonite (SB) slurry trench cutoff walls have been used for over 30 years as subsurface vertical barriers to control ground water flow and contaminant transport. Despite the millions of square feet of cutoff wall that have been constructed, little is known about the time-dependent behavior of the backfill and, in particular, the change in shear strength with aging. From experience, practitioners know that the backfill, which is initially placed as a semi-fluid material, gains strength with time. What has not been known is whether this time-related strength gain is due entirely to consolidation of the backfill or some other mechanism. This paper presents the results of laboratory and field testing of a SB slurry trench cutoff wall. Laboratory studies included consolidation and slump testing. Field studies included testing a constructed wall using vane shear, earth pressure cells, and settlement plates. The results of these tests demonstrate an increase in shear strength within a few days of backfill placement. This initial increase in shear strength is attributed to consolidation of the low-permeability backfill. The shear strength continues to increase with time, behavior that the authors attribute to two factors. The first is secondary consolidation or creep. The second is broadly termed "aging" and is attributed in part to the thixotropic nature of the bentonite used in the backfill mixture. Recommendations for the design shear strength for SB backfill are also included.

Introduction

The authors were presented with a unique opportunity to sample, test and instrument a SB slurry wall under construction in Delaware City, DE for containment of contaminated groundwater at an industrial site. The wall was approximately 1000-m long and typically 12- to 19-meters deep.

Field testing consisted of vane shear tests that were conducted at various time increments after construction and earth pressure cells that were installed in the trench at the time of backfill placement and monitored for some time afterwards. Samples of field-mixed backfill were taken for laboratory testing.

Physical property testing

Samples from the site were obtained as grab samples from field-mixed SB backfill (which includes a sandy base soil and bentonite) immediately prior to backfill placement in the trench. Based upon field requirements, the bentonite conent is estimated to be approximately 5%. The material was found to be a medium to fine silty clayey sand (SC) with an average of 23.7% fines with little variability from sample to sample as shown in Fig. 1 below. The average moisture content from 12 determinations was found to be 26.7%, typical of field-mixed and placed SB backfill.

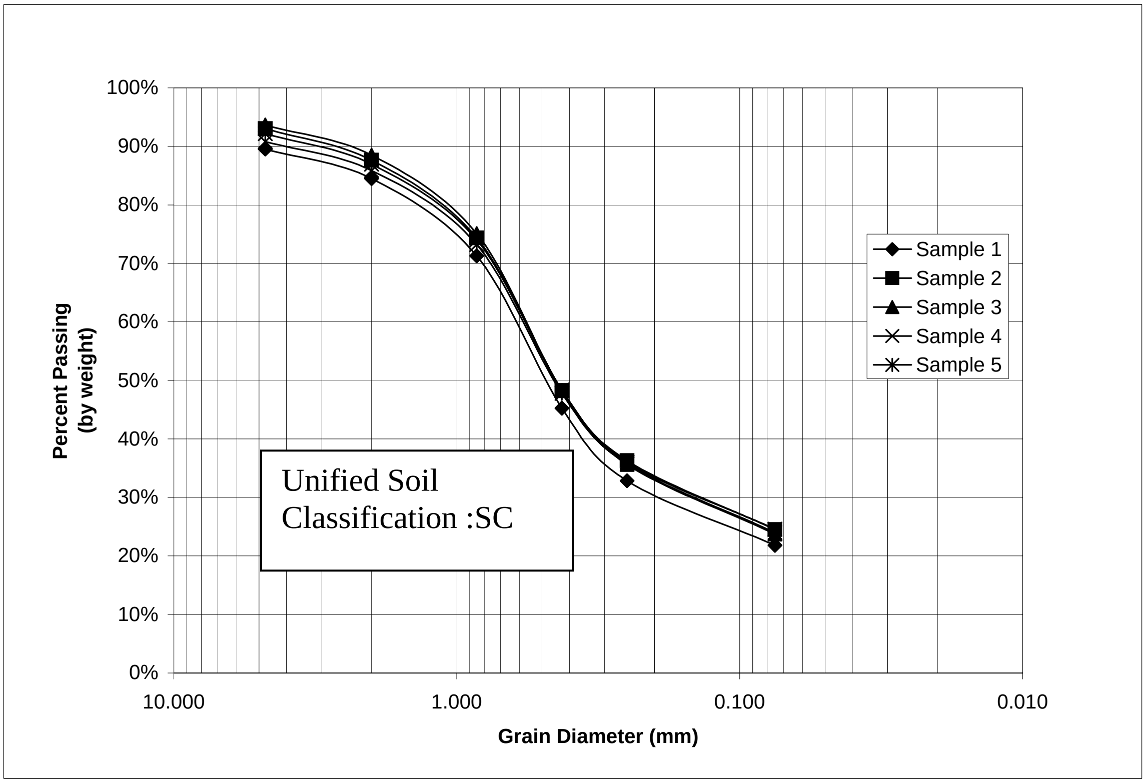

Figure 1 Grain size distribution of Delaware City backfill (ASTM D422)

The permeability of this material, based on extensive quality control testing of the field-placed backfill, was generally in the range of 3-6 x 10^{-8} cm/s. Permeability tests were run in flexible-wall tests in triaxial cells using ASTM Method D5084.

Slump testing

The time-dependent behavior of SB backfill was investigated in the laboratory using a simple slump test (ASTM C143). Field mixed samples of soil-bentonite backfill were tested and found to have a slump of 8.9 cm (3.5 inches) at a water content of 23.1%. The same material was formed in the slump cone but left to age at 100% humidity for a period of 18 hours prior to testing. After 18 hours, the cone was removed and the slump was 0.0 cm (0.0 inches). The water content was again determined and found to be 23.4% indicating that no drying of the sample occurred. Another conical sample was formed in the slump cone and allowed to remain in the cone undisturbed for a period of nearly one-month. After remolding, the backfill was found to have a slump of 8.9 cm (3.5 inches) at a water content of 22.8%. The zero-slump condition after only 18 hours demonstrates that indeed some strength gain with time is occurring in the SB backfill. The return to the original slump upon remolding suggests that the mechanism for strength gain is thixotropy.

Mitchell (1993) defines thixotropy as an "isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby a material stiffens while at rest and softens or liquefies upon remolding." The slump test results described above on soil-bentonite backfill materials are consistent with thixotropic behavior.

Consolidation testing

Three consolidation tests were conducted to evaluate the time rate of consolidation. The average values for the coefficient of consolidation, $c_{v,}$, determined for each loading increment using both Taylor's square root of time method and Casagrande's logarithm of time method are plotted on Figure 2. The results exhibit a general trend of decreasing c_v with increasing load. Note that these values of c_v on field-mixed SB backfill are consistent with those reported by Yeo, et al (2004) for sand-bentonite model slurry wall materials and by Baxter, et. al (2005) for laboratory-fabricated samples.

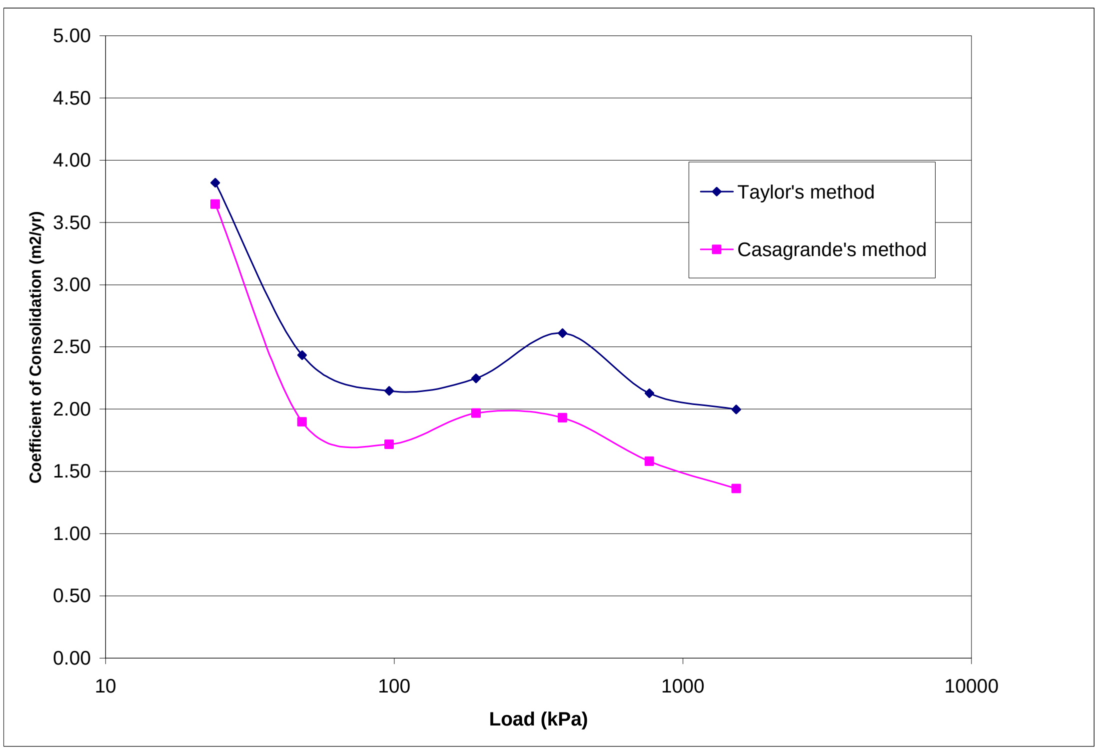

Figure 2 Coefficient of consolidation, $c_{v,}$ values for SB backfill as a function of Consolidation Pressure

The time-dependent behavior of the SB backfill was examined using especially designed and conducted procedures in consolidation tests. Three samples were loaded using a standard load increment ratio of one for consolidation stresses ranging from 24 to 192 kPa (0.25 to 2 tsf) applied for 24-hour increments. At 192 kPa (2 tsf), the sample remained under constant stress for a period of seven days. After seven days, sample loading continued using a small load increment ratio. Specifically, the samples were loaded using 12 kPa (0.125 tsf) increments from 192 kPa (2 tsf) to 264 kPa (2.75 tsf) at 24-hour increments. After 264 kPa (2.75 tsf), the sample was loaded to 383 kPa (4 tsf) and loading continued using a load increment ratio of one to 1532 kPa (16 tsf).

Additional results of the consolidation testing presented in the form of void ratio versus the log of pressure are shown in Figure 3. Note that the overall behavior is that of a normally consolidated material with a log-linear virgin compression curve, interrupted by the impact of the maintenance of the 192 kPa (2 tsf) load for seven days followed by the small load increment ratio. Analysis of the virgin compression data (not including the small load increment ratio readings) yields compression index, Cc, values of 0.027, 0.030 and 0.033 for the three samples. These values are slightly lower than the lowest value of 0.053 reported by Yeo, et. al (2004). The rebound portion of the curves is likewise log-linear and the computed values of swell index, C_s, were 0.0017, 0.0019 and 0.0021 for the three samples. These values are again slightly lower than the lowest value of 0.079 for sand-bentonite model backfill mixtures tested by Yeo, et. al (2004). The authors believe the lower values can be attributed to the fact that this backfill is slightly better graded than the material tested by Yeo, et. al. Similarly, given the sandy nature of the SB, the compressibility would be expected to be slightly lower than that of more clayey backfill mixtures. Similarly, the coefficient of secondary compression, ca, was measured during the time the 192 kPa (2 tsf) load was held on the sample. The values were 0.000251, 0.000214 and 0.000168 with R2 values of 0.80, 0.89 and 0.81 respectively. These values are quite low indicating that once this sandy SB material is fully consolidated, creep deformations are low.

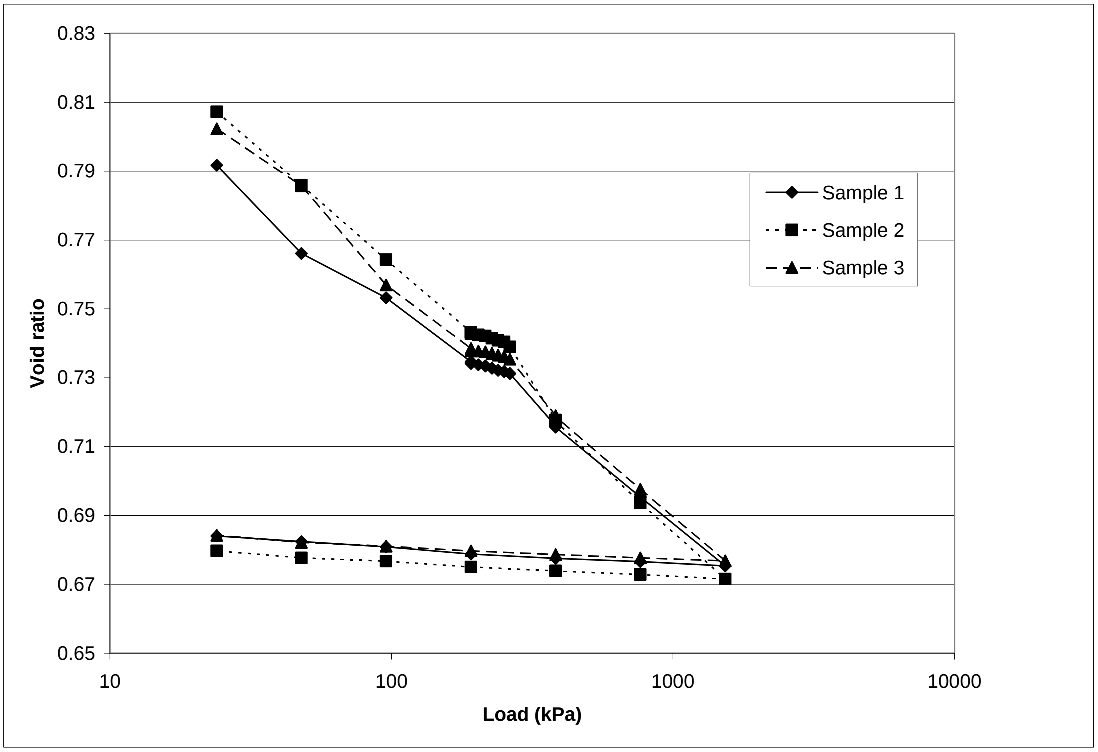

Figure 3 Consolidation test results for SB backFill

A portion of the data shown in Figure 3 for stresses ranging from 96 kPa to 383 kPa (1 to 4 tsf) is replotted on Figure 4 to examine the impact of time upon the consolidation behavior of the soil-bentonite. From a stress history standpoint, the data shown in Figure 4 clearly represent virgin loading, even though a preconsolidation pressure (termed a quasi-preconsolidation pressure by Leonards and Ramiah, 1959) is also evident. While these samples were consolidated for a period of seven days to a consolidation pressure of 192 kPa (2 tsf), application of a small load increment ratio resulted in behavior that mimics overconsolidated materials with an over-consolidation ratio (OCR) of about 1.4. This is observation is consistent with an analysis of data from seven other sources as summarized in Leonards and Altshaeffl (1964).

The development of a quasi-preconsolidation pressure for materials that have aged at constant stress is offered as evidence of an increase in the interparticle shear strength. One mechanism proposed to explain this increase is that, as a result of the creep that occurs at constant stress, the bond strength increases due to a more efficient orientation of water molecules in the vicinity of contact points (Leonards and Altshaeffl, 1964). In a similar manner, thixotropic behavior is well-documented and can be similarly explained in terms of adsorbed water layers (Mitchell, 1993). Finally, this observed interparticle strength gain evidence by the appearance of a quasi-preconsolidation pressure after only seven days at constant stress is consistent with field behavior observed during construction where strength gains are evident after a period of a week or more.

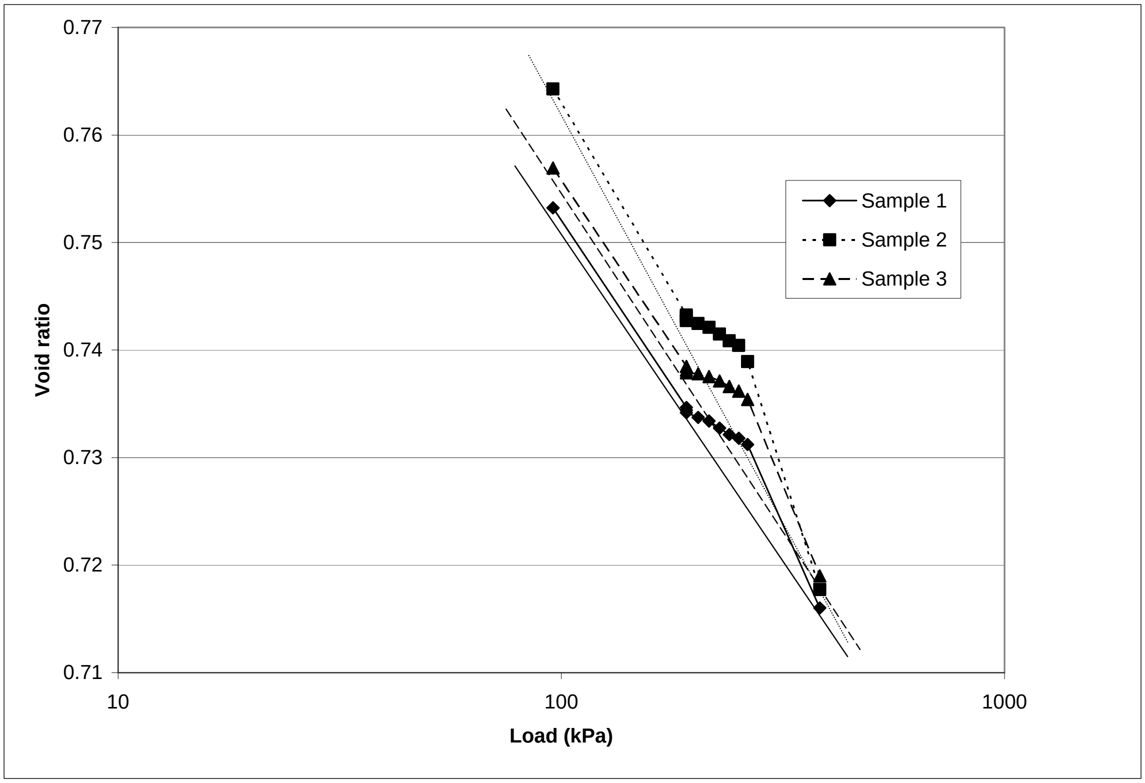

Figure 4 Quasi-preconsolidation effects in SB backfill

Field shear strength testing

Vane shear tests were conducted at the Delaware City site to examine effects of time upon the strength profile of the soil-bentonite backfill. Freshly placed backfill had shear strengths too weak to measure with the vane shear device. This is not surprising since the backfill is placed as a viscous liquid and testing was done within two hours of placement. At another location, testing was performed in backfill that was one-month old and again after the backfill had aged a total of six months. The results, shown in Figure 5 reveal no detectable change in the shear strength of the backfill during the period between one month and six months. From these data, most of the strength gain that takes place as soil-bentonite ages, evidently occurs within about the first month. This observation is consistent with longer term data showing that while there is some strength gain from the initial liquid state during backfill placement, the backfill is still quite soft even after periods of up to 10 years (Evans, et al., 1995). There is no significant increase in shear strength with depth for these data. As a result of the support of the backfill by the friction of the trench side walls, there is not a geostatic increase in stress and thus no geostatic increase in consolidating pressures. These findings are consistent with previous studies of the state-of-stress in the shallow subsurface environment. (Evans, et al., 1995 and Filz, 1996)

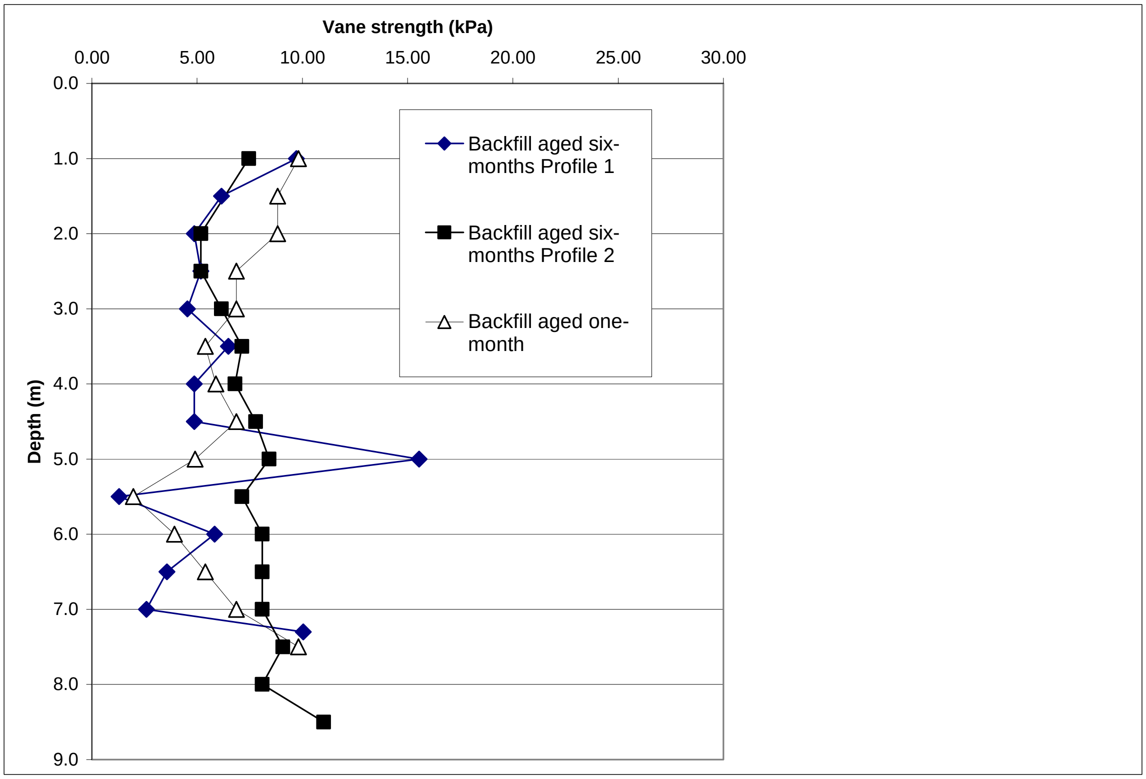

Figure 5 Vane Shear Strength of SB Backfill vs Depth

Field pressure cell testing

Earth pressure cells were installed in freshly placed backfill and monitored over time at the Delaware City site. The earth pressure cells were mounted on a steel sheet pile and surrounded on the edges with a plexiglass shield of the same thickness to protect the cell during placement in the trench. The transducer was protected with a half-round pipe and the data cable protected with electrical conduit. The pressure cell as mounted on the sheet pile is shown in Figure 6 below.

Figure 6 Earth pressure cell mounted on steel sheetpile before placement

The sheet pile with attached load cell was then lowered to a depth of approximately 6 m (20 ft.) into freshly placed backfill and anchored in place with cables attached to cross-ties over the trench. The results, in terms of total lateral stresses, for seven days of monitoring are shown in Figure 7. The lateral stress decreases with time. With the results plotted as a function of the logarithm of time (in a manner similar to the deformation versus logarithm of time plots for laboratory studies of the time-rate of consolidation), a polynomial fit is shown with an R^2 of 0.97 indicating that the initial portion of the curve is a parabola similar to an idealized plot in a laboratory consolidation test. Using c_v = 3.7 m2/yr (the highest value from the Casagrande method for the soils from this site) yields a time for 95% consolidation of 16 days assuming a 0.75m (30-inch) wide trench (Filz, 2003). This information, coupled with an observation from the plot that the pressure has not yet stabilized, indicates that the final lateral pressures have not yet developed. A complete analysis of the lateral pressures observed and their comparisons to calculations of the state-of-stress in the trench is the subject of another paper. The results do show the substantial time (more than a week) that the soil-bentonite backfill is equilibrating under its own self-weight.

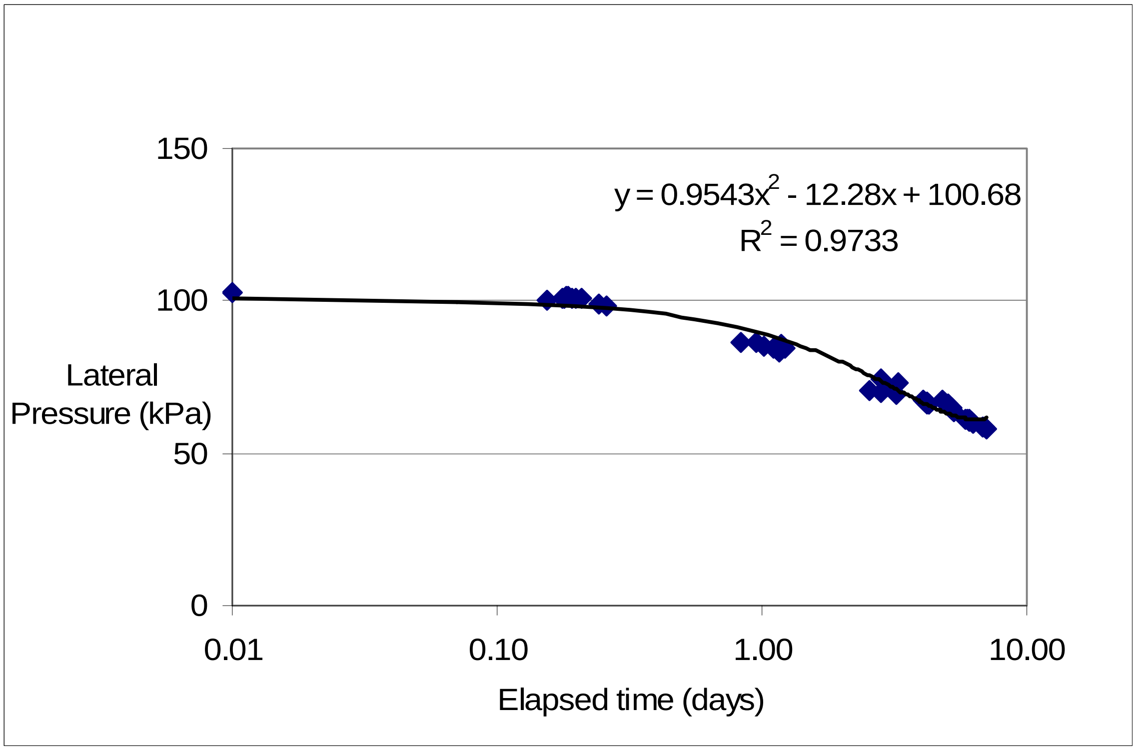

Figure 7 Time-dependent earth pressure readings in SB backfill

Summary and conclusions

The field observations clearly indicate that the SB backfill evaluated in this study gains strength with time. When placed, the backfill is a viscous liquid, typically with a slump of 75 to 150 mm (3 to 6 inches). The backfill typically slumps in the trench to a slope of between 5 and 10 horizontal to 1 vertical when placed. Later, excavation into this material reveals a material strong enough to stand vertically when exposed in a slurry-filled trench.

Based on this one project, the authors would suggest undrained shear strength for design for SB backfill after consolidation as follows: Shear strength of 5-10 kPA (0.7 to 1.4 psi)

The multi-faceted laboratory and field testing program described above indicates several mechanisms are at play to explain the increase in strength that occurs in soil-bentonite backfill. These mechanisms are consolidation, creep, aging, and thixoptropy.

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