FIBRE REINFORCEMENT OF CSM WALLS TO ENHANCE STRENGTH, CRACK RESISTANCE AND SEEPAGE CUT-OFF

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ABSTRACT

Cutter soil mix (CSM) walls are created by mixing soils while in situ with cement and bentonite slurry to produce a soil mix with modest tensile and compressive strengths. CSM walls may be stabilised using internal steel beams and ground anchors. Presented here are results of a CSM wall field trial in which polypropylene fibres were added to a soil mix. One objective of the trial was to explore whether or not fibres have the potential to increase wall resistance to bending and reduce the quantity of steel needed to provide stability. Another objective was to explore whether or not the fibres provide a reduced tendency for crack formation and thus the potential for enhanced seepage cut-off. The trial involved mixing fibres into a 4 m deep single CSM wall panel using a conventional mixing procedure employed by Wagstaff Piling. 24 hours after placement a 20 tonne excavator was used to remove the wall panel. Samples were collected and tested 28 days and 2 years later to assess unconfined compressive strengths, indirect tensile strengths and flexural tensile strengths. The fibre orientation distribution in the soil fibre mix was also assessed. The testing confirmed that the mixing technique resulted in a uniform orientation distribution of fibres and significantly improved strength characteristics. The testing also showed that the fibres made the CSM wall mix very ductile and prevented brittle failure. Adding fibres to the CSM material enabled larger bending deformations to be tolerated before major cracking and failure occurred. Also presented is a hypothetical design of a fibre reinforced CSM wall to show that steel quantity can be reduced while maintaining stability and crack prevention, leading to significant cost reductions.

1 INTRODUCTION

Cutter Soil Mix (CSM) walls may be used as a shoring wall and to provide seepage cut-off. They are made by mixing soil in situ with cement and bentonite slurry. The mixing tool involves two sets of vertically mounted cutting wheels rotating about a horizontal axis to produce rectangular panels of the soil mix. Panels are overlapped to form a continuous rectangular wall. Steel beams are often inserted to provide structural stability, particularly bending resistance. Following excavation in front of the wall, tieback ground anchors may be installed to provide additional shoring capacity (Kvinsland and Plum, 2010; Lindquist *et al.*, 2010). CSM walls have fewer overlapping joints compared to secant pile walls reducing potential for leakage. They also have less material waste than secant pile walls (Brunner *et al.*, 2006). However, one drawback of CSM walls is the low strength of the soil mix, particularly the tensile strength. The steel beams needed to provide structural strength are a significant cost, and need to be closely spaced to reduce bending induced stress in the wall panels to only a few hundred kilopascals. In this paper a new fibre reinforcement technology is introduced to increase the strength properties of CSM walls. It involves mixing discrete flexible polypropylene fibres into the wall panels. A successful procedure used to create a soil fibre mix is presented, which resulted in an isotropic fibre orientation distribution. Laboratory testing results indicated that strengths were elevated by the presence of fibres necessitating less steel in a typical wall design, fewer anchors and an overall cost saving. Also, the fibres made the CSM wall mix very ductile and minimised crack formation pre-failure indicating the potential for enhanced seepage cut-off.

2 THE FIELD TRIAL

A field trial was conducted in which Forte Ferro polypropylene fibres were mixed into a 4m deep single panel CSM wall. The soil at the site of the trial consisted of fine to medium grained aeolian sand and silty sand, tending from loose to dense at depths greater than 3.2m below existing surface level. The in situ soil was mixed with a slurry of a water cement ratio of 0.8. 400kg of cementitious material was added per cubic metre of soil with a target slurry injection rate of 601 litres per lineal meter of CSM panel.

The fibres were supplied in dissolvable paper bags. The fibres in their bags were placed between the teeth of the cutter as shown in Figure 1. The first round of mixing involved placing fibres amounting to 0.25% of the dry mass of the premixed soil. The cutter was then lowered into the soil mix, then rotated to mix in the fibres. The second and final round of mixing involved placing additional fibres bringing the total amounting per dry mass of premixed soil to 0.5%.

Samples of the wet mix were taken during construction. This happened immediately prior to and immediately after each round of fibre mixing. The ‘during constriction’ sampling technique involved lowering an open topped sampler into the wet mix and pouring the contents into the plastic tubes that were 1 m long and 100 mm diameter.

24 hours after placing the panel a 20 tonne excavator was used to remove the panel from ground. Initially the excavator attempted to cut into the panel. It was apparent from the excavator resistance that the CSM-fibre wall panel had a strength that far exceeded a conventional CSM wall. The excavator was unable to cut into the fibre reinforced wall in any way, but was only able to scrape the exposed surface and break off pieces that were 50 mm to 100 mm thick.

The lowest 1.5m section of the wall was removed from the ground using the excavator and kept intact. 2 years after mixing it was cut into cylinders and beams which were tested to assess various strength and stiffness properties.

Figure 1: Fibres in paper bags add to the cutter (left). Surface of soil fibre mix showing effective mixing and dispersion (right)

3 LABORATORY TESTING AND FIBRE ORIENTATION DISTRIBUTION ANALYSIS

A program of laboratory testing and analysis was conducted to:

1. Determine the fibre orientation distributions achieved at different depths in the 4 m wall panel, using the analytical counting procedure outlined by Diambra *et al.* (2007). If fibres tended to have a preferred orientation because of the mixing technique then this would be identified. Orientation distribution is an important consideration as fibres provide most benefit when aligned with the direction of tensile strains.
2. Conduct unconfined compressive strength tests and indirect tensile strength tests on cylinders cut from the tubes and the intact 1.5m section (length = 2 × diameter). Tests were conducted 28 days and 2 years after mixing.
3. Conduct flexural strength (bending beam) tests on prisms cut from pieces recovered during excavation and cut from the 1.5m intact section. Load and deflection up to and beyond failure were recorded to indicate flexural tensile strength (also referred to as the modulus of rupture), stiffness and post failure ductility. Tests were conducted 28 days and 2 years after mixing.

3.1 FIBRE ORIENTATION DISTRIBUTION

Fibre orientation was analysed for samples cut from pieces recovered during excavation. The numbers of fibres intersecting areas on three orthogonal planes were counted. The numbers of fibres per area on each plane were put into the solution procedure of Diambra *et al.* (2007).

It was determined that the mixing technique used resulted in an isotropic fibre orientation distribution. In other words, the fibres provide comparable strength gains whatever the loading direction. This is the most ideal orientation distribution. As will be discussed below there are two types of bending that have the potential to cause cracking in the wall. The fibres having an isotropic orientation distribution offer the most optimal resistance to both.

3.2 UNCONFINED COMPRESSIVE STRENGTH

Measured unconfined compressive strengths (at 28 days and 2 years) are given in Table 1 for nine samples, two with no fibres, two with 0.25% of fibres and five with 0.5% of fibres. The 'during construction' sampling method used resulted in very variable sample densities, listed in Table 1. The largest strengths were observed for the densest samples.

It can be seen that adding 0.5% fibres by dry mass of soil increased the 28-day strength by at least 100% from the unreinforced value of 3.25MPa. It can also be seen that the 2-year strength was approximately three times larger than the 28-day strength.

Table 1: Unconfined compressive strengths for samples recovered from tubes

Fibres content (% by dry mass of soil)	Unconfined compressive strength (MPa)		Sample density (kg/m^3)
	(after 28 days)	(after 2 years)	
0	13.0	-	1830
0	3.3	-	1540
0.25	4.5	-	1400
0.25	7.0	-	1810
0.5	11.3	-	1820
0.5	6.5	-	1600
0.5	-	31.0	1870
0.5	-	21.8	1800
0.5	-	32.3	1870

3.3 INDIRECT TENSILE STRENGTH

Measured indirect tensile strengths (at 28 days and 2 years) are given in Table 2 for seven samples, two with no fibres, one with 0.25% of fibres and four with 0.5% of fibres. Adding 0.5% fibres by dry mass of soil increased the 28-day indirect tensile strength by about 80% from the unreinforced strength of 0.9MPa. Also, the 2-year strength was approximately twice the 28-day strength.

Table 2: Indirect tensile strengths for samples recovered from tubes

Fibres content (% by dry mass of soil)	Indirect tensile strength (MPa)		Sample density (kg/m^3)
	(after 28 days)	(after 2 years)	
0	1.1	-	1860
0	0.9	-	1870
0.25	1.9	-	1870
0.5	1.6	-	1880
0.5	-	3.2	1830
0.5	-	2.4	1850
0.5	-	3.9	1860

3.4 FLEXURAL TENSILE STRENGTH

Measured flexural tensile strengths (at 28 days and 2 years) are given in Table 3 for samples each with 0.5% of fibres by dry mass of soil. Some tests were conducted using a 3-point bending beam and others were conducted using 4 point bending beam. Adding 0.5% fibres by dry mass of soil produced a 28-day flexural tensile strength of at least 0.84 MPa. The 2-year strength was at least 1.81 MPa. On average the 2-year strength was 2.6 times the 28-day strength.

For each sample tested Table 3 also lists secant Young's moduli at the instances when peak strength had been mobilised (E_{100}) and for when 50% of peak strength had been mobilised (E_{50}). In computing these values for the 4-point tests shear deformation effects were ignored. On average the 2-year E_{50} was 2.3 times the 28-day E_{50}.

Table 3: Flexural tensile strength for samples cut from fragments recovered during excavation

Fibres content (% by dry mass of soil)	Flexural tensile strength (MPa) (after 28 days)	(after 2 years)	Test type	Young's modulus at peak strength – E_{100} (MPa)	Young's modulus at 50% of peak strength – E_{50} (MPa)
0.5	1.27	-	4-point	125	339
0.5	1.0	-	4-point	57.5	169
0.5	0.84	-	3-point	91	194
0.5	-	1.81	4-point	170	343
0.5	-	3.44	4-point	283	709
0.5	-	3.96	4-point	228	636
0.5	-	1.98	3-point	155	492
0.5	-	2.76	3-point	173	496
0.5	-	2.25	3-point	131	623

Figure 2 plots flexural load versus displacement for a typical sample. As this was a 4-point bending test, the displacement plotted is the average of that measured at the two inner loading points. The cross section of this sample was 67.5mm deep and 39.2mm wide. The load versus deflection response observed was non-linear. Also, the post-failure flexural tensile strength was about 60% of the peak value, indicating a very ductile behaviour and a good ability to maintain significant tensile strength at very large amounts of deflection and bending.

Figure 3 shows a photograph of one of the samples post-test which was subjected to a 4-point bending. The cracking that is evident developed as the peak strength was attained. The crack is approximately 'Y' shaped and extended from near the two central load contact points on the upper sample surface to the near the centre of the sample's underside. This pattern was typical. What is also notable is the absence of minor cracks away from the main central Y shaped crack. From this it can be implied that good water tightness would be obtained in fibre reinforced CSM walls during pre-failure loading.

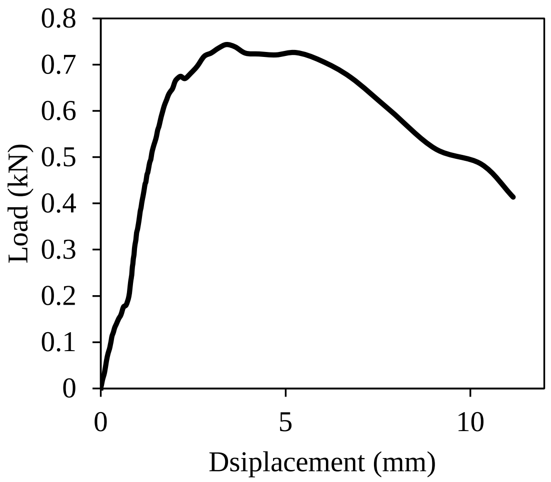

Figure 2: Load versus displacement for a 4-point bending test on the soil fibre mix

Figure 3: Typical crack pattern in a sample subjected to 4-point bending

4 ANCHORED WALL DESIGN AND COST ANALYSIS

A hypothetical wall design is presented here in which the strength gain provided by the fibres is incorporated. The wall is to be used as shoring for an 8 m excavation in medium dense sand. The water table is assumed to be at the excavation level on both sides of the wall in the worst case. Although the wall is not required to provide seepage cut off, it is designed to prevent cracking in the soil fibre mix. The geometry, soil properties and surcharge loading are shown in Figure 4.

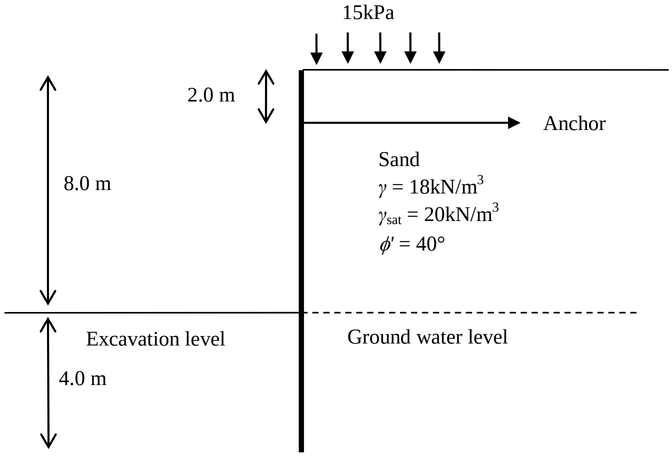

Figure 4: Problem considered in wall design

In the design it is assumed that a CSM wall panel without fibres has compressive and tensile strengths of 3.0 MPa and 0.5 MPa, respectively, and a Young's modulus of 280 MPa. It is also assumed that a CSM wall panel with 0.5% fibres has compressive and tensile strengths of 3.0MPa and 0.8MPa, respectively, and a Young's modulus of 280 MPa. Notice the conservative assumption that only the tensile strength is increased by the presence of fibres. Further conservatism is introduced through use of strengths and stiffness which are around the 28-day values rather than 2-year values.

The design procedure is as follows:

1. For a certain wall length use the free earth support method to compute the maximum bending moment in the wall. In doing so the soil friction angle is reduced by a factor for safety prior to computing the active and passive earth pressure coefficients.
2. Reduce the maximum bending moment computed from the free earth support method by some amount to achieve the design value. The moment reduction accounts for the soil–wall interaction, wall deflection, and relative stiffness of the soil with respect to the wall. The results of Rowe (1952, 1955) and Potts and Fourie (1985) are used to quantify the moment reduction.
3. Determine the size and spacing of steel beams necessary to provide bending resistance, applying a strength reduction factor to the steel. Iteration may be needed to incorporate the bending stiffness of the wall into the moment reduction calculations in step 2.
4. Ensure the maximum tensile stress induced in the soil fibre mix does not exceed the tensile strength (after having been reduced by some amount for safety).
5. Determine the maximum tieback anchor force necessary to provide stability.
6. Analyse the bending of the soil fibre mix wall sections between steel beams to ensure adequate strength is available, again after having made strength reductions for safety. The location where bending induced stresses will be largest is near the anchor connections, as indicated by Potts and Fourie (1985). Note that the earth pressure used in this type of analysis should be larger than that used in computing the maximum bending moment. The earth pressure may be determined using a coefficient between the at rest earth pressure coefficient and the passive earth pressure coefficient. Here the unfactored passive earth pressure coefficient will be used, representing the worst case.

In computing the maximum bending moment for the problem shown in Figure 4, the soil friction angle of 40° is reduced to atan(tan(40°)/1.3) = 32.8°, resulting in earth pressure coefficients of $k_a = 0.30$ and $k_p = 3.37$. The maximum bending moment is then 335 kNm/m (computed by taking moments about the anchor). The maximum moment occurs at 6.7 m from the top of the wall, or 1.3 m above excavation level. The required anchor capacity is 150 kN/m. To make the moment reduction it is necessary to know the dimensionless quantity $m\rho$, where $\rho = H^4/EI$, H is the total wall height (12 m), E is the effective Young's modulus of the soil fibre wall containing the steel beams, I is the moment of inertia of the soil fibre wall containing the steel beams, and m is the rate at which modulus of subgrade reaction for the soil increases with depth. A wall that is 0.55 m wide, and which contains two 360 UB 57 beams every 2.2 m, has an equivalent EI = 33200 kNm^2/m (using E = 200000 MPa for steel). Assuming m = 10 MPa/m, a value typical for medium dense sands (Terzaghi, 1955), leads to $m\rho$ = 6246. The reduced moment in the wall is then 218 kNm/m. For this design moment the maximum tensile stress in the steel beams is 240 MPa, sufficiently below the yield strength of 410 MPa. Also, assuming elastic bending in the soil fibre mix and that cracking does not occur, the maximum tensile stress in the soil fibre mix is 0.54 MPa, below the tensile capacity of 0.8 MPa (ie. the assumption on no cracking is valid). The design will now be progressed by assuming that the two beams are positioned near each other at the centre of a wall panel. One anchor will be located at the two beams, that is at every 2.2m along the wall, such that a single anchor must carry 330 kN. The earth pressure on the wall at the anchor depth, assuming a passive earth pressure coefficient of k_p = 4.60, is p = 97.8 kPa. The widest clear span between beams is L = 1.9 m. The centre of the span is also where two panels of the CSM wall join, and no tensile load can be carried across the join. Instead, the span must act as a deep beam and resist the earth pressure by compression. The maximum compressive stress in the span configured in this way may be computed (approximately) using the expression $\sigma_{c,max} = pL^2/2b^2$, where b is the depth of the wall section (0.55 m). Using this, the maximum compressive stress is 0.58 MPa, well below the soil fibre mix compressive strength of 3.0 MPa. If no fibres are added, two 360 UB 57 steel beams must be placed at every 1.2m to keep the maximum tensile stresses in the soil fibre mix to 0.31 MPa, sufficiently below the unreinforced tensile capacity of 0.5 MPa. This results in a stiffer wall, having an equivalent EI = 57500 kNm^2/m. This would be associated with a slightly larger moment in the wall for use in design, equal to 234 kNm/m. The maximum tensile stress in the steel beams is well below the steel yield strength. The maximum compressive stress in the wall near the anchors is also well below capacity. It is the maximum tensile stress in the soil fibre mix in the wall at about 1.3 m above excavation level that governs design.

The costs for the designs with and without fibres are now analysed. Both designs ensure that cracking does not occur in the wall at the location where the bending moment is largest. The cost analysis is limited to the steel beams, fibres and anchors. The cost of supplying and handling on site a single 12 m long 360 UB 57 steel beam is assumed to be $1840 AUD. The cost of an anchor in sand above the water table is assumed to be $1200 AUD. The cost of fibres and adding to the mix is assumed to be $12 AUD per kg, or $108 AUD per m^3 of wall. Using these numbers, the cost of steel beams and anchors per linear meter of wall without fibres is $4070 AUD. The cost of steel beams, anchors and fibres per linear meter of wall with fibres is $2930 AUD.

5 CONCLUSION

This study has showed that discrete flexible polypropylene fibres may be successfully added to a soil mix to create a fibre reinforced CSM wall that does not crack significantly during bending until the peak strength is attained. The tensile strength of the soil fibre mix is above 0.8 MPa. A hypothetical design situation shows that the amount of steel reinforcing may be reduced in an anchored wall, while ensuring cracking is prevented where the bending moment is a maximum, providing significant cost reductions. The absence of cracking also indicates the potential for enhanced seepage cut-off.

6 REFERENCES

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