Unconfined interfacial friction of Geosynthetic Cementitious Composite Mats

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Abstract. Geosynthetic Cementitious Composite Mats (GCCMs) are flexible, cementitious material-filled geosynthetics that harden on hydration to form thin concrete layers and are primarily used for surface erosion protection applications. When installing GCCMs on steep slopes and channels, the interfacial friction between the GCCM and the substrate must be understood to determine if anchoring is required to secure the material in place. Determining interface shear resistance using test methods such as ASTM D5321 require a shear box and confining load acting on the soil/GCCM, which may not accurately represent GCCM resistance, as when installed there is typically no confining load other than GCCM self-weight and water. To provide a more detailed understanding of 'unconfined' interfacial friction properties of GCCMs, the authors created a tilt table which could be filled with different substrates and inclined to record the angle of GCCM specimen slip on the substrate surface. This paper reviews the tilt table testing on two common GCCMs with different backing layers (PVC and LLDPE), tested on a number of substrates that are typically lined in GCCMs. Both the interfacial friction angle and adhesion are determined, with discussion on the relationship between adhesion and surcharge for some substrate types.

1 Introduction

Geosynthetic Cementitious Composite Mats (GCCMs) are flexible, cementitious material-filled geosynthetics that harden on hydration to for thin concrete layers and are primarily used for surface erosion applications, such as drainage channel/irrigation canal lining, slope protection and berm lining. On sloping surfaces, GCCMs may be exposed to shear forces due to their self-weight and water (particularly for channel/canal lining). GCCMs are typically anchored at their perimeter to prevent movement, but the interfacial friction between the GCCM backing layer and the substrate must be understood to determine if the perimeter anchoring, combined with the frictional resistance provided by the GCCM/soil interface, is sufficient to provide resistance to the destabilising shear forces and prevent GCCM material movement. Additional anchoring may be required to secure the material in place.

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Direct shear testing of geosynthetics on geosynthetic and soil interfaces is well researched, and data on the geosynthetic backing layer materials of common GCCMs (for example LLDPE and PVC) are included resources such as in GRI Report #30 'Direct Shear Database of Geosynthetic to Geosynthetic and Geosynthetic to Soil Interfaces'[1].

However, because GCCMs are surface erosion control materials, they are exposed in service and only buried at the perimeter anchor trenches. Therefore they are not subjected to confining loads other than the depth of water that the material is providing erosion protection from. Therefore, current test methods to determine the interfacial friction of a geosynthetic and a subgrade may not actually represent in-service conditions for GCCMs. For example, ASTM D5321/D5321M-21 'Standard Test Method for Determining the Shear Strength of Soil-Geosynthetic and Geosynthetic-Geosynthetic Interfaces by Direct Shear'[2] uses a shear box and a confining load acting on the soil/GCCM. This confining load varies for each test and is necessary to determine the interfacial friction and adhesion for a given interface. D5321/D5321M confining loads used can typically vary from 50 to 500 kPa (roughly equivalent to 5 m – 50 m of water load on top of the GCCM). In reality, GCCMs are rarely used in more than 3 m water depths, although most drainage channels with fast flowing water have very shallow water depths, so the normal loads used in the D5321/D5321M testing may not be representative of 'unconfined' interfacial friction of GCCMs in the field.

2 Initial research into unconfined friction testing

GRI Test Method GS7 is the 'Standard test Method for Determining the Index Friction Properties of Geosynthetics'[3] and describes two procedures for determining the index friction angle between a geosynthetic and geosynthetic or soil surfaces. The incline plane method uses a sliding block mass with a specified contact surface, placed on top of a geosynthetic specimen that is secured flat to a surface, which is then inclined. The angle is recorded at the point at which the block begins to slide. This is a useful index test, but cannot determine performance properties of a GCCM on a variety of surfaces.

The second procedure in GS7, the slide block sled method, is performed on a horizontal surface to determine the interfacial friction of a GCCM specimen on a variety of substrates, which is beneficial for assessing GCCM interfacial friction. The GCCM is attached to the slide block, connected by a rope to a bucket which is gradually filled with lead shot to increase the shear force on the GCCM until the specimen moves. Unwanted forces acting on the specimen could potentially arise from dynamic vibrations from loading the bucket, or the location of the connection of the rope to the slide block sled (causing rotation).

3 New test methodology – the Tilt Table

Considering the advantages of each procedure in GS7, the authors created a 'Tilt Table' to determine the interfacial of GCCMs on a number of common substrates.

The Tilt Table would comprise a timber box that could be filled with the soil, surface or geosynthetic to be tested. A GCCM specimen would be placed on top and the box would then be inclined. The angle at which the specimen begins to slide would be recorded.

3.1 GCCMs tested

Unconfined interfacial friction data is primarily used for hydraulic shear calculations, so it was decided to test the CCT2™ GCCM, which has a PVC backing layer[5] ('GCCM-PVC') and the CCX-M™ GCCM, which has an LLDPE backing layer[6] ('GCCM-LLDPE'). Both are Type II GCCMs according to ASTM D8364/D8364M-21[4] and commonly used in channel lining applications.

3.2 Preparation of Test Specimens

To prevent the edges of the GCCM specimens from catching or digging into the substrate, 'tray shaped' specimens were created so that only the GCCM backing would be in contact with the substrate. These were formed by compressing the GCCM in a mould immediately after hydration, so that all edges curved upwards.

To consider the effect of a nominal channel water loading on the interfacial friction angle (and determine any potential adhesion), it was decided to test the tray shaped specimens under 2 conditions:

1. Tray specimen only (considering the curved edges as a surcharge to the contact surface area of the specimen)
2. Tray specimen with additional surcharge using steel plates (to represent additional water loading)

Each GCCM-PVC and GCCM-LLDPE tray shaped specimen was labelled, with specimens labelled '1' being used for 'specimen only' testing, and specimens labelled '2' being used with additional steel plates attached to them. Each specimen was weighed, with specimen 2 being weighed a second time when the steel plates were attached (using double sided tape to prevent movement).

The contact surface area of the specimens was also measured to be 130 by 100 mm and was consistent for all specimens (as they were prepared from the same mould to create the tray shape). To determine the mass per unit area of the specimens, the mass of three GCCM-PVC and GCCM-LLDPE 'standard' samples were measured. These standard samples were flat and had a surface area of 64 cm^2 so the average mass per unit area of the cured GCCM samples could be calculated and used to determine the weight of the non-contact surface area component of the GCCM tray sides. Using the above information, the additional weight of the tray sides and the steel plates could be converted into an effective additional depth of water surcharging each specimen. The effective additional depth of water surcharging specimen labelled '1' (specimen only testing) was 1 cm for GCCM-PVC and 2 cm for GCCM-LLDPE. The effective additional depth of water surcharging specimens labelled '2' (with the additional steel plates) was 14 cm for both GCCM-PVC and GCCM-LLDPE specimens.

3.3 Interfaces Tested

Typical substrates for channel lining applications were tested:

- Clayey Topsoil
- Sharp Sand
- Gravel (14-20 mm sub angular)
- Concrete (paving flag)
- Geotextile (a needle punched non-woven)
- HDPE (0.6 mm smooth) [not a common channel lining substrate but assumed to have a low friction angle]

4 Methodology

The GCCM-PVC and GCCM-LLDPE GCCM specimens were tested separately. 3 tests were carried out for each GCCM type on each substrate. Specimens 1 and 2 were placed alongside each other on the substrate surface so they could be tested at the same time. The tile table angle was measured when the specimen began to slip.

For soil substrates, the surface was tamped smooth with a wooden block to create a uniform surface. This was possible for the sand, but not entirely possible for the gravel (due to the angular nature of the material) or clayey topsoil (due to the variability in the presence of small pebbles and organic matter). The geotextile and HDPE were taped to the concrete slab. Setups with each substrate used are shown in Figures 1 to 6.

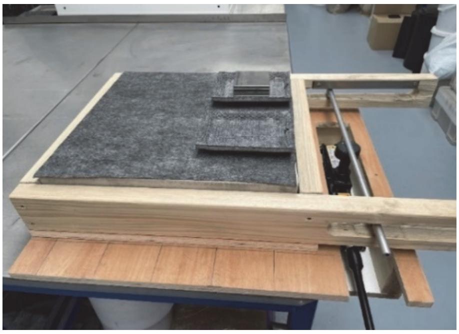

Fig. 1. GCCM-LLDPE specimens on geotextile

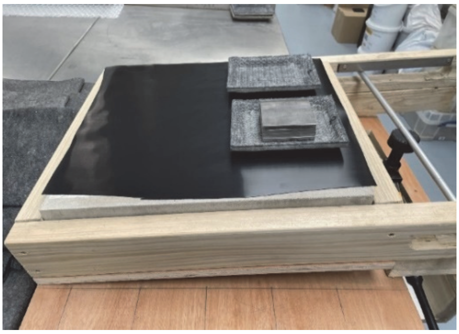

Fig. 2. GCCM-LLDPE specimens on HDPE

Fig. 3. GCCM-PVC specimens on concrete slab

Fig. 4. GCCM-LLDPE specimens on gravel

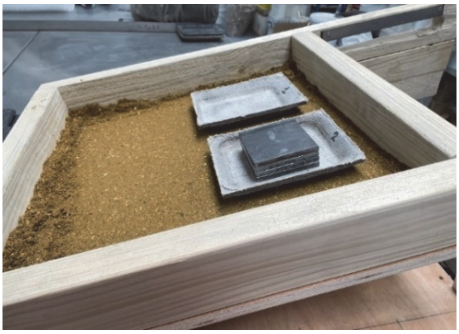

Fig. 5. GCCM-PVC specimens on sand

Fig. 6. GCCM-PVC specimens on clayey topsoil

5 Observations, results and discussion

The angle of slip of the PVC backing to the GCCM-PVC specimens on any given substrate was observed to be higher than for the LLDPE backing to the GCCM-LLDPE specimens. The minimum recorded angle, average angle and average angle minus 2 standard deviations was determined for each substrate and presented in Table 1.

Table 1. Summary of all tilt table angle of slip measurements for GCCM-PVC and GCCM-LLDPE GCCMs *37° is the maximum angle attainable by the tilt table

GCCM-PVC (with PVC backing)

Substrate	Minimum Angle (°)	Average Angle (°)	Av. -2s.d. (°)
Concrete	37*	37	37
Geotextile	25	28	23
Gravel	30	31	28
Sand	24	26	23
Clayey Topsoil	37*	37	37
HDPE	16	20	16

GCCM-LLDPE GCCM (with LLDPE backing)

Substrate	Minimum Angle (°)	Average Angle (°)	Av. -2s.d. (°)
Concrete	20	22	19
Geotextile	16	18	16
Gravel	13	19	13
Sand	15	17	15
Clayey Topsoil	23	30	20
HDPE	11	14	9

5.1 Determining Interfacial Friction Angle and Adhesion

If adhesion is present between the GCCM backing and the substrate, the measured tilt table angle of slip may not represent the actual interfacial friction angle. By following the methodology in ASTM D5321 (where the shear stress is plotted against the normal stress, giving the gradient as tanδ, where δ is the interfacial friction angle irrespective of the adhesion, which itself is simply the y-intercept value), it was possible to calculate this shear stress and corresponding normal stress at the tilt table angle of slip, for which the average angle minus 2 standard deviation (-2s.d.) values were used.

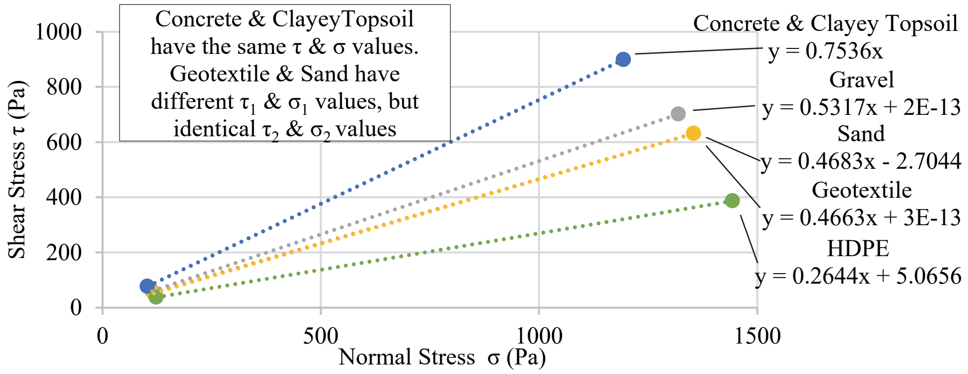

Fig. 7. Plot of Shear Stress vs Normal Stress for GCCM-PVC GCCM Specimens.

Table 2. Calculated GCCM-PVC GCCM Interfacial Friction Angle (Delta) and Adhesion

Substrate	Tan *δ* ('*m*' from graph)	Delta *δ* (°)	y-intercept ('*c*' from graph) (Pa)	Hypothesis
Concrete	0.7536	37	0.000	Maxed out test angle - adhesion not measured
Geotextile	0.4663	25	0.000	No adhesion
Gravel	0.5317	28	0.000	Gravel sheared internally first - adhesion not measured
Sand	0.4683	25	-2.704	Adhesion is a function of σ
Clayey Topsoil	0.7536	37	0.000	Maxed out test angle - adhesion not measured
HDPE	0.2644	15	5.066	Adhesion constant, equal to c

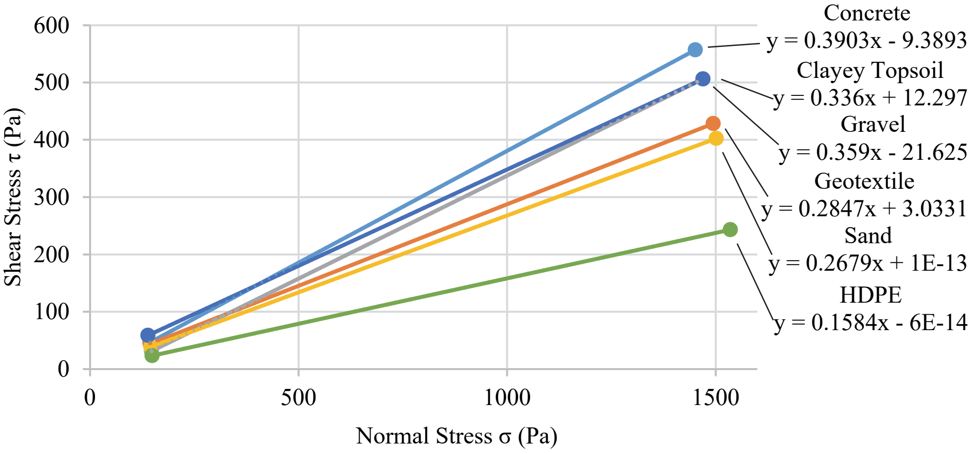

Fig. 8. Plot of Shear Stress vs Normal Stress for GCCM-LLDPE GCCM Specimens.

Table 3. Calculated GCCM-LLDPE GCCM Interfacial Friction Angle (Delta) and Adhesion

Substrate	Tan *δ* ('*m*' from graph)	Delta *δ* (°)	y-intercept ('*c*' from graph) (Pa)	Hypothesis
Concrete	0.390	21	-9.389	Adhesion is a function of σ
Geotextile	0.285	16	3.033	Adhesion constant, equal to c
Gravel	0.359	20	-21.625	Adhesion is a function of σ
Sand	0.268	15	0.000	No adhesion
Clayey Topsoil	0.336	19	12.625	Adhesion constant, equal to c
HDPE	0.158	9	0.000	No adhesion

For all substrates, the calculated value for delta (the inverse tangent of the line of best fit gradient 'm') is the same as the -2s.d. angle of tilt for specimen 2 (the specimen with steel plate surcharge), when rounded to the nearest degree, with the exception of GCCM-LLDPE on gravel where delta is 20°and the test 2 angle of tilt -2s.d. is 19° (discussed further below). Adhesion varied between substrate types as determined from the values of their y-intercepts:

- The values of the intercepts of GCCM-PVC /HDPE, GCCM-LLDPE /geotextile and GCCM-LLDPE /clayey topsoil were positive, so the adhesion was inferred as constant on these surfaces. The adhesion of 5 Pa GCCM-PVC /HDPE is 14% of the shear stress value for the self-weight specimen 1, but only 1% of the shear stress for the self-weight and surcharged specimen 2. The adhesion of 3 Pa for GCCM-LLDPE /geotextile is 7% of the shear stress value for the self-weight specimen 1, but only 1% of the shear stress for the self-weight and surcharged specimen 2. The adhesion of 12.6 Pa for GCCM-LLDPE /clayey topsoil is 21% of the shear stress value for the self-weight specimen 1, but only 2% of the shear stress for the self-weight and surcharged specimen 2. This relationship occurs because the adhesion being constant means that for greater water depths, the adhesion is a smaller fraction of the total frictional shear stress, and thus holds less significance.

- The intercepts of GCCM-PVC /sand, GCCM-LLDPE /concrete and GCCM-LLDPE /gravel were negative values. It is inferred from this that adhesion is not constant, but is a function of the normal stress, such that the true relationship between normal stress and shear stress intercepts somewhere on the positive y-axis. There is insufficient data to determine the nature of the relationship, but the relationship should not be linear and should have a positive curvature. One possibility is that the adhesion is proportional to the square of the normal stress. As such, it is inferred that adhesion increases with water depth. A theoretical explanation for this would be that the granular/rough substrate digs into the underside of the GCCM more as the normal stress increases, making the resistance to slip (adhesion) progressively higher. For GCCM-PVC /sand, the -2s.d. angle of tilt result for specimen 1 (24°) would be valid for surcharges up to that of specimen 2, containing the steel plate mass (equivalent to 14 cm of water surcharge loading). For greater water depths than 14 cm, the -2s.d. angle of tilt results for specimen 2 (25°) will be valid. For GCCM-LLDPE /concrete, the -2s.d. angle of tilt result for specimen 1 (18°) would be valid for surcharges up to that of specimen 2, containing the steel plate mass (equivalent to 14 cm of water surcharge loading). For greater water depths than 14cm, the -2s.d. angle of tilt results for specimen 2 (21°) will be valid. For GCCM-LLDPE /gravel, the -2s.d. angle of tilt result for specimen 1 (12°) would be valid for surcharges up to that of specimen 2, containing the steel plate mass (equivalent to 14 cm of water surcharge). For greater water depths than 14 cm, the -2s.d. angle of tilt results for specimen 2 (19°) will be valid.
- The intercept of GCCM-PVC /geotextile, GCCM-LLDPE /sand and GCCM-LLDPE /HDPE were 3×10^{-13} Pa, 1×10^{-13} Pa and 6×10^{-14} Pa respectively. These are values of 0 Pa to 12 to 13 decimal places, which suggests a high confidence in the data, because it suggests the size of the experimental error is very small.
- For GCCM-PVC /concrete and GCCM-PVC /clayey topsoil, the measured angle of tilt was recorded as the maximum angle that was attainable by the tilt table, because the specimens did not slip for the tilt table's full range of angles. This means that the adhesion could not be determined and the delta value of 37° is conservative.
- For GCCM-PVC /gravel, the gravel failed internally (collapsed) before the specimens slipped, so the delta value of 28° is the angle of internal friction of the gravel, not the interfacial friction, and the adhesion therefore could not be determined.

The concluding unconfined interfacial friction angles, adhesion values and notes are provided in Table 4 below.

Table 4. GCCM Interfacial Friction Angle and Adhesion varying with water depth

GCCM-PVC (with PVC backing)

Substrate	Unconfined Interfacial Friction Angle, Delta (°)	Adhesion (Pa)	Notes
Concrete	>37	No data	Max. slope of test equipment – adhesion not measured
Geotextile	25	0	-
Gravel	28	No data	Gravel collapsed first – adhesion not measured
Sand	>24 (for water depth 1 to 14 cm)	Function of surcharge	Above 14 cm water depth, delta >25°
Clayey Topsoil	>37	No data	Max. slope of test equipment – adhesion not measured
HDPE	15	5	-

GCCM-LLDPE (with LLDPE backing)

Substrate	Unconfined Interfacial Friction Angle, Delta (°)	Adhesion (Pa)	Notes
Concrete	>18 (for water depth 2 to 14 cm)	Function of surcharge	Above 14 cm water depth, delta >21°
Geotextile	16	3	-
Gravel	>12 (for water depth 2 to 14 cm)	Function of surcharge	Above 14 cm water depth, delta >20°
Sand	15	0	-
Clayey Topsoil	19	12.5	-
HDPE	9	0	-

6 Conclusions

Although additional testing at different surcharges could be carried out on the substrates where the adhesion increases as a function of normal stress to understand the relationship further, the tilt table testing herein has provided useful, useable information on unconfined interfacial friction for use in GCCM hydraulic design. Some of these values may be conservative, as testing was performed using pre-cured, smooth GCCM specimens which would have a limited effective contact surface area, especially on gravel substrates. In the field, the GCCM is flexible prior to hydration, so would drape and cure to the contours of the substrate, improving the surface contact area and interlock with the substrate. So even though the unconfined interfacial friction values for gravel and sand (and geotextile for GCCM-PVC) are relatively low, in the field the interfacial friction is likely to be higher than determined in the tilt table tests.

A tilt table test is a simple test to estimate the shear strength parameter of an interface. The tilt-angle is determined by the peak friction of the interface plus adhesion (apparent or real) along the interface. In essence, the tilt table test is a direct shear test with minimal stress applied. The normal stress applied is due to the self-weight of the GCCM specimen (and any steel plate surcharge) acting perpendicular to the direction of the tilted base of the box, and the shearing force applied is the component of the same self-weight acting in the direction of the tilted base box. The tilt table test provides the peak strength but not the residual strength. This is the big difference between the tilt table test and a direct shear test. However, this is all that is needed for the design of GCCMs in channel and canal applications. The tilt table test provides friction angle results in a very economical and repeatable manner. One would be remiss to disregard it because of its primitive nature.

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