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A study on thin cementitious composite (TCC) materials for soil reinforcement applications

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Abstract

This paper highlights some experimental results on the performance behavior of TCC elements under shear tests in soil. It is demonstrated that using small stone and making small channels on the surface of TCC element enhances frictional resistance of TCC in soil. This leads to significant improvements of their structural performance as compared to conventional materials in reinforced soil structures. The angle of friction increases by 1.66, 14.81, 21.57 and 23.78%, and the cohesion increases by 29.15, 69.30, 104.05, 132.04% for TCC containing stone, 2, 4 and 6 channels, respectively. Test results of TCC elements are evaluated with other conventional reinforcements such as geogrid, geosynthetics and wire meshes. It is revealed that the TCC elements can be used as a unique reinforcing material for soil reinforcement applications.

Keywords: Thin cementitious composite materials, soil-reinforcement, shear behavior, analyses

Abbreviation: CCR2 = Cement composite with rough surface made by 2 channels; CCR4 = Cement composite with rough surface made by 4 channels; CCR6 = Cement composite with rough surface made by 6 channels; CCRS = Cement composite with rough surface made by stone; CCSS = Cement composite with smooth surface; CM = Chicken mesh (hexagonal mesh); EMM = Expanded metal mesh; GM = Geogrid mat (fortrac); JGS = Japanese Geotechnical Society; JIS = Japan Industrial Standards; SGS = Stabilanka geosynthetic sheet; SM10 = Steel mesh with 10mm opening; TCC = Thin cementitious composite; SS = Ultimate shear strength; c = Cohesion; kPa = Kilopascals; psi = Pounds per square inch; $w_{opt} =$ Optimum water content; $\phi =$ Angle of internal friction; $\tau =$ Shear stress; $\sigma =$ Shear stress; $\gamma_d =$ Dry unit weight; $\rho_s =$ Specific gravity

Introduction

It is known that inadequate frictional resistance and meager cohesion of conventional reinforcements in reinforced soil structures such as geogrids, geosynthetics and wire meshes are serious shortcomings which not only imposes constraints in structural design but also affects the stability of reinforced soil structures. In this regard, the benefits of soil reinforcing materials in improving the interaction resistances are eminent. For the reinforcement to be effective, two conditions need to be satisfied. In particular, it must possess enough strength to withstand tension failure and adhesion failure. To date, a number of efforts have been made to ensure enough tensile strength and frictional resistance, simultaneously, for the reinforcements (Fukuoka, 1998; Jones, 1996; Koerner, 1994; Murray and Irwin, 1981). Reinforcement of soil with various materials, nonetheless, still remains an art in its rudimentary level, and ideas are evolving towards assessing the uniqueness of an optimal reinforcement system thus far. Recently, composite reinforcement for effective application in reinforced soil structures is gaining much concern. In a composite reinforcement, two or more different types of materials are rationally combined to produce a new composite that derives benefits from each of two components and exhibits a synergetic response. Composite reinforcement using single steel wire in cement mortar for reinforced soil application is one of the examples (Sivakumar et al., 2003). Thin cementitious composite materials (TCC) is, in essence, a unique cementitious matrix acting compositely with an elasto-plastic material made of high tensile steel wire mesh and sand-cement mortar. If it is properly applied in soil reinforcement, it attains its optimal reinforcing capability owing to the synergetic action of mortar with backfill and mortar with mesh (Hossain 2003). TCC elements with enough tensile resistance provided by the steel wire mesh and enough frictional resistance provided by the interfacial friction between the cement mortar and backfill can be a significant reinforcing material for reinforced soil structures as compared to conventional reinforcements (Hossain and Kajisa 2006; Hossain 2007, 2008). In spite of the volume of information available, little or no research work was reported in the technical literature on the TCC materials-soil interface shear behavior and comparative study between various types of TCC materials and conventional reinforcements. In this research work, shear tests of five types of TCC panels made with plain surface, rough surface with small stone, rough surface with 2, 4, 6 channels were performed. For a better comparison, shear tests of conventional reinforcements such as geogrid, geosynthetics and wire meshes were carried out. All the tests were performed under four normal stress conditions such as 80, 120, 160 and 200 kPa (11.60, 17.40, 160.20 and 29.01 psi). Results of shear stress-displacement relationships are reported for a clear understanding on the comparative study among the reinforcement materials. Pertinent discussions regarding the uniqueness of TCC as soil reinforcing material are depicted.

Shear force and failure modes

When TCC elements are used as soil reinforcement materials, it may fail under shear force due to the movement of soil mass as shown in Fig 1. As a result, there may be four possible modes of failure of the TCC due to shear force acting on it as depicted in Figs 2-5. Among the four different failure modes, a most commonly occurring mode is the frictional failure between soil and reinforcement which is

Table 1. Identity and description of thin cementitious composite materials panels

Reinforcement	Identity	Name	Description
	CCSS	Thin cementitious composite materials with smooth surface	The FSS are prepared according to the usual way as of thin cementitious composite materials casting without applying small stone on its surface or channels. Therefore, the surface is plain in nature.
	CCRS	Thin cementitious composite materials with rough surface (made by stone)	The rough surface of FRS is made by applying small stone (size varying from 4.0 to 8.0 mm (0.15 to 0.31 in)) into the mortar (randomly distributed).
	CCR2	Thin cementitious composite materials with rough surface (2-channels)	The rough surface of FR2 is made with 2 small channels of 15 mm (0.59 in) width and 5 mm (1.96 in) depth. The channel-to-channel spacing is 50 mm (1.96 in).
	CCR4	Thin cementitious composite materials with rough surface (4-channels)	The rough surface FR2 is made with 4 small channels of 15 mm (0.59 in) width and 5 mm (0.19 in) depth. The channel-to-channel spacing is 50 mm (1.96 in).
	CCR6	Thin cementitious composite materials with rough surface (6-channels)	The rough surface FR2 is made with 6 small channels of 15 mm (0.59 in) width and 5 mm (0.19 in) depth. The channel-to-channel spacing is 50 mm (1.96 in).

1 in=25.4 mm

shown in Fig 2. This mode of failure occurs when the interfacial friction between reinforcement and soil is less than the shear force, and the tensile capacity of mortar and mesh. If the tensile capacity of mortar is more than the interfacial friction then this mode of failure would be dependant on the surface properties of TCC. The second possible and frequently occurring mode of failure can be noted as mortar failure as shown in Fig 3. This mode of failure occurs when the shear force exceeds the tensile stress of mortar, but is less than the frictional resistance of TCC and tensile capacity of mesh. The third possible mode of failure may be mesh failure as shown in Fig 4. If the frictional capacity of interface exceeds the tensile capacity of mesh, then this mode of failure would be taken place. The forth possible and comparatively less frequently occurring failure mode may be noted as bond failure between mesh and mortar as depicted in Fig 5. When the bond force between mesh and mortar is less than the shear force, frictional resistance of interface and tensile capacity of mesh, then this failure mode might be occurred. These four possible modes of failure need to be investigated under shear tests.

Materials and methods

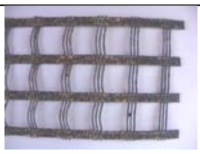
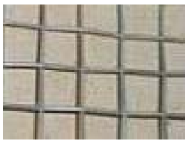
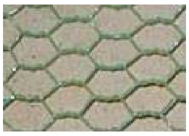
Specimens

The specimens were prepared in wooden moulds. The requisite amount of sand and cement was dry-mixed in a pan, and then the requisite quantity of water was added gradually while the mix was continuously stirred. Ordinary Portland cement and river sand passing through No.8 [2.38mm (0.093in)] sieve, having a fineness modulus of 2.33 were used for casting. The cement-sand ratio and water-cement ratio both were 0.5 by weight. The square mesh obtained from the market was cut to obtain the desired size. The diameter of wire was 1.0 mm (0.039 in) with center-to-center opening of 10 mm (0.39 in). The sand-cement mortar layer was spread at the base of the mould. On this base layer, the first mesh was laid, and then covered by further application of mortar. TCC panels with ordinary plain surfaces and rough surfaces were prepared. Thickness of the rough surface was approximately 2-4 mm (0.07-0.15 in) made of stone and small parallel channels (depth of channel was 5 mm (0.19 in)) and width of channel was 15 mm (0.59 in). Five types of TCC panels along with five types of conventional reinforcements were investigated. Details of the TCC panels and the conventional reinforcements are given in Table 1 and Table 2. Thickness and size of the TCC panels are 10.0 mm (3.93 in) and 315×380 mm (12.40×14.96 in), respectively.

Properties of soil

The particle size distribution curve of soil used in this research work is shown in Fig 6. It is revealed that nearly 9% of the soil is coarse clay, 7% is fine silt, 6% is coarse silt, 14% is fine sand, 44% is medium sand and more than 20% is coarse sand which means that more than 90 percent of the soil is in the silt and sand fraction. According to the unified classification system, the soil is classified as SC. The other properties of soil are depicted in Table 3.

Table 2. Identity and description of conventional reinforcements

Reinforcement	Identity	Name	Description
	GM	Geogrid mesh	It is made from polyester yarns of cross-section 2×6mm (0.07×0.23in). Mesh opening 20×24 mm (0.78×0.94 in). Tensile strength of 150 kN/m (36088.8 lb/yd) in the longitudinal direction and 30 kN/m (7217.76 lb/yd) in the transverse direction.
	SGS	Stabilanka geosynthetic sheet	This is made of polyester yarns (2 mm (0.07 in) dia.) by interweaving each other in such a way that there is no gap among the filaments. Tensile strength of 800 kN/m (191840 lb/yd) in the longitudinal direction and 100 kN/m (23980 lb/yd) in the transverse direction.
	EMM	Expanded metal mesh	It is made of steel wires by electrical welding. The cross section of wire is 1.5×1.7 mm (0.05×0.06 in) with grid opening of 9.6×28.8 mm (0.37×1.13 in). Young's modulus and Poisson's ratio of EMM are 138 kN/mm^2 (138×10^6 kPa) and 0.3, respectively.
	SM10	Square mesh with 10mm opening	The SM10 is made of steel wire of diameter of 1.2 mm （0.04 in） and center-to-center mesh opening is 10 mm (0.39 in). Young's modulus and Poisson's ratio of SM10same as EMM.
	CM	Chicken mesh	The cell is 9×11.2 mm (0.35×0.44 in) in size with 59.53^o angle of diagonal wire. Wire diameter, Young's moduli and Poisson's ratios of the CM are 0.8 mm (0.03 in), 104 kN/mm^2 (138×10^{6}kPa) and 0.3, respectively

1 psi=6.895 kPa, 1 in=25.4 mm

Test apparatus

The apparatus used in this study is shown in Fig 7. For convenience of the readers, the important components of the testing equipment are numbered numerically starting from top-left to right-down in the increasing way such as, the number from [1] to [8] where the number [1] is the normal load application plate for upper box, [2] is the shear stress measuring device, [3] is the upper box filled with soil, [4] is the thin cementitious composite materials panel, [5] is the lower box, [6] is the electrically operated shear jack, [7] is the displacement measuring dial gauge and [8] is the device taking normal load which acted on the upper box.

Method of testing

The TCC panels were rectangular pieces of 316 mm by 380 mm (12.40in by 14.96 in) in size with 120 mm (4.72 in) extended mesh. The specified length of the pieces was selected in order to facilitate clamping with the shear apparatus. The panels were clamped in the box in such a way that the embedded length of the panel is 380 mm (12.40 in) in the loading direction and 316 mm (14.96) in the transverse direction. Water was added gradually to the soil, and mixed up to obtain desired water content of 14.8% uniformly throughout the soil. After embedding the TCC panel on the lower box, the upper box was set on the panel, and then the soil was filled in the upper box. The shear tests were carried out in the way of pushing out the panel along with the lower box. The constant selected shear speed was 1.0 mm (0.039) per minute applied by means of screw jack under electrically operated constant pressure. The shear forces were measured using a tension load cell with least count of 5 N (1.1 lbs). The shear displacements were measured by means of a mechanical dial gage with least count of 0.001mm (0.000039 in). All the shear tests were conducted according to the standard of the Japanese Geotechnical Society (JGS), T941-199X. During the test, parallel channels on TCC surface were transverse to the loading direction.

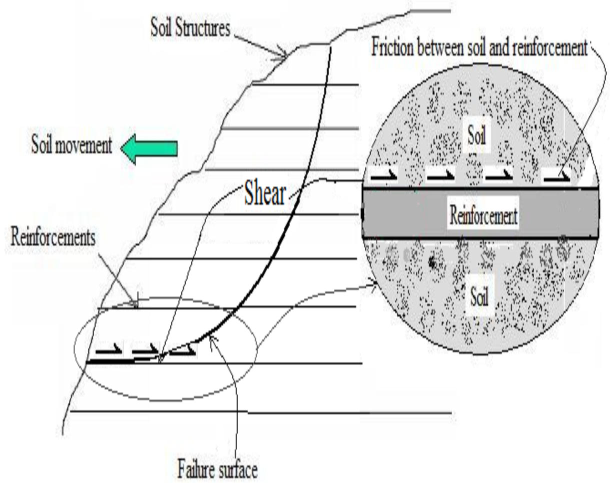


Fig 1. Shear force developed on reinforcement due to movement of soil mass

Results and discussion

Shear stress-displacement relationships of CCSS

Shear stress-displacement relationships of CCSS under normal stresses of 80 kPa, 120 kPa, 160 kPa and 200 kPa (11.60, 17.40, 160.20 and 29.01 psi) are given in Fig 8. It

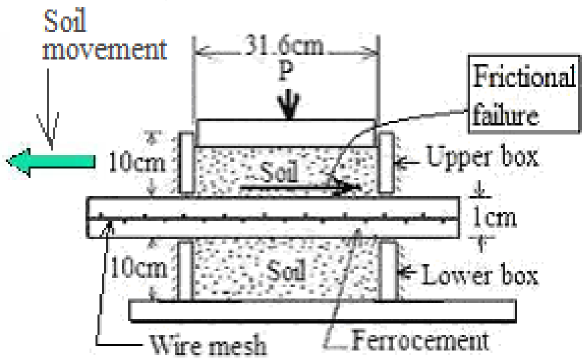


Fig 2. Frictional failure (1 inch=2.54 cm)

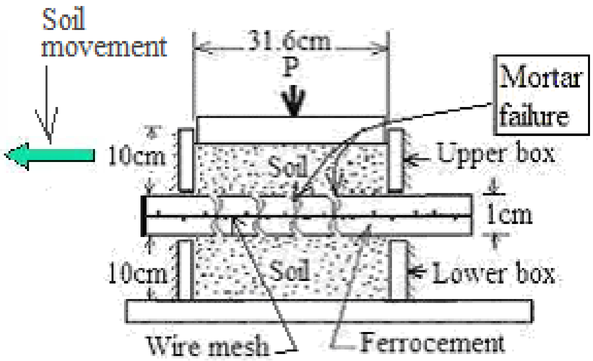


Fig 3. Mortar failure (1 inch=2.54 cm)

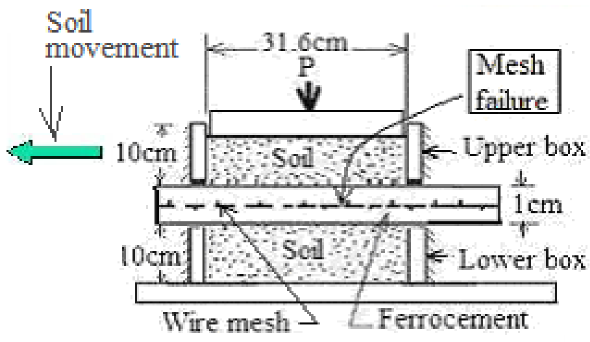


Fig 4. Mesh failure (1 inch=2.54 cm)

can be seen from these figures that the shear stresses are increasing linearly with the increases in the shear displacement up to about 2-3 mm (0.078-0.12 in). After that, the shear stresses are almost horizontal and increases very slowly with an increase in the shear displacement. This may be due to the failure of bonding stresses between the CCSS and the backfill soil. As expected, for all the test results, the shear resistance is more for higher normal stress. The ultimate shear strength are recorded as 40.14, 70.00, 98.00 and 114.46 kPa (5.82, 10.15, 14.21 and 16.60 psi) for normal stresses of 80 kPa, 120 kPa, 160 kPa and 200 kPa (11.60, 17.40, 160.20 and 29.01 psi), respectively.

Shear stress-displacement relationships of other reinforcements

Shear stress-displacement relationships are almost similar trend for different normal stresses but varies for different reinforcements. Therefore, it is not repeated for all normal stresses but representative curves of CCR2, CCR4, CCR6, CCRS, CCSS, CM, EMM, GM under normal stress of 200 kPa are compared in Fig 9 and Fig 10 for TCC and conventional reinforcements, respectively. It is observed that shear stresses are higher for TCC than that for conventional reinforcements.

Ultimate shear strengths

In order to obtain a comprehensible insight of the ultimate shear strength of TCC and other conventional reinforcements, the ultimate shear strengths corresponding to different normal stresses are depicted in Fig 11 and Fig 12 for TCC and conventional reinforcements, respectively. It is evident that the ultimate shear strengths are increased with the increase in the normal stress for all types of TCC panels and conventional reinforcements. The rate of increase of ultimate shear strength for TCC materials of any type is higher than that of the conventional reinforcements. Cohesion and angle of internal friction From the straight lines given in Fig 11 and Fig 12, the following equations for shear strengths of TCC and other conventional reinforcements are obtained.

$$\tau_{CCSS} = 0.62\,\sigma_{CCSS} + 5.18 \tag{1}$$

$$\tau_{CCRS} = 0.64\,\sigma_{CCRS} + 6.69 \tag{2}$$

$$\tau_{CCR2} = 0.74\,\sigma_{CCR2} + 8.77 \tag{3}$$

$$\tau_{CCR4} = 0.68\,\sigma_{CCR4} + 10.57 \tag{4}$$

$$\tau_{CCR6} = 0.82\,\sigma_{CCR6} + 12.02 \tag{5}$$

$$\tau_{GM} = 0.38\,\sigma_{GM} + 9.11 \tag{6}$$

$$\tau_{SGS} = 0.45\,\sigma_{SGS} + 1.40 \tag{7}$$

$$\tau_{EMM} = 0.27\,\sigma_{EMM} + 11.93 \tag{8}$$

$$\tau_{SM10} = 0.50\,\sigma_{SM10} + 4.20 \tag{9}$$

$$\tau_{CM} = 0.32\,\sigma_{CM} + 12.10 \tag{10}$$

where, τ is the shear resistance of reinforced soil on the surface of reinforcement in kPa and σ is the applied normal stress on reinforcement in kPa. Therefore, cohesion and angle of internal friction of TCC and conventional reinforcements are calculated and given in Table 4.

Discussion

The four possible modes of failure were investigated and analyzed under shear tests in soil for the uniqueness of TCC elements over conventional reinforcements. It is observed that the failure mode depends on the TCC shear resistance which is relevant to the surface characteristics of TCC, strength of the mortar which is relevant to the cement/sand ratio and the tensile capacity of mesh which is relevant to the type of mesh. It is noted that only the friction failure (Fig 2) under all shear tests was occurred throughout the study and no other modes of failure such as mortar failure (Fig 3), mesh failure (Fig 4) and bond failure (Fig 5) described above were not observed. It is obvious that the frictional angle, a measure of frictional resistance of TCC elements, increases significantly due to the presence of stone and small channels on the surface of TCC. Notice also a general enhancement in the performance of frictional angle owing to the increase number of channels. Compared to the control specimens (CCSS), the percentage of increase is recorded as 1.66, 14.81, 21.57 and 23.78% for TCC of CCRS, CCR2, CCR4 and CCR6, respectively. This clearly implies that TCC impart very unique mechanism to the soil – a fact that often remains obscured in the conventional reinforcements. On the other hand, in case of cohesion which is a measure of bonding phenomena of TCC with soil, the value is increased by 29.15,

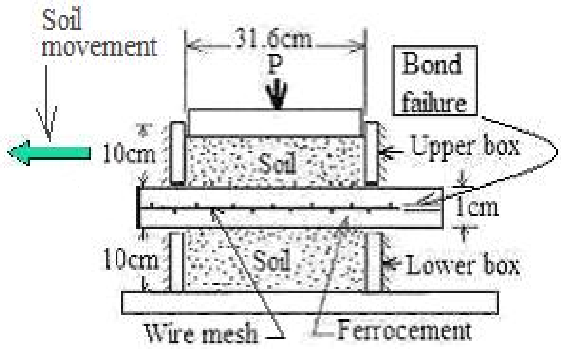


Fig 5. Bond failure (1 inch=2.54 cm)

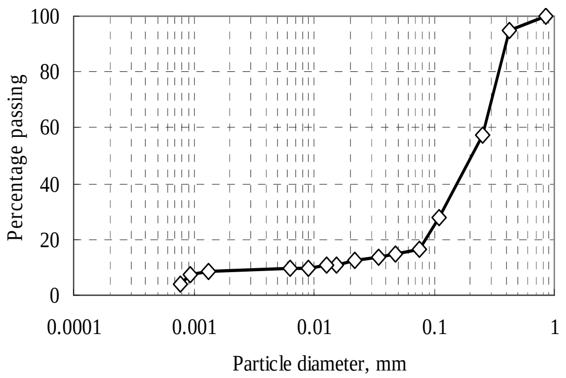


Fig 6. Particle size distribution curve of soil (1 in=25.4 mm)

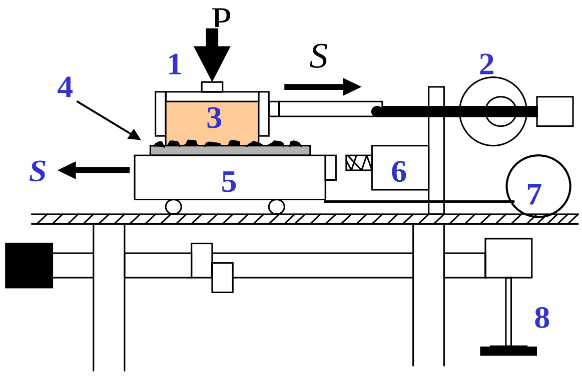


Fig 7. Shear testing apparatus (schematic diagram)

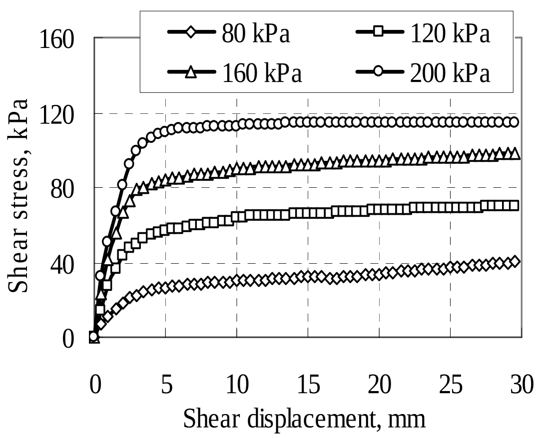


Fig 8. Shear stress-displacement relationships of CCSS (control specimen) (1 psi=6.895 kPa, 1 in=25.4 mm)

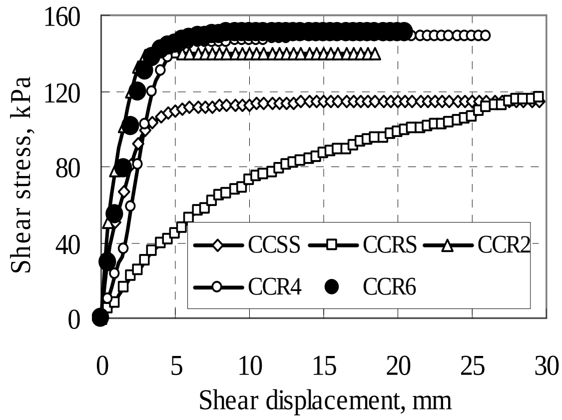


Fig 9. Shear stress-displacement relationships of TCC (1 psi=6.895 kPa, 1 in=25.4 mm)

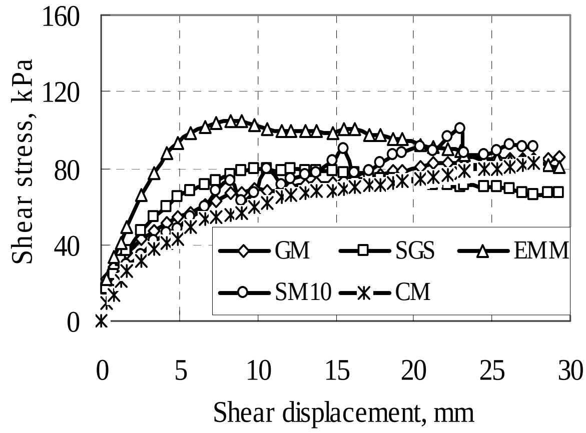


Fig 10. Shear stress-displacement relationships of conventional reinforcements (1 psi=6.895 kPa, 1 in=25.4 mm)

69.30, 104.05, 132.04% for CCRS, CCR2, CCR4 and CCR6, respectively. The research depicted here is rudimentary and is not available in the technical literatures for comparison. However, this line of thinking can be reinforced by some other researches carried out under pullout tests (Hossain, 202, 2007a, b, 2008; Hossain and Sakai 2008). It is interesting to note that the TCC elements can deform at the joint depending on the design of joint and field requirement. Thus, TCC possesses flexibility like as conventional reinforcements for reinforced soil structures. Moreover, results indicates that it has more cohesion and frictional resistance which give more reliable design of reinforced soil structures as compared to conventional reinforcements to resist slope failure. This type of phenomena can be observed in case of rigid reinforcements such as steel reinforcements (Yasufuku and Ochiai, 2005). The backfill materials used in this study contain nearly 24% clay and silt fractions which is mainly responsible for obtaining the cohesion intercept of reinforcements. When these particles are come in contact to the reinforcements, they give a synergetic action between the soil and the reinforcement. This produces a cohesion intercept at the surface of the reinforcement depending on the type of reinforcement. These type of behavior was observed in case of flexible and rigid reinforcements (Long et al., 2007; Khedkar and Mondal, 2009). Reinforcement of soil with different materials still remains a science in its infancy, and ideas are evolving towards assessing the optimal material for soil reinforcement applications. Although field applications of this works have not been thoroughly examined, it can be considered a good

Table 3. Properties of soil

Component	Parameter	Value
Dry unit weight	γ_d	1.83 t/m^3 (116.16 lb/cft)
Optimum water content	w_{opt}	15.3%
Specific gravity	ρ_s	2.64
Cohesion	c	5.01 kPa
Angle of internal friction	ϕ	32.19^o
Sand, >75μm		78%
Silt, 5-75μm		13%
Clay, <5μm		9%

1 psi=6.895 kPa, 1 in=25.4 mm

Table 4. Cohesion and angle of internal friction

Reinforcements	Frictional angle, degree	Cohesion, kPa
CCSS	31.79	5.18
CCRS	32.32	6.69
CCR2	36.50	8.77
CCR4	38.65	10.57
CCR6	39.35	12.02
GM	20.80	9.10
SGS	24.22	11.40
EMM	15.10	11.90
SM10	26.56	4.20
CM	17.74	12.10

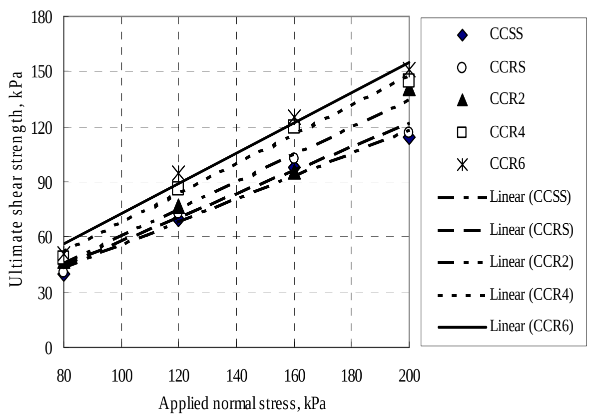


Fig 11. Ultimate shear strength of TCC (1 psi=6.895 kPa)

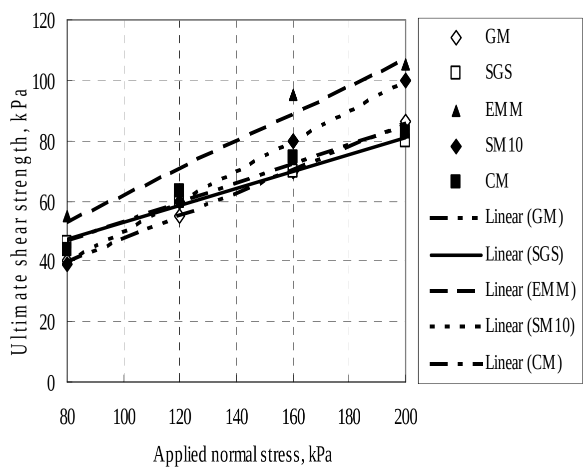


Fig 12. Ultimate shear strength of conventional reinforcements (1 psi=6.895 kPa)

start to achieve the goal towards the development of composite reinforcement as supplementary construction materials made with mesh and mortar. It was observed that the composite reinforcements gained maximum shear strength than the ordinary reinforcements indicating that the composite reinforcement performed much better than the ordinary reinforcement alone. This line of thinking is compatible with the results of cement composite reinforced by a single fiber (Sivakumar et al., 2003).

Conclusions

1. Studies of interface properties of TCC elements with soil based on fundamental shear tests are useful in characterization of materials performance for soil reinforcement's applications.
2.The use of small channels on the surface of TCC elements appears to be highly effective in enhancing the efficiency. Among the five types of TCC tested, the CCR6 appears to be most effective.
3. Based on the comparative study, it is noted that TCC elements can suitably be used as a unique reinforcement in reinforced soil applications owing to the synergetic action between mortar/soil and mortar/mesh.
4.An analyses of the failure mechanism of TCC elements under shear tests showed that only the friction failure under all shear tests was occurred. Other modes of failure such as mortar failure, mesh failure and bond failure were not observed.
5. The paper depicted the results of laboratory experiments only and thus the field applications as well as theoretical models of this reinforcement have not been thoroughly examined. However, the results depicted in this paper are fairly encouraging, especially for improving the engineering properties of reinforced soil and stability performance of soil structures.

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