Reinforcement of completely decomposed granite with discrete fibres

Renforcement de granite complètement décomposé avec des morceaux fibres

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ABSTRACT :The use of discrete fibres as reinforcing material for soils has been researched by many, e.g. Gray and Al-Refeai (1986), Maher and Ho (1994), Crockford et al. (1993), Santoni et al. (2001), Consoli et al. (2009a), but these studies have been generally done independently and have not always been consistent. Silva dos Santos et al. (2010) used data gathered through many years of study to develop a framework of behaviour for a poorly graded quartzitic sand reinforced with polypropylene fibres. In Hong Kong, the construction industry has used reinforcement with continuous fibres for some time, but it is mainly applied to landscaping of otherwise stabilised slopes, for example as a green cover on an existing shotcreted slope. Using randomly distributed short discrete fibres in Hong Kong completely decomposed granite (CDG) could help stabilise the soil while keeping the density low enough to allow growth of vegetation. It is not guaranteed, however, that a well graded residual soil like CDG would behave in the same way as sands used by previous researchers. Laboratory tests have been carried out on completely decomposed granite using short discrete polypropylene fibres as a reinforcing material. The fibres are randomly distributed in the soil. It was found that the fibres increase the unconfined compressive strength of the CDG prepared at its maximum dry density by up to tenfold for fibre contents less than 1%. The behaviour of the fibre-CDG mixture during drained triaxial compression changed from dilative to compressive, with more effects at low confining pressures. These tests seem to indicate that discrete fibres could be considered for improving the performance of CDG.

RÉSUMÉ : L'utilisation de fibres pour renforcer les sols ont déjà fait l'objet de nombreux travaux de recherche e.g. Gray and Al-Refeai (1986), Maher and Ho (1994), Crockford et al. (1993), Santoni et al. (2001), Consoli et al. (2009a), mais ces études ont été généralement faites indépendamment et elles n'ont pas toujours été synthétisées. Silva dos Santos et al. (2010) ont utilisé les données obtenues au cours d'années de recherche pour développer un modèle de comportement pour un sable quartzitique uniforme renforcé avec des fibres en polypropylène. A Hong Kong, l'industrie de la construction a utilisé des fibres continues comme moyen de renforcement depuis longtemps, mais l'application se limite à l'aspect paysager de pentes déjà stabilisées, par exemple pour la plantation de surfaces de pentes recouvertes de béton projeté. L'utilisation de fibres courtes distribuées de façon aléatoire dans le granite complètement décomposé de Hong Kong (CDG) pourrait aider à stabiliser le sol tout en gardant sa densité assez basse pour permettre à la végétation de pousser. Il n'est pas garanti cependant qu'un sol résiduel a la distribution granulométrique bien calibrée comme le CDG se comportera de la même façon que les sables utilises par les chercheurs précédents. Des essais de laboratoire ont été faits sur du granite complètement décomposé en utilisant du béton projeté et des fibres courtes en polypropylène comme matériau de renforcement. Les fibres sont distribuées de façon aléatoire dans le sol. On a trouvé que les fibres ont pour effet de multiplier par presque dix fois la résistance en compression simple du CDG préparé à sa densité sèche optimale, pour une teneur en fibres de moins de 1%. Le comportement du mélange CDG-fibres lors de l'essai triaxial drainé en compression es tpassé de dilatant a contractant avec plus d'effet aux pressions faibles. Les essais paraissent indiquer que l'utilisation de fibres courtes pourrait être considérée pour améliorer la performance du CDG.

KEYWORDS: laboratory tests ; reinforced soils ; residual soil

1 INTRODUCTION

Adding fibres to soil can be an effective way of strengthening it, by providing tensile strength at high strains. The factors influencing the effectiveness of the fibre-reinforced soils are a) the type of soil and its deformation behaviour; b) the type of fibre and its specifications (fibre length, fibre content and its aspect ratio). A careful study of the mechanics of the fibre-reinforced soil will help practising and design engineers to understand better its behaviour under different loading conditions.

Hong Kong is a modern city with growing population, so that engineers are pressed to optimise land utilisation. The topology of Hong Kong has led to urban development on natural or man-made slopes. Conventional methods of stabilising slopes such as shotcreting the whole face of the slope (current practice) are neither cost effective nor environmentally friendly and alternative sustainable methods are being sought after.

Many researchers have produced a large body of research on the performance of discrete fibres with soils (Gray and Al-Refeai, 1986; Maher and Ho, 1994; Crockford et al., 1993; Santoni et al., 2001; Consoli et al., 2009a), but these studies have been generally done independently and they have not always been consistent (Silva dos Santos et al., 2010). This paper presents initial results from laboratory tests performed on completely decomposed soil reinforced with discrete fibres.

2 MATERIALS AND METHODS

Completely decomposed granite was used as the host soil. It originates from in-situ weathering of the parent igneous rock, and is one of the most common geo-materials in Hong Kong. The short discrete fibres used in the tests presented here were similar to those used by Silva dos Santos et al. (2010).

2.1 *Materials tested*

The completely decomposed granite (CDG) host soil was obtained from a construction site near Beacon Hill, Hong Kong. Completely decomposed residual soils are well-graded in nature as the tropical climate has weathered the parent rock to a material comprising gravel and sand grains down to silt and clay-sized particles. Coarser particles are usually of quartz origin owing to its high chemical resistance while finer particles are most likely other primary hydrous minerals, such as kaolinite and feldspar (Yan and Li, 2012). The grain size distribution (shown in figure 1) reflects that the soil has 16% particles finer than 63μ. The specific gravity of the soil was found to be 2.65. From Standard Proctor compaction tests, the maximum dry density of the soil was determined as 1.93Mg/m^3 with an optimum moisture content of 12.3%. Tests on particles finer than 425μ indicated the plastic and liquid limits to be 25.6% and 35.6% respectively. Using the Unified Soil Classification System (USCS) the soil can be classified as clayey sand of low plasticity (SC-CL).

The fibres used are short filaments made of polypropylene similar to those used by Silva dos Santos *et al*. (2010). They are chemically inert and have uniform characteristics, with a relative density of 0.91, a tensile resistance of 120MPa, an elastic modulus of 3GPa and a range of linear deformation at rupture between 80% and 170%. The dimensions of the fibres used in the tests were 0.023mm in diameter and 24mm long (Silva dos Santos et al., 2010). After performing a series of unconfined compression tests on CDG reinforced with a range of fibre contents (0.3 – 1%), it was decided to continue the study with 0.3% of fibre per weight in the triaxial tests.

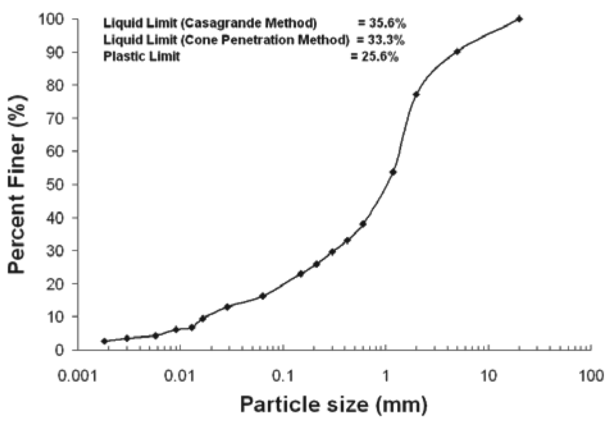

Figure 1. Particle size distribution of CDG.

2.2 *Testing apparatus, methods and sample preparation*

2.2.1 *Uniaxial Compression Test*

Unconfined compression tests on CDG and CDG+fibre soils were performed in a uniaxial compressive testing machine. The particle sizes passing 2mm diameter sieve were used for preparing specimens in a 38mm diameter; 76mm height mould at maximum dry density and optimum moisture content. The compression tests were performed at 0.5mm/min in all cases.

2.2.2 *Triaxial Testing*

Drained triaxial tests were performed using a conventional triaxial apparatus with a computer controlled GDS cell and back pressure controllers. The shearing tests were performed with a constant effective stress on specimens of both unreinforced and reinforced (with polypropylene fibres) CDG soil.

The soil was first soaked in water with a deflocculating agent and left for air drying, then it was sieved to constituent particle sizes so that the samples could be prepared in exact proportion as shown in figure 1, discarding particles above 5mm. Loose specimens were prepared, avoiding macro-voids and taking care of minimising membrane penetration. The specimens of 76mm diameter and 152mm height were prepared in a sample preparation mould.

The samples were saturated under back pressure and the effective confining pressures ranged from 100 to 500kPa. Saturation was monitored in each test, ensuring Skempton *B* values of at least 0.92 throughout the testing programme. The axial strains were measured outside the cell using a standard displacement transducer. The triaxial tests were run at a low axial strain rate of 0.01% per minute to ensure no excess pore pressure development within the sample (this was checked by measurement at the opposite end of specimen). The membrane and area corrections were made as per the recommendations proposed by La Rochelle et al. (1988). The void ratios are calculated averaging from that obtained by the initial density of the sample and the final moisture content, taking account of the measured volume change in all the stages. In all tests the difference in specific volume compiled was less than 0.02.

3 TEST RESULTS

3.1 *Unconfined compressive strength*

Representative unconfined compression test results on pure CDG and CDG + 0.5% fibre are presented in figure 2. The plot clearly shows that the specimens of reinforced CDG yielded at very high strain, contributing an additional tenfold strength to the soil. On the other hand unreinforced CDG yielded at very low strength (131kPa) and low strain.

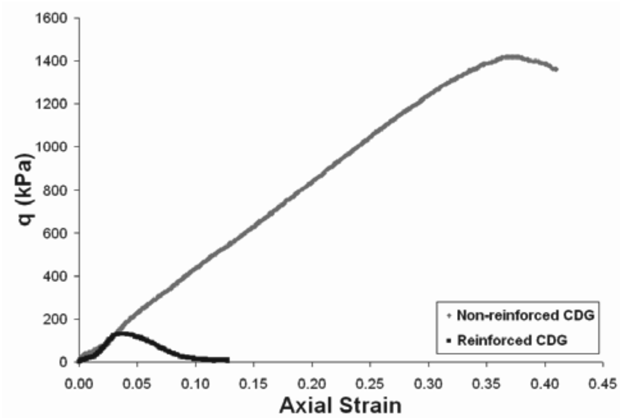

Figure 2. Unconfined compression of CDG and fibre-reinforced CDG.

3.2 *Triaxial shearing*

Triaxial drained tests were performed on isotropically consolidated specimens of pure CDG and reinforced CDG (Table 1). Some specimens were over-consolidated by a ratio of OCR=5 before being sheared. Details of the tests are shown in Table 1 (UR and R refer to unreinforced and reinforced specimens respectively).

Table 1. Summary of the triaxial tests.

Test	v_0	v_c	p_c'(kPa)	OCR
UR 100	1.42	1.32	112.0	5
UR 200	1.42	1.37	210.4	1
UR 500	1.48	1.32	499.6	1
R 100	1.58	1.36	98.9	5
R 200	1.43	1.32	202.9	1
R 500	1.58	1.41	499.4	1

The void ratios determined after consolidation (before shearing) were found to vary between 0.32 and 0.37 for pure CDG specimens and 0.32 and 0.42 for CDG-fibre specimens. Only dense specimens were prepared for the test programme. Looser specimens were difficult to prepare due to the presence of macro-voids which caused an initial collapse of the specimen, resulting in void ratios after consolidation within the same range as those for the dense specimens.

The stress-strain and volumetric responses during shearing are shown in figure 3. The stress-strain response (figure 3a) shows that the reinforced specimens generally have higher strength and higher initial stiffness at the beginning of shearing, when compared to their unreinforced counterparts. However the reinforced specimens that mobilised their full strength only did so at shear strains in excess of 20%. The unreinforced specimens on the other hand either reached a constant stress by 20% strain or they showed strain-softening, depending on their consolidation history. Unlike the other reinforced specimens, R100 kept gaining strength and never reached critical state even at large strains (about 50%). This may be due to the over-consolidation history of the specimen, which may have released some of the tension in the fibres prior to shearing. The peak strengths of reinforced CDG were calculated to be 1.76 (100kPa), 1.29 (200kPa) and 1.26 (500kPa) times that of the pure CDG.

Similar behaviour on fibre-reinforced sands is reported by Consoli *et al.*, 2007, Consoli *et. al* (2005) and Silva dos Santos *et al*. (2010). For example Silva dos Santos *et al*. (2010) found that the effect of fibres depends on the effective stress at which they are sheared, reducing marginally with increasing effective stress. For sands, it is already reported that at low effective stress, adding fibres contributes to reducing the degree of dilation in the reinforced specimens (Silva dos Santos *et al*., 2010). The persistent strain hardening behaviour (figure 3a, R100) was also observed by Consoli *et. al* (2005) on Botucatu residual soil, however their data were limited to strains of about 25%. In the present study, the specimens were sheared to strains up to 50% and it is clear that the strain hardening behaviour of specimens R200 and R500 stopped beyond ε_s>35% to reach a critical state. The governing mechanism for the strain hardening behaviour of R100 specimen might therefore be due either to the effect of low effective stress or to the effect of over-consolidation, or a combined effect.

The effect of the fibres on the volumetric response of the reinforced CDG in comparison seems to be that of restricting the degree of dilation in the specimen sheared at lower effective stresses, while at higher effective stress this effect is not so evident (figure 3b). The over-consolidated specimen of reinforced CDG shows a different volumetric response i.e. it tends to dilate after 20% shear strain even though it is expected that reinforcement will impede dilation. This behaviour is again either due to over-consolidation or to low effective confining stress. Previous findings on Botucatu residual soils (Consoli *et. al,* 2005) and other pure sands may be extrapolated to normally consolidated CDG, but the effect of over-consolidation is new and more test results are required to explain it within the critical state framework.

The stress-dilatancy behaviour of CDG (black symbols) and reinforced CDG (grey symbols) samples tested at different effective stress are shown in figure 4. All normally consolidated specimens, reinforced and unreinforced, show a typical frictional behaviour. The pure CDG specimens converge to a unique critical state stress ratio ranging from *M*=1.57 to *M*=1.61. The reinforced CDG specimens tested at effective stresses of 200 and 500kPa converged to a critical stress ratio of *M* = 1.83. For the lower effective stress of 100kPa (R100), the specimen reached a higher stress ratio of *M* = 2.14, which is similar to what was found by Silva dos Santos *et al*. (2010) on fibre-reinforced sand. The over-consolidated specimens, UR100 and R100, did not follow the frictional trend but showed much less volumetric deformation up to critical state, which was also observed in the stress-strain behaviour. This may have been caused by locking of the fibres during compression and swelling prior to shearing.

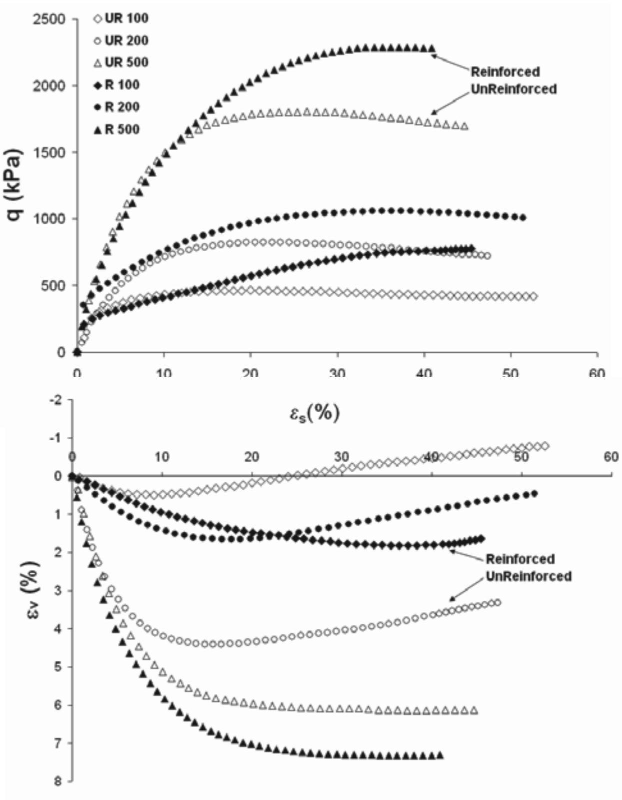

Figure 3. Stress-strain-volumetric response of CDG and fibre-reinforced CDG sheared at different effective confining stresses.

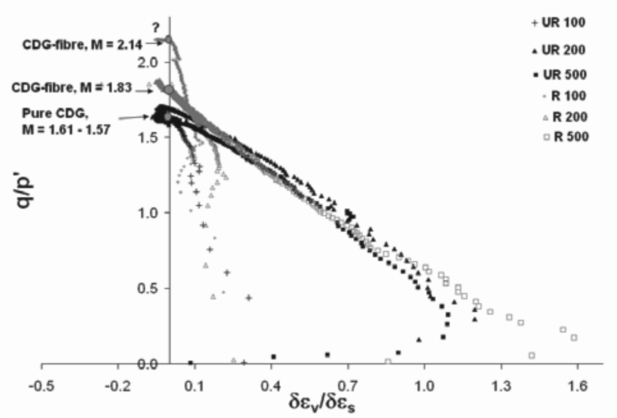

Figure 4. Stress-dilatancy response of CDG and fibre-reinforced CDG.

The deviatoric stress and corresponding mean effective stress in the test that reached a stable critical state are plotted in a q-p' plane in figure 5. These points form a critical state envelope for the pure CDG with a critical state gradient *M*=1.57. This is found to be consistent with critical stress ratio *M* = 1.57 - 1.61, obtained from the stress-dilatancy plot (figure 4). The end of test points are also plotted for the reinforced specimens but no attempt has been made in this paper to define the critical state envelop for fibre-reinforced CDG because at low stresses, the deviatoric stress does not stabilise (figure 3a). More tests are required over a larger range of stresses to do so, as was done by Silva dos Santos *et al*. (2010) who found that the critical state lines of the unreinforced and reinforced specimens converge at large stresses of the order of 5MPa.

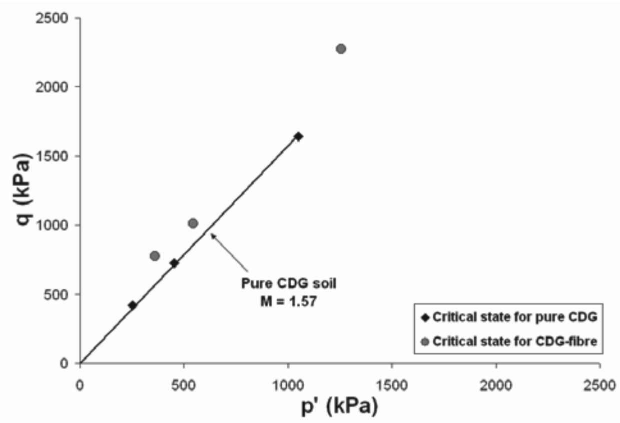

Figure 5. Critical states and end of test points for CDG and fibre-reinforced CDG in q-p' plane.

4 CONCLUDING REMARKS

The results presented indicate that using discrete fibres can be an effective means of reinforcing CDG, specifically at low effective stresses. The unconfined compressive strength tests showed a tenfold increase in strength with 0.5% fibres content in the soil prepared at maximum dry density and optimum moisture content. In triaxial drained tests, adding fibres seems to increase the shear strength by up to two times the strength of the unreinforced specimens, as well as its initial stiffness. Dilation was also found to be reduced. Unique critical states were reached for the unreinforced CDG and reinforced CDG tested at high effective stress. The stress-dilatancy was found to be frictional for all normally consolidated specimens, but with different critical state stress ratios (*M*) for the fibre-reinforced specimens depending on their effective confining stress. Initial results also seem to indicate that the over-consolidation ratio affects the performance of the reinforced CDG, noticeably in the stress-dilatancy response, but more work is needed to confirm it.

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