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Numerical Investigation of Confining Pressure Effects on Fibre-Reinforced Soil Behaviour

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ABSTRACT: This study investigates the influence of confining pressure on the mechanical performance of fibre-reinforced kaolin clay through numerical modelling of triaxial compression tests. Simulations were conducted using a finite element load–deformation analysis, with fibre contents of 0%, 1%, 1.5%, 2%, and 3% by dry weight. Material behaviour was modelled using the Mohr–Coulomb failure criterion, and confining pressures of 50, 100, 200, and 500 kPa were applied to represent a range of geotechnical stress conditions. Results are presented in terms of peak deviator stress and peak volumetric strain, highlighting how the relative benefits of fibre reinforcement change with increasing confinement. The findings show that while 2% fibre content delivers the greatest strength improvement at low pressures, 3% becomes more effective under high confining stress. The reduction in volumetric strain becomes more pronounced with increasing pressure, indicating a beneficial interaction between reinforcement and confinement. These outcomes provide insight into the pressure-dependent behaviour of fibre-reinforced soils, offering guidance for their application in foundations, embankments, and other compacted geotechnical structures.

KEYWORDS: Numerical Model, Fibre Reinforcement, Shear Strength

1 INTRODUCTION

Fibre reinforcement is increasingly recognized in soil mechanics and geotechnical engineering as a sustainable method for enhancing soil performance under various loading conditions. While much research has investigated detailed stress–strain behaviour and volumetric responses under controlled conditions, the influence of confining stress on the effectiveness of fibre reinforcement remains less explored. This is a critical knowledge gap, as many practical applications, such as foundations, embankments, and slope stability works, are subject to widely varying in-situ confining stresses.

Extensive research has demonstrated the benefits of fibre reinforcement across a wide range of soil types. Polypropylene fibres, have been shown to improve soil strength even at low contents in distinctly graded soils (Stefania et al., 2011), while other studies report increased compression index without significant changes to the coefficient of consolidation (Kaniraj & Havanagi, 2001). Numerical analyses suggest that higher fibre contents may lead to a more ductile response, often without a pronounced failure peak (Sivakumar et al, 2008). Laboratory evidence further indicates that the failure envelope of fibre-reinforced sand can remain independent of the applied stress path in triaxial compression (Consoli et al., 2007).

Investigations into different reinforcement materials highlight the diversity of mechanical responses. For example, three-dimensional galvanized iron sheet and rigid plastic sheet reinforcements have been shown to enhance both cohesion and internal friction angle of sand (Zhang & Min, 2006). Polypropylene fibres improve peak and residual shear strength, ductility, and toughness, albeit sometimes with a reduction in initial stiffness (Hamidi, 2013). These benefits are often maximized at an optimal fibre content, beyond which mechanical properties may decline (Yang et al., 2011). In cement-treated soils, fibres have been found to reduce post-peak brittleness and enhance resilience under repeated or sustained loading (Khattak & Alrashidi, 2006).

In cohesive soils, fibre reinforcement typically increases effective cohesion and promotes a transition from strain-softening to strain-hardening behaviour (Hou et al., 2020). At low confining pressures, shear strength gains have been recorded, with fibre length exerting a comparatively minor influence (Zhao & Zheng, 2022). In sand–gravel–cement composites, polypropylene fibres have improved both shear strength and energy absorption capacity, though high gravel contents can reduce these benefits under drained conditions (Dehghan & Hamidi, 2016). Recent findings also report that fibre inclusion in low-plasticity clays enhances ductility and deformation capacity, with performance improving alongside increases in fibre content and length (Yazici & Keskin, 2024).

The present study focuses on quantifying how peak deviator stress and volumetric strain performance vary across a range of confining pressures for soils reinforced with different fibre contents. Using finite element modelling, the investigation identifies pressure-dependent trends, diminishing returns at higher confinement, and potential optimal reinforcement levels for different stress environments. By concentrating on confining-pressure-driven behaviour rather than curve-level analysis, the findings aim to support more targeted and reliable geotechnical design.

2 METHODOLOGY

2.1 *Material Selection and properties*

White kaolin clay reinforced with fibreglass fibres was selected for the analysis. Material parameters for both unreinforced and fibre-reinforced specimens were obtained from existing laboratory-based triaxial shear testing, primarily referencing the work of (Alkaisi et al, 2012). These properties, summarized in Table 1, were implemented into the numerical model by defining a Mohr–Coulomb constitutive law within the Sigma/W load-deformation analysis. Fibre contents of 0% (control), 1%, 1.5%, 2%, and 3% by dry weight were modelled to assess reinforcement effects under identical loading conditions. A constant void ratio of 0.3, unit weight of 15.7 kN/m³, and Poisson's ratio of 0.35 were assumed for all models, representing a dense or over-consolidated state typical of foundation subgrades, embankment fills, and other compacted geotechnical structures.

Table 1. Material Properties used within numerical model

Parameters	Fibre content	Young's modulus	Friction angle	Cohesion
Symbol	-	*E*	Φ	c
Values	0	*2854*	*12*	34
	1	*5469.5*	*10.8*	39
	1.5	*7134.2*	*11*	45
	2	*8322.8*	*11*	47
	3	*9512.2*	*11.5*	44
Unit	%	kPa	*Degrees*	kPa

2.2 *Numerical Modelling Framework*

Numerical simulations were conducted using the Sigma/W module of GeoStudio, which applies finite element analysis (FEA) for load-deformation problems. FEA discretizes the soil mass into finite elements connected at nodes, solving governing equations iteratively to predict soil response under applied loading (Zienkiewicz et al, 2005).

A two-dimensional axisymmetric model was developed to represent a vertical slice of a cylindrical triaxial specimen (Figure 1). This configuration allowed computational efficiency while maintaining geometric accuracy and boundary condition realism, reflecting the symmetrical nature of triaxial loading.

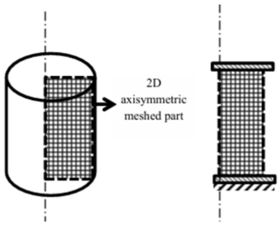

Figure 1. 2D axisymmetric model representing cylindrical specimen (Mir et al, 2015).

Boundary conditions were defined to replicate standard triaxial testing practice: the specimen base was fixed in the vertical direction, while radial constraints simulated the confining membrane. These settings ensured that the numerical model reproduced the uniform confinement and drainage conditions typically employed in laboratory tests.

2.3 *Constitutive Modelling and Analysis Phases*

Material parameters were implemented into the numerical model by defining a Mohr–Coulomb constitutive law within the Sigma/W load-deformation analysis. This approach ensures that the model accurately represents the mechanical behaviour of both unreinforced and fibre-reinforced soils at varying fibre contents.

The analysis was conducted in two sequential phases:

2.3.1 *Initial Setup*

During the initial setup, confining pressure was applied using an isotropic elastic material model Figure 2, with properties listed in Table 1. This phase allowed the model to reach a stable stress equilibrium around the specimen without causing plastic deformation or artificial stress buildup, effectively simulating the consolidation stage in physical triaxial testing.

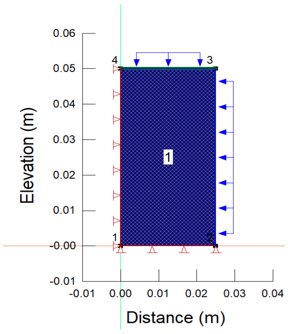

Figure 2. Initial Triaxial Model setup in numerical analysis software

2.3.2 *Shear Loading Phase*

Once the confining pressure was established, the second phase involved updating the material model to reflect the Mohr-Coulomb parameters corresponding to either unreinforced or fibre-reinforced soil at the relevant fibre concentration. Controlled axial loading was then applied to simulate shear stress during compression. Figure 3 shows the unreinforced soil sample undergoing compression loading. This two-stage approach ensured both numerical stability and an accurate replication of physical triaxial test conditions.

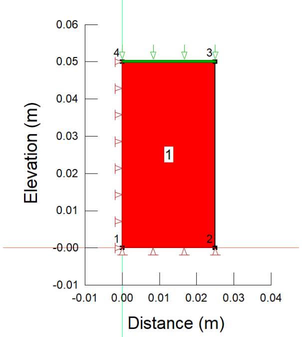

Figure 3. Load Consolidation setup in numerical analysis software

3 RESULTS

The analysis results are presented in terms of how peak deviator stress and peak volumetric strain vary with confining pressure for each fibre content.

3.1 *Peak Deviator stress variation*

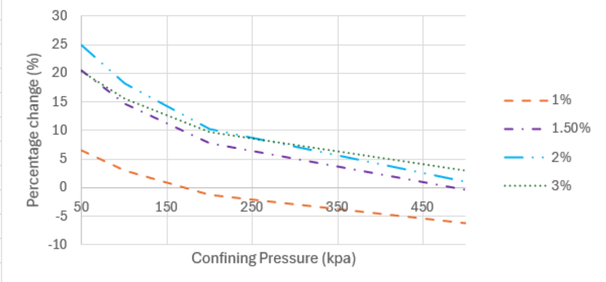

Figure 4. Variation of Deviator Stress depending on confining pressure

The results shown in figure 4 reveal that fibre reinforcement consistently increases peak deviator stress compared to unreinforced soil, with the greatest relative improvements observed at lower confining pressures. At 50 kPa and 100 kPa, the 2% fibre content shows the most significant performance gains, while at 200 kPa and 500 kPa, 3% fibre content achieves the highest absolute strengths. However, the relative benefit of fibre inclusion diminishes as confining pressure increases, indicating that reinforcement effects are more pronounced under lower confinement. The fitted trend line enables interpolation to estimate expected deviator stress performance at untested confining pressures.

3.2 *Peak volumetric strain variation*

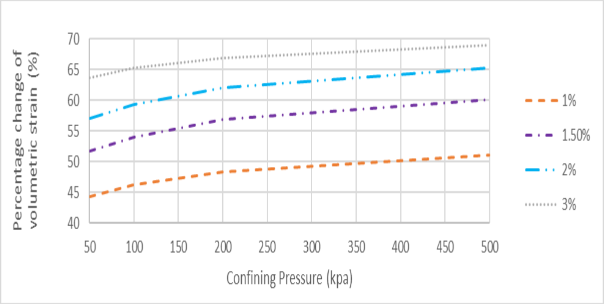

Figure 5. Variation of Volumetric Strain depending on confining pressure

Figure 5 shows how fibre reinforcement reduces peak volumetric compression under triaxial loading across all confining pressures. At lower pressures, the differences between fibre contents are modest; however, as confining pressure increases, the improvement in volumetric strain resistance becomes more pronounced, with 3% fibre content consistently showing the least compression. The fitted trend line supports predictive estimates of volumetric strain at intermediate confining pressures, offering a useful tool for evaluating compressibility in design scenarios.

Table 2 - Results Summary

Confining Pressure (Kpa)	Fibre content (%)	Peak Deviator Stress (Kpa)	Peak Volumetric Strain
50	0	110.26	0.01162
	1	117.41	0.00646
	1.5	132.85	0.00561
	2	137.72	0.00499
	3	132.76	0.00421
100	0	*136.51*	*0.01437*
	1	*140.46*	*0.00772*
	1.5	*156.43*	*0.00660*
	2	*161.30*	*0.00584*
	3	*157.66*	*0.00500*
200	0	*189.00*	*0.01989*
	1	*186.58*	*0.01025*
	1.5	*203.58*	*0.00858*
	2	*208.45*	*0.00753*
	3	*207.46*	*0.00657*
500	0	*346.48*	*0.03643*
	1	*324.92*	*0.01784*
	1.5	*345.06*	*0.01453*
	2	*349.93*	*0.01263*
	3	*356.85*	*0.01128*

Table 2 presents the absolute values of peak deviator stress and peak volumetric strain for each fibre content under the confining pressures examined. It provides the underlying numerical data used to generate the figures and enables direct verification and comparison across fibre contents and pressures.

4 DISCUSSION AND CONCLUSIONS

4.1 *Discussion*

The 3% fibre content curve in Figure 4 shows a distinct behaviour compared with the 2% fibre content curve. At lower confining pressures (50–100 kPa), the 3% mix records lower peak deviator stresses, indicating that a lower cohesion diminishes performance under low confinement. In contrast, the 2% mix achieves higher stresses due to its greater cohesion. As confining pressure increases, however, cohesion becomes less significant. Under these conditions, the 3% fibre content achieves the highest peak deviator stress, showing that higher pressures allow the fibre-reinforced composite to mobilize greater shear resistance. This behaviour is consistent with triaxial test findings that show cohesion effects dominate at low pressures but diminish under increased confinement (Consoli et al., 2007).

This behaviour reflects fundamental soil mechanics principles, where cohesion governs strength at low confining pressures but becomes less relevant as confinement increases. These findings highlight a clear interaction between confining stress and the mechanical benefits of fibre reinforcement in soils. At lower confining pressures (50–100 kPa), moderate fibre contents (around 2%) provide the highest relative improvement in deviator stress, suggesting efficient crack-bridging and tensile resistance without excessive fibre clustering (Sivakumar et al., 2008). At higher confining pressures (200–500 kPa), higher fibre contents (3%) become more effective, likely due to improved particle–fibre interlock under increased confinement (Hou et al., 2020; Zhao & Zheng, 2022).

The diminishing marginal gains in deviator stress improvement at higher pressures suggest that the reinforcing mechanism is partially replaced by the natural strength gains from increased confinement (Zhang & Min, 2006). This aligns with fundamental soil mechanics principles, where confinement enhances interparticle friction and dilatancy control, reducing the relative role of tensile reinforcement (Stefania et al., 2011).

For volumetric strain, the trend is reversed in terms of relative benefits because improvements become more significant as confining pressure increases. This indicates that fibres are particularly effective in restraining volumetric compression when particles are already constrained by high lateral stresses (Yang et al., 2011).

These results provide valuable guidance for geotechnical design. For lightly confined structures (e.g., shallow footings, embankment shoulders), lower fibre contents may be most efficient. In contrast, for deep foundations or heavily confined fills, higher fibre contents offer improved volumetric stability with only modest gains in deviator strength.

4.2 *Conclusions*

Fibre reinforcement increases both peak deviator stress and resistance to volumetric compression across all confining pressures tested.

The relative improvement in deviator stress is greatest at low confinement, while the absolute strength benefit shifts toward higher fibre contents as confining pressure increases.

Reduction in volumetric strain becomes more pronounced with increasing confinement, with 3% fibre content showing the most consistent benefit.

The interaction between fibre content and confining pressure suggests that optimal reinforcement levels are context-dependent, varying with the expected in-situ stress environment.

Predictive trend lines enable estimation of soil performance at untested pressures, offering practical tools for design in soil mechanics and geotechnical engineering.

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