Multiscale and Multidisciplinary Modeling, Experiments and Design (2025) 8:328
https://doi.org/10.1007/s41939-025-00894-0

ORIGINAL PAPER

Tensile capacity enhancement of piles in Kaolin clay using recycled crushed glass: physical modelling and numerical analysis

Mohamed Ahmed Hafez[1,2] · **Shin To Amiri**[3] · **Ali Dehghanbanadaki**[4,5,6] · **Shervin Motamedi**[7] · **Ahmad Safuan A. Rashid**[3] · **Iman Golpazir**[4]

Received: 20 November 2024 / Accepted: 29 April 2025 / Published online: 29 May 2025

Abstract

Reusing waste materials such as crushed glass (CG) in geotechnical applications presents a promising and environmentally sustainable approach to improve the geotechnical engineering properties of soft soils. This study conducted a comprehensive analysis to assess the influence of varying the content of CG on the failure tensile load of single piles in Kaolin clay. The investigation included a wide range of CG ratios, ranging from 10 to 50% in 10% increments. Thirty physical modelling tests were performed, considering various amounts of CG and pile diameters ranging from 10 to 50 cm. The clay soil samples were mixed with CG, and the mixtures were consolidated to achieve homogeneity with an average shear strength of 10 kPa. Additionally, the $Optum^{G2}$ and $Optum^{G3}$ software packages were used to simulate the stabilisation process using the 2D and 3D Finite Element Method (FEM). The findings of this study indicate that adding CG to Kaolin clay can enhance the stress–strain behaviour of the soil, which leads to a significant increase in the tensile failure load. The results suggest that adding CG to Kaolin soil alters its characteristics from cohesive to more granular. Moreover, 40–50% CG significantly enhances the skin friction between the pile and soil. Furthermore, the 2D FEM modeling accurately simulated the stabilisation process, while the 3D modeling overestimated the tensile failure load. Extending the analysis to pile groups, a case study of a 4 × 4 pile configuration demonstrated the broader implications of CG improvement, resulting in a 27.4% enhancement in pile group tensile capacity.

Keywords Clay · Crushed glass · Tensile ultimate bearing capacity · FEM modelling

1 Introduction

Glass waste represents a significant environmental challenge globally, with approximately 130 million tons produced annually while achieving an average recycling rate of only 21% (Perera et al. 2023). This material does not naturally decompose, leading to persistent accumulation in landfills. Production volumes and recycling efficiencies vary considerably across nations: the United States generates 11.4 million tons annually with a 27% recycling rate, while India produces 21 million tons with 45% recycled. European nations demonstrate more advanced waste management practices, particularly Germany, which achieves an 80% recycling rate despite generating only 2.5 million tons of glass waste. Other countries show moderate recycling success, including Australia (57% of 1.1 million tons), the United Kingdom (45% of 2.4 million tons), and Canada (40% of 0.75 million tons). These statistics underscore the substantial volume of glass waste available for geotechnical applications and the significant opportunity to enhance sustainability through innovative repurposing strategies (Ahmed and Rana 2023).

It is well-recognised that weak soils often require stabilisation measures before they can be considered suitable for a structure to be built on them (Roshan and Rashid 2024; Fawaz et al. 2024). Generally, weak soils are defined as those with low bearing capacity, poor compaction characteristics, or high susceptibility to settlement (Li et al. 2024). These soils create significant challenges in construction projects, as they do not provide adequate support for structures or may undergo excessive deformation over time (Zafar et al.

Extended author information available on the last page of the article

2023). Methods for stabilising weak soils, such as incorporating chemical binders, have the potential to enhance the engineering characteristics of the soil notably (Anburuvel 2023). These methods improve the soils' load-bearing capacity, stability, and strength, making them more suitable for construction and ensuring the long-term integrity of structures built on such soils (Zada et al. 2023).

Many studies (e.g., Chen & Wang 2006; Wei and Ku 2020; Onyelowe et al. 2022) examined the use of conventional binders, such as cement, gypsum, and lime for soil stabilisation purposes. Despite all the benefits, chemical stabilisation introduces adverse ecological consequences, primarily related to carbon footprint during the manufacturing of stabilising agents such as cement (Sudhakar and Reddy 2023; Komkova and Habert 2023; Zanovello et al. 2023). Considering the drawbacks of chemical soil improvement methods, exploring alternative materials or minimising the use of conventional materials becomes vital.

Many research works investigated the ground improvement techniques that promote leveraging waste materials to enhance the ultimate bearing capacity (UBC) of soft soils (e.g., Kamei et al. 2015; Amiri et al. 2018; Galvin et al. 2021; Deboucha et al. 2020; Dehghanbanadaki et al. 2020; Indraratna et al. 2022; Gidebo et al. 2023; Zaini et al. 2023; Sargent et al. 2024; Mazaheri et al. 2024; Long et al. 2024). However, from the onset, less attention has been given to recycled crushed glass as an alternative material to the traditional binders for chemical stabilisation. Incorporating this readily available waste offers a win–win: reducing environmental effects whilst enhancing soil engineering properties (Tushar et al. 2023; Surendran and Akhas 2024). Reusing waste glass diverts it from landfills, conserving space and reducing the need for resource extraction. This translates to a lower carbon footprint, as recycling glass requires less energy than processing virgin materials. Moreover, incorporating recycled glass into ground improvement contributes to a circular economy, promoting sustainable construction practices (Ferdous et al. 2021). Performance-wise, crushed waste glass exhibits properties comparable to traditional aggregates or other binders in strength, permeability, and drainage. This makes it suitable for ground improvement applications, including creating load-bearing columns, enhancing soil stability, and mitigating liquefaction risk (Kazmi et al. 2021; Zachariah and Ravi 2024).

Column-like ground improvement techniques, including deep cement mixing (DCM) columns, stone columns, and piles, have proven highly effective in enhancing the bearing capacity and reducing settlement of soft soils (Hajiazizi et al. 2018; Mazaheri et al. 2021; Dehghanbanadaki et al. 2022; Pham et al. 2025). These vertical reinforcement elements function by transferring structural loads to deeper, more competent soil strata while simultaneously providing lateral confinement to the surrounding soft soil matrix, thereby significantly increasing the composite strength and stiffness of the entire foundation system. Recent investigations suggest that integrating these established column techniques with crushed glass (CG) treatment of the surrounding soil matrix could produce synergistic effects, potentially amplifying the overall ground improvement outcomes. The complementary mechanisms—with columns providing structural reinforcement and CG-treated soil offering enhanced matrix properties—could lead to more cost-effective and environmentally sustainable foundation solutions with superior load-bearing characteristics and reduced settlements compared to conventional approaches.

1.1 Geotechnical behaviour of treated soil by waste glass by-products

The utilisation of Crushed Glass (CG) in hydraulically bound materials as a substitute for traditional aggregates and its role in reducing cement content has been documented (Jalal et al. 2022; Baikerikar et al. 2023; Maurya et al. 2023; Peng et al. 2023; Zhao et al. 2024; Zhen et al. 2024). However, investigations (e.g., Wartman et al. 2004; Ate 2016; Onyelowe et al. 2019; Kumar et al. 2020; Lawanwadeekul et al. 2023; Anglaaere et al. 2023) have explored the use of CG for improving the geotechnical engineering properties of weak soils. Generally, Glass materials in soil stabilisation exist in three distinct forms: (a) Glass Powder (GP) (< 75 μm), offering pozzolanic properties; (b) crushed glass (0.075–4.75 mm), providing mechanical stabilisation through friction; and (c) glass fibers (10-25 μm diameter and lengths of 3-50 mm), enhancing tensile strength (Wartman et al. 2004).

Combined with traditional stabilisers, GP's (GP) pozzolanic properties can enhance engineering soil characteristics. Sheob et al. (2023) examined the efficacy of a mixture comprising cement and waste GP to enhance the attributes of clay-rich soil. Their research assessed the effect of powdered CG on compaction properties such as maximum dry density (MDD) and optimum moisture content (OMC) of clay soils. The findings showcased that the incorporation of 5% cement and 10% waste GP led to a 6% increase in the MDD of the soil specimen and a 3% reduction in the OMC. Ate (2016) conducted experimental research to explore the impact of incorporating cement and Glass Fibres (GF) on the geotechnical characteristics of sandy soils. The findings revealed that introducing 3% GF alongside a consistent 15% cement content elevated the UCS of the stabilised mixture. However, surpassing the 3% GF threshold led to a decrease in UCS.

In a recent study by Ilman and Balkis (2023), the mechanical properties of clay materials enhanced with GP were examined. Each type interacts differently with soil and is selected based on specific engineering requirements. The study also investigated the mechanical properties of clay materials reinforced with GP and Silica Fume (SF). For experiments, the clays were combined with varying proportions of 10%, 15%, and 20% GP, along with an additional 10% SF. The findings indicate an optimal outcome is achieved with a combination of 15% GP and 10% SF. In this optimally formulated mixture, a substantial enhancement of 390% in compressive strength and a notable increase of 322% in direct shear strength were observed compared to the control specimens.

In another study, Kumar et al. (2020) investigated the effect of adding various percentages of reclaimed asphalt pavement and waste CG on the geotechnical properties of black cotton soil and loam soil, including MDD, OMC, and California Bearing Ratio (CBR). The findings showed that including waste materials enhanced the shear strength of the mixes. For instance, adding 65% reclaimed asphalt pavement and 5% glass increased the CBR value of the soil by up to 3.5 times compared to untreated soil. Anglaaere et al. (2023) conducted a comparative study to assess the engineering characteristics of clay soil stabilised with GP and rubber particles. The findings revealed a more substantial enhancement in the direct shear test using rubber particles than waste GP. Alternatively, the CBR test indicated that GP had a more beneficial effect on the soil's CBR values than rubber particles.

Up to this point in the literature review, previous studies have primarily utilised a modest proportion of Crushed Glass content (CG%), typically not exceeding 15%, to investigate the alterations in geotechnical properties within treated soils via various testing methodologies. In contrast, a recently published research article has concentrated on the implications of using increased CG percentages, ranging from 10 to 40%, to assess their impact on the behaviour of improved expansive clays (Al-Taie et al. 2023). The study involved CBR and UCS tests. The outcomes of this investigation revealed noteworthy improvements, indicating an approximate 45% increase in UCS and a substantial 130% boost in CBR values with the incorporation of 25% more significant reinforced glass particles. Introducing a relatively small quantity, approximately 6%, of GP effectively enhanced both UCS and CBR values to around 100% and 200%, respectively.

Demir and Cabalar (2024) recently conducted a novel study on waste glass's (WG) influence on bentonite's geotechnical behaviour. Their research delved into various aspects, including dispersion, viscosity, and UCS of soil samples stabilised with WG. The research incorporated two different sizes of waste glass: fine WG (FWG) and medium WG (MWG), which were separately blended with different amounts of bentonite samples. The research findings demonstrated a noteworthy effect of WG content on the UCS of pure bentonite, with an increasing trend observed. The UCS reached its peak value at 30% MWG, exhibiting a remarkable 56% enhancement compared to the pure bentonite samples. Furthermore, the specimens exhibited a maximum energy absorption capacity of 11.50 kJ/m^3, indicating a substantial 76% improvement compared to clean bentonite. Significantly, the study revealed that the medium-sized WG performed better in enhancing the UCS of the stabilised samples than the fine WG. This distinction in performance highlights the importance of considering WG size as a contributing factor in achieving optimal results when improving the geotechnical properties of bentonite.

This study investigates how incorporating CG into Kaolin clay affects the tensile load capacity of single piles and pile groups. This research addresses a critical knowledge gap in geotechnical engineering by providing the first comprehensive numerical modelling approach for CG-stabilised soil under tensile loading conditions. While previous experimental studies have examined aspects of this behavior, our work pioneers the application of both 2D and 3D Finite Element Method (FEM) simulations to accurately predict tensile failure mechanisms in CG-improved soils. The study systematically evaluates varying CG contents (10% to 50% in 10% increments) and pile diameters (10–50 cm), analysing stress–strain behaviour, soil characteristic modifications, and skin friction enhancement. By extending the analysis to a 4 × 4 pile group configuration, this research provides unprecedented insights into the group effects of CG improvement, offering practical design guidelines that could significantly reduce construction costs and environmental impact through beneficial reuse of waste glass in geotechnical applications.

2 Experimental procedures

2.1 Source of the experimental data

This study aims to build upon the findings of primary geotechnical tests by Amiri et al. (2018), highlighting the potential enhancement of geotechnical strength properties in Kaolin clay by including CG. Furthermore, sample preparation details for physical modelling tests, including consolidation tests, are outlined in Amiri et al.'s prior work (2020). It is important to note that the critical difference in the experimental physical modelling between our study and Amiri et al. (2020) lies in the shear strength of the pure soil. While Amiri et al. (2020) reported a shear strength of 20 kPa for samples in the box, this study maintains a shear strength of 10 kPa. However, given our focus on FEM techniques, we provide a concise overview of the experimental test details. Tables 1 and 2 summarise the geotechnical engineering properties of materials used in this investigation.

Table 1 Geotechnical engineering properties of the soil

Soil	Atterberg limits		Specific gravity	Compaction test		Shear strength		USCS classification
	LL (%)	PL (%)		OMC (%)	MDD (Kg/m^3)	Friction angle (degree)	Cohesion (kPa)	
	42	28.63	2.58	17.5	1626.45	0	36	CL

Table 2 Geotechnical properties of the CG

CG	Specific gravity	Compaction test		Shear Strength	USCS classification
		OMC (%)	MDD (kg/m^3)	Friction angle (degree)	
	2.51	9.2	1830.39	37	SP

2.2 Experimental details

The experimental investigation employed three key materials: white Kaolin clay, CG, and concrete piles. The CG component was derived from recycled glass bottles of various types, shapes, colours, dimensions, thicknesses, and brands, demonstrating the versatility of common glass waste in geotechnical applications. Before testing, the CG underwent a 24-h drying process at 110 °C, followed by granulometric classification through sieve analysis. Specifically, particles passing through a No. 8 sieve while retained on a No. 16 sieve were selected, yielding a consistent particle size distribution between 1.18 mm and 2.36 mm per ASTM C136-06 standards (ASTM 2014). For incorporation into the physical models, the CG was mixed with Kaolin clay using a slurry technique, where water was added at 1.5 times the clay's liquid limit. This specific water content ratio was selected based on preliminary testing demonstrating optimal particle distribution and mixture homogeneity while maintaining appropriate workability during sample preparation and consolidation. This slurry was subsequently blended with crushed glass in proportions varying from 10 to 50% by weight to create the composite soil specimens.

Before the main experimental program, preliminary unconfined compression strength (UCS) tests were conducted on samples with CG contents ranging from 0 to 70%. The specimens containing more than 50% CG exhibited pronounced instability, characterised by premature brittle failure and inability to maintain structural integrity during testing. At these higher CG percentages, the material behaviour transitioned from predominantly cohesive to granular, with the crushed glass particles forming a disconnected matrix that significantly reduced the sample cohesion. This preliminary testing established 50% as a practical upper boundary for our investigation.

The experimental physical models utilised concrete piles fabricated from a composite of gravel, sand, Portland cement type II, and distilled water. To maintain proper scale relationships, all pile specimens incorporated appropriately sized aggregate materials—specifically, gravel components were passed through a #10 sieve to ensure maximum particle dimensions remained below one-fifth of the minimum pile diameter (10 mm). The binding matrix consisted of Portland cement type II combined with distilled water at a water-cement ratio of approximately 0.6 by weight, creating a workable paste that effectively bonded the granular constituents into structural elements with consistent properties across all test configurations.

Following preparation, the soil-glass composite underwent a controlled consolidation process to achieve uniform consistency throughout the test medium. This resulted in a homogeneous matrix with a measured undrained shear strength (C_u) of 10 kPa across all specimens. This shear strength was verified using in-situ *Vane Shear Tests* (VST) performed directly on the consolidated soil mixtures to ensure consistency between experimental conditions.

For the pile testing apparatus, a cylindrical pneumatic jack with a maximum pressure capacity of 10 bars (approximately 1000 kPa) was employed, generating approximately 87 kPa on the chamber surface and producing a maximum force of 1.5 kN on the 300 mm × 300 mm box surface. The pile installation process mimicked field drilling operations using a custom-designed extruder system. Initially, a 1 mm-thick plastic cylindrical mould (300 mm in height, exceeding the 200 mm pile length) was inserted at the chamber's centre to serve as casing, preventing soil collapse while minimising soil displacement. Subsequently, the drilling extruder created the pile cavity within this casing. A specialised connection system featuring a hook-shaped pile cap was implemented for pull-out testing to transfer tensile force from a strain-controlled tension motor via a metal wire. This configuration accommodated load-cell and LVDT attachments to measure applied loads and pile displacements simultaneously. A pull-out rate of 1.3 mm/min (0.05 in/min) was maintained through voltage adjustments to the electric motor to ensure undrained conditions during testing.

Figures 1a–e present visual representations of the fundamental tests, including the (a) UCS test, (b) DS test, (c) consolidation process, (d) tensile loading procedure in physical modelling, and (e) a schematic view of the physical modelling tests.

Figures 2a–c provide statistical information regarding the used CG% and strength parameters. The number of physical modelling tests conducted in this study is represented by the count of 30 in Fig. 2. The Figures also present statistical data, including mean, standard deviation, skewness, and kurtosis values. It is worth noting that negative skewness indicates a distribution where most data points are concentrated on the right side, resulting in an elongated left tail. In such cases, the mean is typically less than the median. A distribution with negative kurtosis, known as platykurtic, exhibits a lower peak and lighter tails compared to a normal distribution, indicating a decreased likelihood of extreme values or outliers. The statistical data presented in this section outline our efforts to stabilise pure clay for 30 physical modelling tests, each incorporating an average of 25% CG. We observed an average cohesion of 22.42 kPa for these tests and a friction angle of 16.5 degrees. These average geotechnical values define the parameters and focus of our study.

3 Numerical modelling

We simulated the stabilisation of the Kaolin-CG mixture using the *Optum*^{G2} (*Optum*^{G2} 2020) and *Optum*^{G3} (*Optum*^{G3} 2020) software, which both ran with educational licenses. *Optum*^{G2} can model geotechnical structures in plane strain and axisymmetric conditions, while *Optum*^{G3} is designed to solve 3-D problems. The pure soil and the mixes were considered '*soft soil*' (Soft clay-MC) in the simulation, while the pile was modelled as a rigid element. The geotechnical engineering properties of the pure Kaolin and the mixed soil were assigned based on experimental data obtained through tests on both stabilised and undisturbed samples (see Fig. 3).

A fine mesh of 1000 elements was used in the meshing process to ensure accurate numerical results, as recommended by the software (OptumG2, 2020). In each test, mesh adaptivity was employed to optimise the orientation and size of the mesh elements according to the simulated failure mechanisms. The direct tensile load of the piles was determined using the *Limit Analysis* method, in which a unit vertical tensile stress was applied as a multiplier distribution stress along the pile, and *Optum*^{G2} and *Optum*^{G3} were used to determine the coefficient at which the pile failed. Figure 3 displays the parameters utilised in each physical modelling test for FEM modelling. These average geotechnical values were then used to define the parameters for the scope of the study.

Based on Fig. 3, which presents UCS test results for CG-treated clay, we observed significant improvements in mechanical properties with even modest CG additions. Incorporating just 10% CG increased the UCS from 10 kPa in pure clay to 32 kPa while simultaneously developing a friction angle of 12° compared to the negligible friction angle of untreated clay. This dual improvement in cohesion and internal friction angle substantially enhances the mechanical behaviour of the soil. The findings demonstrate distinct advantages over Tire-Derived Aggregate (TDA) treatments compared to alternative waste material applications. Arefnia et al. (2021), working with the same kaolin clay, reported that TDA incorporation decreased the internal friction angle by up to 8% at 60% TDA content. Furthermore, their study showed that TDA addition reduced the MDD of the composite material by up to 45%, which could negatively impact bearing capacity in field applications. However, it should be emphasised that after these baseline characterisation tests, the researchers specifically utilised these TDA-clay mixtures for reducing lateral earth pressure behind retaining structures, not for strength enhancement.

There are two primary methods for determining limit analysis in *Optum* software: *Strength Reduction Finite Element Limit Analysis* (SR-FELA) and *Mixed Element Limit Analysis* (MELA). SR-FELA is a general method that can be used to analyse various problems. The soil strength parameters in SR-FELA are gradually reduced until the structure reaches a 'Limit Equilibrium State'. The safety factor is then calculated as the ratio of the applied load to the UBC at the point of limit equilibrium. MELA is more efficient than SR-FELA for problems where the soil strength is constant throughout the domain. In MELA, the soil is divided into upper- and lower-bound elements.

Upper-bound elements are designed to provide an upper bound on the true UBC. In contrast, lower-bound elements are designed to provide a lower bound on the true UBC. The safety factor is then calculated as the ratio of the upper-bound ultimate bearing capacity to the lower-bound UBC (OptumG2, 2020). Figure 4 a–f shows an example of the meshing process, boundary conditions, loading stages, pile modelling, soil properties, and determination of the failure load in TS-1.

4 Results and discussion

4.1 Experimental tensile failure load

Figure 5 presents the experimental tensile failure load of the piles obtained from each physical modelling test. As can be seen, the range of CG% was from 0% (pure clay) to a maximum of 50%, and the range of pile diameter was from 10 to 50 mm. To be noticed this study focused on samples

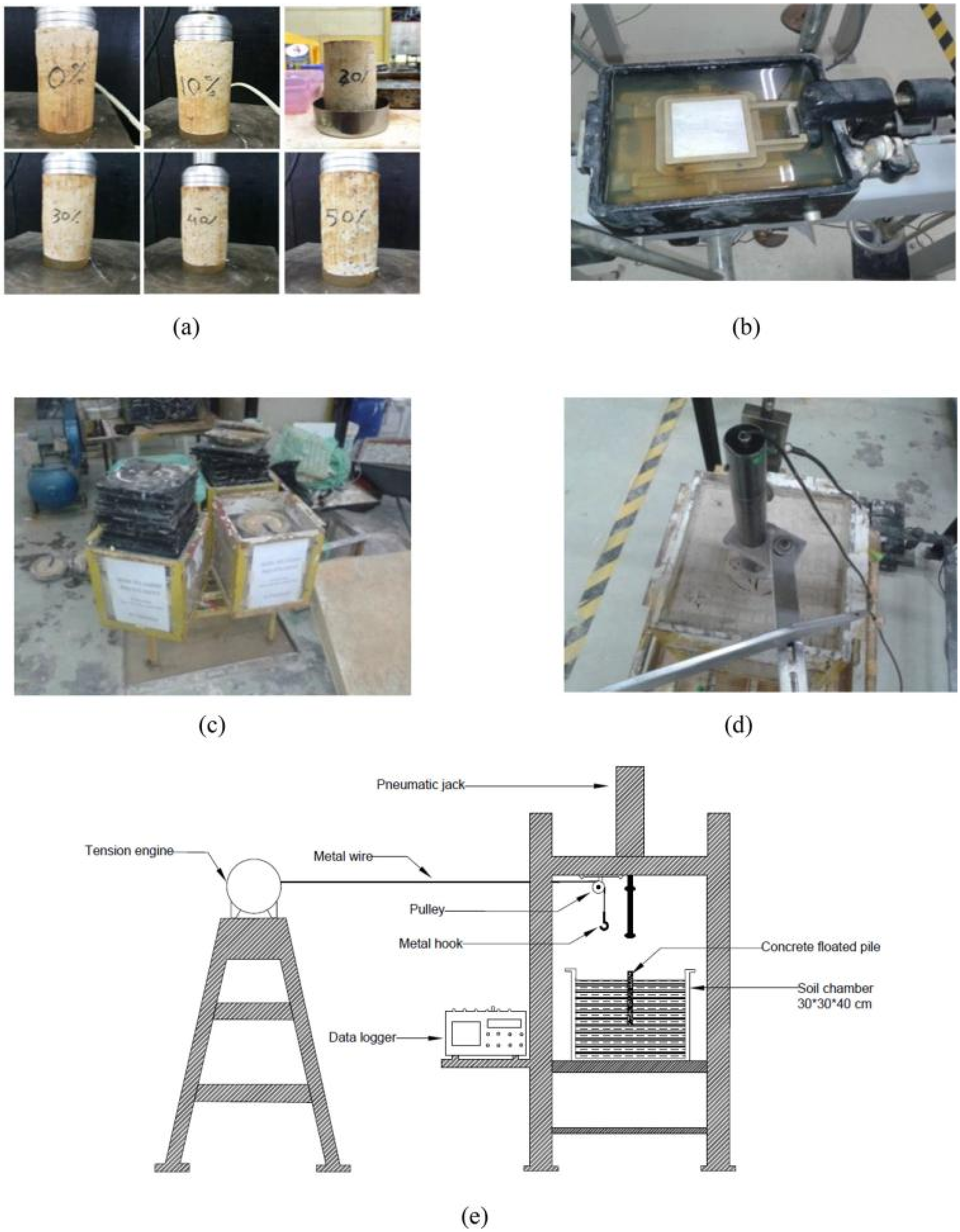
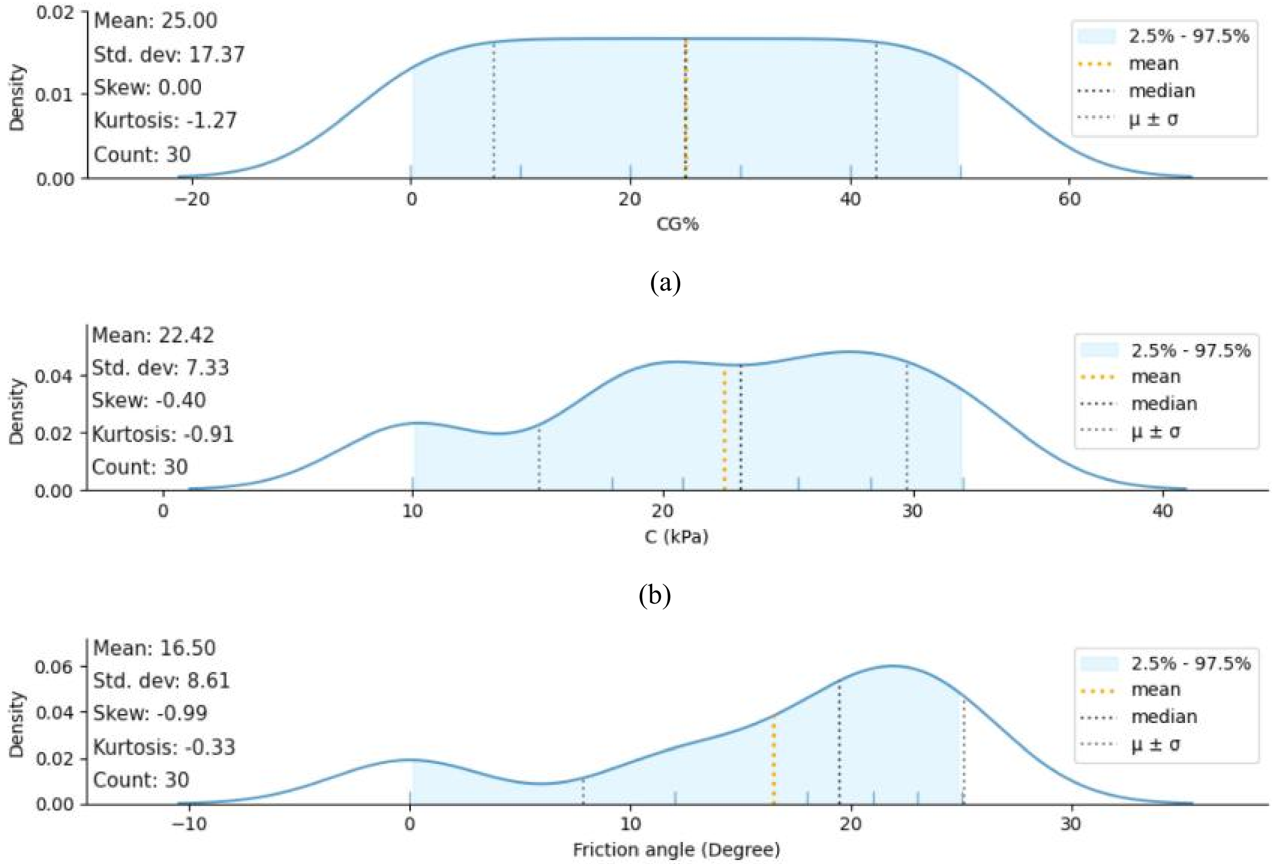


Fig. 1 **a** UCS tests; **b** DS tests; **c** Consolidation process; **d** Tensile loading procedure in physical modelling tests; and **e** Schematic of the physical modelling tests



(a)

(b)

(c)

Fig. 2 Statistical distribution of the used CG% and strength parameters of the soil in the dataset: **a** CG%; **b** C (kPa); and **c** Friction angle (degree)

containing less than 50% CG, and we did not extend the experimental and FEM modelling to those with higher CG content. Analysing pull-out test results in clay soils with over 50% CG presents a complex challenge due to a fundamental shift in soil behaviour. Our prior research (Amiri et al. 2018) delved into this complexity, revealing that conventional geotechnical equations and FEM modelling may lose validity beyond this threshold. Our earlier work demonstrated unsatisfactory outcomes in UCS and DS tests for clay soils treated with CG exceeding 50%, showing a notable decrease in cohesion. Additionally, specific UCS test samples exhibited instability in vertical positions even before testing initiation.

Figure 5 clearly illustrates that as the pile diameter increases, the pile tensile failure load rises significantly due to the greater pile weight. The influence of crushed glass (CG) on tensile failure loads can be evaluated by comparing tests with equivalent pile diameters (see Fig. 5). The Figure demonstrates that incorporating CG improves the tensile capacity, with particularly significant increases observed when clay samples were mixed with 50% CG. The configuration with maximum pile diameter (50 mm) and 50% CG content yielded the highest failure load, measuring 134 N.

4.2 Improvement ratio of the failure load

Each test was meticulously compared under identical pile dimensions to assess the impact of CG addition on enhancing the uplift load of individual piles. The *Improvement Ratio* (IR), calculated per Eq. 1, was employed to quantify the failure load enhancement rate of piles. The outcomes of these improvement ratios are visually depicted in Fig. 6. As illustrated in Fig. 6, the IR% variations across different piles with varying CG proportions are evident. Notably, for all pile diameters, there is an obvious yet not statistically significant increase in IR% when CG is raised from 10 to 30%. For instance, when comparing a 50 mm pile diameter in clay, the Improvement Ratio (IR) increased from approximately 110% with 10% CG addition to 257% with 50% CG addition, relative to the unmodified clay baseline. The trends remained relatively consistent within the CG addition

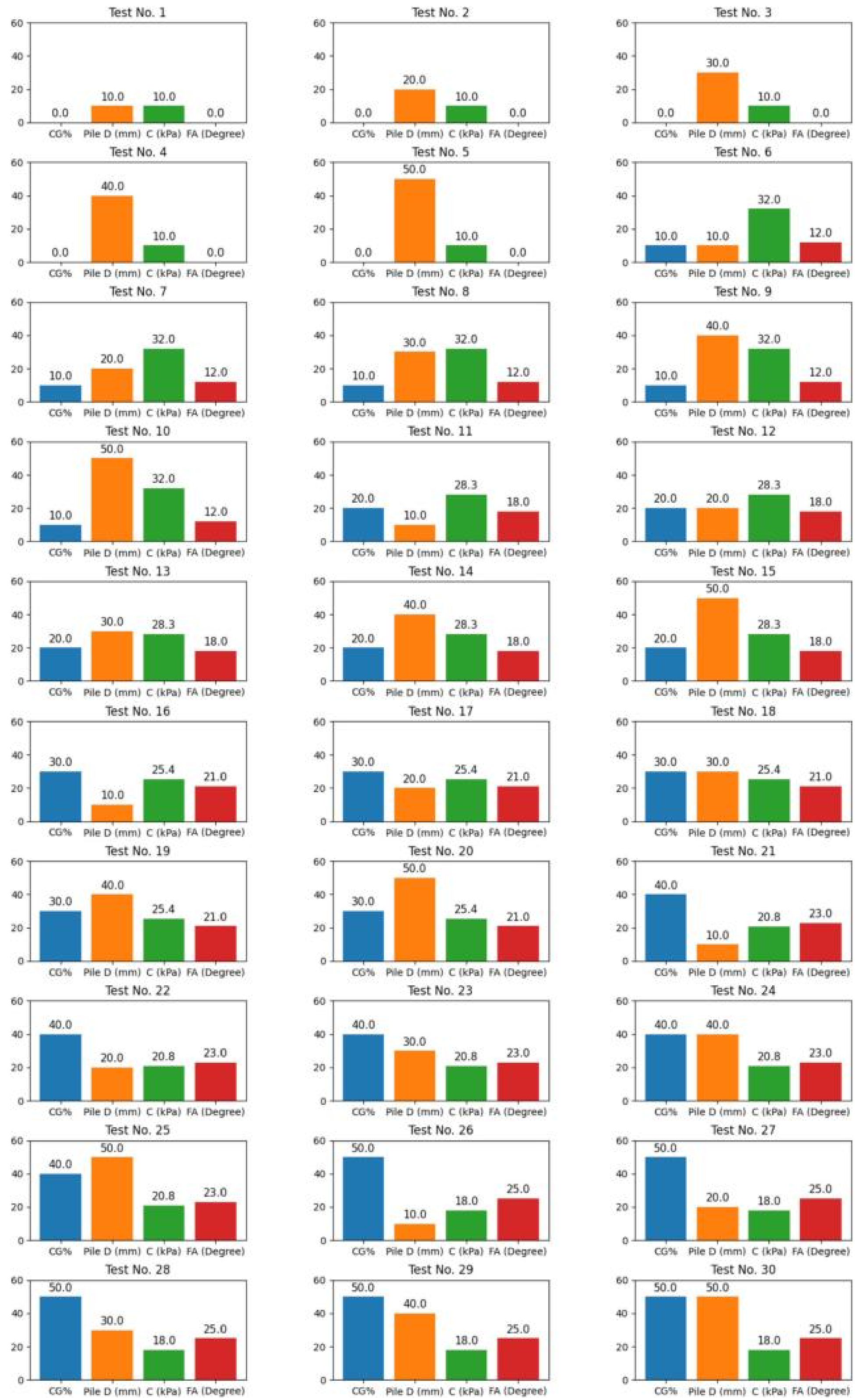


Fig. 3 Details of input parameters of each test in FEM modelling

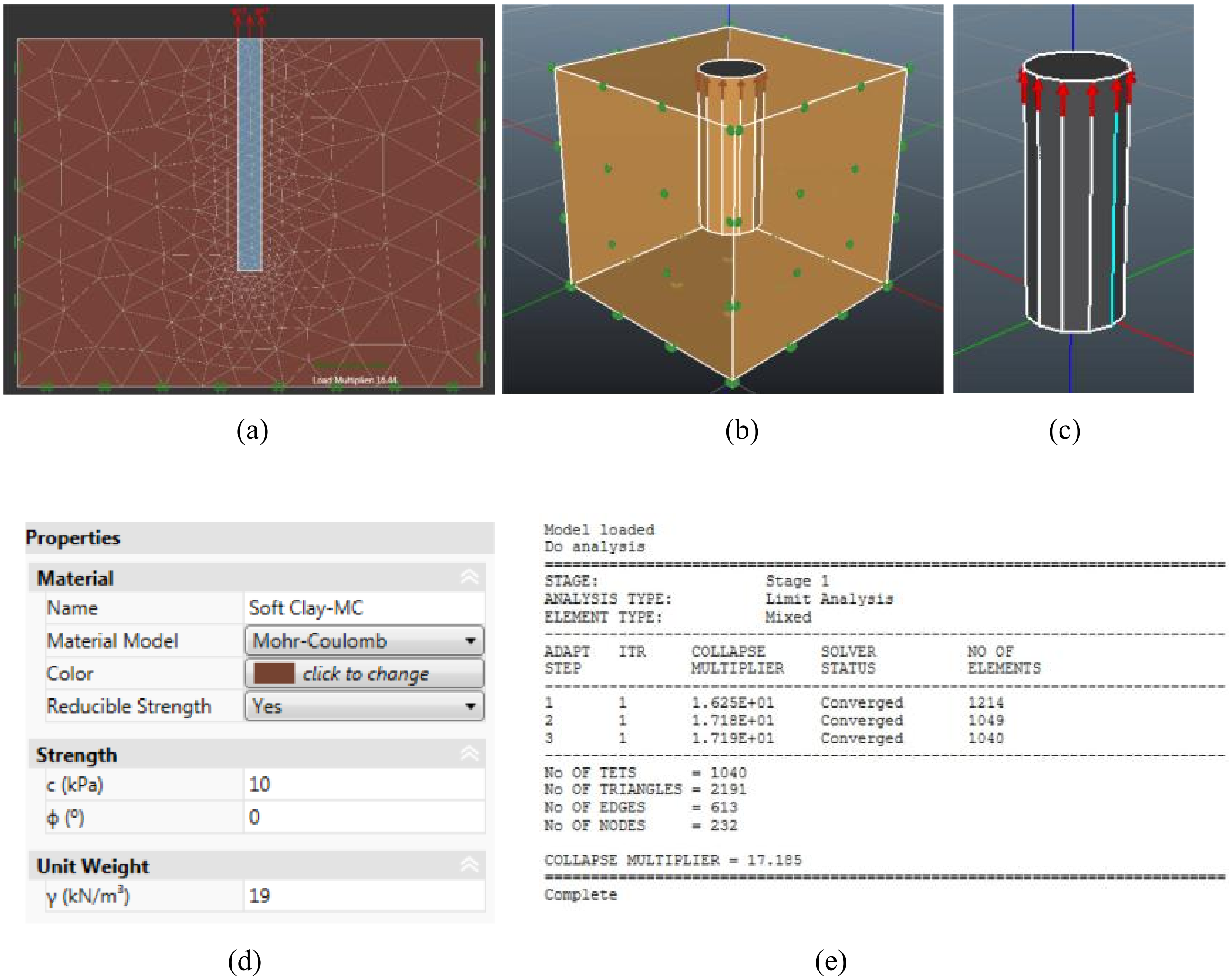


Fig. 4 **a** Meshing process in 2D; **b** Loading conditions in 3D; **c** Pile modelling; **d** Soil properties (Test No. 1); and **e** A sample of failure load (Test No. 1)

range of up to 30%. Remarkably, an evident surge in IR was observed across all tests, with CG additions ranging from 30 to 50%. This surge is attributed to the heightened friction between the clay and the piles induced by the presence of CG.

An essential observation from these comparisons was the influence of the effective weight of the piles. In lighter piles, the influence of CG was notably more significant compared to heavier piles. For instance, in the test with a diameter of 10 mm and CG content of 50%, the IR was approximately 650%. However, as the pile diameters increased, the corresponding IR decreased proportionally. This decrease can be attributed to the additional load required to uplift the heavier piles. This detailed analysis highlights that while smaller diameter piles exhibit a more significant improvement ratio due to the higher relative influence of CG on the uplift capacity, larger diameter piles show a diminishing IR due to their greater inherent weight and load requirements. These findings suggest that the effectiveness of CG stabilisation is more pronounced in lighter and smaller diameter piles, emphasising the need for tailored approaches when applying CG stabilisation across varying pile dimensions.

$$Improvemt\ ratio = \frac{Failure\ tensile\ load\ of\ improved\ samples}{Failure\ tensile\ load\ of\ pure\ clay} \times 100\% \quad (1)$$

4.3 FEM modelling results

Failure load was assessed at lower, upper, and mixed-mode levels using $Optum^{G2}$ and $Optum^{G3}$ software for numerical modelling. The numerical analysis tests revealed that the disparity between lower and upper-bound tensile failure loads was approximately 10% to 18% when employing

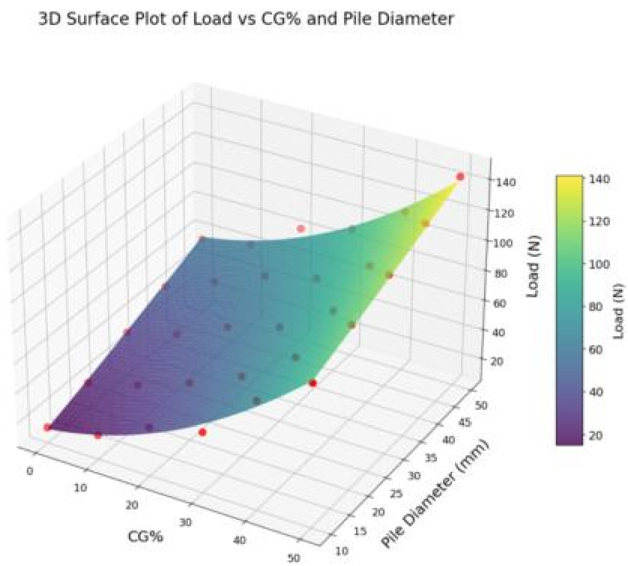


Fig. 5 Three-dimensional surface plot depicting experimental failure loads

the *Optum*^{G2} software (2-D modelling). This difference increased from 15 to 23% when using the *Optum*^{G3} software (3-D modelling). For instance, the measured tensile loads were 14.62 N, 16.43 N, and 17.18 N for the lower, upper, and mixed-mode. Consequently, based on the software's recommendation, the mixed mode was selected as the representative tensile failure load.

Ones can note that observed disparities between the upper bound and lower bound results in the FEM modelling of the present study can be attributed to the variability in material properties. Geotechnical characteristics, including cohesion, friction angle, and other mechanical parameters, may exhibit spatial variability in the field. Consequently, in FEM modelling, distinct values for these properties in upper-bound and lower-bound scenarios can result in divergent outcomes. Another potential factor contributing to these differences is geometrical variability. The geometry of the modelled domain, encompassing the shape and dimensions of slopes or foundations, can influence the results. Varied geometry representations in upper and lower-bound analyses may lead to discrepancies in the predicted outcomes (OptumG2, 2020).

4.4 Comparison between 2-D and 3-D failure load

Figure 7 illustrates a comparison of tensile failure load trends among experimental results, 2D modelling (FEM 2D), and 3D modelling (FEM 3D). When CG% is zero (pure clay), there is minimal difference between the experimental failure load and FEM modelling in both 2D and 3D, as evident in Fig. 7, where all three dots are closely aligned. The disparity between FEM modelling and experimental outcomes becomes considerable with increased pile diameters and CG content in the soil mixture, particularly at CG% values of 40% and 50%. These discrepancies arise because a higher CG content in the soil causes the treated samples to behave in more granular soils, such as sand, instead of clay.

As depicted in Fig. 7, the discrepancies between the points (EXP, FEM 2D, and FEM 3D) become more pronounced due to the transformation of the soil behaviour from clay-like to more granular, resembling sand. This observation indicates that FEM modelling loses its accuracy in estimating uplift

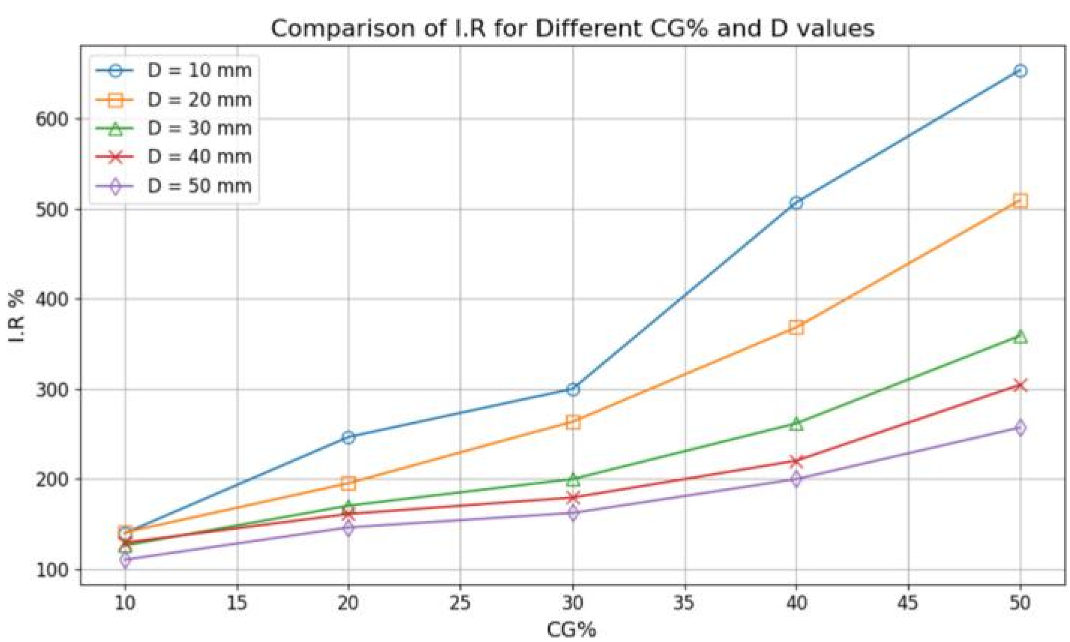


Fig. 6 Improvement Ratio of the tensile failure load

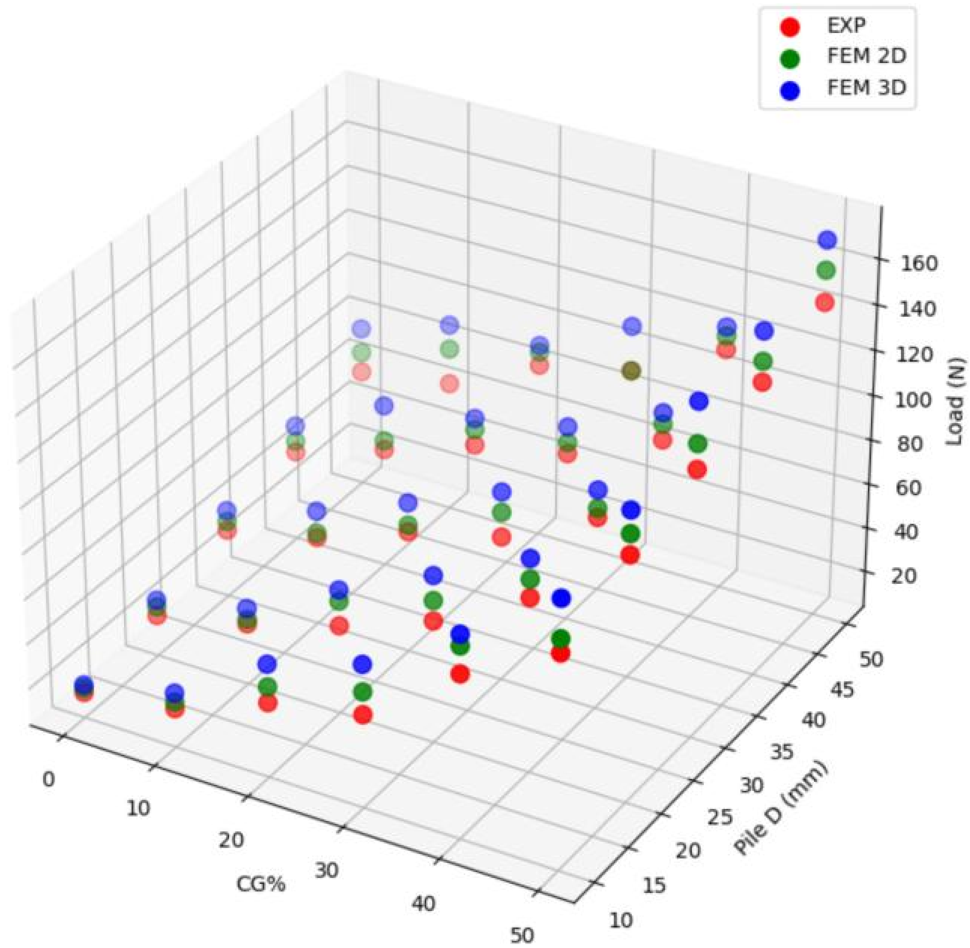


Fig. 7 Comparison between 2-D and 3-D tensile failure load

loads when simulating experimental tests with a CG content exceeding 40% in the present study.

Figure 8a illustrates the failure scenario depicting the vertical displacement of TS-14, while Fig. 8b presents the corresponding failure condition in FEM modelling. The results of all tests confirmed the accuracy of the chosen boundary conditions, as no displacements were observed around the boundaries of the tested box. Notably, in all experimental tests, the failure mechanism unfolded in a manner where, as the uplift load increased, no vertical displacement occurred. The piles withstood the forces with the aid of their weight and the friction angles between the piles and the improved clay. Precisely at the moment of failure, the piles abruptly separated from the soil and rapidly moved upward. For instance, the vertical displacement of the pile in Fig. 8b occurred within just one second after the failure event. Figure 8c and d show the other tests at the moment of failure. This mechanism cannot be precisely replicated in FEM modelling, both in 2D and 3D conditions.

4.5 Comparison of theoretical methods for estimating pile uplift in practical field applications

The practical implementation involved a group of sixteen concrete piles arranged in a 4 × 4 configuration (Fig. 9). Each pile had a diameter of 500 mm and a length of 2 m, with centre-to-centre spacing of 2.5 times the pile diameter (1.25 m). The reinforced concrete piles had a unit weight of 24 kN/m^3. The group configuration resulted in overall dimensions of 4.25 m × 4.25 m. The native soil consisted of soft clay with C_u of 10 kPa and a unit weight of 20 kN/m^3. The soil improvement involved mixing with 50% crushed glass (by volume), which resulted in enhanced C_u of 18 kPa and modified soil unit weight of 18 kN/m^3 due to the incorporation of crushed glass.

In our evaluation of pile group behaviour under tensile loading, we analysed the combined effects of various resistance mechanisms to determine the overall uplift capacity. This theoretical assessment incorporated shaft resistance, soil block weight, perimeter shear resistance, and pile self-weight as the primary contributing factors. While these

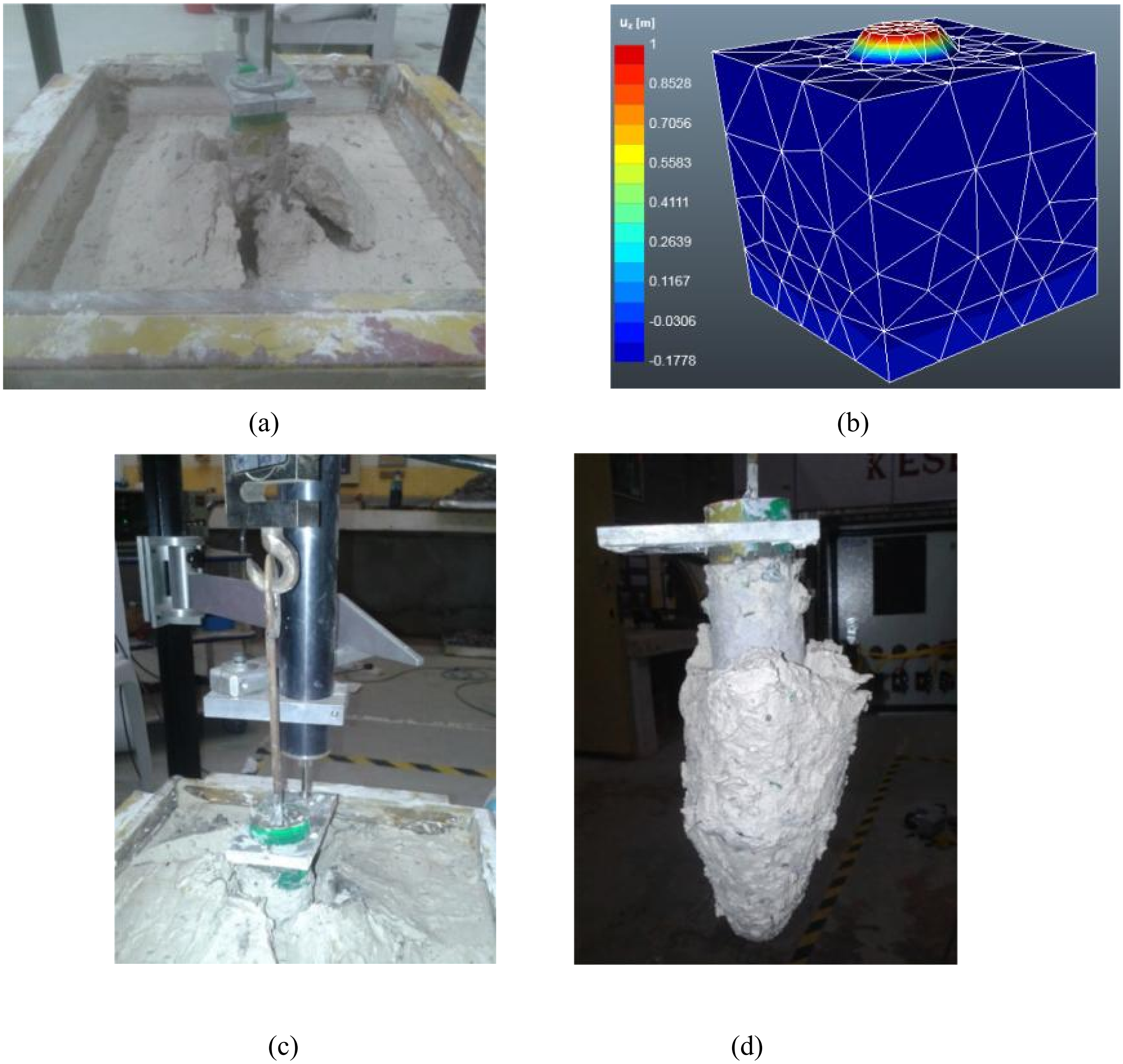


Fig. 8 Vertical displacement of TS-14 at failure: **a** Experimental; **b** FEM; **c** Failure moment of TS-12; and **d** failed pile (TS-18). (Note: Pile dimensions are not scaled)

components represent the standard approach recommended by reviewers and commonly used in practice, we acknowledge that alternative calculation methods incorporating additional parameters such as group efficiency factors, soil arching effects, or advanced numerical modelling could provide further insights into pile group performance. The following equations were applied to estimate the tensile capacity:

- Individual pile shaft resistance

$$Q_t = \alpha \times C_u \times \pi \times d \times H \tag{2}$$

where α is the adhesion factor (0.5 for soft clay), C_u is the undrained shear strength, d is the pile diameter, and L is the pile length.

- Soil block weight:

$$W_s = B \times L \times H \times \gamma_s \tag{3}$$

where B and L are the group dimensions, H is the pile length, and γs is the soil unit weight.

- Perimeter shear resistance:

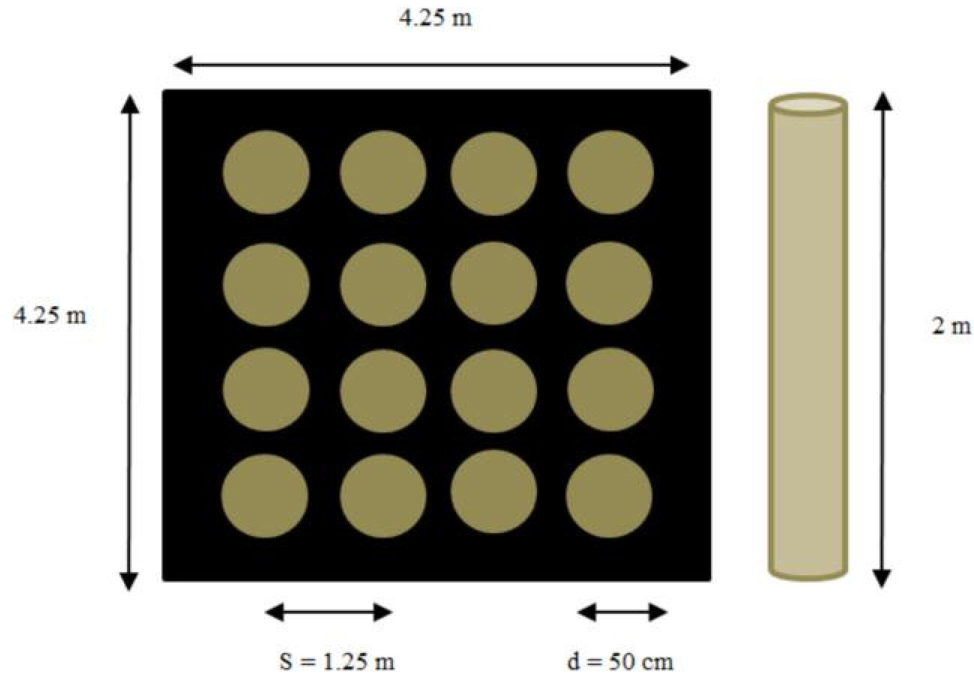


Fig. 9 An example of the practical implementation of the group pile arrangement in the field

$$Q_p = 2(B + L) \times H \times C_u \tag{4}$$

- Pile weight:

$$W_p = n \times \pi \times \left(\frac{d}{2}\right)^2 \times L \times \gamma_c \tag{5}$$

where n is the number of piles and γc is the concrete unit weight.

- The total uplift resistance was calculated as:

$$Q_{total} = \Sigma(Q_t + W_s + Q_p + W_p) \tag{6}$$

Figure 10 depicts the comparison between tensile capacity components. As seen from this Figure, the incorporation of 50% crushed glass into the clay soil demonstrated significant but varying effects across different resistance components of the pile group system. The most notable enhancement was observed in the perimeter shear resistance, which increased substantially from 340 to 612 kN, representing an 80% improvement This dramatic increase can be attributed to the enhanced C_u of the soil-glass mixture, which improved from 10 to 18 kPa. Similarly, the individual pile shaft resistance showed a considerable improvement, increasing from 251.20 kN to 452.80 kN (an 80% increase), directly correlating with the enhanced soil strength properties. However, the soil block weight component decreased from 722.50 kN to 650.25 kN (a 10% reduction) due to the lower unit weight of the glass-soil mixture (18 kN/m^3) compared to the native clay (20 kN/m^3). The pile weight remained constant at 150.80 kN, independent of soil properties. Despite the reduction in soil block weight, the overall tensile capacity of the pile group increased by 401.35 kN (from 1464.50 kN to 1865.85 kN), representing a 27.4% improvement. This net positive effect demonstrates that the enhanced shear strength properties of the glass-soil mixture more than compensate for the reduction in soil weight, making crushed glass an effective, sustainable solution for improving pile group performance under tensile loading conditions. The redistribution of resistance components also indicates a shift towards more reliance on shear strength parameters rather than gravitational effects, potentially leading to more stable and predictable long-term performance.

Several limitations should be considered when interpreting the results of this pile group analysis. Firstly, the calculations assume perfect homogeneity in the glass-soil mixture, which may not be achievable in field conditions where mixing uniformity can vary significantly. The analysis also assumes a constant adhesion factor (α = 0.5) for intact and improved soil conditions. However, this parameter might vary with the addition of crushed glass and requires further experimental validation. The block failure mechanism is considered perfect, without accounting for potential variations in the failure surface or partial mobilisation effects. Additionally, the analysis does not consider time-dependent behaviours, such as potential changes in soil-glass interaction over time, effects of weathering on crushed glass, or long-term settlement implications. Lastly, while the C_u improvement has been quantified, the analysis does not address potential changes in other crucial soil parameters such as internal friction angle, cohesion, and consolidation characteristics, which could significantly influence long-term performance.

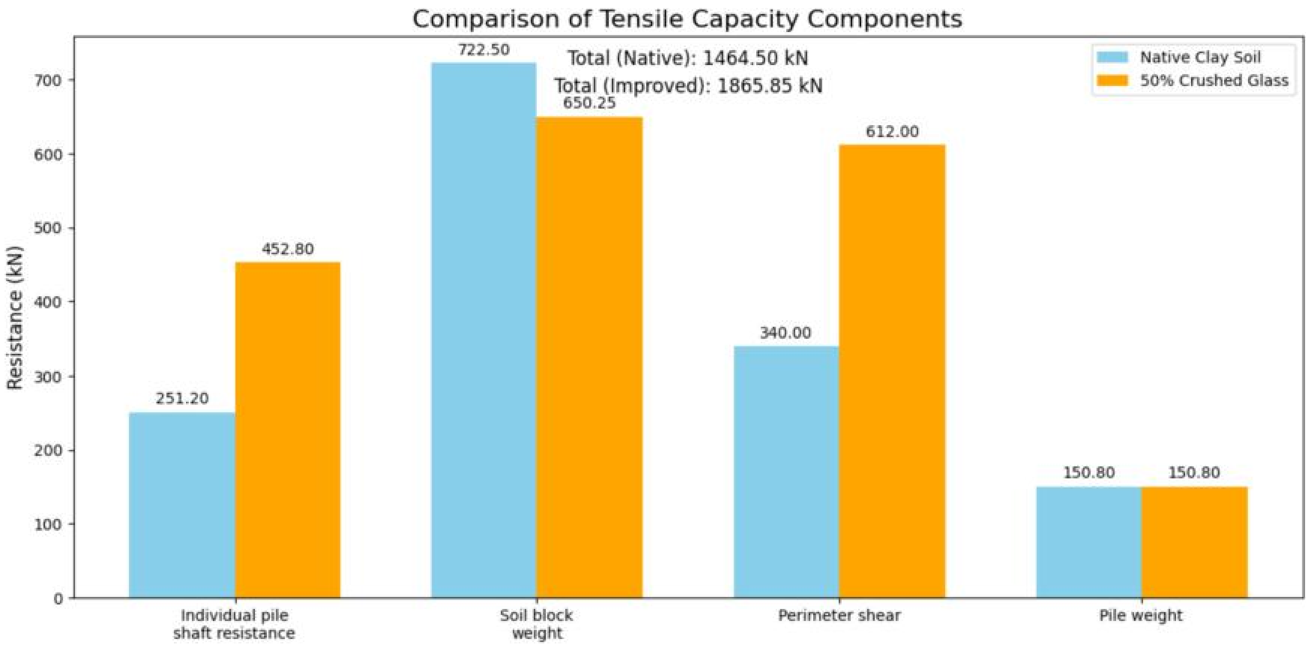


Fig. 10 Comparison between tensile capacity components

4.6 Limitations and future work

While this study offers significant insights into the tensile load capacity of single piles in Kaolin clay mixed with varying proportions of CG through controlled laboratory tests, it is essential to note the limitations of this methodology. Laboratory environments do not always fully replicate the complex and variable conditions of real-world field applications. Factors such as fluctuating moisture content, temperature variations, and other soil constituents may affect the performance of CG-stabilised soils in ways that our laboratory tests do not capture.

Future research should prioritise extensive field testing to validate and extend the laboratory findings discussed in this study. Field tests are essential to evaluate the performance of CG-stabilised soils under a more comprehensive array of environmental conditions and loading scenarios. Moreover, long-term monitoring of these field tests would provide valuable data on the durability and longevity of CG-enhanced soil stabilisation techniques. Integrating field data with our laboratory results will enable a more comprehensive understanding of the behaviour and efficacy of CG-stabilised soils. This approach ultimately leads to more robust and reliable applications in geotechnical engineering, ensuring that the benefits observed in controlled environments can be translated into '*buildable*' schemes (i.e., '*from research to reality*').

Future studies should investigate CG content exceeding 50% to establish upper feasibility thresholds, as our findings show a significant transition from cohesive to granular soil behaviour at higher CG percentages. Research should systematically quantify the relationship between CG content, pile diameter, and tensile capacity, particularly focusing on the mechanisms driving enhanced skin friction. Additionally, varying CG particle sizes and distributions should be evaluated to optimise soil-pile interface properties and develop practical design guidelines for field applications.

In future research, careful consideration of the effects of stress level is essential to bridge the gap between laboratory models and field applications. The non-linear relationship between confining pressure and soil mechanical behaviour, particularly for mixed materials containing crushed glass, warrants dedicated investigation using geotechnical centrifuge testing or carefully calibrated numerical models that can adequately account for stress-dependent stiffness, dilation, and strength parameters.

Acknowledging that significant practical challenges exist in implementing crushed glass improvement at depths required for typical pile foundations is essential. While our laboratory results demonstrate promising mechanical behaviour of CG-clay composites, field implementation at depths of 15-20 m represents a substantial engineering challenge. We propose that techniques similar to deep soil mixing processes currently employed for cement and lime stabilisation might be adapted for crushed glass application. However, it remains unclear whether crushed glass particles can be effectively distributed and integrated into in-situ soils using existing equipment and methodologies developed for cementitious materials. The physical properties of crushed glass, including particle angularity, size distribution, and surface characteristics, differ substantially from traditional stabilisers, potentially necessitating modified equipment or installation procedures. Additionally, the economic and environmental costs of deep implementation need careful assessment against potential performance benefits. For future research, we recommend: (a) pilot-scale field trials investigating modified deep mixing equipment designed explicitly for crushed glass application; (b) evaluation of different particle size distributions to optimise workability during deep mixing processes; (c) development of specialised installation procedures that account for the unique properties of crushed glass; and (d) comprehensive life-cycle assessment comparing the environmental and economic impacts of crushed glass improvement against conventional stabilisation methods at various implementation depths.

5 Conclusions

This study comprehensively investigates the tensile failure behaviour of single piles embedded in Kaolin clay-crushed glass (CG) composite soil through rigorous physical modelling and complementary finite element analysis. The experimental program encompassed thirty meticulously controlled physical model tests exploring the effects of CG content (10–50% by weight) and pile diameter (10–50 cm) on tensile capacity. All soil specimens were prepared following standardised protocols to achieve uniform consistency with a target C_u of 10 kPa. Fundamental geotechnical characterisation through direct shear and unconfined compression testing revealed a significant transformation in soil behaviour with increasing CG content, demonstrating a progressive shift from predominantly cohesive to semi-granular mechanical properties. Most notably, the incorporation of 50% CG resulted in a remarkable enhancement of pile-soil interface friction, yielding a 6.5-fold increase in tensile failure load compared to unmodified clay, with the most pronounced improvements observed for smaller diameter (10 cm) piles.

Complementary numerical analyses conducted using $Optum^{G2}$ and $Optum^{G3}$ finite element platforms provided a valuable assessment of modeling accuracy for these innovative composite soil systems. The three-dimensional analyses consistently overestimated failure loads, suggesting potential limitations in capturing the complex interface behaviour between concrete piles and glass-reinforced soil. In contrast, two-dimensional models demonstrated superior alignment with experimental measurements, offering a more reliable predictive tool for practical applications. Extending the investigation to pile group configurations through a case study of a 4 × 4 pile arrangement further validated the substantial benefits of CG inclusion, documenting a 27.4% enhancement in overall tensile capacity. These findings collectively establish crushed glass as a promising sustainable material for improving pile foundation performance in cohesive soils, with significant implications for geotechnical design practice and construction waste management strategies.

Author contributions Mohamed Ahmed Hafez: Supervised the research project, provided technical guidance throughout the experimental and numerical phases, and oversaw the overall research methodology and quality control. Shin To Amiri: Conducted the experimental tests, performed physical modeling of single piles and pile groups, and executed the laboratory testing program for different CG-Kaolin clay mixtures. Ali Dehghanbanadaki: Performed data analysis and interpretation, carried out the numerical analysis using FEM software (OptumG2 and OptumG3), and analyzed the stress–strain behavior of the composite materials. Shervin Motamedi: Created visualizations of experimental and numerical results, developed graphical representations of the data, and prepared technical figures and diagrams for the manuscript. Ahmad Safuan A Rashid: Contributed to the conceptualization of the research methodology and provided critical review and feedback on the manuscript drafts. Iman Golpazir: Developed the initial research concept, designed the experimental program, reviewed and edited the manuscript, and provided overall project coordination and correspondence (*Corresponding author). All authors have read and agreed to the published version of the manuscript.

Funding This research did not receive any funding.

Data availability No datasets were generated or analysed during the current study.

Declarations

Conflict of interest The authors declare no competing interests.

Ethical approval and consent to participate This research did not involve the participation of human subjects.

Consent for publication This study does not include identifiable information about individuals or entities.

References

Ahmed KS, Rana LR (2023) Fresh and hardened properties of concrete containing recycled waste glass: a review. J Build Eng. https://doi.org/10.1016/j.jobe.2023.106327

Al-Taie A, Yaghoubi E, Wasantha PLP, Van Staden R, Guerrieri M, Fragomeni S (2023) Mechanical and physical properties and cyclic swell-shrink behaviour of expansive clay improved by recycled glass. Int J Pavement Eng 24(1):2204436. https://doi.org/10.1080/10298436.2023.2204436

Amiri ST, Nazir R, Dehghanbanadaki A (2018) Experimental study of geotechnical characteristics of crushed glass mixed with kaolinite soil. Int J 14(45):170–176. https://doi.org/10.2160/2018.45.83839

Amiri ST, Dehghanbanadaki A, Nazir R, Motamedi S (2020) Unit composite friction coefficient of model pile floated in kaolin clay reinforced by recycled crushed glass under uplift loading. Transport Geotech 22:100313. https://doi.org/10.1016/j.trgeo.2019.100313

Anburuvel A (2023) The engineering behind soil stabilization with additives: a state-of-the-art review. Geotech Geol Eng. https://doi.org/10.1007/s10706-023-02554-x

Anglaaere DLM, Enquan Z, Kahama EK, Illo FI (2023) Engineering properties of clay soil stabilised with glass powder and rubber particles–a comparative study. Geomech Geoeng. https://doi.org/10.1080/17486025.2023.2288927

Arefnia A, Dehghanbanadaki A, Kassim KA (2021) Sustainable implementation of recycled tire-derived aggregate as a lightweight backfill for retaining walls. KSCE J Civ Eng 25(11):4196–4206. https://doi.org/10.1007/s12205-021-0218-3

ASTM C136/C136M-14 (2014) Standard Test Method for Sieve Analysis of Fine and Coarse Aggregates. ASTM Int, West Conshohocken

Ate (2016) Mechanical properties of sandy soils reinforced with cement and randomly distributed glass fibers (GRC). Composit Part b: Eng 96:295–304. https://doi.org/10.1016/j.compositesb.2016.04.049

Baikerikar A, Mudalgi S, Ram VV (2023) Utilization of waste glass powder and waste glass sand in the production of Eco-friendly concrete. Constr Build Mater 377:131078. https://doi.org/10.1016/j.conbuildmat.2023.131078

Chen H, Wang Q (2006) The behaviour of organic matter in the process of soft soil stabilisation using cement. Bullet Eng Geol Environ 65(4):445–448. https://doi.org/10.1007/s10064-005-0030-1

Deboucha S, Aissa Mamoune SM, Sail Y, Ziani H (2020) Effects of ceramic waste, marble dust, and cement in pavement sub-base layer. Geotech Geol Eng 38(3):3331–3340. https://doi.org/10.1007/s10706-020-01211-x

Dehghanbanadaki A, Motamedi S, Ahmad K (2020) FEM-based modelling of stabilised fibrous peat by end-bearing cement deep mixing columns. Geomech Eng 20(1):75–86. https://doi.org/10.12989/gae.2020.20.1.075

Dehghanbanadaki A, Rashid ASA, Ahmad K, Yunus NZM, Said KNM (2022) A computational estimation model for the subgrade reaction modulus of soil improved with DCM columns. Geomech Eng 28(4):385–396. https://doi.org/10.12989/gae.2022.28.4.385

Demir S, Cabalar AF (2024) Dispersion, viscosity, unconfined compression and bender element testing of bentonite-waste glass mixtures. Eur J Environ Civ Eng 28(4):900–929. https://doi.org/10.1080/19648189.2023.2231527

Fawaz A, AlhakimG JL (2024) The stabilisation of clayey soil by using sawdust and sawdust ash. Environ Technol. https://doi.org/10.1080/09593330.2024.2304674

Ferdous W, Manalo A, Siddique R, Mendis P, Zhuge Y, Wong HS, Schubel P (2021) Recycling of landfill wastes (tyres, plastics and glass) in construction—a review on global waste generation, performance, application and future opportunities. Resources Conserv Recycl 173:105745. https://doi.org/10.1016/j.resconrec.2021.105745

Galvín AP, López-Uceda A, Cabrera M, Rosales J, Ayuso J (2021) Stabilization of expansive soils with biomass bottom ashes for an eco-efficient construction. Environ Sci Pollut Res 28:24441–24454. https://doi.org/10.1007/s11356-020-08768-3

Gidebo FA, Yasuhara H, Kinoshita N (2023) Stabilization of expansive soil with agricultural waste additives: a review. Int J Geo-Eng 14(1):14. https://doi.org/10.1186/s40703-023-00194-x

Hajiazizi M, Nasiri M, Mazaheri AR (2018) The effect of fixed-tip piles on stabilization of earth slopes. Scientia Iranica 25(5):2550–2560. https://doi.org/10.24200/sci.2017.4211

Ilman B, Balkis AP (2023) Mechanical properties of clays stabilised with glass powder and silica fume. Int J Geosynth Ground Eng 9(4):50. https://doi.org/10.1007/s40891-023-00463-w

Indraratna B, Qi Y, Tawk M, Heitor A, Rujikiatkamjorn C, Navaratnarajah SK (2022) Advances in ground improvement using waste materials for transportation infrastructure. Proc Institut Civil Eng-Ground Improvement 175(1):3–22. https://doi.org/10.1680/jgrim.20.00007

Jalal FE, Zahid A, Iqbal M, Naseem A, Nabil M (2022) Sustainable use of soda lime glass powder (SLGP) in expansive soil stabilization. Case Studies Construction Mater 17:e01559. https://doi.org/10.1016/j.cscm.2022.e01559

Kamei T, Ahmed A, Horai H, Ugai K (2015) A novel solidification technique for fluorine-contaminated bassanite using waste materials in ground improvement applications. J Mater Cycles Waste Manage 17:380–390. https://doi.org/10.1007/s10163-014-0251-0

Kazmi D, Serati M, Williams DJ, Qasim S, Cheng YP (2021) The potential use of crushed waste glass as a sustainable alternative to natural and manufactured sand in geotechnical applications. J Clean Prod 284:124762. https://doi.org/10.1016/j.jclepro.2020.124762

Komkova A, Habert G (2023) Environmental impact assessment of alkali-activated materials: Examining impacts of variability in constituent production processes and transportation. Constr Build Mater 363:129032. https://doi.org/10.1016/j.conbuildmat.2022.129032

Kumar CR, Gadekari RS, Vani G, Mini KM (2020) Stabilization of black cotton soil and loam soil using reclaimed asphalt pavement and waste crushed glass. Mater Today: Proceed 24:379–387. https://doi.org/10.1016/j.matpr.2020.04.289

Lawanwadeekul S, Srisuwan A, Phonphuak N, Chindaprasirt P (2023) Enhancement of porosity and strength of clay brick fired at reduced temperature with the aid of corn cob and waste glass. Constr Build Mater 369:130547. https://doi.org/10.1016/j.conbuildmat.2023.130547

Li S, Wang D, Wu Y (2024) Strength and load-bearing behaviors of cement-industrial by-products solidified crust layer over soft subsoil. Constr Build Mater 412:134744. https://doi.org/10.1016/j.conbuildmat.2023.134744

Long L, Nasiri M, Amiri E (2024) Optimal preservation of oil-containing sands using zeolite: a physical and chemical analysis. J Geotech and Geoenviron Eng 150(12):04024121. https://doi.org/10.1061/JGGEFK.GTENG-1257

Maurya N, Srivastav Y, Rawat S, Ranjan Y, Srivastava R, Shukla BK, Varadharajan S (2023) Reinforcing civil infrastructure with waste glass-enhanced concrete: a comprehensive review of properties, performance and applications. Mater Today Proc. https://doi.org/10.1016/j.matpr.2023.07.177

Mazaheri AR, Paknahad M, Nasiri M, Hajiazizi M (2021) Limit analysis, numerical, and physical modeling of pile stabilized slopes using image processing analyses. Iranian J Sci Technol Trans of Civil Eng 45(2):891–900. https://doi.org/10.1007/s40996-021-00581-3

Mazaheri AR, Nasiri M, Javadi A, Amiri E (2024) Stabilization of crude oil-contaminated Bushehr carbonate sand: physical and chemical study. Bull Eng Geol Env 83(9):373. https://doi.org/10.1007/s10064-024-03867-8

Onyelowe K, Igboayaka C, Orji F, Ugwuanyi H, Van DB (2019) Triaxial and density behaviour of quarry dust based geopolymer cement treated expansive soil with crushed waste glasses for pavement foundation purposes. Int J Pavement Res Technol 12:78–87. https://doi.org/10.1007/s42947-019-0010-7

Onyelowe KC, Onyia ME, Aneke FI, Bui-Van D, Rollins KM (2022) Assessment of compressive strength, durability, and erodibility of quarry dust-based geopolymer cement stabilised expansive soil. Multiscale Multidiscip Model Exp Design 5(1):81–90. https://doi.org/10.1007/s41939-021-00104-7

“$Optum^{G2}$,” http://www.optumce.com/, 2020.

“$Optum^{G3}$,” http://www.optumce.com/, 2020.

Peng L, Zhao Y, Ban J, Wang Y, Shen P, Lu JX, Poon CS (2023) Enhancing the corrosion resistance of recycled aggregate concrete by incorporating waste glass powder. Cement Concr Compos 137:104909. https://doi.org/10.1016/j.cemconcomp.2022.104909

Perera STAM, Saberian M, Zhu J, Roychand R, Li J, Ren G, Yamchelou MT (2023) Improvement of low plasticity clay with crushed glass: a mechanical and microstructural study. Int J Pavement Res Technol. https://doi.org/10.1007/s42947-023-00339-2

Pham TA, Akan R, Tabaroei A (2025) A simplified soil-structure interaction model for load-settlement analysis of piles. Canadian Geotech J. https://doi.org/10.1139/cgj-2024-0173

Roshan MJ, Rashid ASBA (2024) Geotechnical characteristics of cement stabilized soils from various aspects: a comprehensive review. Arab J Geosci 17(1):1. https://doi.org/10.1007/s12517-023-11796-1

Sargent P, Sandanayake M, Law DW, Hughes DJ, Shifa F, Borthwick B, Scott P (2024) Strength, mineralogical, microstructural and CO2 emission assessment of waste mortars comprising excavated soil, scallop shells and blast furnace slag. Constr Build Mater 411:134425. https://doi.org/10.1016/j.conbuildmat.2023.134425

Sheob M, Sajid M, Ansari MA, Rais I, Sadique MR, Ahmad S (2023) Using a blend of cement and waste glass powder to improve the properties of clayey soil. Mater Today: Proc. https://doi.org/10.1016/j.matpr.2023.05.440

Surendran H, Akhas PK (2024) Unraveling the strength and enhanced durability of concrete using toughened waste glass aggregate. J Mater Civ Eng 36(3):04023634. https://doi.org/10.1061/JMCEE7.MTENG-16502

Tushar Q, Salehi S, Santos J, Zhang G, Bhuiyan MA, Arashpour M, Giustozzi F (2023) Application of recycled crushed glass in road pavements and pipeline bedding: an integrated environmental evaluation using LCA. Sci Total Environ 881:163488. https://doi.org/10.1016/j.scitotenv.2023.163488

Venkata Sudhakar C, Reddy U (2023) Impacts of cement industry air pollutants on the environment and satellite data applications for air quality monitoring and management. Environ Monit Assess 195(840):840. https://doi.org/10.1007/s10661-023-11408-1

Wartman J, Grubb DG, Strenk P (2004) Engineering properties of crushed glass-soil blends. In Geotechnical engineering for transportation projects (pp. 732–739). https://doi.org/10.1061/40744(154)60

Wei X, Ku T (2020) New design chart for geotechnical ground improvement: characterising cement-stabilised sand. Acta Geotech 15(4):999–1011. https://doi.org/10.1007/s11440-019-00838-2

Zachariah P, Ravi J (2024) State-of-the-art review on utilization of waste materials in the mitigation of soil liquefaction. Indian Geotech J. https://doi.org/10.1007/s40098-023-00853-x

Zada U, Jamal A, Iqbal M, Eldin SM, Almoshaogeh M, Bekkouche SR, Almuaythir S (2023) Recent advances in expansive soil stabilization using admixtures: current challenges and opportunities. Case Studies Construction Mater. https://doi.org/10.1016/j.cscm.2023.e01985

Zafar T, Ansari MA, Husain A (2023) Soil stabilization by reinforcing natural and synthetic fibers–a state of the art review. Mater Today: Proc. https://doi.org/10.1016/j.matpr.2023.03.503

Zaini MSI, Hasan M, Jusoh WNBW (2023) Utilization of bottom ash waste as a granular column to enhance the lateral load capacity of soft kaolin clay soil. Environ Sci Pollut Res. https://doi.org/10.1007/s11356-023-25966-x

Zanovello M, Baldusco R, John VM, Angulo SC (2023) Strength-porosity correlation and environmental analysis of recycled Portland cement. Resour Conserv Recycl 190:106763. https://doi.org/10.1016/j.resconrec.2022.106763

Zhao H, Li W, Gan Y, Mahmood AH, Zhao X, Wang K (2024) Nano- and microscopic investigation on the strengthening mechanism of ITZs using waste glass powder in modeled aggregate concrete. J Mater Civ Eng 36(4):04024007. https://doi.org/10.1061/JMCEE7.MTENG-1695

Zhen H, Xiong Z, Song Y, Li L, Qiu Y, Zou X, Ji Y (2024) Early mechanical performance of glass fibre-reinforced manufactured sand concrete. J Build Eng. https://doi.org/10.1016/j.jobe.2024.108440

Authors and Affiliations

Mohamed Ahmed Hafez[1,2] · Shin To Amiri[3] · Ali Dehghanbanadaki[4,5,6] · Shervin Motamedi[7] · Ahmad Safuan A. Rashid[3] · Iman Golpazir[4]

✉ Iman Golpazir
I.golpazir@iau.ac.ir

Mohamed Ahmed Hafez
mohdahmed.hafez@newinti.edu.my

Shin To Amiri
ashinto2@live.utm.my

Ali Dehghanbanadaki
dehghanbanadaki.a@iau.ac.ir

Shervin Motamedi
ac5172@coventry.ac.uk

Ahmad Safuan A. Rashid
ahmadsafuan@utm.my

1 Faculty of Engineering and Quantity Surveying, INTI-IU, Nilai, Malaysia

2 Faculty of management, Shinawatra University, Pathum Thani, Thailand

3 Faculty of Civil Engineering, Universiti Teknologi Malaysia, Johor Bahru, Johor, Malaysia

4 Department of Civil Engineering, Dam.C., Islamic Azad University, Damavand, Iran

5 Research Center of Concrete and Soil, Dam.C., Islamic Azad University, Damavand, Iran

6 Faculty of Civil Engineering, INTI-International University, 71800 Nilai, Malaysia

7 School of the Environment, Coventry University, Damavand, Iran