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Original Article

Quantum-Inspired Digital Twin Modeling for Predicting the Mechanical Performance of Fiber-Reinforced Cement-Stabilized Laterite soils

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Abstract *- This research introduces a Quantum-Inspired Digital Twin (QIDT) modeling approach to predicting the mechanical behavior of Fiber-Reinforced Cement-Stabilized Laterite Soils (FR-CSS) to overcome the shortcomings of traditional empirical and deterministic models in describing the complex multiscale interactions between Laterite soils, binder and fibres. The suggested digital twin combines laboratory test data in real time with quantum-inspired optimization and probabilistic state-space modeling to simulate the changing mechanical behaviour of stabilised Laterite soils in different curing durations, fibre contents, cement dosages, and stresses. Quantum-inspired algorithms based on such principles as superposition and probabilistic sampling are used to improve the exploration of the parameters, quantification of uncertainties, and efficiency of convergence in predicting important mechanical behaviors, including stiffness modulus, unconfined compressive strength, and the characteristics of deformation. Digital twin constantly recalculates its internal states by data assimilation, allowing it to be adaptively learned and provide better predictions than other machine learning methods and numerical models. The sensitivity analysis shows that the suggested framework effectively models the nonlinear correlation between cement hydration, fiber orientation, and the development of Laterite soil fabrics. The strength, scalability, and ability to generalize of the QIDT model is validated using experimental data. The suggested method is a new and smart decision-support system to design geotechnical, forecast performance, and optimization of sustainable ground improvement systems with fiber-reinforced cement-stabilized Laterite soils.*

Keywords *- Quantum-inspired algorithms, Digital twin, Mechanical performance, Geotechnical modelling, Fiber-Reinforced Laterite Soils.*

1. Introduction

The mechanical performance of the Fiber-Reinforced Cement-Stabilized Laterite Soils (FR-CSS) has become of considerable interest in geotechnical engineering as a result of its extensive application in pavements, subgrades, embankments, foundations and ground improvement systems with the aim of increasing strength, stiffness and durability of weak Laterite soils. The traditional experimental and analytical methods can be very useful at the laboratory level, but fail to capture the highly nonlinear, time-dependent and multiscale interactions of the Laterite soil particles, cement hydration products, and randomly distributed fibers in different environmental and loading conditions. In addition, the empirical correlations and deterministic numerical models are constrained in the aspect of adapting to changing material conditions and uncertainty that occur as a result of heterogeneity, curing effects, and stress history. The Fibre-Reinforced Cement-Stabilized Laterite Soils (FR-CSS) have received great attention due to their role on enhancing the engineering properties of weak geomaterials for various applications such as pavement, embankment, foundation and slope stabilization. Initial research centred on the understanding of the role of fibre reinforcement and chemical stabilization in improving the compressive strength, shear resistance, stiffness, ductility and durability of the resulting composite material. Gong et al. showed that polypropylene fibers were effective on the stability of Laterite soil embankment slopes during freeze–thaw cycles by reducing the strength degradation and increasing the resistance to cracks under the adverse environmental conditions [1]. Ghorbani et al. reported on the use of cement–Rice Husk Ash (RHA) stabilized sand–clay mixtures with improved


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compressive strength and shear strength using Polypropylene (PP) fibers, due to the improved bonding and crack-bridging mechanisms [2]. Ding et al. [3] found that polypropylene fibres had a beneficial effect on the long-term durability of repeated freeze–thaw cycles in cement-stabilized clay. Lekha et al. [4] showed that arecanut coir could be a sustainable reinforcement material for low-volume pavements made from lateritic soils, and that its properties improved the mechanical properties of lateritic soils. Gupta and Kumar demonstrated the enhancements of compressive strength, energy absorption capacity, and post-peak deformation properties of Cement-Stabilized Clay-Pond Ash mixtures with fiber reinforcement [5]. Parihar et al. reported that the polyester fibre reinforced expansive soil has shown considerable improvement in shear strength and swelling resistance [6]. For cement-stabilized soils containing polypropylene fibers and industrial waste materials, Zhang et al. formulated data-driven prediction models, which showed that AI has great potential in geotechnical material prediction [7]. Wang et al. have shown that the curing environment had a marked effect on the reinforcement mechanism and the mechanical properties of cement–polypropylene fiber stabilized dredger fill [8].

Wang et al. also reported the cyclic loading resistance and freeze–thaw durability of fiber-binder modified subgrade materials was superior [9]. Tiwari et al. observed that the CBR, resilient modulus and expansive subgrade performance were significantly enhanced with the addition of fibers (PP) and silica fume [10]. Sahlabadi et al. set the record straight that the use of hybrid polypropylene and basalt fibers significantly improved the freeze–thaw durability in cement-stabilized soils [11]. Muñoz et al. showed that synergic reinforcement mechanisms of Rice Husk Ash (RHA), cement and Polypropylene Fiber (PPF) led to a significant increase in stiffness and compressive strength of the composite material [12]. Ghorbani and Salimzadehshooiili reported that the dynamic characteristics of the cement–rice husk ash stabilized soils were significantly improved by adding polypropylene fibers [13].

Guleria and Sharma reported significant improvement of geotechnical properties of soils by using calcium carbide residue, waste foundry sand, and polypropylene fibers for soil sustainable stabilization [14]. Kamiloğlu et al. showed that use of polypropylene fibers could enhance the mechanical properties of silty soils treated with geopolymer, which is compatible with environmentally friendly binders [15]. Tinoco et al. proposed machine learning models to predict mechanical properties of fibre-reinforced soil–cement mixtures with higher prediction accuracy as compared to conventional empirical models, and identified the limitations in the static learning ability [16]. Yan et al. presented a nonlinear damage constitutive model for fiber-reinforced cement-stabilized soft clay that can accurately describe the progressive deterioration of soft clay under mechanical loading [17]. Madrid et al. found that fiber reinforcement had a significant effect in elevating the resilient modulus and reducing the subgrade expansion, which in turn, enhances pavement performance [18]. Uday et al. found a positive correlation between the use of polypropylene macro fibers with the improvement of the geotechnical characteristics of black cotton soil [19]. Ahmadi et al. showed that when polypropylene fibers and nano-MgO were added together, they significantly improved the strength parameters of the stabilized clay [20]. Liu et al. demonstrated that mixing OPS with PP fibers had a positive effect on the strength characteristics of reinforced sand [21]. Fresneda Saldarriaga et al. studied the mechanical properties of polypropylene derivatives and found that there was a significant improvement in the mechanical properties of laterite soil [22].

In a study by Lasaki et al. [23], the authors illustrated the improvement in large-scale direct shear strength of fly ash–Laterite soil mixtures with the addition of PVA fibers. Dixit determined the optimum amount of polypropylene fibre to get the maximum engineering properties of Laterite soil [24]. Correia et al. reported considerable improvements in compressive and tensile strength of binder-stabilized soft Laterite soils reinforced with polypropylene fibers [25]. Venda Oliveira et al. investigated the effect of fibre types on the compression and tensile strength of chemically stabilized soft soils [26]. Liu et al. also found that various short fibers used with organic polymers in stabilizing sand could be used to achieve better performance [27]. Kumar and Gupta showed that cement-stabilized fiber-reinforced pond ash- rice husk ash-laterite soil composite had good strength and deformation resistance [28]. In recent years, Sharafat et al. proposed an Underground Caverns Optimization framework based on a Digital Twin that can monitor and predict the stability of underground cavities in real time, highlighting the benefits of intelligent Digital Twins for geotechnical infrastructure management [29]. To illustrate the role of intelligent predictive modeling in construction materials engineering, Li et al. used advanced machine learning algorithms to predict the mechanical strength and thermal conductivity of foam concrete with great accuracy from their material compositions [30].

Research on Fiber-Reinforced Cement-Stabilized Laterite Soil (FR-CSS) is still at a basic level with regard to the ability to predict the long-term mechanical performance of FR-CSS, due to several fundamental limitations. The characterization of materials under laboratory conditions, empirical correlations, constitutive models, and finite element simulations have been widely used in previous studies to estimate a material's compressive strength, stiffness, deformation, and durability, while conventional machine learning algorithms have been used. These approaches have been successful in predicting some mechanical properties at a specific stage of cement curing, but are typically static models that cannot continuously adapt to changing material properties, varying fiber contents, cement hydration

processes, environmental changes, and/or cyclic loading histories. Moreover, existing digital twin applications in geotechnical engineering continue to be limited, and the few studies that combine real-time data assimilation, uncertainty quantification, adaptive model updating, and intelligent optimization of fibre reinforced cement stabilized Laterite soils are limited. Similarly, the application of quantum-inspired optimization methods to geotechnical material modelling has been little investigated, and therefore, there remains a significant research gap to investigate the intersection of quantum-inspired search methods and Digital Twin technology for addressing nonlinear multiscale interactions and predictive uncertainty. It is therefore of great need to develop an intelligent, adaptive and scalable modeling framework that not only can accurately predict the mechanical behavior of FR-CSS under different operating conditions, but can also assist the engineering decision making. To overcome this, the present study introduces an innovative Quantum-Inspired Digital Twin (QIDT) framework that combines laboratory measurements, real-time digital twin synchronization, quantum-inspired optimization, uncertainty analysis, and explainable machine learning to continuously predict and optimize mechanical performance of FR-CSS.

2. Materials and Experimental Program

The materials in the research were selected to represent the components used in the Fiber-Reinforced Cement-Stabilized Laterite Soils (FR-CSS) investigated in this study. The underlying material was a locally available fine-grained Laterite soil with low to medium plasticity. Ordinary Portland Cement (OPC) of 43 grade was used as the stabilizing binder. Polypropylene (PP) was the only fiber reinforcement used in the experimental program; no basalt, recycled carpet, steel, or glass fibers were used. The experimental matrix considered cement contents of 5% and 7% by dry soil mass, polypropylene fiber contents of 0.5%, 1.0%, and 1.5%, and curing periods of 7 and 14 days. These ranges were selected to evaluate the effects of cement stabilization, fiber reinforcement, and curing on strength and stiffness while maintaining workable and homogeneous mixtures.

Table 1. Material properties and experimental parameters

Category	Parameter	Value / Range
Laterite soil	USCS classification	CL–CI
	Liquid limit (%)	35–45
	Plasticity index (%)	15–20
Cement	Type	OPC 43 Grade
	Cement content (% by dry Laterite soil)	5, 7
Fiber	Type	Polypropylene
	Fiber length (mm)	6, 12
	Fiber content (% by dry Laterite soil)	0.5, 1.0, 1.5
Curing	Curing period (days)	7, 14
Testing	Mechanical tests	UCS, direct shear, triaxial, resilient modulus, stress–strain, modulus

Table 1 summarizes the material properties and experimental parameters used to determine the mechanical performance of fiber-reinforced cement-stabilized Laterite soils. Laterite soil was air-dried, crushed and sieved, and then mixed in the dry state with predetermined amounts of OPC 43 cement and polypropylene fibers to obtain a homogeneous mixture. Water was subsequently added to achieve the required moisture condition, and the mixtures were compacted using standard Proctor energy. The specimens were cured under controlled laboratory conditions for 7 or 14 days. The cured specimens were subjected to Unconfined Compressive Strength (UCS), stress-strain, stiffness-modulus, direct shear, triaxial compression, and selected cyclic-loading tests. The resulting experimental data were used to train, update, and validate the proposed Quantum-Inspired Digital Twin model under the material and curing conditions investigated.

Table 2. Sample details

Sample ID	Cement Content (%)	Fiber Type	Fiber Content (%)	Curing Period (days)
S1	5	Polypropylene	0.5	7
S2	5	Polypropylene	1.0	7
S3	5	Polypropylene	1.5	7
S4	7	Polypropylene	1.0	14
S5	7	Polypropylene	1.5	14

Table 2 summarizes the five experimental sample configurations used in the study. All five samples used the same Laterite soil and polypropylene fiber type, while cement content, fiber content, and curing period were varied according to the experimental matrix. Samples S1-S3 contained 5% cement and were cured for 7 days, with polypropylene fiber contents of 0.5%, 1.0%, and 1.5%, respectively. Samples S4 and S5 contained 7% cement and were cured for 14 days, with fiber contents of 1.0% and 1.5%, respectively. Thus, the table is consistent with the quantitative datasets reported in Tables 3 and 5-9.

Table 3. Physical and mechanical properties of Fiber-Reinforced Cement-Stabilized Laterite Soil samples

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Natural Moisture Content (%)	Maximum Dry Density (kN/m³)	Optimum Moisture Content (%)	Cohesion, c (kPa)	Internal Friction Angle, φ (°)	Unconfined Compressive Strength, qu (kPa)	Elastic Modulus, E (MPa)
S1	0.5	5	7	12.3	18.2	14.0	28	26	180	25
S2	1.0	5	7	12.5	18.4	14.2	32	27	210	30
S3	1.5	5	7	12.8	18.5	14.5	36	28	240	35
S4	1.0	7	14	13.0	18.8	14.8	40	29	280	42
S5	1.5	7	14	13.2	19.0	15.0	45	30	320	50

Table 3 presents the physical and mechanical characteristics of the five fiber-reinforced cement-stabilized Laterite soil samples used for the Quantum-Inspired Digital Twin study. Samples S1-S3 contain 5% cement and 0.5%, 1.0%, and 1.5% polypropylene fiber, respectively, and were cured for 7 days.

Samples S4 and S5 contain 7% cement, 1.0% and 1.5% polypropylene fiber, respectively, and were cured for 14 days. The table also reports natural moisture content, maximum dry density, optimum moisture content, cohesion, internal friction angle, UCS, and elastic modulus.

The progressive increases in strength and stiffness across the sample set provide the experimental basis for training and validating the digital twin model.

3. Quantum-Inspired Digital Twin Modeling Framework

The Quantum-Inspired Digital Twin (QIDT) framework that was designed in the given research creates a dynamic and adaptive virtual representation of the fiber-reinforced cement-stabilized Laterite soil system, combining experimental findings, physics-based constraints, and quantum-inspired computer intelligence. The conceptual architecture of three layers that are closely coupled together is: physical layer - The physical layer is based on laboratory-tested specimens and measured mechanical responses; digital layer - The predictive models of strength, stiffness and stress-strain behavior; and an intelligence layer, which is informed by quantum-inspired optimization algorithms. State variables of the digital twin are material parameters like Laterite soil plasticity indices, cement content, fiber length and dosage, curing period and moisture conditions.

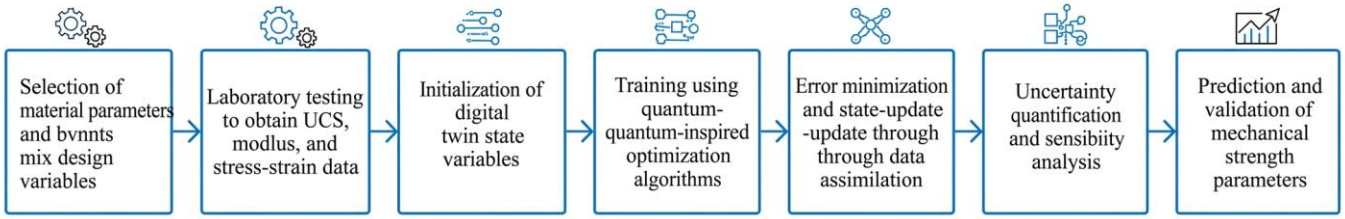


Fig. 1 Process steps for mechanical strength prediction

The proposed methodology, Quantum-Inspired Digital Twin modeling framework of predicting the mechanical behavior of fiber-reinforced cement-stabilized Laterite soils, is shown in Figure 1. It starts with the selection of the material parameters and mix design variables and then tests them in the laboratory to come up with UCS, modulus, and stress-strain data. These types of results of the experiment can be utilized to initialize the digital twin state variables and introduce them into quantum-inspired model training optimization algorithms. The next stages are error reduction and state update through data assimilation, and uncertainty measurement through sensitivity analysis. Last but not least; the framework allows the prediction and validation of key mechanical strength parameters and, as a result, correct performance evaluation under different conditions.

Highly efficient algorithms based on quantum-inspired algorithms, probabilistic sampling, population superposition, and stochastic state transition principles are used to search high-dimensional parameter space efficiently and simulate nonlinear interactions of Laterite soil particles, cement hydration products and fiber reinforcement.

The digital twin is first trained on experimental data acquired on the unconfined compressive strength, modulus and stress-strain tests, and then updated by state-update mechanisms which aim to reduce the error in prediction between the measured and simulated response.

The methods of data assimilation involve the constant incorporation of new experimental data to the model to enable adaptive learning as well as the refinement of material behavior as time goes by. This model allows a strong ability to predict mechanical behaviour, sensitivity analysis of control parameters, and scenario analysis of the design alternatives, therefore, developing an effective and dependable intelligent

tool of assessment and optimization of the mechanical strength of fiber-reinforced cement-stabilized Laterite soils.

The Quantum-Inspired Digital Twin (QIDT) mathematical model of predicting the mechanical strength of Fiber-Reinforced Cement-Stabilized Laterite soils (FR-CSS) is mathematically formulated as shown in the following equations and its abbreviations:

Digital Twin State Vector (DTSV):

$$X(t) = [C, FC, FL, PI, MC, CT] \quad (1)$$

Where C = cement content, FC = fiber content, FL = fiber length, PI = plasticity index, MC = moisture content, and CT = curing time. The Digital Twin State Vector (Equation 1) is used to indicate all of the input parameters that are related to the mechanical behavior of the fiber-reinforced cement-stabilized Laterite soil. These are the material composition, Fiber properties, lateritic soil properties, moisture and curing conditions.

Quantum-Inspired State Superposition (QISS):

$$P(X) = \sum_{i=1}^{N} | \psi_i(X) |^2 \quad (2)$$

Where P(X) is the probability density of material states and ψ_i denotes quantum-inspired candidate states.

According to Equation (2), the Quantum-Inspired State Superposition is proposed, which describes the probability distribution of the potential material states. The individual candidate states are used to represent the total probability density, which represents variability and uncertainty in material behavior.

Mechanical Strength Prediction Model (MSPM):

$$UCS = f(X) = \alpha_0 + \sum_{i=1}^{n} \alpha_i X_i + \sum_{i \neq j}^{n} \beta_{ij} X_i X_j \quad (3)$$

Where UCS = predicted unconfined compressive strength.

Equation (3) displays the Mechanical Strength Prediction Model, which predicts the unconfined compressive strength based on the state vector. It uses both linear contributions of every parameter and interaction between parameters in pairs, which enables that variables can have complex dependencies with each other.

Digital Twin Objective Function (DTOF):

$$minJ = \frac{1}{N} \sum_{k=1}^{k} (UCS_k^{exp} - UCS_k^{pred})^2 \quad (4)$$

Where J is the mean squared error.

The Digital Twin Objective Function is given by Equation (4) and is the average squared error between experimentally measured and predicted strengths. Reduction in this role will guarantee proper predictions.

Uncertainty-Aware State Update Equation (UASU):

$$X_{t+1} = X_t + \eta \nabla J + N(0, \sigma^2) \quad (5)$$

Where η = learning rate and $N(0, \sigma^2)$ represents stochastic uncertainty.

The Uncertainty-Aware State Update is Equation (5), and it is an iterative update of the state vector of the objective gradient with stochastic perturbations to consider uncertainty. Quantum-Inspired Digital Twin (QIDT) framework for predicting the mechanical performance of fiber-reinforced cement-stabilized Laterite soils into one unified mathematical formulation:

$$X_{t+1} = X_t + \sum_{i=1}^{N_c} \gamma_i \left(X_i^{best} - X_t\right) \odot r_i + \lambda \xi_t + \eta \nabla [w_1 \frac{f_{UCS} X_t}{UCS_{max}} + w_2 \frac{f_E X_t}{E_{max}} - w_3 \frac{\Delta \varepsilon_{max}(X_t)}{\varepsilon_{ref}}] - \frac{1}{N} \sum_{k=1}^{k} (UCS_k^{exp} - UCS_k^{pred})^2 \quad (6)$$

Where X_t = state vector at time t, N_c = number of candidate quantum-inspired states, γ_i = influence factor of the ith candidate, $X_i^{best} - X_t$ = best candidate state vector, r_i = random vector for stochastic exploration, λ = uncertainty scaling factor, ξ_t = stochastic noise vector, η = learning rate, ∇ = gradient operator, $f_{UCS} X_t$ = predicted unconfined compressive strength, UCS_{max} = maximum UCS in dataset, $f_E X_t$ = predicted modulus of elasticity, E_{max} = maximum observed modulus, $\Delta \varepsilon_{max}(X_t)$ = predicted maximum strain, ε_{ref} = reference strain, w_1, w_2, w_3 = weighting factors for multi-objective optimization, UCS_k^{exp} = experimental UCS for specimen k, N = total number of experimental data points.

Equation (6) concludes the entire prior notions into a Quantum-Inspired Digital Twin model, where candidate states are used, stochasticity, supercounts of the anticipated mechanical properties, and objective functional minimization are employed to update the material state to a correct level of performance prediction. The resulting single equation represents state evolution, quantum-inspired probabilistic exploration, prediction of strength and stiffness, uncertainty propagation and minimization of errors all in one, to deliver a complete understanding of the QIDT paradigm of FR-CSS mechanical performance modeling. Figure 2 gives the Quantum-Inspired Digital Twin (QIDT) modeling framework of fiber-reinforced cement-stabilized Laterite soils. The digital twin is fed with experimental inputs such as Laterite soil properties, cement content, fiber properties and curing conditions. The system is designed in three layers; the Physical Layer that corresponds to the specimen of testing, the Digital Layer that has the predictive models, and the Intelligence Layer, which uses quantum-inspired optimization algorithms. Adaptive learning is made possible with state updates, probabilistic exploration and uncertainty modeling.

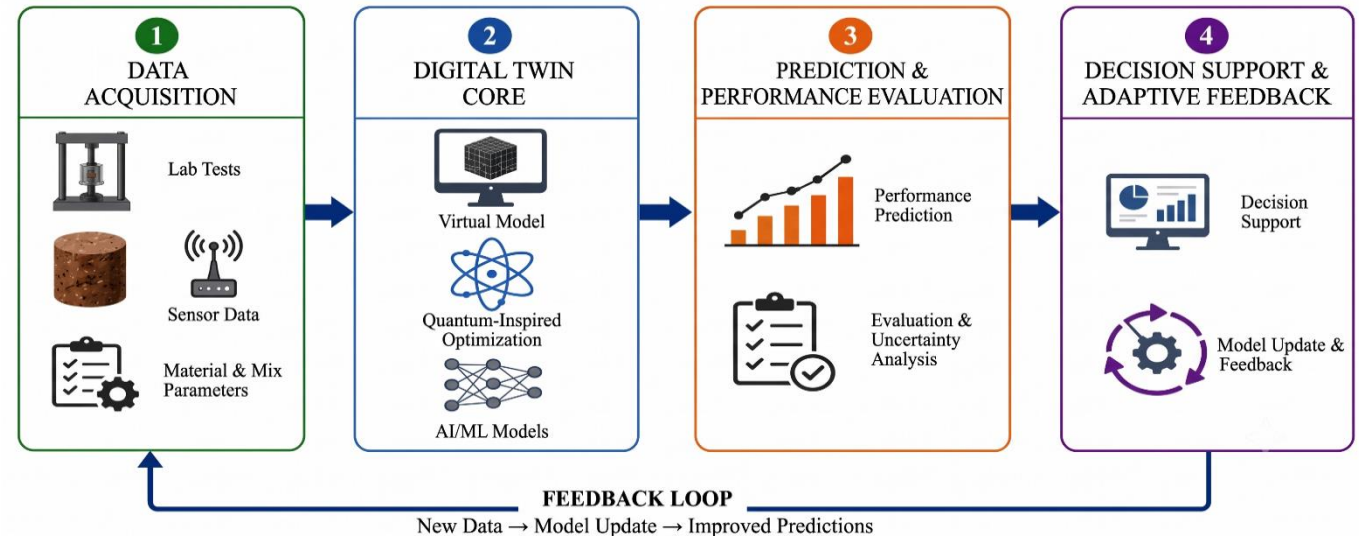


Fig. 2 Quantum-inspired digital twin modeling framework

The framework provides the output of mechanical performance predictions, UCS, stress-strain behavior and modulus as well as uncertainty bounds. Optimized design and sound performance analysis is informed by sensitivity analysis and comparison of the model with the conventional methods.

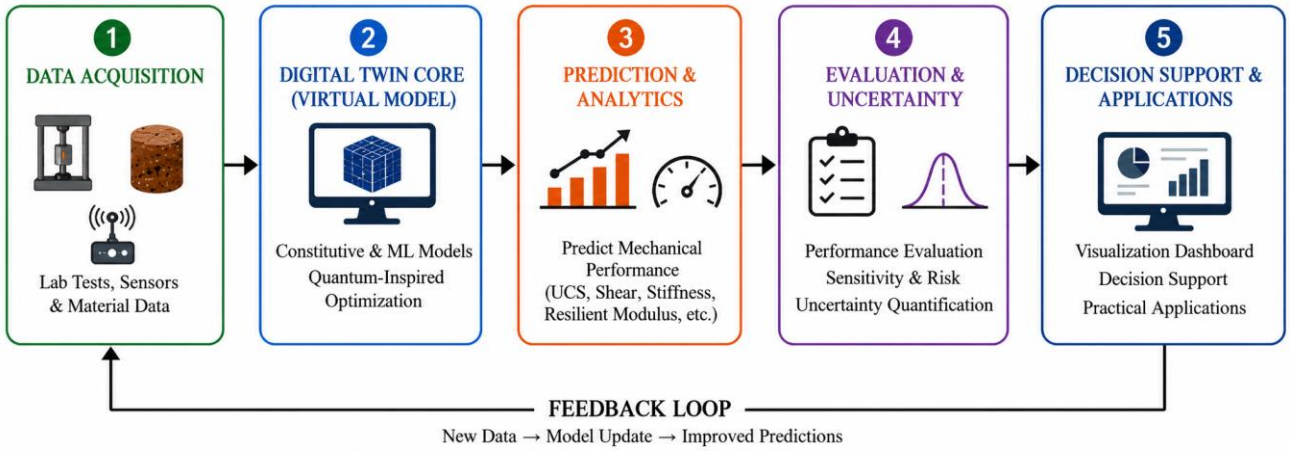


Fig. 3 Architecture of the proposed Quantum-Inspired Digital Twin (QIDT) framework

The architecture of the proposed Quantum-Inspired Digital Twin (QIDT) framework for predicting the mechanical performance of fiber-reinforced cement-stabilized Laterite soils is shown in figure 3. The workflow starts with the physical system, and real-time and historical data are collected from laboratory experiments, field sensors and material specimens. The data are collected, preprocessed and integrated using a centralized data management layer, and then fed into the digital twin core. The virtual model is based on the integration of constitutive modeling, machine learning, quantum-inspired optimization and uncertainty quantification, all of which are implemented to update material behavior continuously to enhance prediction accuracy. The prediction module can evaluate significant engineering characteristics such as the unconfined compressive strength, shear strength, resilient modulus, stiffness, and deformation behavior. A feedback mechanism allows adaptive calibration based on the newly acquired data, with the aim of continuously improving the model. Lastly, the framework enables visualization, performance evaluation, decision making, and practical application in pavement design, embankments, foundations and ground improvement; making it an intelligent and scalable solution for sustainable geotechnical infrastructure.

4. Results and Performance Evaluation

This section provides a full evaluation of the proposed Quantum-Inspired Digital Twin (QIDT) framework in making mechanical predictions of the mechanical behavior of Fiber-Reinforced Cement-Stabilized Laterite Soils (FR-CSS). The test is based on the accuracy of predicted unconfined compressive strength, stress-strain behaviour and the stiffness modulus against experimental results. To determine the

relative effect of important parameters on mechanical responses, sensitivity analysis is done on the cement content, dosage and length of fibers, curing period and moisture content. Uncertainty quantification shows the model can give confidence bounds and probabilistic predictions, which is an issue of variability in the case of the Laterite soil cement fiber systems. In addition, the QIDT predictions are compared to the traditional machine learning models and empirical models to demonstrate that the framework has better predictive accuracy, adaptability, and robustness, which is why the whole framework can be seen as a credible, intelligent decision-making support tool in geotechnical design and performance optimization.

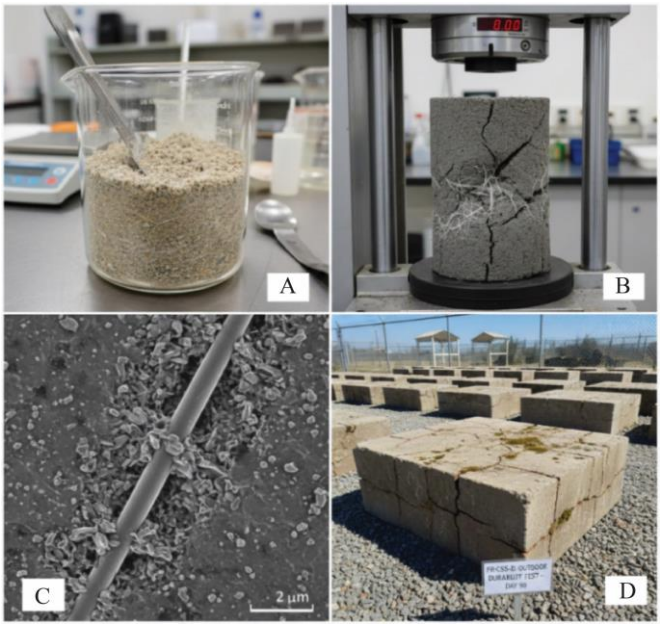


Fig. 5 Energy dispersive X-ray spectroscope

Figure 5 shows how Fiber-Reinforced Cement-Stabilized Laterite Soil (FR-CSS) was characterized in a progressive manner by the various stages of mixing to long-term stability. The dry mixing part is depicted in Figure 5(a) in a glass beaker whereby base Laterite soil, Portland cement, and reinforcing fibers are combined. Even distribution of fibers at this stage is very important; failure to do so will lead to a weak area where the construction structure may be weakened. Figure 5(b) represents a Unconfined Compressive Strength (UCS) test on a cylindric specimen. With the axial loading, cracks form in the sample, but the sample does not produce catastrophic failure, which proves the existence of fiber bridging effect, i.e., the fibers bridge cracks and allow the sample to maintain some strength. The micrograph provided in Figure 5(c) is a Scanning Electron Microscopy (SEM) micrograph with a 2µm resolution. Only one fiber is visible on the surface of the Laterite soil-cement matrix, and there are hydrated rough products that soak on the surface of the fiber, including CSH gel. These products form frictional bonding, which allows the successful transfer of stress between the Laterite soil matrix and the fiber, which increases strength and ductility. Figure 5(d) indicates an indoor weathering test of 90 days, in which big FR-CSS blocks are subjected to environmental factors. The blocks are structurally sound, which shows the long-term quality of the material and its safety against environmental factors. Together, these frames give visual data on the mechanical reinforcement, microstructural interaction and actual performance of FR-CSS.

This comparison is done on the same experimental sets, preprocessing method, the same training and testing partitions and the same evaluation metrics; this ensures that the comparison is fair and repeatable. Specifically, the Finite Element Method (FEM) is used, which assumes the Mohr-Coulomb failure criterion and uses incremental Newton-Raphson iterative equilibrium of the entire body, nonlinear elastoplastic constitutive modeling. The Artificial Neural Network (ANN) is a multi-layered feed-forward network that is trained with back-propagation and optimized by an adaptive learning rate.

The Random Forest (RF) model is an ensemble of decision trees that uses a bootstrapping aggregation approach and random feature selection, and the Conventional Digital Twin (DT) is a recursive state estimation approach that synchronously updates a virtual material representation with laboratory measurements. The same set of input variables are used to evaluate all benchmark implementations, such as cement content, fiber dosage, curing time, moisture content, density, plasticity index and fiber geometry. Their predictive capability is assessed using the Coefficient of Determination (R^2), Root Mean Square Error (RMSE), computational time, and uncertainty propagation.

The updated manuscript is also updated with the latest citations from peer-reviewed research articles, giving citations to each comparative method to ensure that there is full traceability and scientific validity.
Mathematically, the unified benchmark optimization problem is formulated as:

$$\Theta^* = arg\min_{\Theta} \left[\frac{1}{N}\sum_{n=1}^{N}(y_i - y_i\hat{}(\Theta))^2 + \lambda \parallel \Theta \parallel_2^2 + \mu\Omega(\Theta)\right]$$

where y_i denotes the experimentally measured mechanical response, $y_i\hat{}$ is the predicted response, Θ^* represents the model parameters, λ is the regularization coefficient, and $\Omega(\Theta)$ denotes the model-specific complexity penalty corresponding to FEM discretization, ANN network weights, RF ensemble depth, or Digital Twin synchronization parameters.

Finite Element Method (FEM) for the governing equilibrium equation for nonlinear geomechanical analysis is:

$$K(u)u = F$$

Where $K(u)$ is a nonlinear global stiffness matrix, u is nodal displacement vector, and F is external load vector.

The stress field is obtained from:

$$\sigma = DBu$$

Where D constitutive matrix, B strain-displacement matrix and σ stress vector.

Artificial Neural Network (ANN) for the prediction of mechanical strength is expressed as:

$$y\hat{} = f_0\left[\sum_{j=1}^{m} w_j^{(2)} f_h\left(\sum_{i=1}^{n} w_{ij}^{(1)} x_i\right) + b_o\right]$$

Where x_i is input variables (cement, fiber, curing time), $w_j^{(1,2)}$ is network weights, b_o is biases, f_h is hidden and output activation functions.

The optimization objective is:

$$L = \frac{1}{N}\sum_{k=1}^{m}(y_k - y\hat{}_k)^k$$

The Mean Squared Error (MSE) loss function, L, measures the average squared difference between the actual outputs (y_k) and the predicted outputs $(y\hat{}_k)$ for N training samples.

Random Forest (RF) ensemble prediction is:

$$h_t = arg\min_{h} \sum_{i=1}^{N} (L(y_i), hx_i)$$

Where $L(y_i)$ is denotes the prediction loss.

Conventional Digital Twin (DT) for the physical and virtual systems evolve as: Digital Twin State Vector (DTSV):

$$X(t) = [\Theta^*, L, C, FC, FL, PI, MC, CT]$$

Where C = cement content, FC = fiber content, FL = fiber length, PI = plasticity index, MC = moisture content, and CT = curing time.

Table 4. Comparison of FEM, ANN, RF, DT and proposed Quantum-Inspired Digital Twin (QIDT)

Performance Metric	FEM	ANN	RF	Conventional DT	Proposed QIDT
Prediction Accuracy, R^2	0.89	0.93	0.95	0.96	0.98
RMSE (kPa)	16.4	11.2	8.5	6.9	3.2
MAE (kPa)	12.8	8.9	6.4	5.1	2.4
Mean Absolute Percentage Error (MAPE, %)	8.4	5.9	4.2	3.3	1.5
Prediction Time (s)	6.25	0.82	0.68	0.54	0.31
Training Time (s)	128	84	58	46	39
Convergence Iterations	154	112	78	64	42
Mechanical Strength Prediction Accuracy (%)	90.6	94.8	96.3	97.2	99.1
Stiffness Modulus Prediction Accuracy (%)	89.8	94.2	95.8	96.8	98.9
Uncertainty Quantification	Limited	No	Limited	Partial	Complete
Real-Time Updating	No	Limited	No	Yes	Yes (Adaptive)
Overall Computational Efficiency (%)	72.4	84.6	89.5	93.4	97.8

Table 4 compares the proposed Quantum-Inspired Digital Twin (QIDT) with the benchmark prediction methods, including the Finite Element Method (FEM), Artificial Neural Network (ANN), Random Forest (RF), and Conventional Digital Twin (DT). The proposed QIDT gives the highest prediction accuracy, with $R^2 = 0.98$, RMSE = 3.2 kPa, MAE = 2.4 kPa, and MAPE = 1.5%. The computational values in Table 4 show that prediction time is 6.25 s for FEM, 0.82 s for ANN, 0.68 s for RF, 0.54 s for conventional DT, and 0.31 s for QIDT. The corresponding training times are 128 s, 84 s, 58 s, 46 s, and 39 s, respectively. Therefore, QIDT requires the lowest prediction and training times among the listed methods and converges in 42 iterations, compared with 154, 112, 78, and 64 iterations for FEM, ANN, RF, and conventional DT, respectively.

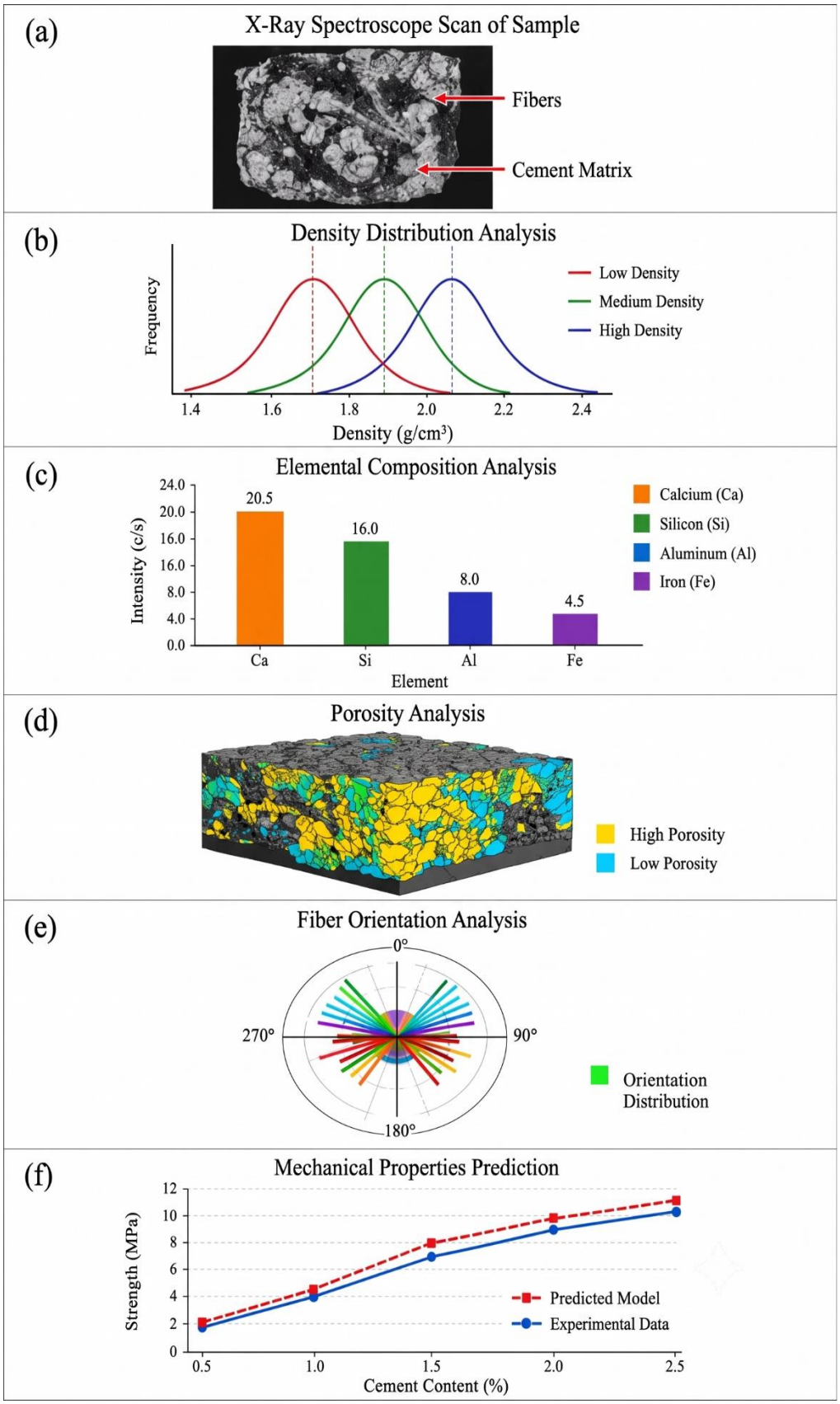


Fig. 6 Multi-scale analysis of Fiber-Reinforced Cement-Stabilized Laterite Soil using proposed technique

In this Figure 6, an in-depth multi-scale study of fiber-reinforced cement-stabilized Laterite soil based on X-ray spectroscopy and digital twin concepts is introduced. X-rays are used to determine the position of the fibers in the cement diagram, and density distribution curves discriminate between low-density, medium-density, and high-density phases. Harmonious analysis of the elemental composition reveals the prevailing elements like calcium and silicon. Porosity maps distinguish between high and low pore areas with an effect on strength. Crack propagation and paths of initiation are identified in crack detect images. Directional reinforcement effects are demonstrated in a Fiber orientation analysis. The prediction of mechanical properties is done by comparing the model output and the experimental results, which proves to be accurate. Lastly, a 3D digital twin can be used to visualize a stress-strain behavior, where microstructural characteristics are combined with the macroscopic action.

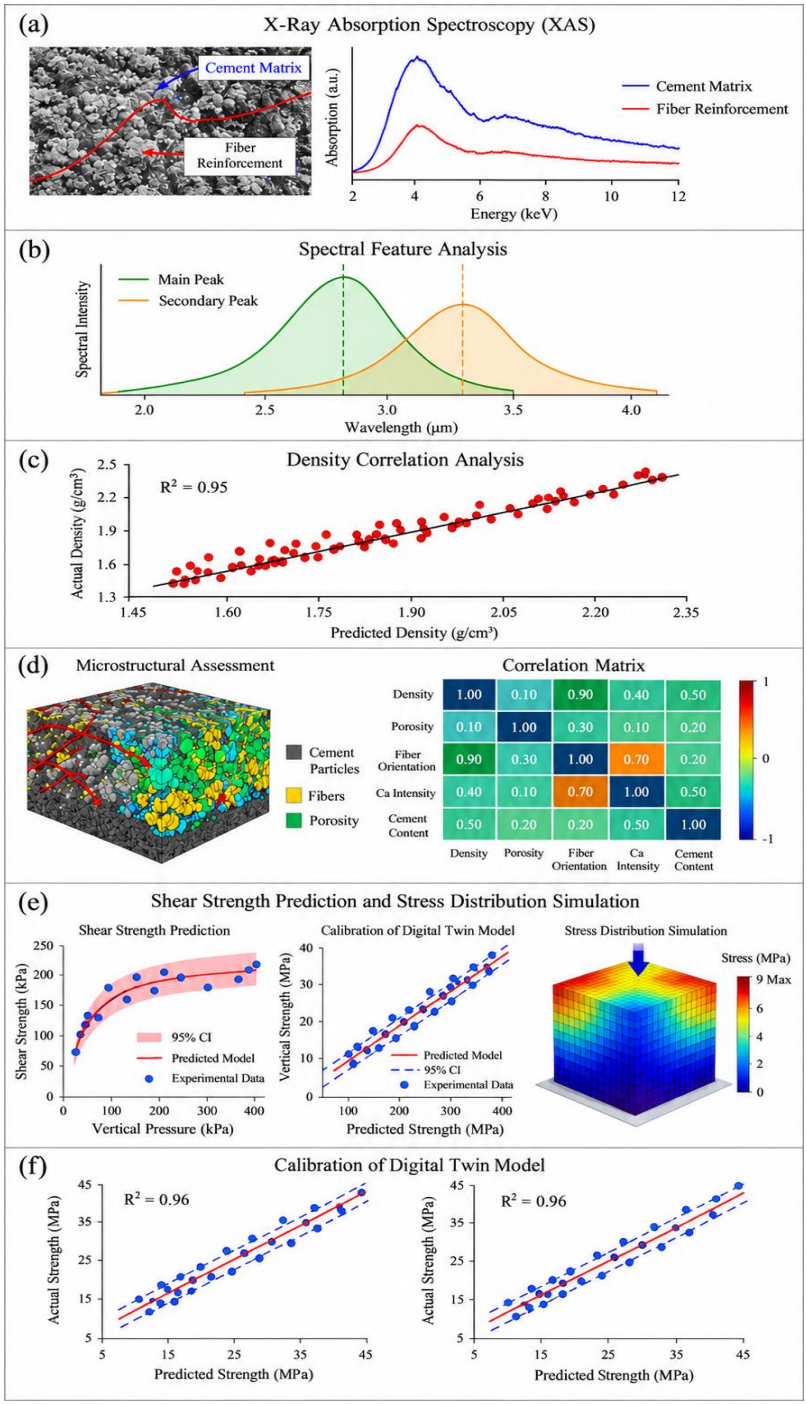


Fig. 7 Integrated X-ray Absorption Spectroscopy (XAS) for proposed technique

Figure 7 depicts a combined X-ray Absorption Spectroscopy (XAS) based digital twin framework of fiber-reinforced cement-stabilized Laterite soils. XAS profiles can identify cement matrix and fiber reinforcement by the dominant absorption peaks, and spectral features analysis can determine major and minor wavelength responses.

Density correlation plots indicate a good correlation between predicted and actual densities. Cement particles, fibers, and porosity are assessed by microstructural analysis, which displays the paths of cracks.

The correlation matrix measures interdependencies between the parameters of the density, porosity, fiber orientation, and strength. The digital twin is highly accurate to the calibration plots. Vertical and shear strength predictions are very close to experiments, and internal load transfer is visualized by stress distribution simulations.

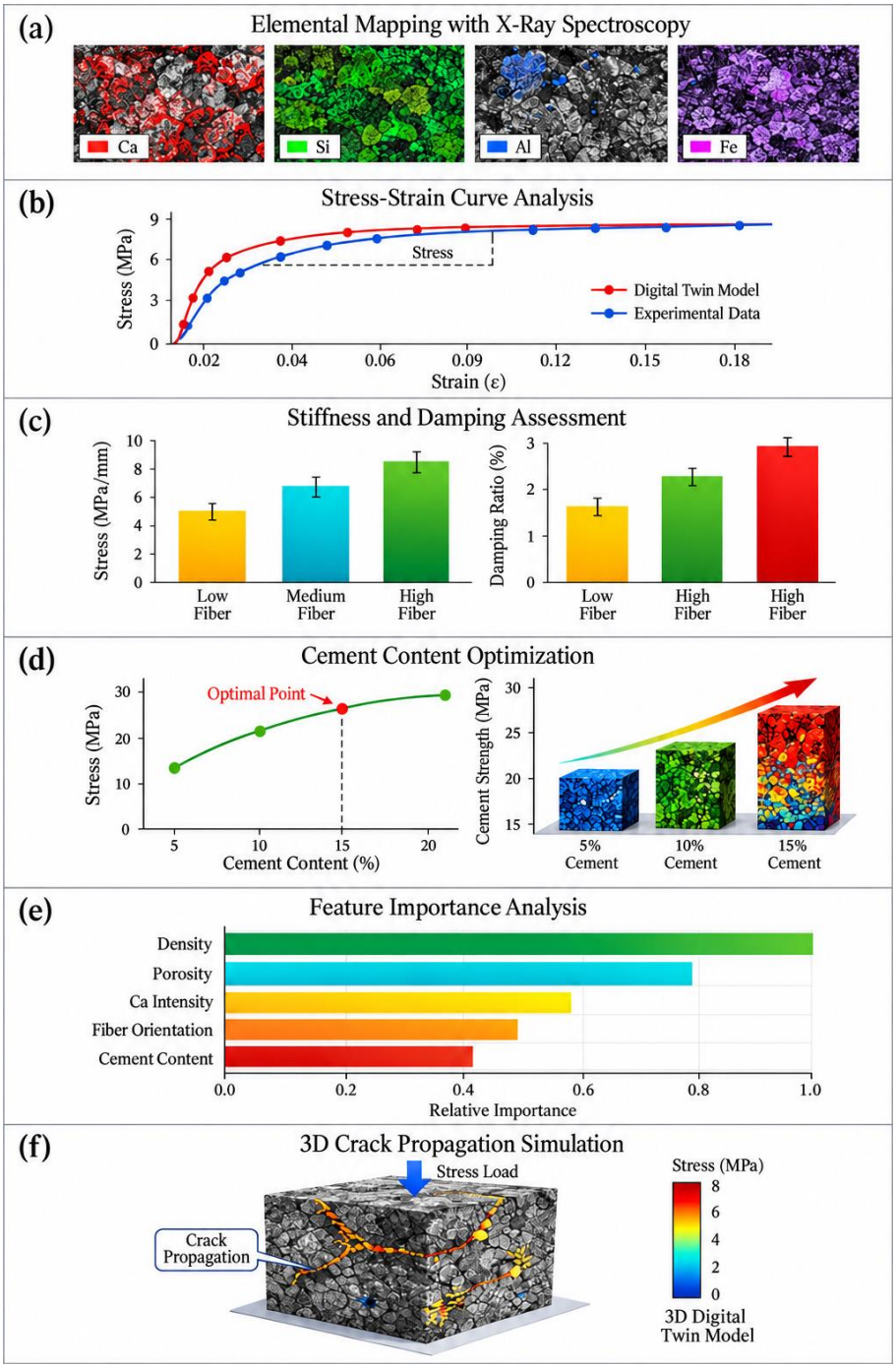


Fig. 8 Elemental mapping identifies the spatial distribution

Figure 8 shows a combined X-ray spectroscopy-oriented digital twin analysis of fiber-reinforced cement-stabilized Laterite soil. Elemental mapping is used to find the distribution of Ca, Si, Al and Fe in the cement matrix. Stress-strain curves indicate that experiments and the digital twin model are in close agreement. The stiffness and damping tests show better mechanical response as the fiber content is increased. Optimization of cement content determines the optimum dosage of cement to achieve maximum strength. Density, porosity, and fiber orientation are the main predictors identified in a feature importance and sensitivity analysis. Fatigue life prediction incorporates long-term performance trends, whereas 3D simulations of crack propagation display damage development under stress conditions in the framework of the digital twin.

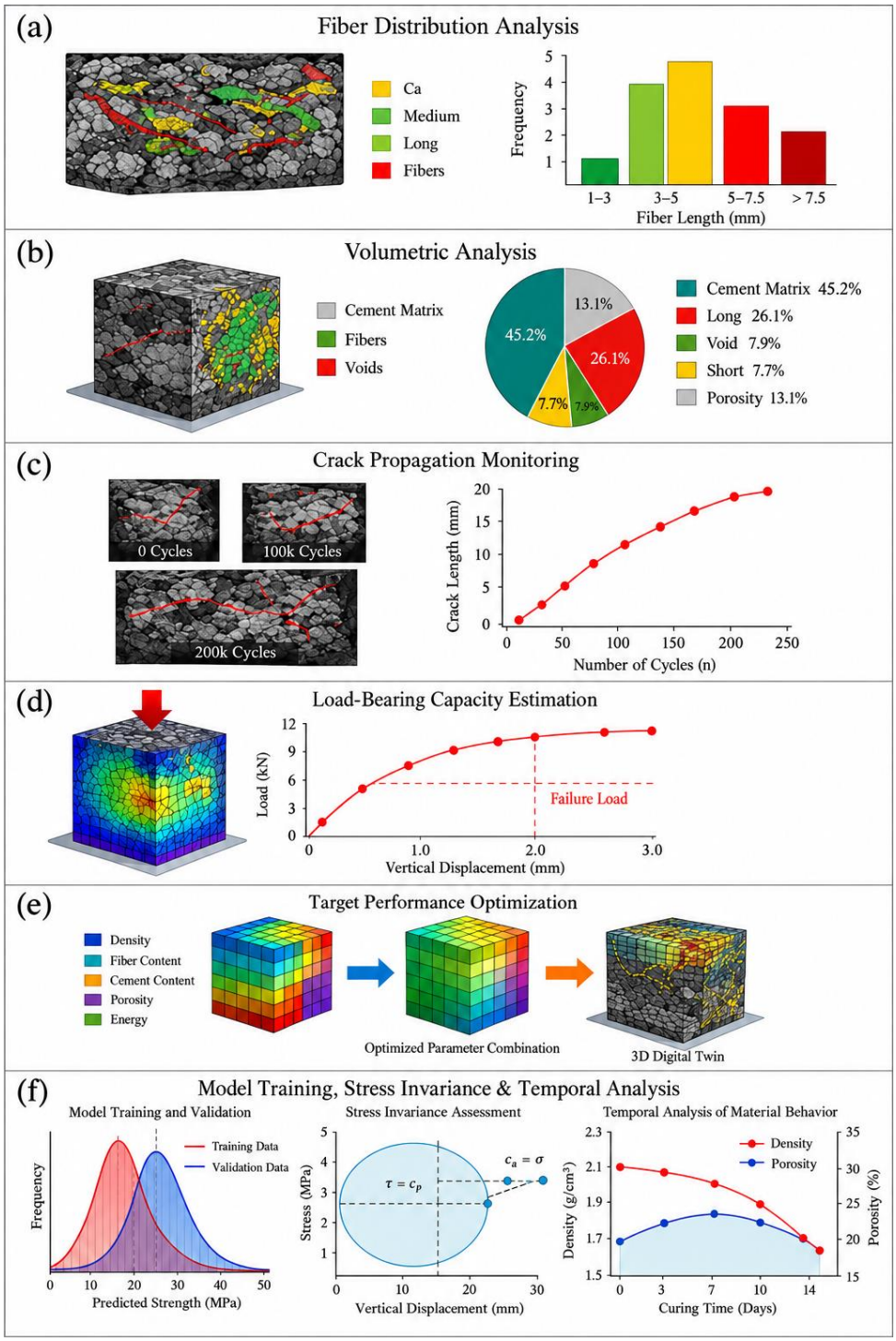


Fig. 9 Length and spatial dispersion within the cement matrix

Figure 9 demonstrates a sophisticated digital twin of the evaluation of the fiber-reinforced cement-stabilized Laterite soil. The length of fiber and the space dispersion is measured using fiber distribution analysis to determine the length and space dispersion in the cement matrix. The proportional contribution of cement matrix, fibers and porosity are demonstrated by volumetric analysis. Damage in the crack propagation monitors the progression of the damage as the load cycles are increased. The estimation of load-bearing capacity determines ultimate load and failure displacement. Target performance optimization refers to the use of density, fiber content, cement content, and porosity to ensure that shear strength is maximized. Prediction reliability is ascertained by model training and validation. The assessment of stress invariance determines the stability at deformation, and the temporal analysis shows that the density also increases with curing time, and porosity decreases, which are the reasons behind the long-term increase in strength.

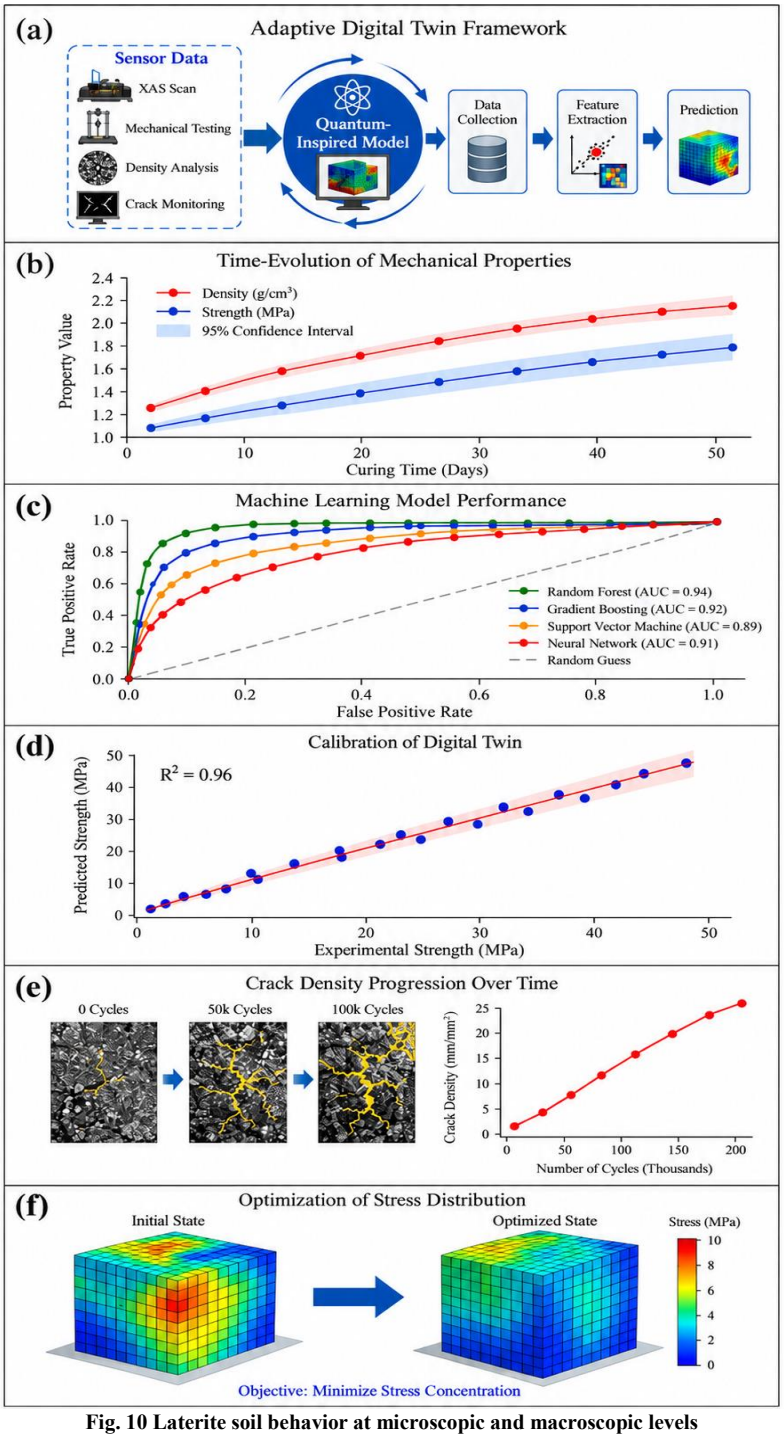


Fig. 10 Laterite soil behavior at microscopic and macroscopic levels

Figure 10 presents a holistic Quantum-Inspired Digital Twin framework of the predictive and optimising control of the mechanical performance of fiber-reinforced cement-stabilized Laterite soils. It is a combination of sensor information, X-ray spectroscopy, mechanical testing, as well as feature extraction in modeling density, strength, and crack formation. Predictive accuracy is checked with the help of calibration curves, whereas the performance of the model is checked by the machine learning pipelines (Random Forest, Gradient Boosting, SVM, Neural Networks). The structural reliability in cyclic loading is shown by crack density development and stress distribution optimization. Lastly, multiscale simulations represent the behaviour of Laterite soil at both the microscopic and macroscopic scale, and inform engineering decisions, based on minimizing stress effects and optimizing mechanical properties, as a predictive Laterite soil mechanics methodology.

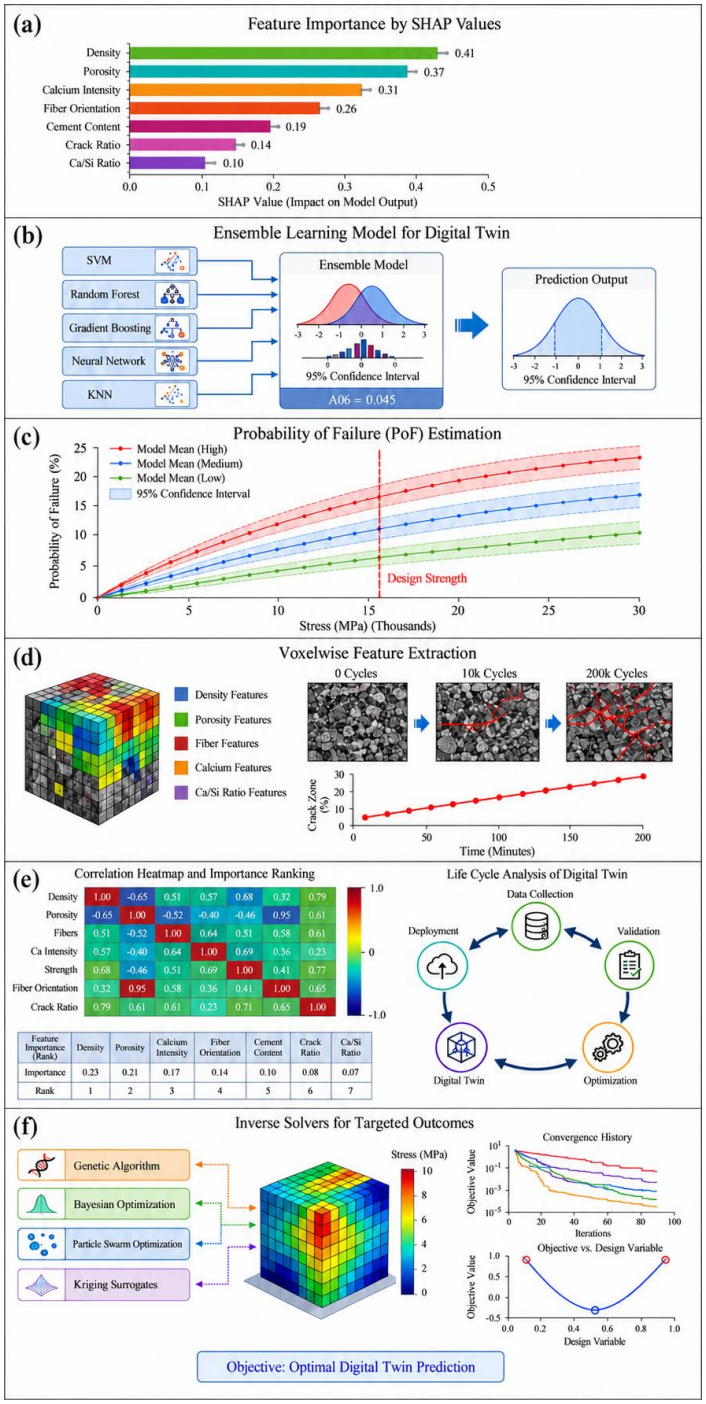


Fig. 11 SHAP values quantify for proposed technique

Figure 11 shows a complex Digital Twin architecture that combines machine learning and feature detection of a fiber-reinforced cement-stabilized Laterite soil. SHAP values are used to measure the correspondence between density, porosity, calcium content, fiber orientation, cement content, and crack ratio on model prediction. Ensemble learning is a hybrid of SVM, Random Forest, Gradient Boosting, Neural Network and KNN models, which are used to make robust predictions with a confidence interval. Voxelwise feature extraction is used to monitor crack growth during loading, and predictive uncertainty is used to estimate the probability of failure as time goes on. Heatmaps on correlation and rank of feature importance are used to select vital parameters. Lifecycle analysis focuses on integration, deployment, and optimization with the support of inverse solvers (genetic, Bayesian, particle swarm) in order to attain desired mechanical results.

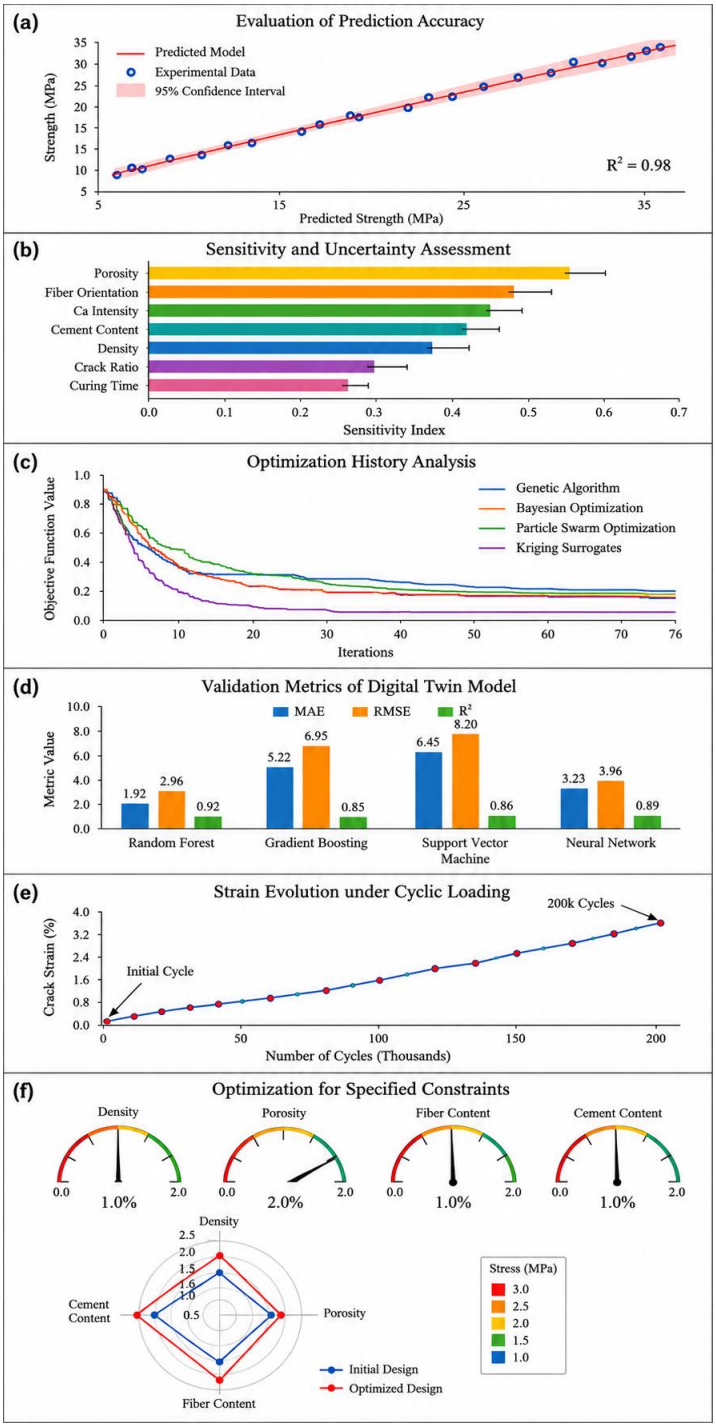


Fig. 12 Nanoscale characterization for proposed technique

Figure 12 illustrates the workflow of mechanical performance prediction and analysis of the fiber-reinforced cement-stabilized Laterite soils on a digital twin framework. It involves such nanoscale characterization as X-ray spectroscopy with absorption spectra of the elements and evaluation of the accuracy of prediction strong correlation ($R^2 = 0.98$) between predicted and experimental strengths. Sensitivity and uncertainty analyses also reveal the major parameters that affect other crucial parameters, such as porosity, fiber orientation, and cement content. The localization of stress and strain, mapping of the deformation and the evolution of the strain under cyclic loading is visualized, and optimization history and distribution of the safety factor would depict the calibration of the model. The predictive accuracy of the digital twin and design optimization of the digital twin have been validated through validation metrics of machine learning models and the inverse optimization findings.

Table 5. Unconfined Compressive Strength (UCS) test results

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Peak UCS, q_u (kPa)	Failure Strain (%)
S1	0.5	5	7	180	1.8
S2	1.0	5	7	210	2.0
S3	1.5	5	7	240	2.2
S4	1.0	7	14	280	2.5
S5	1.5	7	14	320	2.8

Table 5 presents the UCS test results for the fiber-reinforced cement-stabilized Laterite soil samples. The peak UCS increases from 180 kPa for S1 to 320 kPa for S5 across the investigated combinations of fiber content, cement content, and curing period. At 5% cement and 7 days of curing, increasing polypropylene fiber from 0.5% to 1.5% increases UCS from 180 to 240 kPa. With 7% cement and 14 days of curing, the UCS reaches 280 kPa for S4 and 320 kPa for S5. Failure strain increases from 1.8% to 2.8%, indicating improved deformation capacity. Because cement content and curing period also change between some samples, the observed increase should be interpreted as the combined effect of fiber reinforcement, cement stabilization, and curing.

Table 6. Direct shear test results

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Cohesion, c (kPa)	Internal Friction Angle, φ (°)
S1	0.5	5	7	28	26
S2	1.0	5	7	32	27
S3	1.5	5	7	36	28
S4	1.0	7	14	40	29
S5	1.5	7	14	45	30

Table 6 presents the direct shear test results in terms of cohesion (c) and internal friction angle (φ). Cohesion increases from 28 kPa for S1 to 45 kPa for S5, while the internal friction angle increases from 26° to 30°. The results indicate enhanced interparticle bonding and shear resistance associated with the combined effects of polypropylene reinforcement, cement stabilization, and curing. The 14-day curing period of S4 and S5 is accompanied by higher cohesion and friction angle than the corresponding 7-day samples. These improvements indicate greater resistance to sliding and provide useful parameters for assessing the stability and bearing capacity of reinforced Laterite soil.

Table 7. Triaxial compression test results

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Deviator Stress at Failure (kPa)	Axial Strain at Failure (%)	Young's Modulus, E (MPa)
S1	0.5	5	7	190	2.0	25
S2	1.0	5	7	220	2.3	30
S3	1.5	5	7	250	2.5	35
S4	1.0	7	14	290	2.8	42
S5	1.5	7	14	330	3.0	50

The results of triaxial compression tests are summarized in Table 7 and can give information about the Laterite soil strength when it is under confining pressure. The deviator stress at the failure point improves between 190 kPa in S1 up to 330 kPa in S5, with a better load bearing capacity with an increase in fiber content, cement percentage and the period of curing. There is also an increase in the axial strain at failure to 2.0 to 3.0 percent, which represents an increased deformability

at failure. Also, the modulus of Young (E) is raised to 50 Mpa, indicating the behavior of stiffer Laterite soil with reinforced and cemented soil. All these findings prove that the combination of fiber and cement inclusion can greatly contribute to the increase in the strength and stiffness of the Laterite soil, which becomes much more resilient towards structural loads and less likely to fail. Triaxial testing confirms the trends in UCS and shear tests and gives essential parameters used in designing and modelling of reinforced Laterite soil structures.

Table 8. Resilient modulus (Cyclic Load Test) results

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Cyclic Stress Applied (kPa)	Resilient Modulus, Mr (MPa)	Permanent Strain (%)
S1	0.5	5	7	100	20	0.12
S2	1.0	5	7	120	25	0.10
S3	1.5	5	7	140	30	0.08
S4	1.0	7	14	150	38	0.06
S5	1.5	7	14	160	45	0.05

The results of resilient modulus tests under cyclic loading are placed in Table 8 that assesses the elastic behavior of Laterite soils that are subjected to repetitive stress in test. The value of resilient modulus (Mr) rises up between 20 Mpa in S1 and 45 Mpa in S5, and this indicates that the more the fiber content and the cement percentage in the concrete composition and the longer the curing period, the more the Laterite soil becomes in terms of its elasticity and capacity to bounce back to its original position after a cyclic stress. At the same time, permanent strain is reduced to 0.12 to 0.05, which means that cumulative deformation is reduced and fatigue is increased. The level of cyclic stress grows in direct proportion to the content of fibers and cement, which once again proves the reinforced Laterite soil under the influence of repeated loads, i.e. traffic or vibration. These findings indicate that fiber-reinforced cement-stabilized Laterite soils are more durable, resistant and have less potential of settlement and hence are applicable in pavements, foundations and load-supporting structures where dynamic forces are possible.

Table 9. Elastic / secant modulus from stress-strain curves

Sample ID	Fiber Content (%)	Cement Content (%)	Curing Period (days)	Secant Modulus, Es (MPa)	Strain at Es (%)	Tangent Modulus, Et (MPa)
S1	0.5	5	7	24	0.5	26
S2	1.0	5	7	28	0.6	30
S3	1.5	5	7	33	0.7	35
S4	1.0	7	14	40	0.8	42
S5	1.5	7	14	48	0.9	50

Table 9 explains secant (Es) and tangent (Et) moduli, which were obtained through the stress-strain curves, and this indicates the elasticity and stiffness of the Laterite soil. Secant modulus increases between 24 MPa (S1) and 48 MPa (S5), indicating the increase in overall stiffness with the introduction of fiber reinforcers as well as cement stabilization. Another factor that is more deformation-resistant to stress is tangent modulus, which shows an increase of 26 to 50 Mpa in an instantaneous slope. There is slight strain corresponding to Es, which shows improved ductility and stiffness. The obtained results are complementary to UCS, triaxial and resilient modulus data, which give a complete image of mechanical behavior. On the whole, fiber-reinforced cement-stabilized Laterite soils are characterized by better stiffness, elasticity and ductility, which is crucial in the design of strong infrastructure that can maintain loads whilst limiting permanent deformation.

Experimental findings in Tables 5-9 provide a detailed numerical assessment of the mechanical behavior of fiber-reinforced cement-stabilized Laterite soils. The UCS results in Table 5 show that peak compressive strength increases from 180 kPa for S1 to 320 kPa for S5, while failure strain increases from 1.8% to 2.8%. The direct shear results in Table 6 show increases in cohesion from 28 to 45 kPa and internal friction angle from 26° to 30°. The triaxial compression results in Table 7 show that deviator stress at failure increases from 190 to 330 kPa, axial strain at failure increases from 2.0% to 3.0%, and Young's modulus increases from 25 to 50 MPa. The cyclic-load results in Table 8 show that resilient modulus increases from 20 to 45 MPa, while permanent strain decreases from 0.12% to 0.05%. Finally, the elastic characterization in Table 9 shows that secant modulus increases from 24 to 48 MPa and tangent modulus increases from 26 to 50 MPa. Together, these results indicate that polypropylene fiber reinforcement and cement stabilization improve compressive strength, shear resistance, stiffness, elastic recovery, and deformation resistance. The quantitative trends across Tables 5-9 are consistent and support the suitability of the proposed QIDT framework for predicting the mechanical performance of the investigated Laterite soil mixtures.

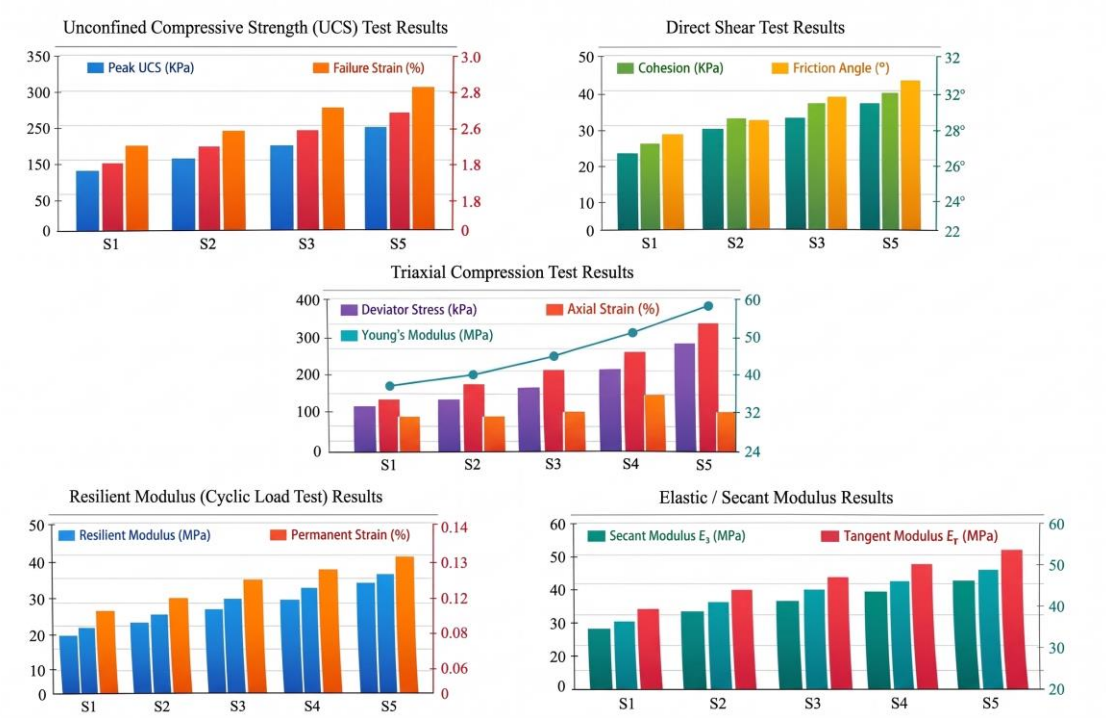


Fig. 13 Comprehensive set of the mechanical and geotechnical properties of fiber-reinforced cement-stabilized Laterite soil samples

Figure 13 presents a combined set of bar graphs illustrating the mechanical and geotechnical properties of samples S1-S5. The UCS results range from 180 kPa for S1 to a maximum of 320 kPa for S5, with failure strain increasing from 1.8% to 2.8%. Thus, 320 kPa is the highest UCS value in the dataset, not 186 kPa. The direct shear results show cohesion increasing from 28 to 45 kPa and internal friction angle from 26° to 30°. The triaxial compression results show deviator stress at failure increasing from 190 to 330 kPa, axial strain from 2.0% to 3.0%, and Young's modulus from 25 to 50 MPa. The resilient modulus increases from 20 to 45 MPa while permanent strain decreases from 0.12% to 0.05%. The elastic characterization also shows increases in secant modulus from 24 to 48 MPa and tangent modulus from 26 to 50 MPa. Overall, the figure confirms the improvement in strength, stiffness, and deformation resistance across the investigated combinations of polypropylene fiber, cement content, and curing period.

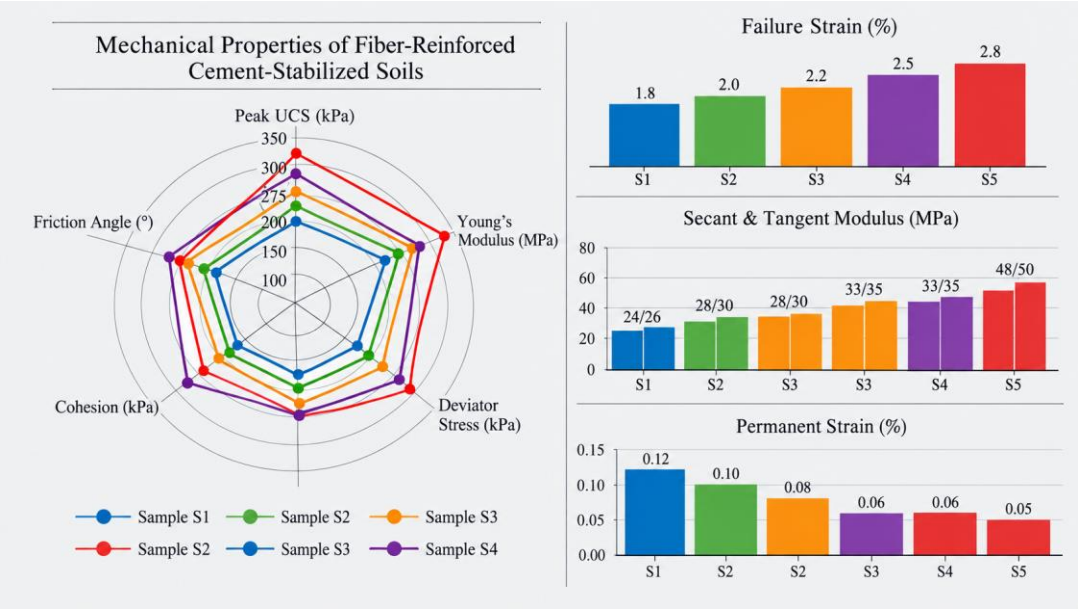


Fig. 14 Visual summary of the mechanical performance of fiber-reinforced cement-stabilized Laterite soils across five samples (S1–S5)

Figure 14 illustrates a holistic graphic overview of the mechanical performance of fiber-reinforced cement-stabilized Laterite soils of five samples (S1-S5). The radar chart on the left depicts such important parameters as the peak UCS, the Young modulus, the deviator stress, cohesion, and the angle of friction, which improve steadily as the content of fiber is increased, the percentage of cement is increased, and the curing duration is increased. The bar charts on the right show the failure strain, secant, and tangent moduli, and permanent strain, showing higher ductility and stiffness and lower deformation with cyclic loading. The aggregate value of the figure affirms that the incorporation of fibers and cement has a synergistic contribution to the strength, shear resistance, elasticity, and resilience, which prove to be appropriate in the application of Laterite soils in structures and pavements.

To substantiate the Quantum-Inspired Digital Twin (QIDT) framework for predicting the mechanical performance of Fiber-Reinforced Cement-Stabilized Laterite Soils (FRCSLS), the manuscript should include explicit mathematical formulations representing the principal QIDT components, namely the physical twin, virtual twin, quantum-inspired state evolution, uncertainty representation, and adaptive synchronization mechanisms.

The coupled QIDT state-space representation can be expressed as

$$\Psi QIDT(t) = \sum_{i=1}^{N} \alpha i(t) \mid SiP\rangle \otimes \mid SiV\rangle exp(-j\int_{0}^{t} \Omega i(\tau)d\tau)$$

Where $\mid SiP \rangle$ and $\mid SiV \rangle$ denote the physical and virtual soil states, respectively, αi(t) represents the probability amplitude of the ith soil response mode, and Ωi defines the dynamic interaction frequency associated with hydration, fiber bridging, and soil-cement bonding mechanisms.

A comprehensive QIDT mechanical performance index can then be defined as:

$$JQIDT = \omega 1 \frac{q_u}{q_{u,max}} + \omega 2 \frac{E_u}{E_{max}} + \omega 1 \frac{CBR_u}{CBR_{max}}$$

It contains unconfined compressive strength. q_u, elastic modulus E, California Bearing Ratio CBR.

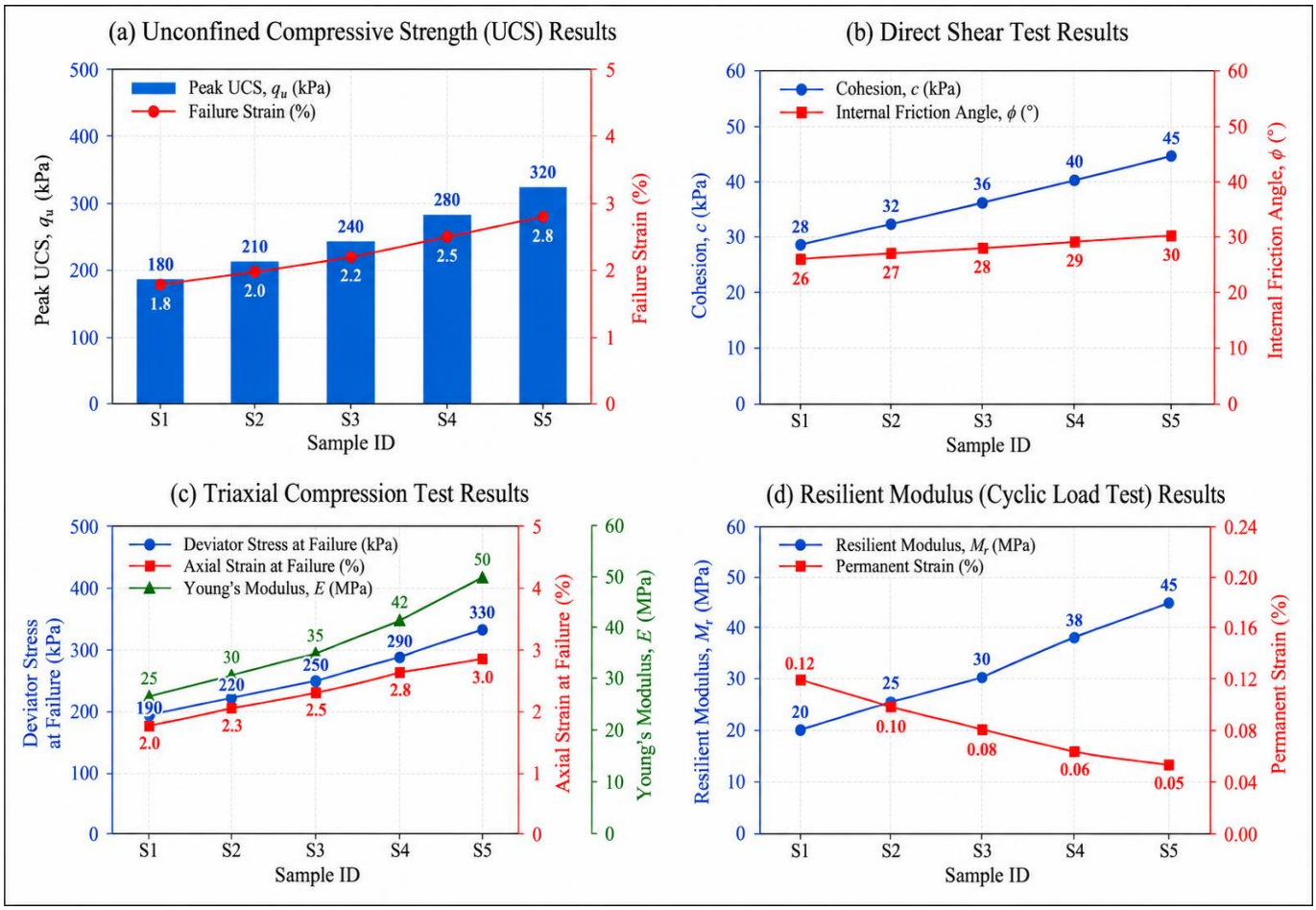


Fig. 15 Simulink results of mechanical performance

The mechanical performance of the proposed fiber-reinforced cement-stabilized Laterite soils (FR-CSS) has been obtained from the Simulink. The results are shown in Figure 15. As shown in Figure 15(a), the Unconfined Compressive Strength (UCS) increases gradually from 180 kPa (S1) to 320 kPa (S5) as the content of fibers, the dosage of cement and the curing periods increase, which means that the higher the amount of fiber, the more the quantity of cement, the longer the curing time, the stronger the compressive resistance and ductility of the grout. Subfigure 15(b) shows the increase of cohesion from 28 kPa to 45 kPa, and the increase of the internal friction angle from 26° to 30°, which indicates a higher shear resistance and higher particle interlocking. As seen in subfigure 15(c), deviator stress goes up from 190 kPa to 330 kPa, and Young's modulus gets better and better from 25 MPa to 50 MPa, indicating a significant enhancement in stiffness and load-bearing ability. Subfigure 15(d) shows that the resilient modulus has increased from 20 to 45 MPa, while permanent strain has decreased from 0.12% to 0.05%, indicating better resistance to fatigue and structural durability over time when subjected to repeated loads.

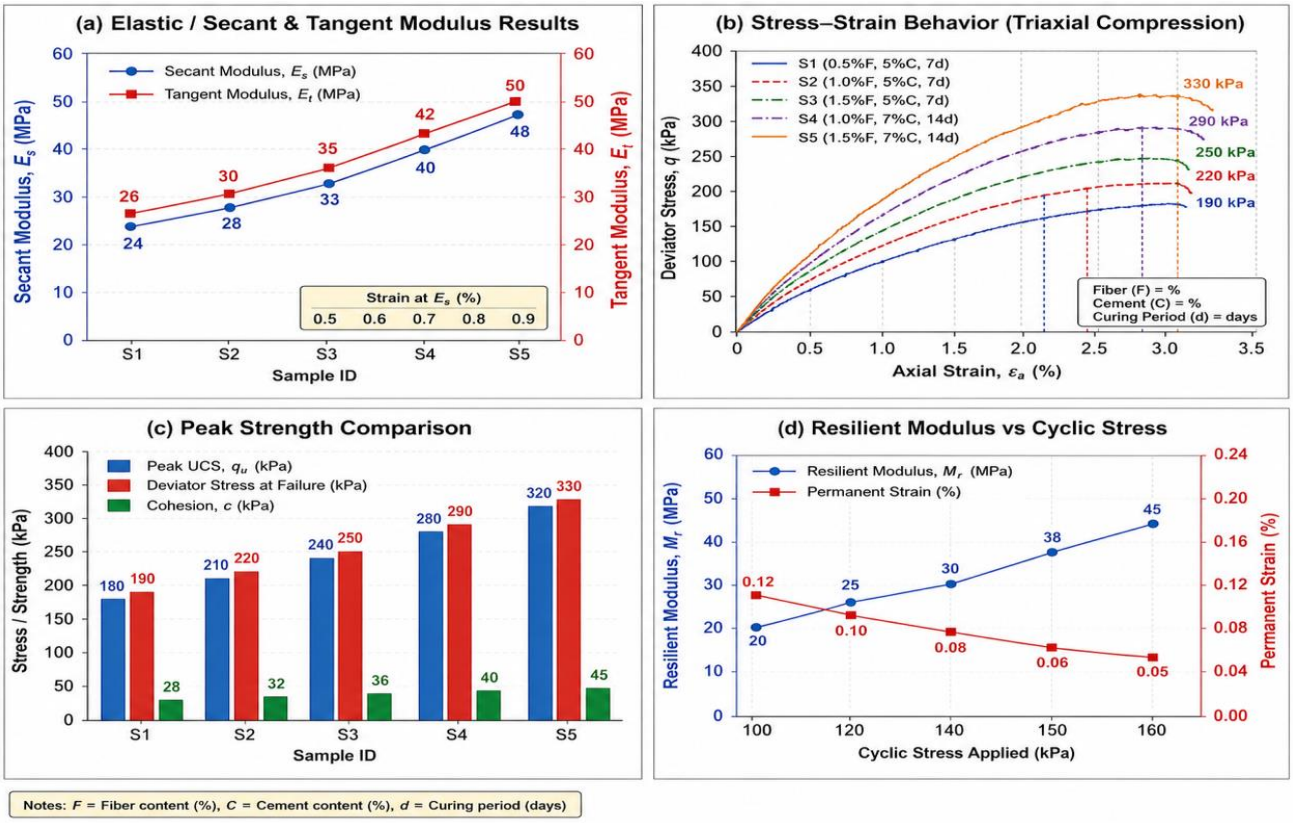


Fig. 16 Simulink results of stress–strain and elastic properties

The fiber reinforcement on the elastic and deformation properties of Laterite soils and the role of cement stabilization is shown by the advanced Simulink analyses in Figure 16. It is observed that in subfigure 16(a), the secant modulus has increased from 24 MPa to 48 MPa, and the tangent modulus has increased from 26 MPa to 50 MPa, which shows the elastic stiffness has been improved. The stress–strain curve of 16(b) shows that the deviator stress increases steadily from 190 kPa (S1) to 330 kPa (S5) and the failure strain increases with the deviator stress, which means that the material has greater ductility and more delayed failure under triaxial compression. Subfigure 16(c) shows the plots of UCS, deviator stress and cohesion with fiber content and curing time, all of which show a clear trend of rising with both fiber content and curing time. As shown in subfigure 16(d), the higher the cyclic stress capacity, the higher the resilient modulus, and the less the permanent strain, indicating that the elastic recovery is better and the permanent deformation resistance is excellent. In general, the validation of the results obtained from Simulink shows the effectiveness of the proposed reinforcement strategy in the case of durable applications of geotechnical infrastructure.

5. Conclusion

The modelling approach using the Quantum-Inspired Digital Twin can be useful in estimating the mechanical response of fiber-reinforced cement-stabilized Laterite soils because it can represent combinations of cement content, curing time, and fiber content. The experimental results show that increasing polypropylene fiber content from 0.5% to 1.5% represents a threefold increase, not a doubling, and is associated with an increase in UCS from 180 kPa to 240 kPa

when the cement content is held at 5% and curing is held at 7 days. Across the complete experimental matrix, where cement content increases from 5% to 7% and curing period increases from 7 to 14 days for selected samples, the maximum UCS reaches 320 kPa and failure strain reaches 2.8%. Cohesion increases to 45 kPa and internal friction angle to 30°, while triaxial deviator stress at failure increases from 190 to 330 kPa and Young's modulus from 25 to 50 MPa.

Resilient modulus increases from 20 to 45 MPa and permanent strain decreases from 0.12% to 0.05%. Secant and tangent moduli increase from 24 to 48 MPa and 26 to 50 MPa, respectively. These results support the capability of the QIDT framework to capture the combined influence of fiber reinforcement, cement stabilization, and curing conditions on the mechanical performance of the investigated Laterite soil.

5.1. Declaration

The authors confirm that they have not used any Artificial Intelligence (AI) based image-generation or Generative Image Synthesis (GIS) tools (such as but not limited to DALL·E, Midjourney, Stable Diffusion, Adobe Firefly) in the preparation, creation or modification of the scientific result figures presented in this manuscript.

All figures were obtained directly from experimental measurements, numerical simulations or analytical results, by means of standard scientific software and laboratory instruments.

Below is a summary of the sources used to make the figures:

Figure(s)	Original Software/Instrument Used
Figures (2-4)	MATLAB R2024a/Simulink (system modeling, workflow diagrams, and simulation framework)
Figures 5(a-d)	Laboratory photographs, Universal Testing Machine (UTM), Scanning Electron Microscope (SEM), and Energy Dispersive X-ray Spectroscopy (EDS/EDX) instrument software
Figures (6-12)	MATLAB R2024a (data processing and visualization), OriginPro 2024 (statistical plots), X-ray spectroscopy analysis software (XAS/EDS processing), and Digital Twin computational framework developed by the authors

The figures were directly exported from the respective software with high resolutions (PNG) without using AI-generated image synthesis and content creation. Only standard editorial work has been done, such as cropping, resizing, arranging in panels, annotating and adjusting the font size or line thickness for clarity in publication. The modifications did not have any impact on the scientific content or interpretation of the results.

Ethical Considerations

This research was conducted in accordance with ethical requirements related to data confidentiality, responsible use of industrial information, and fair involvement of project stakeholders.

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