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Desiccation shrinkage and cracking modelling of laboratory based free and constrained expansive soil using XFEM

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ABSTRACT: This study presents a novel numerical approach for simulating desiccation cracking in expansive soils under laboratory conditions, utilising the Extended Finite Element Method (XFEM) based in ABAQUS, and a User Material (UMAT) subroutine. The model integrates hydro-mechanical behaviours and tensile cracking mechanisms to better evaluate cracking events in real-world scenarios. The global mechanisms of desiccation shrinkage and cracking were numerically modelled via the replication of two laboratory-scale experiments; free and linearly constrained desiccation. The experiment provided data on moisture loss rates, soil properties and internal stress, which were used to validate the numerical model. The key findings demonstrate that employing the refined UMAT code is essential for effectively integrating hydro-mechanical processes in ABAQUS and reveals the impact of numerical parameters on the strain-moisture content relationship until the onset of cracking. This research provides valuable insights for improving the replication and estimation of desiccation-induced cracking in geotechnical engineering, offering a refined framework for simulating cracking under drying conditions.

KEYWORDS: Expansive soil, cracking, desiccation, numerical modelling, shrinkage, field conditions, ABAQUS, XFEM.

1 INTRODUCTION

Desiccation-induced cracking in soils is a significant challenge in geotechnical and geoenvironmental engineering, which is becoming more frequently encountered during the development of soil-supported structures. This damaging challenge is emphasised by the lack of knowledge regarding the exact variables that control the change in soil volume and displacement, and the mechanisms that induce it (Rahardjo & Fredlund, 1993). A good understanding about the characteristics of desiccation in expansive soil is necessary to achieve reliable design of the associated infrastructure. Many approaches have been investigated to uncover the complex nature of unsaturated expansive soil, such as laboratory (Amarasiri et al., 2011; Gui et al., 2018; Peron et al., 2009a; Thyagaraj, 2019; Vo et al., 2016; Yilmaz, 2008) and field-based experimentation (Konrad and Ayad, 1997a, 1997b; Li & Zhang, 2011), as well as in analytical models (Lyu et al., 2020; Morris et al., 1992; Rice & Rosengren, 1968; Scherer 1986, 1988, 1990, 1992, 1999; Sun et al., 2021). Numerical approaches have also been trialed, such as the Discrete Element Method (DEM) (Amarasiri et al., 2011; Gui & Zhao, 2015; Peron et al., 2009b) and the Finite Element Method (FEM) (Abu-Hejleh et al., 1995; Karunarathne et al., 2018; Levatti et al., 2019; Shi et al., 2021; Vo et al., 2016; Weerasinghe et al., 2016). However, studies such as these leave gaps in validated stress information against moisture loss, critical for a consolidated understanding of coupled hydro-mechanics and the numerical modelling of desiccation shrinkage and cracking of expansive soil. This emphasises the need for a three-dimensional model utilising the numerical modelling interface, ABAQUS, using a robust constitutive model and XFEM to reproduce desiccation shrinkage and cracking of expansive soil and generate climatic correlations to the intrinsic properties of the soil.

This paper presents a novel numerical approach for simulating desiccation shrinkage and cracking in expansive soils under laboratory conditions, utilising the Extended Finite Element Method (XFEM) based in ABAQUS and through the definition of a User Material (UMAT) subroutine. The model integrates hydro-mechanical behaviours and tensile cracking mechanisms to better evaluate the nature of expansive soils until the onset of cracking in real-world scenarios. The uniquely coupled model contributes to the field of geotechnical and geoenvironmental engineering, with potential applications in enhancing the durability and resilience of soil-supported structures.

2 METHODOLOGY

The methodology of the experimental laboratory study from literature is described and represented by the framework implemented in ABAQUS via a UMAT subroutine as follows. The comprehensive experimental study completed by Peron et al. (2009a) air dried initially saturated soil samples of Bioley Clayey Silt to uncover the impact of free and linearly constrained desiccation. The free desiccation case's experimental set-up shows a rectangular shaped bar of soil with dimensions for length, width and height of 300mm, 50mm and 12 mm, respectively (Figure 1). The purpose of the sample size selected for the experiment was to study the desiccation of fine-grained soils. The soil bar was placed on a Teflon support, which was treated with a hydrophobic substance to minimise friction between the plate and soil. The friction was minimised to replicate free desiccation which produces baseline shrinkage measurements due to desiccation. In ABAQUS, this free-sliding behaviour is modelled by the tangential behaviour contact properties enabling frictionless displacement and elastic slip within a scalable value of stiffness. The linearly constrained desiccation case was placed on a Teflon support, which included notches to restrain movement along the axial direction, spaced in parallel 2 mm apart (Figure 2). Due to the axial restraint from the notches, typically six to eight cracks initiated and propagated within the experiment (Peron et al. 2009a). In ABAQUS, the notches were not artificially replicated via an equivalent boundary condition (Cheng et al., 2022), but rather numerically drawn to reflect the multiple interacting surfaces. Both test cases were completed in a climatic chamber at a fixed temperature and average relative humidity of 19 ° (±1 °) and 40 % (±4 %), respectively.

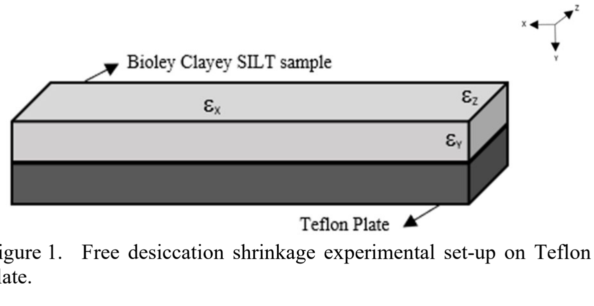

Figure 1. Free desiccation shrinkage experimental set-up on Teflon plate.

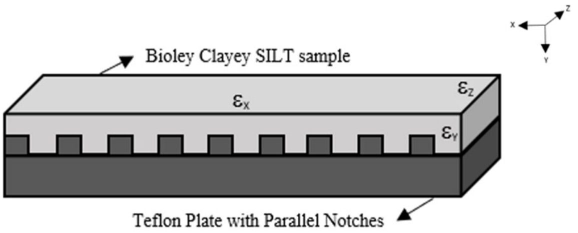

Figure 2. The linearly constrained desiccation shrinkage experimental set-up on notched Teflon plate.

The experimental strain to water content relationship revealed the cracking onset characteristics and the impact to strain in all directions until the onset of cracking. Conclusions drawn from these results included the water content interval for the soil type tested was between 24 % and 20 % at the onset of cracking, which is before the shrinkage limit of the soil. At this point, the mechanical strain in the axial direction was -3.5 %, which governs the threshold of allowable strain before deformation. The axial mechanical strain trend as average water content decreases from drying are shown in Figure 3.

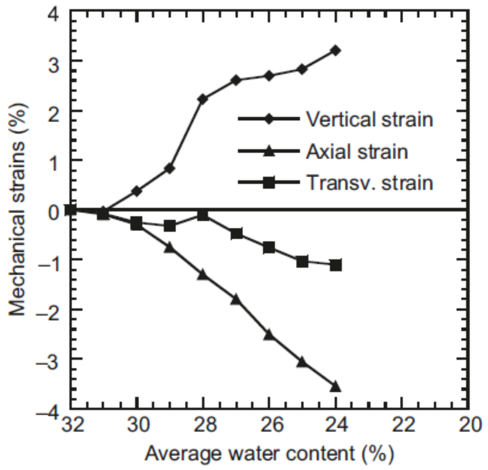

Figure 3. Experimental results from the linearly constrained desiccation test for mechanical strain in three-dimensions with average water content (Peron et al., 2009a).

The external conditions controlled by the climatic chamber and plate characteristics, and the internal factors of the soil are modelled and correlated through a logical framework of validation. The study will compare the bounds of moisture removal to the extent of desiccation shrinkage for the free desiccation case and extent of cracking for the linearly constrained desiccation case of expansive soils. Thus contributing to the gap in coupled hydro-mechanical numerical modelling.

The paper uses ABAQUS as the modelling interface, a User Material (UMAT) subroutine to integrate the constitutive model, Fredlund's (1994) equations as the constitutive model, and XFEM to initiate desiccating cracking (Figure 4). For desiccation cracking, current literature suggests the only way to couple the hydro-mechanical behaviour in ABAQUS would be to use the nonlinear, static-implicit analysis step for fracturing and a user-defined subroutine for hydraulic aspects (Cheng, 2020). This means, ABAQUS will only calculate mechanical output variables by default, while the hydraulic parameters are calculated within the UMAT code and converted into the applicable volumetric deformation for input back into ABAQUS. The paper will use part of this methodology and utilise the static step, as this step outputs the analysis and visual output of the mechanical behaviour. The static step defines the fracture and failure outputs, such as PHILSM, PSILSM and STATUSXFEM, to monitor the cracking surface and the extent of cracking, respectively. However, the paper's methodology is not limited to the static step, as the key numerical modelling contribution uncovered is a unique way to utilise ABAQUS' in-built options for the external hydraulic force to be applied and the resultant hydro-mechanical results to be output within the same model. To simulate a porous media that is partially saturated, the soils step is defined using the incrementation, pore pressure and creep limits, and stabilising coefficients. The ABAQUS step utilises the hydraulic parameters defined by the material properties to inform the mechanical outputs and deformation generated by the UMAT code. Without utilising this feature in ABAQUS, the value of stress, subsequent displacement, and extent of damage could not be generated and monitored incrementally. Instead, interpolation of other hydro-mechanical output variables would be required. In addition, the the model utilises the soils step and pore fluid/stress mesh in ABAQUS to simultaneously consider hydraulic components, such as fluid movement and stress and deformation. Cheng's (2020) research did not utilise this, as experimental data was available to directly correlate water content to the shrinkage rate to inform the change in void ratio and deformation strain. This generated the motivation to establish a climatic correlation for moisture removal rates, enabling the determination of desiccation-induced shrinkage within the UMAT subroutine and the computation of corresponding hydraulic and mechanical parameters.

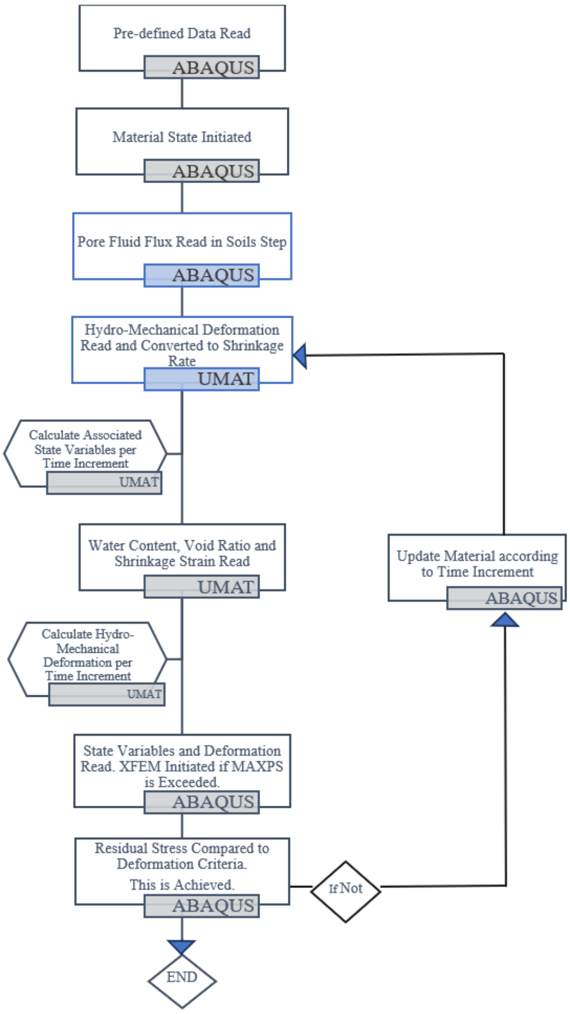

Figure 4. Framework of hydro-mechanically coupled ABAQUS model with UMAT subroutine and XFEM.

The framework and novel numerical approach developed will demonstrate the suitability of ABAQUS, UMAT and XFEM in simulating desiccating expansive soil through the numerical modelling of depth related moisture loss.

The mechanical soil properties inputted in ABAQUS via the user-defined UMAT option are based on research of Peron et al. (2008 and 2009a) and Cheng et al. (2022). The mechanical properties represent an elastic constitutive model and total stresses that are small enough to be recoverable. These components act non-linearly due to the varying mechanical behaviour of expansive soils as the water content changes (Cheng, 2020). Furthermore, the elastic properties, change in stiffness, deformation and subsequent stress and strain are calculated at the end of each increment. This allows for properties, such as the Young's modulus, to be updated as the water content decreases. The relationship between moisture content and stiffness is coded into the UMAT, which is dependent on the difference in strain from the water content evolution.

The initial soil properties for the elastic constitutive model, such as Young's modulus and Poisson's ratio, are obtained from material testing in literature. The simulation desiccates the soil until the extent of shrinkage measured experimentally is reached, or the onset of cracking. The onset of fracturing is dictated by the defined damage criterion, in this case that of the allowable maximum principal stress (ABAQUS, 2022). This user-defined parameter within the simulated ABAQUS model is compared to the generated maximum principal stress from the desiccation volume change. Programmed by default into ABAQUS are Macaulay brackets to signify that soil in the purely compressive stress state will not result in crack initiation (ABAQUS, 2022).

The material properties are defined into separate materials in order to assign unique properties to each part, as illustrated in Table 1 and Table 2. Two parts are used to simulate the experimental cased: soil and Teflon plate. No mechanical components for cracking require definition in the free desiccation case. This better represents real-world conditions and behaviour of unsaturated soil's when desiccating.

Table 1. List of hydro-mechanical model material properties for the free and linearly constrained desiccation case in ABAQUS and UMAT.

Parameter	Soil	Plate	Unit
Young's modulus	*100,000*	$1 \cdot 10^8$	Pa
Poisson's ratio	*0.3*	0.2	-
Specific gravity of solids	*2.726*	10	kg/m^3
Initial water content	*32*	-	%
Initial void ratio	*0.88*	-	-
Fredlund's coefficients (a, b, c)	*0.55, 20, 50*	-	-
Permeability	$1 \cdot 10^{-6}$	-	m/s

Table 2. List of cracking model material properties for the linearly constrained desiccation case in ABAQUS.

Parameter	Soil	Unit
Damage criteria	*3.5*	kPa
Damage evolution	*1.0*	mm
Damage stabilisation	*1.0*	%

In this paper, the objective is for ABAQUS to use a climatically correlated moisture removal rate to determine the extent of shrinkage from desiccation in the UMAT subroutine and output the corresponding hydraulic and mechanical parameters. The correlated water loss rate is represented by the magnitude of pore fluid flux. The UMAT subroutine uses the rate of water loss iteratively with time (Figure 4). This unique piece of code allows the Fredlund (1994) constitutive model to determine its parameters based on the output of ABAQUS, as opposed to predefined constants. The uniquely coupled and UMAT coded model seamlessly integrates the hydro-mechanical behaviour of desiccating expansive soil in a scalable and user-friendly form. The scope includes the accurate numerical modelling of the desiccation effect on the expansive soil up until the onset of cracking. The characteristics of the cracks after onset are not within the paper's scope.

3 RESULTS

Theoretical strain outputs were generated by ABAQUS at unique nodal points at the centre of the soil specimen. During free desiccation, due to the nature of isotropic shrinkage in ABAQUS, only one nodal point and associated data is presented depicting all three strain components. This is because the shrinkage is uniform on the frictionless plate. The successful Fredlund (1994) constitutive model was calibrated to experimental results presented in Figure 5.

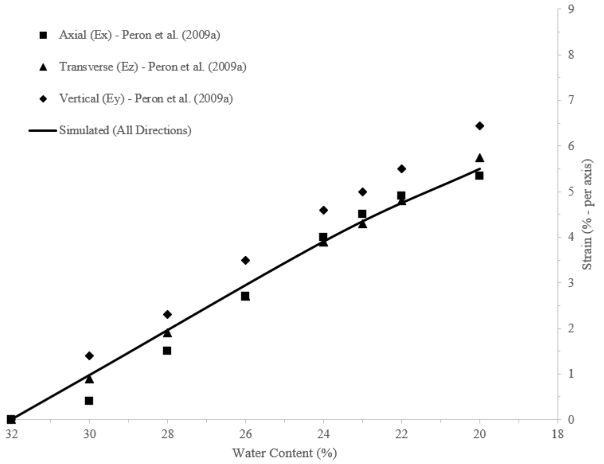

Figure 5. The free desiccation study – strain in the axial (Ex), transverse (Ez) and vertical (Ey) directions as a function of water content for experimental data and the simulated ABAQUS model.

The linearly constrained desiccation experiment was simulated in ABAQUS in a similar manner to the free desiccation case, with the addition of a notched plate, a damage criterion (Table 2), and extra degrees of freedom for crack initiation and propagation. The results from ABAQUS (Figure 6), when compared to the experimental data, are slightly higher in mechanical strain throughout the middle phase of desiccation. However, the trajectory of the linear relationship between mechanical strain and water content aligns with the final recording of axial mechanical strain experimentally.

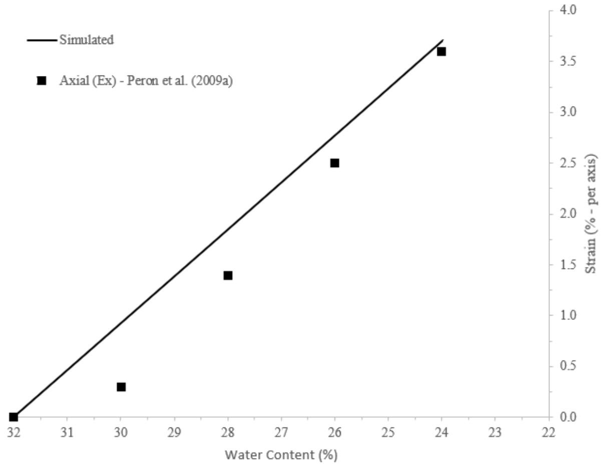

Figure 6. The linearly constrained desiccation study – Horizontal mechanical strain as a function of water content for experimental data and the simulated ABAQUS model.

The ABAQUS output interface (Figure 7) clearly represents the elements of the soil part fracturing at the exceedance of the axial strain threshold (Figure 6), namely the damage criteria. Total facture is achieved as the value of Status XFEM value of 1.0 is reached.

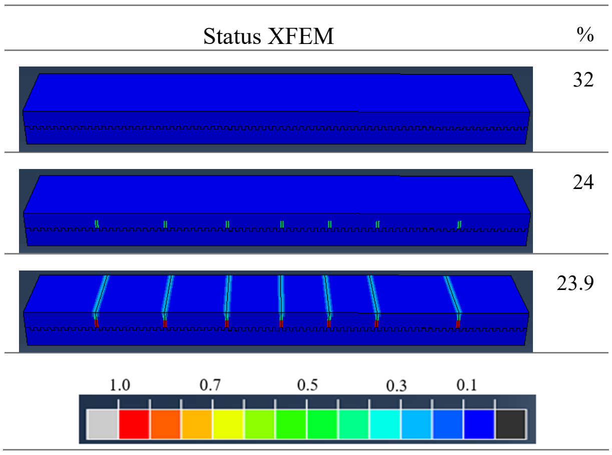

Figure 7. The linearly constrained desiccation study – Status of XFEM development in the simulated ABAQUS model related to water content (%).

4 DISCUSSION

The principal findings of this study highlight several critical aspects of soil desiccation theory and its application to numerical modelling. Firstly, the necessity of employing the refined UMAT code was confirmed, as it enables effective integration of hydro-mechanical processes within ABAQUS to represent the free shrinkage phenomenon. The validity of the free desiccation model is illustrated in Figure 5, where simulated strain results align closely with experimentally measured directional strains.

Secondly, the investigation underscored the significant influence of numerical parameters—including boundary conditions, material stiffness, and Fredlund's coefficients—on accurately representing the relationship between strain and moisture content during shrinkage and up to the onset of cracking. Experimental observations within the free desiccation model revealed discrepancies in transverse and axial directions, primarily caused by the frictionless Teflon plate exhibiting unavoidable friction. Conversely, the ABAQUS model provided a more accurate representation of frictionless behaviour, as demonstrated by the isotropic nature of shrinkage strain development in Figure 5. This finding clearly shows that the numerical model can control and reduce variability in data through consistent and uniform application of loads and boundaries. While natural variance occurs under real-world conditions, the model represents an exact climate, enabling precise calibration of the evaporation rate to match that of the laboratory climatic chamber. In this case, the pore fluid flux, defined as a constant 0.02 L/s, accurately represented a water loss rate of 1.2 %/hr and the associated shrinkage strain. The key contribution of this baseline correlation lies not only in simulating other climatic conditions but also in capturing variability typical of field conditions, such as climatic ranges. This aligns with the third key finding: the modelling framework exhibited substantial adaptability, proving effective across diverse soil types, climatic conditions, and scales—from controlled laboratory tests to potential real-world applications.

The linearly constrained desiccation model demonstrated good agreement with experimental results due to the defined numerical parameters and the UMAT implementation. Drying conditions induced by the pore fluid flux in ABAQUS resulted in shrinkage strain, as calculated in the UMAT subroutine. Boundary restraints from the notches and assigned interactions further influenced axial strain to represent constrained shrinkage of the expansive soil. These defined parameters and behaviours accurately reflected shrinkage strain development as moisture content decreased (Figure 6). The addition of a damage criterion (Table 2), based on the experimentally determined mechanical strain threshold (Figure 3), and the enrichment of elements with XFEM initiated cracking. The relationship between moisture content and mechanical strain governing the onset of cracking produced results consistent with experimental observations, with cracking initiation represented by the final value plotted at 24 % moisture content (Figure 6). The slight numerical discrepancy in shrinkage strain up to the maximum mechanical strain may be attributed to the additional surface area created by crack initiation experimentally, which increased the water loss rate to match the uniform rate simulated in ABAQUS. This highlights the model's ability to replicate behaviours influenced by external variability using uniform input parameters, demonstrating its simplicity and robustness in coupling a hydro-mechanical material model with XFEM.

At the onset of cracking, the notched configuration eliminated the need for an artificial friction relationship. Tensile stress was built up in the model through the defined parameters and constitutive model, enabling accurate initiation of desiccation cracking. The shrinking behaviour of the expansive soil interacted with the constrained notched conditions until cracking occurred. Experimental observations indicated that crack location and frequency were governed by the notch configuration, with parallel notches directly influencing crack direction. These experimentally specified constraints were replicated in the numerical model, successfully demonstrating cracking onset with moisture reduction through XFEM (Figure 7). This reproduction of crack onset location and frequency verifies the assigned boundary conditions, material stiffness, and constitutive model in accurately representing the strain–moisture relationship during shrinkage and up to cracking. While the linearly constrained experiment and numerical replication do not represent real-world restraint conditions, the numerical framework presented here offers the opportunity to simulate more realistic isotropic desiccation.

The significant influence of assigned boundary conditions, material stiffness, and constitutive model was evaluated by comparing computational results to identify governing parameters. The case study revealed that variability in external conditions primarily governs the shrinkage response of homogeneous expansive soil within the ABAQUS model. This occurs because UMAT iteratively updates stiffness and Fredlund coefficients as moisture content decreases. Experimental moisture reduction is susceptible to variance due to climatic conditions and soil heterogeneity. While the paper's ABAQUS model applies a uniform and constant water loss rate across all exposed soil surfaces, its ability to correlate moisture loss and shrinkage strain with experimental results enables further application to heterogeneous climatic conditions and soil types. Nonetheless, as shown in Figure 5, the homogeneous numerical model correlated well with experimentally measured shrinkage strain, with slight differences attributable to experimental variability. Therefore, the framework demonstrates both the ability to replicate experimental conditions using a simple, evenly distributed water loss rate and the potential to increase complexity through heterogeneous application of external and internal parameters. Hence, this case study provides evidence that desiccation shrinkage can be accurately modelled and climatic correlations established in ABAQUS using the unique UMAT code.

5 CONCLUSIONS

The model demonstrated that the rate of desiccation shrinkage, as a function of water content, was strongly influenced by the constitutive model's coefficients and boundary conditions, with friction and moisture reduction identified as key governing factors. Notably, the onset of primary cracking did not occur without constraint and progressed incrementally as the tensile strength of the soil was exceeded, replicating experimental observations.

This study significantly advances the understanding of desiccation-induced soil cracking and provides a robust numerical framework for estimating and correlating such phenomena with internal and external factors at the laboratory scale. The key findings confirm that employing the refined UMAT code is essential for effectively integrating hydro-mechanical processes in ABAQUS. Numerical parameters, such as boundary conditions, stiffness, and Fredlund's coefficients, were shown to substantially influence the accurate representation of the strain, moisture relationship up to the onset of cracking. Furthermore, the modelling framework demonstrated adaptability across diverse soil types, climatic conditions, and scales, from controlled laboratory tests to potential real-world applications.

The discussion of results highlighted the following contributions:

- Successful replication of experimental shrinkage strain development and cracking onset through XFEM enrichment and damage criteria.
- Precise calibration of evaporation rates to laboratory conditions and potential for simulating heterogeneous climatic scenarios and soil variability.
- Opportunities for increased complexity and realistic isotropic desiccation modelling beyond the homogeneous case studied.

Overall, this research delivers a validated modelling approach that couples hydro-mechanical behaviour with fracture mechanics, offering valuable insights for geotechnical and geoenvironmental engineering. Its potential applications include improving the durability and resilience of soil-supported structures and informing industrial-scale modelling under variable climatic conditions.

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