University of Sydney

Department of Civil Engineering

THERMO-MECHANICAL BEHAVIOUR OF TWO RECONSTITUTED CLAYS

BY

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To my parents Mohtaram and Ghorbanali

With love and gratitude

Synopsis

The effect of temperature on soil behaviour has been the subject of many studies in recent years due to an increasing number of projects related to the application of high temperature to soil. One example is the construction of facilities for the disposal of hot high level nuclear waste canisters (150-200°C) several hundred meters underground in the clay formations. Despite this, the effects and mechanism by which temperature affects the soil properties and behaviour are not fully known. A limited amount of reliable experimental data, technological difficulties and experimental methods employed by different researchers could have contributed to the uncertainties surrounding the soil behaviour at elevated temperature. Also several thermo-mechanical models have been developed for soil behaviour, but their validity needs to be examined by reliable experimental data.

In this research, efforts have been made to improve the experimental techniques. Direct displacement measuring devices have been successfully used for the first time to measure axial and lateral displacements of clay samples during tests at various temperatures. The thermo-mechanical behaviour of two reconstituted clays has been investigated by performing triaxial and permeability tests at elevated temperature. Undrained and drained triaxial tests were carried out on normally consolidated and over consolidated samples of M44 clay and Kaolin C1C under different effective stresses, and at temperatures between 22°C and 100°C. Permeability tests were carried out on samples of M44 clay at temperatures between 22°C and 50°C. The effects of temperature on permeability, volume change, pore pressure development, shear strength and stiffness, stress-strain response and critical state parameters for different consolidation histories have been investigated by comparing the results at various temperatures. The results are also compared with the predictions of two models.

It has been found that at elevated temperature the shear strength, friction angle and initial small strain stiffness reduce whereas permeability increases. The slope of the swelling line in the ν-p' plane has been found to reduce with temperature. The slope of the isotropic normal consolidation line (INCL) and critical state line (CSL) in the ν-p' plane, λ, have been observed to be independent of temperature, but both the INCL and the CSL shift downwards to lower locations as temperature increases. The deformations during drained cooling and re-heating cycles have been found to be elastic and to simply reflect the expansivity of the soils solid particles. The thermal volume changes during undrained heating have been observed to be direct results of the thermal expansion of water and clay particles. The internal displacement measuring devices have been found to produce reliable data for the variation of strains at elevated temperature.

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Contents

List of Symbols

a	a parameter related to the shape of thermal plastic strain curve
A	cross section area of sample
α_1	a parameter defining the thermal over consolidation effect
α_p	a parameter defining the slope of thermal plastic strain curve
α	linear coefficient of thermal expansion
α_2	coefficient of drained thermal expansion of soil during thermal cycle
α_0	a parameter defining curvature of the LY locus
α_u	coefficient of undrained thermal expansion of clay
α_{dr}	coefficient of drained thermal expansion of clay
α_w	cubical coefficient of thermal expansion of water
α_s	cubical coefficient of thermal expansion of solid
α_{st}	physico-chemical coefficient of structural volume change
β	the hardening parameter for TY locus
B	pore pressure coefficient
C_V	coefficient of consolidation
C_1	intersection of the HC curve with p′ axis
C_2	a shape parameter related to HC curve
C	electrolyte concentration
C_α	coefficient of secondary consolidation
CSL	critical state line
D	sample diameter
d_i	dielectric constant
$d\varepsilon^e_v$	elastic volumetric strain increment
$d\varepsilon^p_{vm}$	plastic volumetric strain increment due to mechanical loading
ΔV_{dr}	volume of expelled water
ΔT	temperature change
Δv_a	volume of expanded adsorbed water per unit surface area of clay mineral per °C
Δe_{st}	changes in void ratio due to temperature cycling
$d\varepsilon^p_s$	plastic shear strain increment
$d\varepsilon^p_v$	plastic volumetric strain increment

$d\varepsilon^{p}_{vmT}$	thermal plastic strain increment when thermo-mechanical path reaches LY locus due to heating
$d\varepsilon^{p}_{vTm}$	mechanical plastic strain increment at constant temperature
$d\varepsilon^{e}_{vT}$	elastic volumetric strain increment due to thermal loading
e	void ratio
ε_a	axial strain
ε_s	shear strain
ε_v	volumetric strain
E_m	membrane Young's modulus
ε^{p}_{vT}	plastic volumetric strain due to thermal loading
ε_v	volumetric strain
G_s	specific gravity of solid
G_{50}	secant modulus at 50% of maximum deviator stress at failure
G	initial shear modulus at small strain
Γ	specific volume corresponding to $p'_c = 1$ kPa on CSL
H_{dr}	length of drainage path
H	sample height
H_c	sample height after consolidation
INCL	isotropic normal consolidation line
I_P or PI	plasticity index
k_1	a parameter defining the thermal over consolidation effect
k	permeability
K_v	absolute permeability
K	bulk modulus
κ	slope of swelling line in ν-p′ plane
LY	loading yield
L_d	size of double layer
λ	slope of INCL in ν-p′ plane
LL	liquid limit
m_v	comperessibility
μ_w	viscosity of water
M	slope of CSL in q-p′ plane
μ	Poisson's ratio
NC	normally consolidated

N	Specific volume corresponding to $p' = 1$ kPa on INCL
ν	specific volume
n	porosity
OCR	over consolidation ratio
OC	over consolidated
p'	mean effective stress
p'_c	mean effective stress at the end of mechanical consolidation
p'_{c0}	preconsolidation pressure or p'_0
p'_{cs}	mean effective stress at critical state
p'_0	stress controlling the size of the yield locus
ρ_d	dry density
PL	plastic limit
ρ_w, γ_w	density of water
q	deviator stress, $\sigma_1 - \sigma_3$ or $\sigma'_1 - \sigma'_3$
q_f	deviator stress at failure
SG	specific gravity
S_S	specific surface
S	unit electronic charge
σ_1	major principal stress
σ'_1	effective major principal stress
σ_3	minor principal stress
σ'_3	effective minor principal stress
t	time
t_{90}	the time to reach 90% consolidation
t_m	thickness of membrane
T	temperature
T_c	a reference temperature corresponding to intersection of the TY locus with T axis
TY	thermal yield
T_{HC}	temperature at which the expansion-contraction behaviour of OC samples occurs
u	pore pressure
V	volume
V_c	cation valence
V_w	volume of water

V_s	volume of solid
V_C	volume of sample after consolidation
V'_w	volume of water after correction for temperature
V'_s	volume of soil solid after correction for temperature
W_s	weight of solid
W_w	weight of water