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The paper was published in the proceedings of XVI Pan-American Conference on Soil Mechanics and Geotechnical Engineering (XVI PCSMGE) and was edited by Dr. Norma Patricia López Acosta, Eduardo Martínez Hernández and Alejandra L. Espinosa Santiago. The conference was held in Cancun, Mexico, on November 17-20, 2019.

Mechanical Stability of Cemented Porous Heat Storage Media

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Abstract. Thermal energy storage, such as in the form of solid sensible heat storage systems, is one of the widely used technologies for balancing the energy demand and supply in thermal power plants, thermal process industries, domestic hot water production, district heating etc. Hence, understanding the mechanical performance of such systems, in particular when they are designed as part of the sub-structure of buildings with load bearing capabilities, is of utmost importance. In this study, the mechanical stability of a commercial cement-based porous heat storage material is analyzed experimentally by performing uni-axial, oedometer and tri-axial stability tests under controlled temperature conditions between 20 and 70°C. The results show a dependence of the mechanical properties of the porous heat storage material on the medium temperature, which when unaccounted for can result in an inaccurate system design.

Keywords. Mechanical stability, temperature, cemented heat storage media.

1. Introduction

Thermal energy storage systems [1, 2] in the form of sensible heat storage systems [3] are nowadays commonly used to capture and store solar thermal power or other sources of energy for periods of up to several months, for future household and industrial uses. Solid sensible heat storage systems [4, 5] systems generally have load bearing capabilities and are typically designed as part of the sub-structure of buildings [6], and hence accurate assessment of their mechanical properties prior to their design is of paramount importance.

On this basis, in this research, the mechanical stability of a commercial cement-based porous heat storage material (named Füllbinder L) is analyzed experimentally by performing uni-axial, oedometer and tri-axial stability tests under controlled temperature conditions between 20 and 70°C.

2. Experimental program

2.1. Tested material

In Table 1, a summary of the determined physical properties of the investigated Füllbinder L material is presented. The test specimens are generally prepared with a

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selected design water to solids ratio of 0.8, and then stored in water for up to 28 days. Storage in water ensures full saturation and prevents possible early-age cracking of specimen due to cement hydration [7]. A 3-D view and a thin section of a dried porous Füllbinder L heat storage material after 28 days of curing is shown in Figure 1.

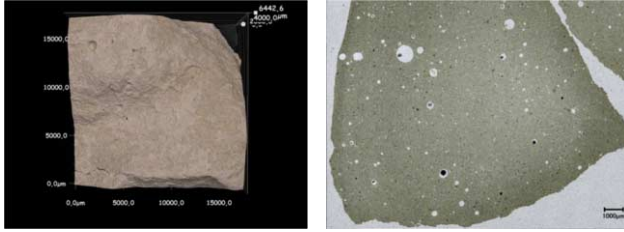


Figure 1. 3-D view (left) and thin section (right) of a Füllbinder L specimen.

Table 1. Physical properties of the Füllbinder L heat storage material

Property	Füllbinder L (saturated)
Bulk density ρ_{sat} (kg m^{-3})	1583
Porosity n (-)	0.543
Specific gravity of solids G_s (-)	2.28
Thermal conductivity λ ($\text{W m}^{-1} \text{K}^{-1}$) ^(a)	0.960
Specific heat capacity c ($\text{J kg}^{-1} \text{K}^{-1}$) ^(a)	2083.4
Hydraulic conductivity K ($\times 10^{-8} \text{ m s}^{-1}$)	11.95
Coefficient of thermal expansion α ($\times 10^{-6} \text{ K}^{-1}$)	10.7
Modulus of elasticity E (GPa)	1.9

^(a): Effective parameters obtained using Decagon KD2 Pro transient needle probes

2.2. Equipments used

Figures 2 to 4 show the equipments employed for investigating the dependence of the mechanical behavior of the Füllbinder L heat storage material on medium temperature. The equipments used include the uni-axial, oedometer and tri-axial devices as well as a climate chamber used for storing the samples at the desired levels of temperature and humidity to maintain the desired test conditions.



Figure 2. UL-60 (left) and UL-25 (right) uni-axial testing devices for large and small sample sizes, respectively.



Figure 3. UL-25 oedometer device (left) and UL-60 climate chamber for storing samples (right).



Figure 4. UL-60 tri-axial devices for: room temperature (left) and elevated temperatures (right).

2.3. Experimental procedure

Analysis of the evolution of strength of the Füllbinder L material with age was conducted at room temperature for different curing periods ranging up to 28 days using uni-axial and oedometer tests (loaded up to a stress level of 800 kPa). All the specimens for room temperature testing were cured by storage under water. For the analysis of temperature effects on the mechanical behavior of the Füllbinder L material, as a worst case scenario, all the tests were performed by curing the specimens at natural condition for a short curing period (7 days). Prior to the temperature controlled tests, the samples were placed inside the climate chamber with a humidity of 50% and the required test temperatures (20, 45 and 70°C) for a duration of 24 hours. The sample sizes were: 50 mm diameter and height of 100 mm for the uni-axial tests, 70 mm diameter and height of 20 mm for the oedometer tests, and 100 mm diameter and height of 200 mm for the tri-axial tests.

3. Results and discussion

In Figures 5 to 9, results of the uni-axial, oedometer and tri-axial tests on the Füllbinder L material are presented.

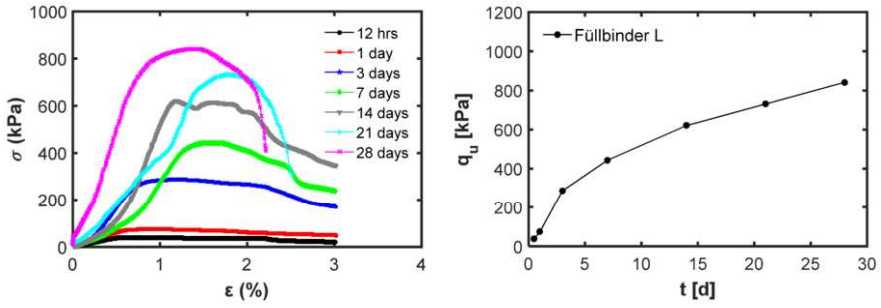


Figure 5. Evolution of the unconfined compressive (uni-axial) strength of Füllbinder L with curing period.

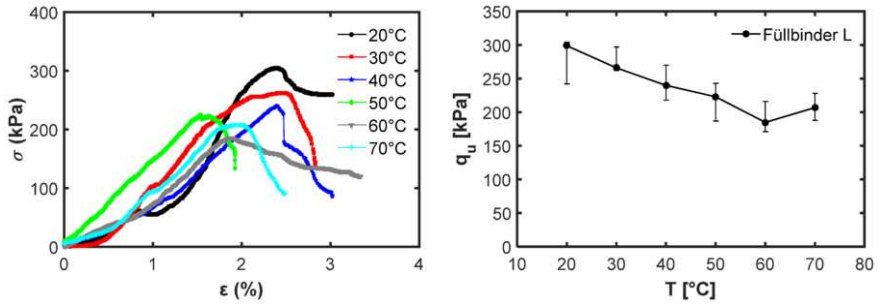


Figure 6. Variation of the uni-axial compressive strength of Füllbinder L with temperature.

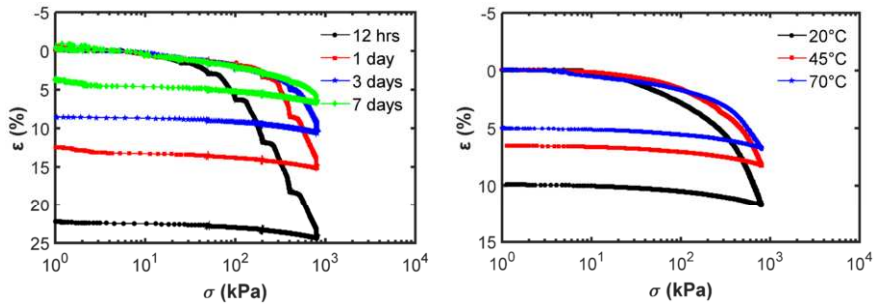


Figure 7. Oedometer test results at different curing periods (left) and temperatures (right).

Generally, the strength/stiffness of the material at room temperature increases with age/curing, due to cement’s binding and exothermic hydration processes, Figures 5 and 7 (left). With regards to the mechanical performance of the Füllbinder L material at elevated temperatures, Figures 6, 7 (right), 8 and 9, the oedometer and tri-axial tests are expected to show a similar behavior, as the specimen is exposed to a confinement (or a confining pressure), and is then loaded vertically until failure or the desired stress level. Whereas, the uni-axial testing is expected to be different from the two, as the sample is unconfined laterally and then loaded vertically until failure.

Generally, exposure of the Füllbinder L material to a higher temperature decreases its ductility (or increases its brittleness) as shown by the higher sample strain at lower temperatures for both the oedometer and tri-axial tests, Figures 7 (right) and 8. This change in the stiffness of the material also results in an increase in the strength of the

material when a confinement is present (i.e. the odometer and tri-axial tests), as shown by the decrease in the measured strain of the odometer tests for the given vertical stress and an increase in the effective cohesion c' of the material from 28.04 kPa at 20°C to 92.08 kPa at 70°C in the tri-axial test. Whereas, as expected, the uni-axial compressive strength of the specimen decreases with an increase in temperature, as the brittle samples fail comparatively early at higher temperatures, as compared to the more ductile samples at lower temperatures, due to the absence of confinement (Figure 6).

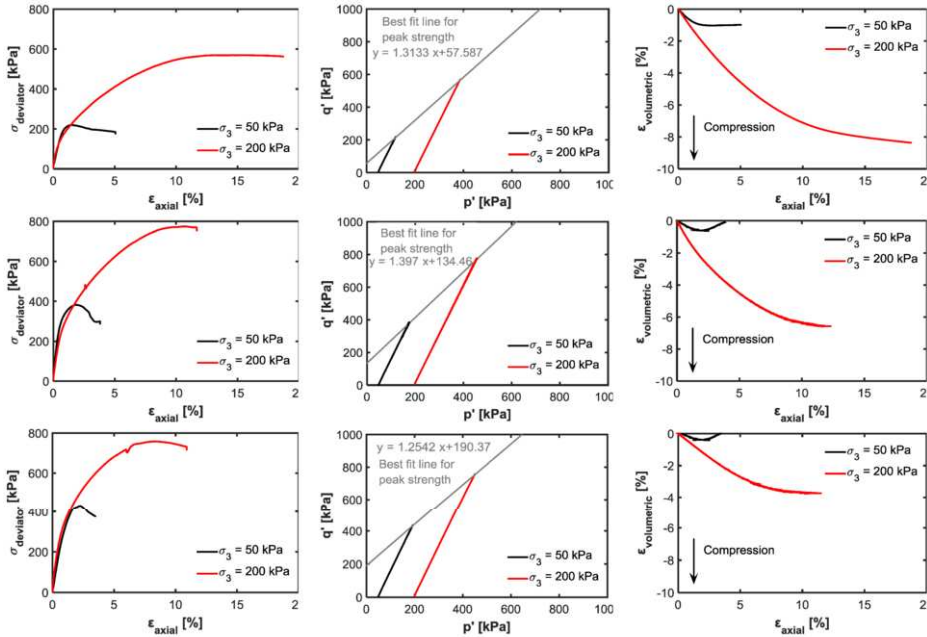


Figure 8. Tri-axial test results at temperatures of 20°C (top), 45°C (middle) and 70°C (bottom).

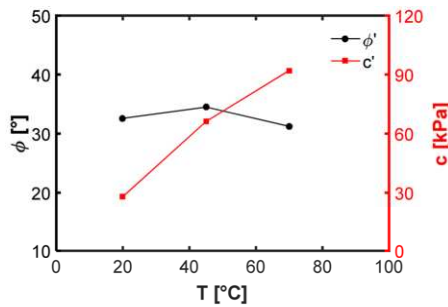


Figure 9. Comparison of the effective shear coefficients (c' and ϕ') of the tri-axial tests at the selected temperatures.

As a summary, the Füllbinder L material is generally mechanically stable at elevated temperatures for use in water-based sensible heat storage systems, with a more robust performance obtained when lateral confinement is provided (e.g when designed as an underground structure or as a part of the load bearing sub-structure of buildings). Whereas, when proper confinement is not provided, the heat storage material has a

significantly lower strength at elevated temperatures, mainly due to a reduction in its ductility, and possible formation of cracks due to its brittleness. When unaccounted for, the formation of significant cracks along the heat storage material can significantly lower the effective thermal conductivity and hence the desired loading/unloading rates of the overall system. Hence, understanding of the mechanical behavior of solid sensible heat storage materials can provide a valuable insight on the design load considerations and allowance of confining pressures for sensible heat storage systems, which are used as part of the sub-structure of buildings.

4. Conclusions

The mechanical stability of a commercial cement-based porous heat storage material, named Füllbinder L, was experimentally investigated by performing temperature controlled (between 20 and 70°C) uni-axial, oedometer and tri-axial tests. The findings indicate the Füllbinder L material is generally mechanically stable when lateral confinement is provided, such as when it is designed as a part of the load bearing sub-structure of buildings, but has a reduced strength due to its brittleness at elevated temperatures, when confinement is not provided. When the reduction of strength at elevated temperatures in a laterally unconfined system is not accounted for in the design and set-up of solid sensible heat storage systems, it can consequently lead to the formation of major diagonal cracks in the heat storage material. Formation of diagonal cracks significantly lowers the effective medium thermal conductivity, resulting in an inefficient heat transport and slower loading/unloading rates of the overall system.

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