Anisotropic features on the thermal conductivity of a deep argillaceous formation

Enrique Romero*, **Núria Sau***, **Analice Lima***, **Hervé Van Baelen****, **Xavier Sillen**** & **Xiangling Li*****

* Universitat Politècnica de Catalunya, Spain
** ONDRAF/NIRAS, Brussels, Belgium
*** EIG EURIDICE, Mol, Belgium

The thermal conductivity of soils and rocks is becoming increasingly important due to the rise of new applications in energy geotechnics, particularly in the design of energy geo-structures, energy geo-storage and deep geological disposal of heat-emitting and long-living radioactive waste. A clear influence of bedding planes on the anisotropic heat conduction has been identified by Chen et al. (2011) and Garitte et al. (2014), when using back-analysis methodology on in situ heating tests and on different sedimentary argillaceous host formations for deep geological disposal of radioactive waste that exhibit cross-anisotropic features (Boom Clay, Opalinus Clay and Callovo-Oxfordian Clay for the Belgian, Swiss and French potential host rocks, respectively). In this research, anisotropy features of Ypresian clays (an argillaceous Belgian reference host rock) have been studied using direct determinations at laboratory scale. Nevertheless, exploring thermal conductivity features on this type of sedimentary rocks with bedding planes is not straightforward. One of the main drawbacks when laboratory tests are performed under low stress conditions refers to the possibility of opening of fissures and gaps along bedding planes that affect the correct determination of the thermal conductivity.

Two expressions for λ / λ_{sat} have been plotted in Figure 1 together with the expected range for the variation in porosity n and degree of saturation S_r for Ypresian clays. Data coming from compacted states on the same clay at different S_r have been also presented. As observed, S_r plays an important role and therefore careful pre-conditioning protocols should be followed to restore the initial state of the material, to ensure its saturation and to avoid gaps and fissures before measuring thermal conductivity.

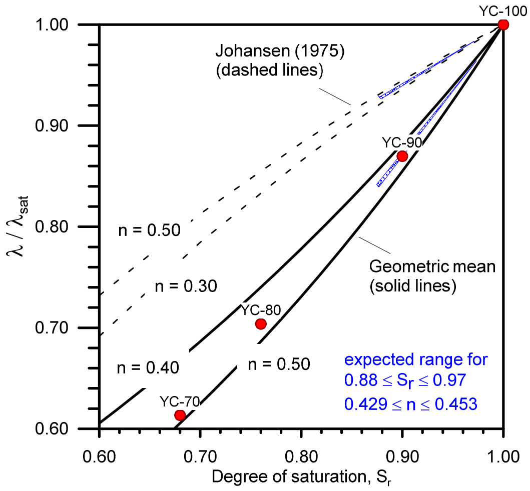

Figure 1. Partial saturation effects on thermal conductivity (expected range for n and S_r of as-retrieved Ypresian clays). Results from statically compacted Ypresian clays.

In this study, pre-conditioning tests have been carried out before thermal conductivity measurements on trimmed samples with beddings planes orthogonal and parallel to heat flux. Different protocols have been followed to perform these pre-conditioning tests in a high-pressure isotropic cell. When following Protocol 1 (Pr-1), the sample has been loaded to a total mean stress close to geostatic condition (3.45 MPa) and then unloaded. These processes have been performed under constant water content and using controlled stress rate. Protocol 2 (Pr-2) follows exactly the same stress paths, but after attaining in situ conditions, the sample has been put in contact with synthetic water.

The thermal conductivity setup (steady-state method) was designed to apply a controlled higher temperature at the top of a cylindrical specimen (38 mm in diameter and 40 mm high) and to maintain the other end at a constant ambient or slightly higher temperature. The temperature at the boundaries was controlled by thermostats with electrical resistances and thermocouples placed inside top and bottom caps. Figure 2 (left) presents a cross-section of the setup. Two heat flux sensors with reference material (1 mm polycarbonate disc with 0.20 $Wm^{-1}K^{-1}$ between two 3 mm high-conductive aluminium discs) were used. Small holes were drilled into the aluminium discs and thermocouples inserted to measure the temperature of the discs.

Thermal conductivity tests were run with an average specimen temperature close to 40°C, with a thermal change ΔT across the sample between 18 and 20°C. To minimize water content re-distribution, testing times were kept as short as possible (usually 60 min to reach steady-state). Figure 2 (right) summarizes the thermal conductivities values of pre-conditioned samples (Pr-1 and Pr-2) and without pre-conditioning. These results highlight the importance of restoring initial degree of saturation. Test results showed good agreement with back-analyses results obtained in a constant volume heating cell by Romero et al. (2013).

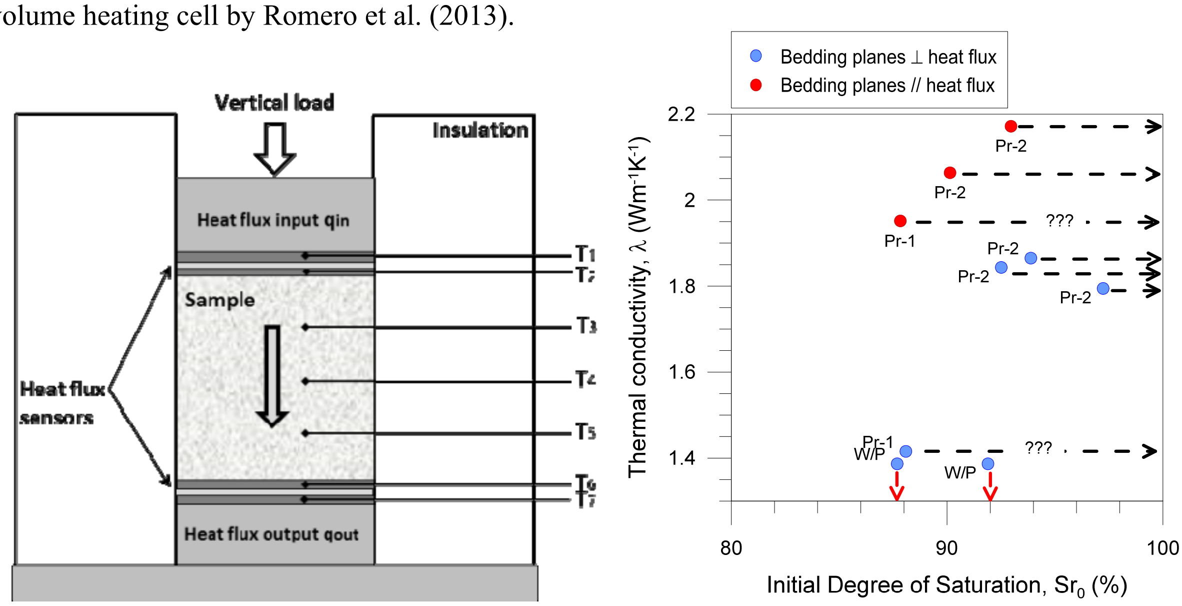

Figure 2. Left: Cross-section of thermal conductivity setup. Right: Thermal conductivity results for natural Ypresian clays.

CONCLUSIONS

Higher values than those reported by previous reports on the same sedimentary clay formation have been measured, as a consequence of the strict pre-conditioning protocols followed on the samples. These higher values were also consistent with the values reported when using back-analysis methodology in a constant volume heating cell. Clear anisotropic features have been detected, with higher thermal conductivity when flow was parallel to bedding planes ($\lambda_{\perp}$ = 1.83 $Wm^{-1}K^{-1}$ versus $\lambda_{//}$ = 2.11 $Wm^{-1}K^{-1}$, with $\lambda_{//} / \lambda_{\perp}$ = 1.15). The results also highlighted the need to follow strict protocols to pre-condition argillaceous materials with bedding planes to ensure high saturation and to minimise the effects of the opening of fissures during thermal conductivity tests.

REFERENCES

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