Insights into the organization of cellulose in ancient Egyptian papyrus

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Written papyri from Ancient Egypt have survived through centuries, providing insights into Egyptian culture a few millennia ago. This long-lasting writing support was made from *Cyperus papyrus* plants, commonly found close to the Nile river. Two layers of raw papyrus strips were stacked together with a 90 degrees relative orientation, and the final writing support was obtained after a phase of drying and polishing. The main constituent of the papyrus plant is cellulose, a polysaccharide of chemical formula $(C_6H_{10}O_5)_n$, consisting of a linear chain of D-glucose units. Several crystal structures of cellulose are reported, with the I_β form, which consist of a two-chain monoclinic structure, predominantly found in plants. Cellulose crystallites tend to organise as fibers and bundles of fibers, giving rise to a multiscale organization. In this project, we investigate a series of papyrus fragments from the Champollion museum (département de l'Isère, Vif, France). High-resolution powder X-ray diffraction data were recorded at the ID22 beamline of the ESRF. Two phases of cellulose I_β with different domain sizes (~3 nm and ~15 nm) are present in the papyrus samples, along with Ca- and Mg-oxalates. Even if possibly present in the raw papyrus plant, oxalates also result from bacterial activity over time. The object here is to understand the origins of the two cellulose phases, either a feature of the papyrus plant and/or the result of mineralisation over time, and the role of the oxalates in the aging of the material and the evolution of its elastic properties. To do so, powder X-ray diffraction maps were recorded at ID13 (ESRF), using a ~2 x 2 μm^2 beam. Each 2D diffraction pattern of the map was divided into 36 sectors and integrated (pyFAI software). A parametric Rietveld refinement was implemented using Topas, refining concomitantly the 36 sectors. Identical values for the scale factors of the two cellulose phases, their cell parameters and peak shape parameters were imposed for each of the sectors. Preferred orientation was modelled using second order spherical harmonics and the March-Dollase function for the two phases of cellulose, respectively, and the corresponding parameters were allowed to refine in an independent way for each sector. The additional oxalate phases, present as large crystals, were described through Le Bail fitting. If the first cellulose phase (~80%wt, small domain size) shows some distribution inhomogeneity in terms of domain size and preferred orientation, the second one (~20%wt, larger domain size) is present in a more homogeneous way. Through this approach, we gain deeper insight into the complex hierarchical organization of this material engineered by Ancient Egyptians, and its evolution with the passage of time.

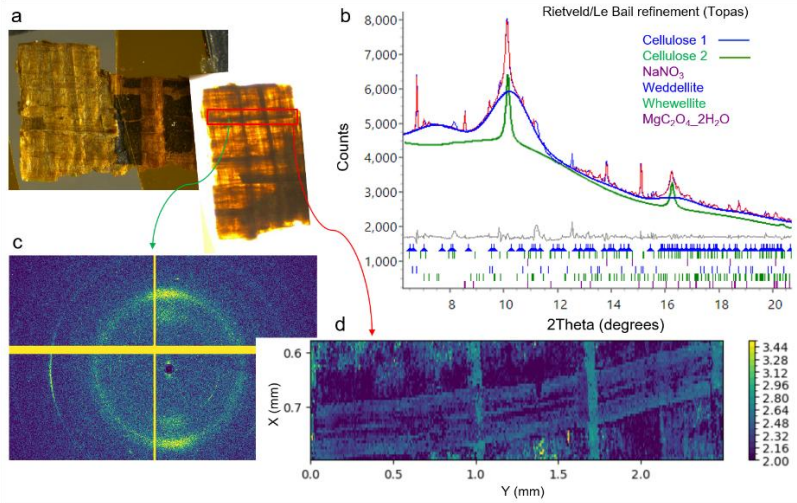


Figure 1. *View of a papyrus fragment from the Champollion museum (a). A Rietveld refinement is carried out against the data collected on the papyrus support, with the presence of two cellulose phases (b). A strong fiber texture effect appears when measuring on horizontal and vertical vascular bundles crossing the papyrus (c). Detailed features of a horizontal vascular bundle following the domain size distribution of the first cellulose phase (d).*