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Water transport through hygroscopic porous materials (paper, wood, textiles, fiber panels): a subtle three-phase flow

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Most bio-based materials, such as paper, natural textiles, sponges, wood or plants, fiber panels for insulation, are porous systems through which water transfers play an essential role in the applications. A specificity of these materials is that they are also hygroscopic: they can absorb huge amounts of water, typically up to about 25% of their dry mass, from ambient vapor, in the form of bound water confined at a nanoscale in the amorphous regions of the cellulose structure, a bound water at the origin of the significant swelling of these materials. Remarkably, this bound water is also strongly mobile inside the solid phase. For example, the bound water contained in a cellulose fiber stack whose porosity has been filled with oil may be extracted by drying, proving that it is transported inside the fibers throughout the network. Moreover, the corresponding transport diffusion coefficient of bound water appears to be rather large, in the order of the self-diffusion coefficient of (free) water. These characteristics imply that, more generally, in hygroscopic porous materials, water can be transported through the system in three different phases, i.e., vapor, free water and bound water, which are strongly coupled via sorption or desorption processes. Finally, the coupling between some or all of these different processes leads to unexpected physical characteristics.
The original implications are illustrated by the long-term evolution of an aqueous droplet, possibly containing particles such as pigments and viruses or solute such as ions and polymers, and reaching the surface of a cellulosic sample. It is generally considered that such a droplet somewhat spreads, penetrates the structure, stabilizes and eventually dries. In fact, it may be shown from NMR (nuclear magnetic resonance) relaxometry and MRI (magnetic resonance imaging) that, instead of drying, the water is absorbed as bound water and diffuses throughout the entire structure. Thus, the initial (free) water rapidly disappears from the porosity, while the non-absorbed solute or particles remain stuck to the solid surfaces in the initial region of liquid penetration.
Another original effect if the imbibition of wood with water. As observed with NMR and MRI, the standard liquid water penetration thanks to capillary effects through vessels is slowed down by several orders of magnitude of time because the structure does not allow the invasion of free water in the regions where cell walls are not saturated with bound water.

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References

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