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Water management of plant tissues during frost-thaw cycles

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Plant tissues have developed several strategies to cope with multiple cycles of freezing and thawing events without being damaged. Some of these strategies are of physiological nature, others arise from structural properties. Understanding the involved strategies and mechanisms of plants exposed to frost conditions is of high interest, as they could potentially be used for the development of bio-inspired construction materials with optimised properties in terms of frost resistance, thermal isolation and guided water/moisture transport.

A decisive factor with regard to frost resistance in plants is the dehydration of the tissue cells leading to an increase of mobile water in the intercellular space. In contrast, freezing within the cells threatens the survivability of the plant. The intercellular water is then transported to species-specific and tissue-specific locations in the plant where freezing is not critical. For this water management, properties of the plant's microstructure are crucial, which are arising from the arrangement of the tissue cells. This arrangement results in highly heterogeneous and anisotropic conditions. Particularly the role of these structural effects is of interest for a transfer to construction materials.

Since the involved thermo-hygro-mechanical processes in plant tissues upon freezing and thawing cycles are strongly coupled, a modelling approach based on the Theory of Porous Media (TPM) is applied, which describes the multiphasic and multicomponent aggregate on the macroscale. In particular, a quaternary model is introduced with a solid skeleton (composed of the tissues cells) and two fluids in the intercellular space, namely, gaseous air and liquid water, which may turn into solid ice. The phase transition of water occurs at a singular surface, which is characterised by a jump in physical quantities, such as the density. The mass transfer can be formulated by using the energy jump at this interface leading to a thermodynamically consistent formulation. In this approach, the interfacial area between liquid and solid water in the partially saturated plant tissues needs to be considered. The freezing of the pore water leads to the necessity to consider the so-called compaction point in the material description, as the bulk material undergoes a transition from a porous material to a solid material. Furthermore, the cell dehydration is included by a production term in the mass balance of the solid skeleton using a Darcy-type law for the cell-wall perfusion. A similar Darcy-type approach was chosen for the fluid flow within the intercellular space with spatially varying anisotropic permeability conditions enabling, thereby, a description of the water management. All these effects are illustrated by selected numerical examples.

References

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