Final version, Febr. 18th 1994

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The Rheology of Wood - Considerations of the Mechano-Sorptive Creep

Abstract

This review of previous investigations is limited to the most descriptive material perceived by the authors to the actual phenomenon called "mechano-sorptive creep in wood". A detailed explanation of the situation today is presented, focusing on the macroscale considerations, highlighting also the influence of microscaled components (morphology, chemistry) in wood, which may provide an important explanation of the phenomenon. A discussion is performed combined with major conclusions on the subject.

Keywords: Wood, Rheology, Mechano-Sorptive Creep, Moisture, Moisture Content, Sorption, Absorption, Adsorption, Desorption, Wood Morphology, Wood Chemistry

Wood Rheology

Rheology deals with the time dependent deformation and flow of materials. To properly design and utilize information obtained from rheological measurements, the wood rheologist must know the details of the material involved. It is equally important to all materials to know if the material is homogeneous or multiphase (heterogeneous), how the material behaves when environmental conditions are changed and how stable the material is seen from a chemical point of view. These questions are valid also for wood as the material for rheological studies. The term rheology is replaced in this review by a commonly used term within the rheological study of wood, called the creep of wood.

The type of deformation called creep is a time dependent increase in deformation beyond the immediate elastic deflection, i.e. surpassing the deflection which is immediately recoverable upon removal of the applied force. Creep varies widely with the prevailing environmental conditions, and constitutes a flow in the material. In the case of wood, creep is considered to exist between the structural units. The differences can arise from various sources, depending generally on the species investigated. Also the wood properties can be considered as contributors, such as: tree trunk anomalies, growth ring structure, tracheid/fiber structure, fiber cell-wall structure, cell-wall components like fibrils combined with their structural orientation or finally the chemical linkages between the structural units (cellulose, hemicellulose, lignin and extractives) that depend on the growth environment, i.e. how these elements are created. The interaction between these components is also important, especially when creep phenomena appearing at different environmental conditions are investigated.

Creep phenomena in wood and wood products are divided into two distinctive categories: - visco-elastic and mechano-sorptive creep. The creep deflection of wood is usually recoverable, at least to a part, over a period of time after removal of the applied forces. This occurs especially in some cases during additional unloaded cycles of absorption and desorption.

Visco-elastic creep is a deformation beyond the immediate (elastically recoverable) deflection, that occurs with loading at a constant moisture content of the material (for example: green, conditioned to a certain level of moisture content or dry). The visco-elastic creep increases with the duration of loading, type of force application, and the temperature level. The visco-elastic creep may also involve effects of changes in temperature during loading, while the moisture content is kept constant.

Mechano-sorptive creep occurs as a consequence of changes in the moisture content of the material, while subjected to applied forces. Related strain phenomena and an associated flow of material components occur if dimensional changes of specimens are limited or prevented during an extended period of force application, either with or without simultaneous moisture changes [1]. The mechano-sorptive creep can also be induced by forces induced from changes in the internal chemical interactions mainly due to changes in the environmental conditions, i.e. moisture content in the wood.

Macroscopical Considerations of the Mechano-Sorptive Creep

In the living tree nature has created a structure which works well in wet condition, i.e. before the tree is cut. When a living tree is cut, certain undefined problems arise in the tree trunk. Creep is to be one of these problems, still to be explained in detail. Dried and conditioned wood under load, when subjected to moisture content changes, exhibits much greater deformations than under constant humidity conditions. This effect, already described as mechano-sorptive creep, was discovered in the late 1950´s and early 1960´s [2]. The Australian researchers Armstrong, Kingston and Christensen [3-4] described how variations in the moisture content in wood combined with an applied load resulted in an excessive creep effect. These findings were studied in detail [5-6] some years later, when they were able to describe comprehensively the basics of the creep behaviour in wood. The investigations comprised different sample sizes, various load conditions, and different species. Despite the differences in tendency to fiber collapse and shrinkage rate of the species investigated, the mechano-sorptive behaviour remained almost similar, Figure 1.

The deformation behaviour varied, mainly depending on the rate of load applied. According to Armstrong, Christensen and Kingston the creep behaviour in bending could be divided by the following:

- For green wood (moisture content above fiber saturation point) and wood of 14 % moisture content (weight water in wood/weight dry wood), when a moderate load was applied and the environmental conditions were not changed (temperature, humidity), a relatively low rate of creep was found.

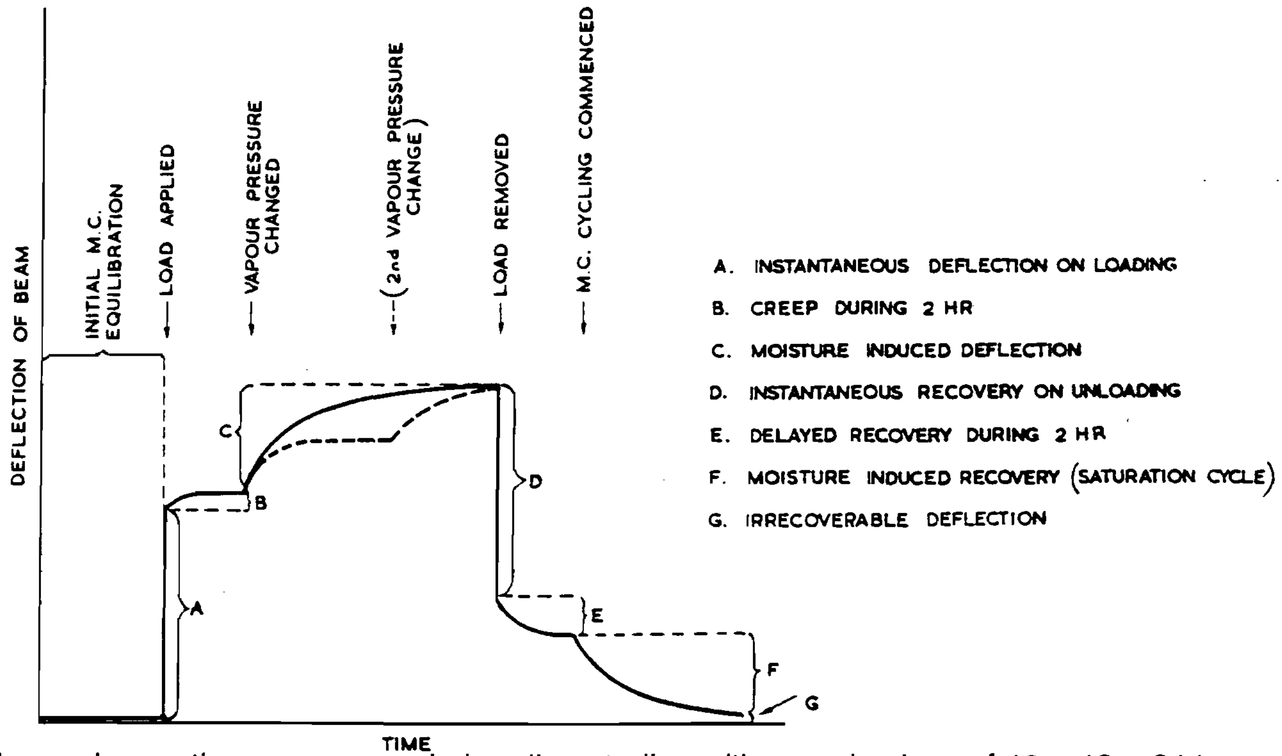
- When the wood samples were subjected to desorption (moisture content diminishing in the wood), the deformation rate increased. This was valid for both green wood and for wood of 14 % moisture content.

- During absorption (increasing the moisture content in the wood) the deformation decreased, except in the case of the wood of 14 % moisture content during the first cycle when a significant increase in deformation was seen.

- The total deformation increased with additional cycles of absorption and desorption (altering the moisture content in the wood).

- The recovery of the observed creep, i.e. the part of deformation that was recovered when the applied load was removed, was approximately 70 % of the total deformation, especially seen when the unloaded wood was subjected to several additional cycles of absorption and desorption. The recovery was only 10 % when the environmental conditions were kept constant after a removal of the applied bending force.

Figure 1. General details of a loading situation (time versus deflection of the beam) during a moisturization cycle [5].



These observations were seen in bending studies with sample sizes of 19 x 19 x 914 mm, 13 x 13 x 610 mm and 1.5 x 1.5 x 80 mm at a loading level of 18 % to 40 % of the short time ultimate stresses for the green wood [5-6].

Creep for compression parallel to grain was investigated for wood of 4 % moisture content and the same wood as initially moisturized to 110 % moisture content. Samples of a size of 13 x 38 x 102 mm were studied at a loading level of 38 % of the short time ultimate stresses for the green wood [6]. Creep deformation was similar in this case as in bending, i.e. an increased deformation at desorption and a decreased deformation at absorption was seen. The initially moisturized samples (110 % moisture content) had a substantially larger total deformation.

Tension creep trials were characterized in the same way as the compression studies [6]. The samples of 4 % moisture content showed a high deformation only during the first absorption phase. Increased deformation was found for the moisturized samples (110 % moisture content) during the first absorption phase, although this was only a fragment of the behaviour observed with the samples of 4 % moisture content. The deformation detected in the initially moistured samples of 110 % moisture content was not recoverable at the unloading of the applied force, not even when applied to changes in the environmental conditions. However, the recovery of 60-80 % occured for the samples that had an initial moisture content of 4 % in the beginning of the trial. This recovery was observed mainly during the absorption phase when additional unloaded cycles of absorption and desorption were included.

These experiments made in the early 1960´s clearly described the creep behaviour of wood under constant as well as varying humidity. To create a concise expression for the phenomenon that wood under load combined with sorption of water gives a mechanical response, which can not be predicted from the mechanical response or sorption individually, the expression mechano-sorption was created [7, 9,12], today generally called mechano-sorptive creep. In a review by Grossman in the early 1970´s [12] these aspects were discussed in detail and he explained the characteristic features of the effects of simultaneous moisture change and load on the deformation of wood. He discussed implications for any model based on the botanical and molecular structure of wood and proposed frames for a model that would deform under increase and decrease of moisture, be capable of strain recovery, be unaffected by water flow and be highly dependent on the previous treatment.

These found mechano-sorptive creep deformations of wood, mentioned above, have been modelled during the years in several ways. Takemura [8] made the first attemp to relate the plastic properties of wood to a non-equilibrium state of moisture content in wood. An additional initial attept was made by Leichester [9], suggesting a model with Maxwell-elements in which the mechano-sorption deformation is represented as the damper. The response of the damper is a function of moisture content and applied load. The elastic deformation is represented by a linear-elastic spring. The model is mainly describing the deflection for an initial green beam under bending load and only during the first desorption cycle.

A model where the strain is a function of applied stress and moisture content has been suggested by Ranta-Maunus [10]. The model is linear with stress and moisture change, with parameters depending on moisture content charge and moisture history.

Hunt [11] claimed that the total compliance of wood exposed to similar cyclic conditions can be divided in an elastic compliance, a mechano-sorptive creep-limit compliance and a characteristic compliance. The model by Hunt characterizes a situation where the deflection is a function of number of humidity cycles with a constant amplitude. This suggested model is not valid when the moisture amplitude is changed, and thus has to be highly modified to characterize a general situation with different humidity cycles of variable amplitudes in the level of relative humidity. Hunt additionally declared that a creep-limit exists, which the compliance mentioned can not exceed.

Endeavours to find new and better models to characterize the mechano-sorptive creep phenomenon are continuously carried on. The two latest suggestions have been proposed by Yahiaoui [13] and Salin [14]. They divided the general creep phenomena into four parts as the sum of an elastic part, a component for the free shrinkage, a visco-elastic part and a mechano-sorptive part. The change in mechano-sorptive deformation with time is suggested by Salin to be a function of the mechano-sorptive deformation itself.

Despite the numerous models suggested so far, we have not yet been able to describe the mechano-sorptive creep completely by mechanical, physical and mathematical approaches. We are starting to feel the need for seeking explanations at a higher magnification, i.e. on a detailed morphological and chemical level of the wood we investigate, in order to better understand the phenomena in detail and thereby describe all necessary components involved.

Microscopical Considerations of the Mechano-Sorptive Creep

The microscopical level is a relatively unexplored area in the field of mechano-sorptive creep phenomena. An analysis today can be made at a chemical level of few ångström:s, i.e. tenths of a nanometer, where the final explanation could be found. Possibilities also exist that the final explanations can be found even on an atomic or a sub-atomic level, which is a totally new area yet to be established.

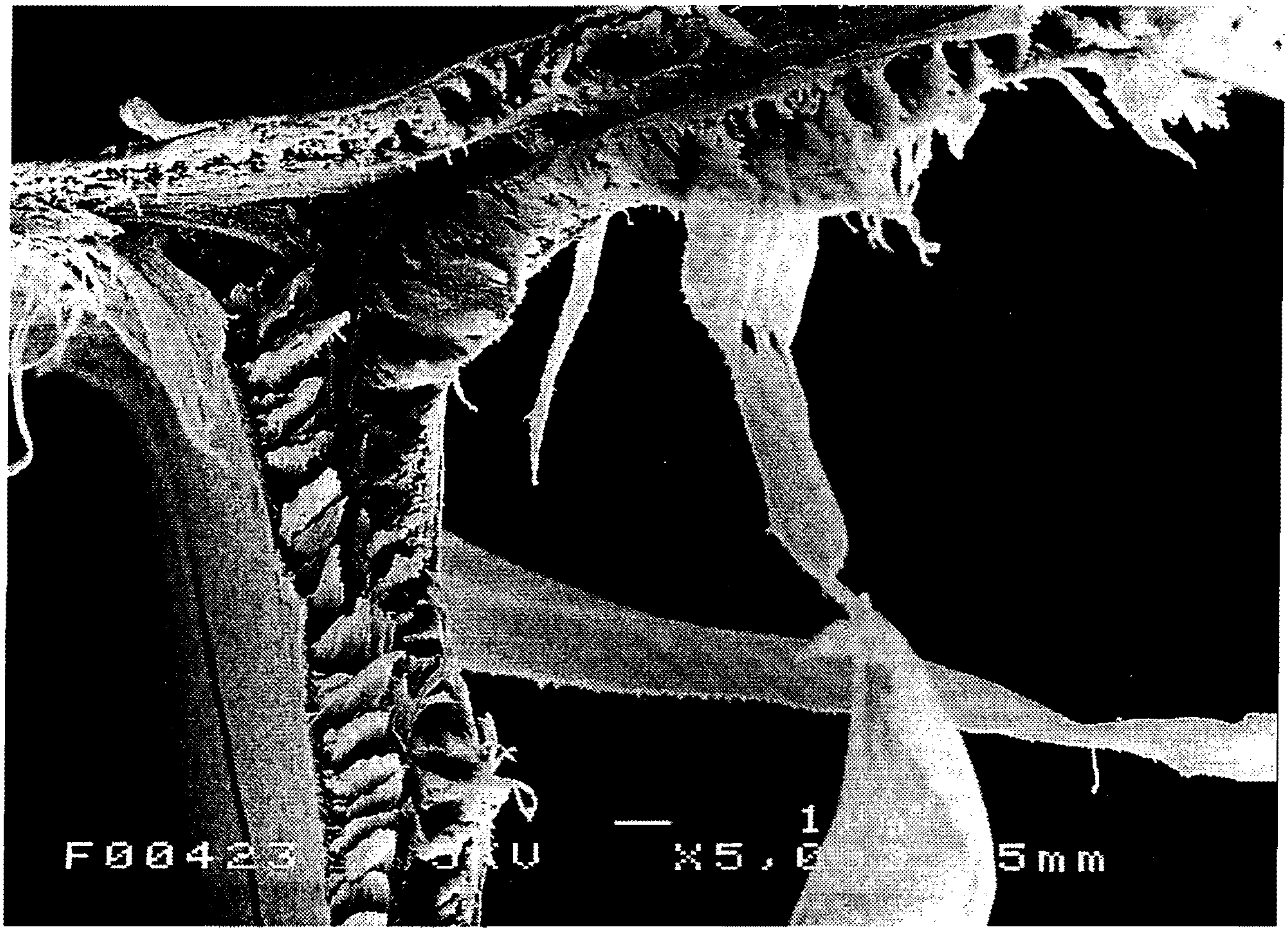
Chemists of today are still arguing about how nature constructs the actual polymer structure in solid wood. The knowledge in this field basically arises from components discovered in mechanical and chemical defibration processes of wood. The components found are coupled with the existing rules in chemistry. Thereby, the basic chemical structure of the components in wood is established. An enormous amount of research has been made in this field, mainly to gain a white, cheap, longlasting, mechanically/chemically stable and suitable fiberproduct for delivering written information on, i.e. a printing process induced/controlled construction,- for example the one that this article is written on. The information from this field has not been completely utilized.

Models from different well defined polymeric materials, combined with the interaction of a solvent, have also been investigated thoroughly to increase the knowledge of wood polymer interactions with water. The structural suggestions made so far are undoubtedly only directing us in the field of mechano-sorptive creep. Thus explanations and further detailed investigations are evidently needed.

Environmental conditions occuring during the growth of a tree deleteriously influence the chemical structure of the polymer components of wood, thus inducing enormous variations within the combined composite structure of these basic polymeric components (cellulose, hemi-cellulose, lignin and extractives). These components and their structures can also be greatly altering during storing, sawing, drying and machining when a tree is processed to a final usable product, for example 2 x 4 inch boards. Therefore detailed information on the history of the wood is needed.

Morphology is the study of the shape and structure of things, especially on objects created by nature. There have been discussions within this field about how to explain the mechano-sorptive creep in wood. One of the fundamental sources is Boyd [1], who suggested an anatomic explanation of the visco-elastic and mechano-sorptive creep in wood, when observing the effects of the loading rate on strength. He demonstrated that creep and the qualitative differences in rate of response for the alternative stress modes can be generally explained in simple terms of stress-induced physical interactions between the crystalline and amorphous components in the cell wall of a wood tracheid. The added influence of moisture reduction or moisture cycling in the wood is explicable in this suggestion. He also claimed that effects this way deduced are fully compatible with extensive experimental data in the literature he presented. Boyd further discussed how deflection, which is associated with axial tension, compression and bending, induces formation of microscopical crinkles across the general alignment of the microfibrills, which constitute the crystalline structural framework of the fibre wall. The fact that these crinkles, accelerated by moisture changes, may induce the fibre cell wall and the wood as a whole to fracture at much lower intensities of stress than can be sustained with force application over a short period of time. These microfibrils have recently been described by Sell and Zimmermann [15] to be arranged radially, when seen against a tracheid, in a spruce earlywood fiber cell wall, Figure 2. They suggested that when tension loading softwood to fracture, the cell wall substance of the tracheids come loose and the different wood components (cellulosic fibrils and the involved matrix of hemicellulose and lignin) are separated in the S_2 wall. Studies in loads at different temperatures and moisture contents were included. They did not find the helical lamellae structure of the S_2 fibrils (parallel to the middle lamellae), which has previously been suggested by several other researchers. The secondary wall (S_2) structure appears to be like a sandwich, consisting of the S_1 and S_3 layers acting as faces and of the S_2 acting as core with a fibril agglomeration perpendicular to the face layers with undefined components in between, possibly a composition of hemicellulose and lignin. As to the mechanical functions of the cell wall, such a S_2 structure would be beneficial as regards to the compression strength of the whole cell tissue, when loaded parallel to the stem axis or grain axis, respectively. This structure is to be examined in the mechano-sorptive considerations mentioned earlier.

Figure 2. Spruce earlywood fracture surface, from Sell and Zimmermann [15]



If the structure of wood is seen on a chemical level, the rheological properties were recently investigated by Norimoto, Gril and Rowell [16]. They treated wood with different chemicals to be able to relate the dimensional stability to creep stability. By using spruce specimens modified by fourteen different types of chemical treatments the relationship between anti-swelling efficiency (ASE) and anti-creep efficiency (ACE) could be determined. Using chemical modifications where the hydrophilic, i.e. hygroscopic nature of the chemicals was not counterbalanced by crosslinking (polyethylene glycol or eterification with epoxides) resulted in relative high stabilization of the wood, i.e. a reduction in load-free moisture expansion, while the mechano-sorptive creep increased. A good correlation could be seen between ASE and ACE when a crosslinking chemical, i.e. formalization was used.

Chow [17] observed time-dependent molecular movements of the basic wood components (cellulose, hemicellulose, lignin) using infrared polarization technique strained parallel to the fiber axis. Regardless of the form of external exitation (creep or stress relaxation) or the time of exitation (ramp- or step-loading), a basic two-stage molecular movement pattern followed, as damping of the molecules accompanied the whole rheological process. The pattern of molecular movement for a wood component is a compensatory result of interaction involving all wood components. Removal of one or more wood components changed the movement patterns of the remaining components. The response of the cellulose in a specimen without the presence of lignin and hemicellulose is comparable to that of the other synthetic linear polymers. The results of this investigation are proposed to represent the native wood properties before drying is involved, i.e. an investigation on water saturated samples. What occures during changes in moisture combined with applied load is yet to be established.

Mechano-sorptive effects may be related to the interactions of a softener, i.e. solvent, within a polymeric material. Salmén [18] proposed that the only factor which affects the mechano-sorptive behaviour of wood is the magnitude of interaction between a polymer and a softener (for example wood components versus water, methanol, ethanol etc.). He generally discusses the effect of a polymer and softener interaction. He concludes that the transient phenomena during sorption occur not only in wood and wood based material sorbing (absorption or desorption) water but also in a variety of polymers sorbing a softener. An essential fact seems to be that the sorbing molecules have the ability to interact with the intermolecular bonds of the polymer molecules in order to induce the mechano-sorptive effects. This means that during sorption the polymer molecules exhibits an increased mobility resulting in dimensional changes. An important factor for the transient effects, e.g. mechano-sorptive creep, seems to be the extent at which sorption takes place, thus influencing directly on the rate of dimensional changes. This is connected to the softening characteristics of the sorbing polymer molecules. If sorption happens during changes in dimensions of the polymeric structure, it gives rise to local stress gradients. These stress gradients are proposed to be the main reason for mechano-sorptive effects in general. When the structure of the material does not influence the sorption behaviour, no local stress gradients should be caused. Although, for example in wood, where the structure of the basic polymer construction is highly altered, these stress gradients can be extreme.

Grossman [12] also suggested a hypothesis based on the many of the suggestions made earlier. The assumption that the breaking and remaking of bonds that must occur during moisture changes in either direction, i.e. absorption or desorption, a stress bias will favour slippage. For example, every temporary break of a hydrogen bond will give rise to a temporary weakening of the piece of wood and a slightly increased strain in response to a fixed applied stress. This is the phenomenon observed during desorption. During absorption of water, there is a partial recovery of the strain against an applied load. When the re-wetting occurs, the rate of deflection, which closely follows the rate of absorption, may causally be connected to the rate of swelling, and further the recovery takes place because of spatial redistribution of cellulose chains with respect to each other as a result of swelling. This leads to the formation of hydrogen bonds in new positions which results in a stiffening of the material.

Discussion

Researchers have been supplying a large number of hypothetical explanations of the mechano-sorptive creep, although no one has yet been able to combine and experimentally verify these hypotheses to be generally accepted. Yet a complete descriptive explanation on an accepted theoretical level is needed.

The model proposed by Yahiaoui [13] seems to be the foremost today in describing the macroscopic mechano-sorptive creep behaviour in wood. This rheological model shows a good correlation with experimental results and this suggested model demonstrates the mechano-sorptive creep phenomenon under cyclic moisture content variations combined with the varying stresses applied. Furthermore, during moisture variations, the model takes into account the accelerated recovery, also after the removal of the applied load.

Both the macroscopic and microscopic considerations seems to be involved in the mechano-sorptive phenomenon in wood. As regards to the macroscopic determination further detailed models are to be combined from the behaviour on the microscopical level to establish a comprehensive model to the questions arised regarding mechano-sorptive creep. Associating the macroscopical and the microscopical considerations on the level of knowledge today we could predict that we could achieve a sufficiently well described material for rheological analysis, i.e. for mechano-sorptive creep experiments, especially when knowing the history of wood during growth, cutting, drying and machining. A detailed chemical analysis of the wood investigated would elaborate these parameters, combined with a detailed sorption determination for the actual sample sizes investigated. The situation when a moisture content gradient exists during sorption before stabilization is gained, i.e. local stress gradients, has also to be included. Results obtained in this way could lead us to a complimentary descripment for the mechano-sorptive creep determinations, and finally a comprehensive model on a macroscopical level.

Conclusions

Mechano-sorptive creep for wood is induced by changes in its moisture contents, especially when an external load is applied. Several important effects of moisture content changes on the behaviour of wood under load have been determined, especially on the aspect of an increase in deformation.

When seen microscopically, the sorption characteristics differ highly within the polymeric construction of wood. Amorphous and crystalline parts in the cellulose, the structural and the quantitative differences in the lignin, and the highly variating amount of other hydrophilic (hemicellulose) or hydrophobic material (extractives) within a cell wall combined with the molecular adsorption of water, or desorption, creates local stress gradients in wood. These stress gradients may induce the creep behaviour in wood, which can be highly deviated also from variations in the morphological structure. The effect of changes in environmental conditions, i.e. moisture content changes, combined with the structural differences and different sorption capabilities of the different polymeric components in wood, increases these internal stress gradients. When external forces are combined with these microscopical considerations, we expect that the mechano-sorptive creep behaviour in wood is created.

Macroscopic and microscopic considerations are to be combined to make it possible to describe comprehensively the mechano-sorptive creep phenomenon in wood. To find a complete model that is compatible with the huge amount of existing parameters still remains one of the challenges of today to the wood scientists around the world.

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