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# Water flow through wooden foundation piles: A preliminary study

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**Abstract**

The process of bacterial wood degradation is not yet fully understood. From recent studies on foundation piles the assumption arose that water flow through wooden piles could be of crucial importance in explaining the intensity and velocity of bacterial decay. In a laboratory experiment we investigated the amount of water that passes through 300-mm-long fresh-cut stems of pine, spruce, larch, Douglas fir, alder, and oak over certain time intervals. The water pathways were traced by using a copper sulphate solution that was stained subsequently. A second laboratory experiment whereby different pressures were applied to the water was performed on spruce and pine only. In addition to axial water flow, radial water flow was also investigated. The results indicated striking differences between the six species. Douglas fir and larch proved to be almost impermeable, whereas huge variations between piles occurred in the other, more permeable species, namely in pine. In general, it became obvious that species that are known to be more susceptible to bacterial decay, such as alder, oak, and especially pine, appeared to be most permeable to water. The second experiment showed that axial water flow through pine and spruce is much—up to 100 times—faster than radial flow. By increasing the pressure in eight steps, up to 185 hPa, water flow increased linearly in both pine and spruce. The results of the two water-flow experiments are discussed in relation to observed patterns in bacterial degradation in the six species, with particular focus on spruce and pine, the most prominent species used in foundation piles. As water flow through foundation piles is strongly related to site hydrology, the impact of site hydrology on pile degradation is also discussed.
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*Keywords:* Water flow; Water pathways; Bacterial wood decay; Pine; Spruce; Oak; Alder; Larch; Douglas fir

## 1. Introduction

Although the degradation process of submerged wood by erosion bacteria is not yet fully understood (Klaassen, 2007), it has been described as a slow process resulting in almost complete degradation, as seen in 2000-year-old archaeological wooden remains (Klaassen, 2007; Huisman et al., 2007). Foundation piles that have been in service for 70–150 years show various degrees of bacterial degradation with the decay process being regarded as still active. This offers the possibility of extracting and identifying wood-degrading bacteria (Nilsson and Börjdal, 2007a, b; Nilsson et al., 2007; Landy et al., 2007) and of investigating the influence of soil chemistry on the degradation process (Kretschmar et al., 2007a). It has been demonstrated that foundation piles are mostly degraded along their whole length. Moreover, it became obvious that timber species with an open wood structure, such as sapwood of pine, are more susceptible to degradation than species with a less open structure (because of, e.g., smaller cross field pits, such as spruce (Klaassen, 2007). Although degradation of archaeological wooden remains is often categorised as severe (Klaassen, 2007), field observations show that less degraded archaeological wooden remains are often located in permeable, e.g., sandy, soil layers (Huisman et al., 2007). Based on these observations, the assumption arose that (the degree of) bacterial wood degradation is related to the presence and intensity of water flow through the wood. Water flow in axial construction elements such as foundation piles is assumed to be related mainly to soil hydrology, i.e., the fluctuation of groundwater and thus its pressure on the pile heads and tips and the permeability of the wood structure, the latter varying between different timber species. In contrast, since archaeological wooden remains are almost exclusively found in a horizontal position, water flow through the wood only occurs if the permeability of

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the wood is higher than that of the surrounding soil. Long-term measurements of groundwater levels in Haarlem and Zaandam, two Dutch cities with many foundation piles (Kretschmar et al., 2007b), documented that no static either negative or positive groundwater pressure gradients occur between the tip and the top of the foundations piles. Instead, the groundwater pressure was found to be dynamic and, moreover, differed considerably in alternating ground layers which are penetrated by the piles.

This makes wood permeability, which determines the water flow through piles, a promising candidate to explain species-specific differences in both susceptibility and the degree of bacterial degradation of wooden foundation piles. Earlier studies on wood permeability and water flow through piles have been conducted mainly in the context of wood preservation, whereby high pressures were applied to impregnate different species with chemical agents (e.g., Militz, 1990; Ulvrcona et al., 2006).

The experiments conducted in this study are inspired by the *Boucherie* process, a technique that was applied from the late 19th century until the beginning of 20th for chemical protection of telegraph poles (Walker, 2006). To do so, metal collars were wrapped around the upper cross section of a vertically positioned telegraph pole and filled with the preservative. The impregnation process was completed as soon as the preservative appeared at the lower cross section of the pole as a result of gravity-feed.

In this study a more sophisticated setup was used to prevent water flow and diffusion along the periphery of the pole in order to generate more exact measurements of the axial (and radial) water flow. It is believed that previously no measurements have been conducted on water flow under low-pressure conditions through fresh, fully water-saturated whole piles with an (almost) intact water-transport system.

A two-step approach was used to study: (1) whether the species-specific difference in water flow through wooden foundation piles is related to the susceptibility of a certain timber species to bacterial degradation, and (2) whether the amount of pressure, i.e., the height of the water column above a pile, is an important factor in explaining differences in water flow between species.

First, the water flow through those six timber species that are frequently found in (archaeological and historical) pile foundations, namely pine (*Pinus sylvestris*), spruce (*Picea abies*), larch (*Larix europaea*), Douglas fir (*Pseudotsuga menziesii*), oak (*Quercus robur*, *Quercus petraea*), and alder (*Alnus glutinosa*), was measured and compared. It was assumed that the dynamic groundwater pressure differences along the pile length will result in a (continuous) water flow in the piles.

Second, water flow under different pressures (up to a water column of 185 cm ( = 185 hPa)) was measured in the two most used timber species, namely pine, which is sensitive to bacterial decay, and spruce, a less sensitive species. The results are discussed in relation to the susceptibility to, and the intensity of, bacterial degradation of piles made from these two species.

## 2. Materials and methods

### 2.1. Sample trees and sample preparation

For the first experiment (water flow through stems of six species), three ca. 1-m-long stem segments of pine, spruce, larch, Douglas fir, oak, and alder—each originating from trees growing in a forest of the Veluwe area, central Netherlands—were used. After cutting, the stems were stored for several weeks in the forest, a common procedure to yield timber for wooden foundation piles. After transport to the laboratory the stems were put into water until fully saturated, and sawn into 300 mm lengths.

The trees for the second experiment (water flow through stems of pine and spruce under varying pressure) originated from the same forest. In contrast to stem treatment in the first experiment, the four 1.2-m-long pine and spruce segments were immediately stored under water after cutting. At the laboratory the stems were sawn into 450 mm lengths for the experiment.

All stem segments had approximately 40 tree rings; their diameter as well as their sapwood width is given in Table 1.

All pine stems of the first series suffered from some blue-stain infection. This was accepted because blue-stain infection is frequently observed in most pine piles that are in use as foundation piling.

All (water-saturated) stems were debarked with a chisel and the outside was coated with a Poly-Service Poly-Pox GT600 epoxy (Harder 455). To guarantee optimal fixation the coating system had to be applied to a dry wooden surface. Therefore, the outside of the stems was dried with a hot air dryer for several minutes until the outermost stem layers of about 1 mm had a reduced moisture content.

### 2.2. Setup of experiment 1—water flow through stems of six species

At the upper end of the 300-mm-long stem segments, a collar of fibreglass was fixed and impregnated with epoxy resin (Fig. 1). In the collar, a constant layer of 10 mm water was kept to leave the cross sections permanently covered with water (without pressure). The stems were resting on plastic plates with a profile (rills) to enable the run-off of the penetrated water. In order to avoid evaporation from the plates, plastic foil was fixed around the stem and on the surface of the plate. A tube was connected to the lowest point of the plate to collect the water that penetrated through the stem. To avoid slime production by bacteria and algae, the water on the cross sections was refreshed weekly. After 4 weeks of continuous water flow through the stems the measurements were started. Throughout a period of 8 weeks, the amount of water that passed through the stems was recorded in weekly intervals.

Table 1
Stem diameter and heartwood amount of sample trees

| Species | *n* | Stem diameter (mm) | | | |
|---|---|---|---|---|---|
| | | Whole stem | | Heartwood | |
| | | Mean | S.D. | Mean | S.D. |
| Pine | 7 | 206 | 24 | 99 | 27 |
| Spruce | 7 | 215 | 5 | 31 | 1 |
| Douglas fir | 3 | 210 | 5 | 155 | 5 |
| Larch | 3 | 201 | 5 | 166 | 15 |
| Oak | 3 | 159 | 5 | 111 | 6 |
| Alder | 3 | 164 | 23 | 0 | 0 |

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Fig. 1. Experimental design to study water flow through 300-mm-long stems without pressure.

### 2.3. Setup of experiment 2—water flow through pine and spruce under various pressures

The 450-mm-long stems were placed horizontally (Fig. 2). At both cross sections, a fibreglass collar with a height of 30 mm and impregnated and fixed with epoxy resin was placed. Both collars were sealed with epoxy-impregnated plywood to form waterproof chambers.

In the middle of the 450-mm-long stems, a zone approximately 50 mm wide around the stem was left uncoated in order to also measure radial water transport. Here, a third chamber was created by wrapping a 10-mm-high collar made from fibreglass material at this location around the whole stem circumference (Fig. 2). To all three chambers, tubes of 300-cm length were connected. After removing all air from the three chambers, water with a pressure of 150 hPa, applied as a 150-cm water column, was put on one cross section. The tubes that were connected to the two remaining chambers were opened to release the water that penetrated the wood.

The first part of the study tested whether water flow from the top to the bottom of the pile was different from water flow from bottom to top. It can be seen that water transport in the living tree is running in one direction, i.e., from roots to leaves, and a difference in the amount of water flux cannot be excluded. In addition, the flow from the middle chamber in the direction bottom-top and vice versa was tested. However, no differences were detected between water flow in the different directions.

After 4 days of water flow through the stems, the measurements were started. The pressure, i.e., the height of the water column applied to the flooded chamber, was set to seven different values (10, 25, 50, 75, 100, 150, and 185 cm water column or hPa). The amount of water that emerged from the two release tubes of the two other chambers was recorded. As the velocity of water transport through the stem segments was assumed to differ in axial and radial direction, the records of axial water transport were registered after 0.5 or 1 h, whereas the radial transport was measured after 5 days.

### 2.4. Identification of water pathways

After experiment 1 was completed, the pathway of the water flow was identified by applying copper sulphate as a low-molecular-weight dye to the water covering the upper cross section. To do so, a groove ($20 \times 20$ mm) was made across the whole diameter, thereby crossing the pith. The groove was filled with copper-sulphate solution and was refilled when necessary. After about 36 h, the stem was sawn open along the axial direction. If the wood was not sufficiently stained green by the copper sulphate, rubeanic acid (in 1% ethanol solution) was applied to the surface. It induces a strong (black) colour reaction with copper sulphate. The stained tissue marked the pathway of the water and indicated major zones of water flow through the stem segments.

Fig. 2. Experimental design to study water flow through 450-mm-long stems under different pressures.

### 2.5. Presentation of results

The results comprise the measurements of water flow through the stem segments of the different species as derived from the two experiments. In both experiments, the water flow was recorded weekly and calculated as litres per hour. In some cases more than one measurement was done at a specific pressure and as the variation between those measurements were low, mean values were calculated. The results are presented in a series of graphs; the number of replications did not justify the application of statistical analyses to test for significant differences between species or the different pressures applied in experiment 2. The graphs serve as a basis for the discussion.

## 3. Results and discussion

### 3.1. Experiment 1—water flow through stems of six species

Fig. 3 shows that water flow differs considerably between the six studied species. However, most striking are the differences in water flow that may occur between the three stem segments of the same species. This is especially true for pine, with one pile showing an average flow of 10 ml/h and another pile reaching on average 130 ml/h.

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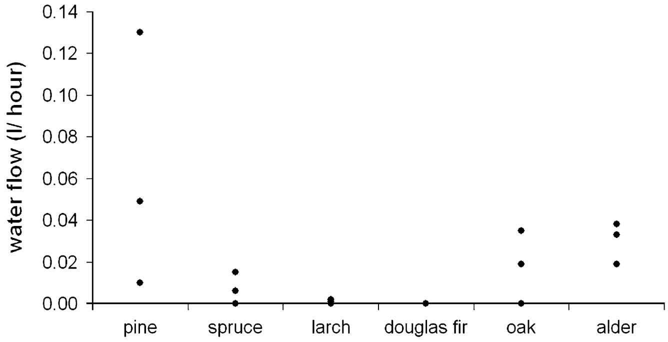


Fig. 3. Water flow through 300-mm-stem segments in the six studied species.

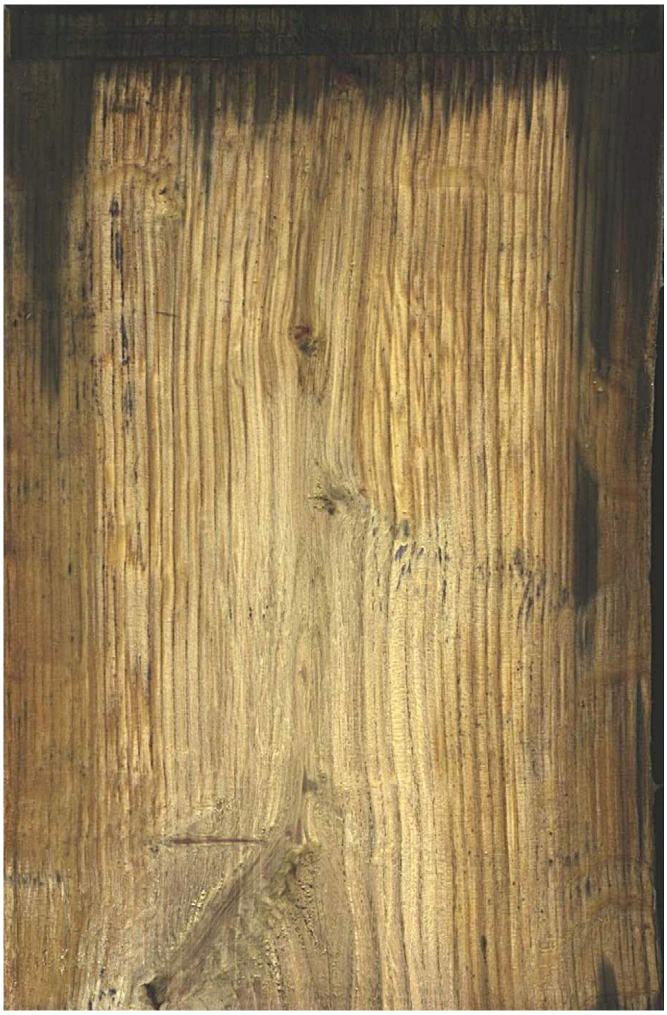

Fig. 4. Examples showing the stained water pathway in oak.

Furthermore, in the three oak stem segments water flow varies considerably between values of 0 and 35 ml/h. Alder also shows about the same water-flow rates as in oak.

Larch and especially Douglas fir appeared to be almost completely impermeable. Water flow through spruce is somewhat higher than in larch and Douglas fir but is, on average, much lower than in (the two most permeable) pine segments.

These results broadly fit what was expected (Klaassen, 2007); however, there are some unexpected observations. In the following, the results are presented per species.

Water flow in oak was expected to be higher than that recorded. The wood structure of oak is characterised by wide and long early-wood vessels, which potentially allow water transport with high speed over large distances, whereas the much smaller late-wood vessels play a minor role when it comes to water-flow capacity. The relatively low water flow, even in the most permeable oak stem segment (35 ml/h) suggests that most of the early-wood vessels must have been blocked. Early-wood vessels can be blocked by tyloses (already in the living tree) as a consequence of heartwood formation, wounding, or embolism. From Fig. 4 it becomes obvious that heartwood formation almost completely seals the cross section and that (relatively little) water flow is restricted to the outer centimeter, i.e., the sapwood (Table 1). It is assumed that water flow in the most permeable oak stem was probably mainly through some unblocked early-wood vessels and the latewood vessels. Besides tylosis formation, contamination of the water by algae might have led to a mechanical blockage of the water pathways through the early-wood vessels

In alder, the variation in water flow between stems was small compared to the other species. As alder does not form heartwood, vessels throughout the whole stem radius can potentially contribute to water flow. Furthermore, the vessel density is high and radial grouping frequently occurs, with the consequence that potentially many alternative water pathways exist. The stained water pathway, seen in Fig. 5, shows several canals running along the whole stem, indicating that alder can be considered a relatively permeable species.

When comparing pine and spruce, the two most prominent species used as wooden foundation piles, it is striking that (1) spruce is on average less permeable than pine, i.e., water flow in the most permeable pine stem was up to four times higher than in the spruce stems; and (2) water flow through spruce stems is less variable than in pine stems. In softwoods, axial water flow propagates from one tracheid (length ca. 3 mm) to another through bordered pits or radially through ray tracheids (pine) and ray cells by passing the cross-field pits. In pine these cross-field pits are wide (simple [window] pits) with the consequence that water flow encounters less resistance, which explains potentially high velocities in pine. In contrast, the cross-field pits in spruce as well as in the two almost non-permeable species larch and Douglas fir are minute (piceoid pits) and therefore offer more resistance to water flow. In addition, softwoods are known to react with irreversible closure of pits, mainly in the wide earlywood tracheids, as a response to drying of the wood (Liese and Bauch, 1967). This might contribute to the generally low water flow in spruce.

One significant observation is the high variation in water flow, as observed with the three pine stems. These

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Fig. 5. Examples showing the stained water pathway in alder.

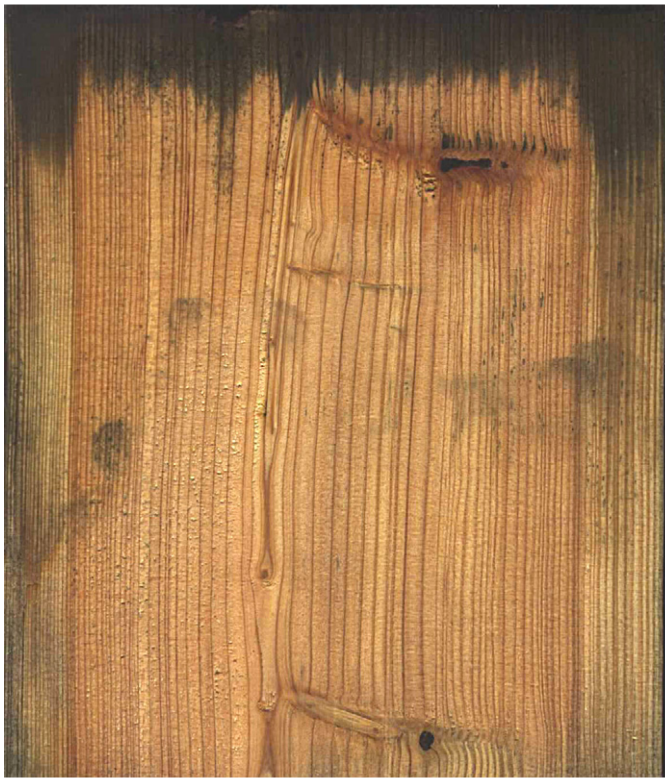

Fig. 6. Examples showing the stained water pathway in larch.

differences in water flow can possibly be explained by the presence of blue-stain fungi. The (commonly occurring) blue-stain infection could have induced partial—and in one heavily infected stem almost complete—obstruction of the water pathways. As this infection starts and most abundantly appears in ray (parenchyma) cells, it is possible that heavy infections with the consequence of intense production of fungal hyphae may lead to mechanical blockage of the low-resistant pathways, i.e., the wide window pits in pine. This interpretation is in conflict with the general idea that blue-stain infection generally enhances the permeability of wood by disintegrating pit membranes (e.g., Jutte, 1971). However, Fig. 8 supports the obstruction theory by showing that in sapwood areas with blue-stain infection (Fig. 8, left) no water flow is indicated.

These results indicate that water flow in all species can be largely explained by the wood structure and secondary processes (tyloses formation, pit closure, blue-stain infection) which considerably influence the axial and radial permeability of the six species.

Another important factor for axial water flow is the amount of sapwood. The heartwood of oak, pine, Douglas fir, and larch is almost completely impermeable due to irreversible closure of all bordered pits in the early-wood and the late-wood tracheids (Figs. 4–8). Alder, a species without heartwood, shows water flow throughout the whole stem (Fig. 5). In spruce, some pathways seem to remain open in the heartwood, which points to the presence of open pits, most likely in the latewood tracheids (Fig. 7).

### 3.2. *Experiment 2—water flow through pine and spruce under various pressures*

Figs. 9 and 10 illustrate the axial and radial water flow through 450-mm-long pine and spruce stems under various pressures, starting from 10 up to 185 hPa. Under low pressure (10 hPa), the axial water flow through the 450-mm-long pine and spruce stems is generally comparable with the measurements on 300-mm-long stems in the first experiment. Also, the variation between stems is in the same range as in experiment 1. However, it is surprising to see that water flow through the 450-mm-long spruce stems is slightly higher than in the shorter stems used in the first experiment. A possible explanation is the presence of more, irreversibly blocked bordered pits in the spruce stems from the first experiment as a consequence of drying of the wood during its storage in the forest. Blocked pits form a serious obstruction for water flow. As the 450-mm-long pine stems did not have blue-stain infection, the variation in water

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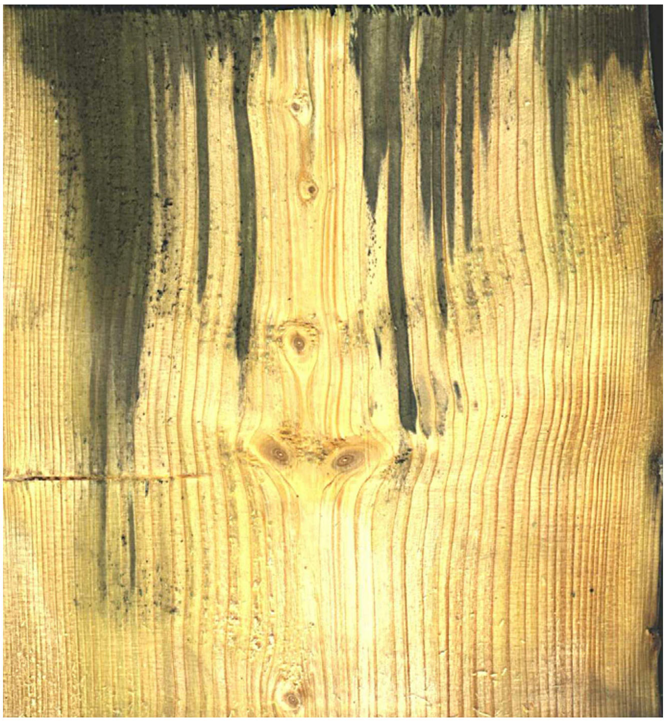

Fig. 7. Examples showing the stained water pathway in spruce.

Fig. 8. Examples showing the stained water pathway in pine.

flow could not be explained by closure of the more open (tracheid—ray tracheid) water pathway. In this study an alternative explanation was not found.

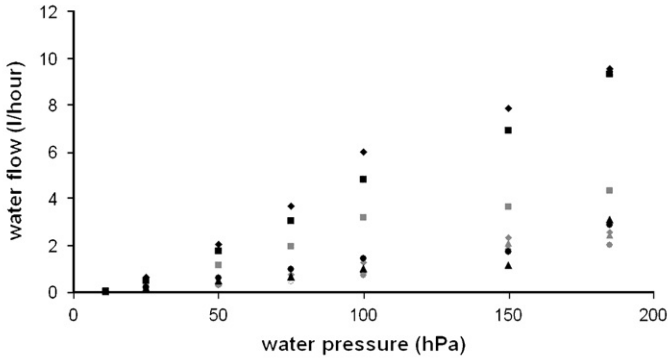


Fig. 9. Axial water flow under pressure in pine (black dots) and spruce (grey dots).

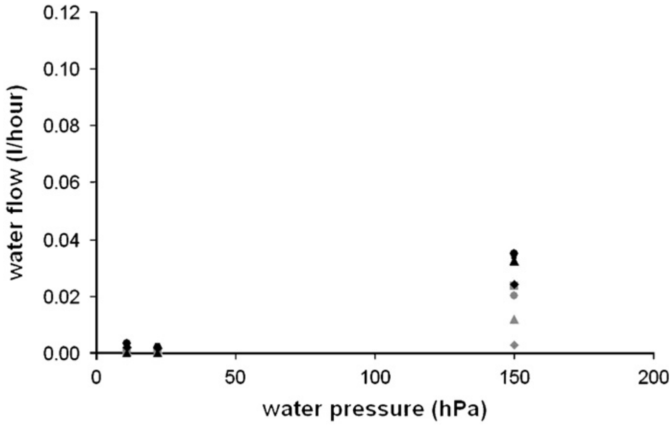


Fig. 10. Radial water flow under pressure in pine (black dots) and spruce (grey dots).

Increasing pressure up to 185 hPa results in an almost linear increase in the axial water flow of both pine and spruce (Fig. 9). As in the first experiment, the variation between the four stems is high, especially in pine. As blue-stain could not be detected in the four pine stems, no explanation for these striking differences in water flow can be given. No problems were detected with the setup of the experiment; radial flow along the epoxy shield can be excluded as this would have resulted in a high radial water flow. However, radial water flow appeared to be up to 100 times lower (Fig. 10) than axial water flow (Fig. 9). Compared to the velocity of axial water flow, the radial water flow in both species, under all pressures, is so low that it can be more or less ignored when considering water movement through foundation piles.

In order to check whether (micro)cracks were involved in the case of high water flow, the water pathways of the pine and spruce stems with the highest water-flow intensity were stained. Figs. 11 and 12 clearly illustrate that water transport in both species occurred only through the wood.

To summarise, the results of the two experiments showed that water flow through wooden stems under low pressure is possible. The application of sequentially higher pressures, up to 185 hPa, leads to a linear increase in water flow in both pine and spruce. From both experiments it became

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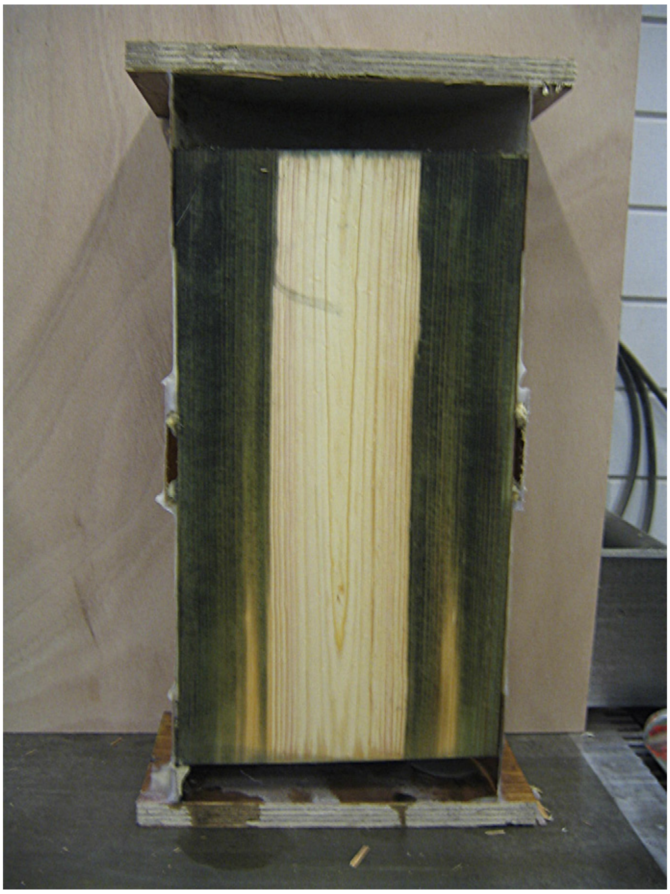

Fig. 11. Stained axial water pathway in pine.

Fig. 12. Stained axial water pathway in spruce.

obvious that water flow differs strongly between species, although variation between water flow in different stems of the same species can be high, especially in the most permeable species—pine. These species-specific differences could be related mainly to wood structure and the presence and amount of sapwood.

The anatomical structure of the sapwood of pine and oak potentially allows high water-flow velocities, but in both species water pathways are sensitive to blocking. In oak, tylosis and mineral deposits can obstruct water transport, whereas in pine blue-stain infection may hamper water flow. However, when using stems as foundation piles (for sometimes more than 100 years), these obstacles, i.e., hyphae, tylosis, could be susceptible to degradation, which results in a higher permeability.

Alder also belongs to the more permeable species, with water being able to penetrate across the whole diameter (no heartwood) and passing quite easily along the stem. From field investigations and inspections it became obvious that these three species, i.e., pine, oak and alder, with the highest (potential) axial water flow are most susceptible to degradation by erosion bacteria (Klaassen, 2007). This supports the hypothesis that the presence (and intensity) of water flow is a crucial factor in the process of bacterial wood degradation. Frequent observations of pyrite in the wood of foundations piles are an indication of water flow through piles in service (Fig. 13). As pyrite is not transported into the wood but is formed in situ inside the cells, reactive iron and sulphate ions need to be transported into the wood through (flowing) water (Huisman et al., 2007). As the axial water flow in stems does not differ from bottom to top and vice versa, the ions are probably able to move up and down within the wood. Pyrite often

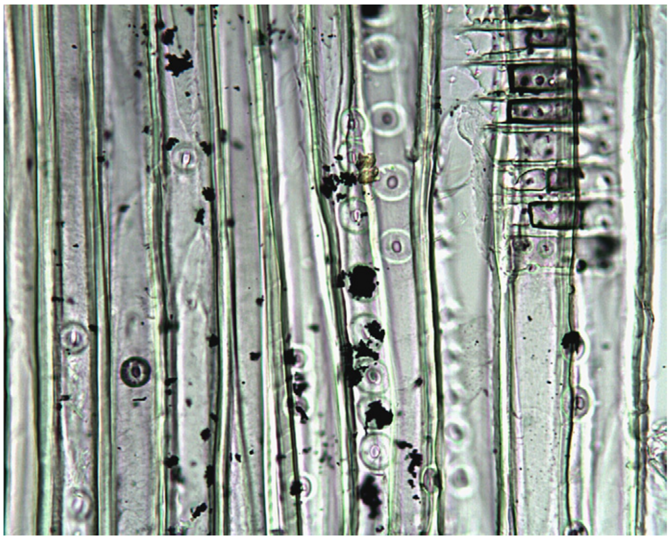

Fig. 13. Pyrite (black) in spruce with moderate erosion bacterial decay.

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concentrates around the bordered pits (Fig. 13), i.e., the places where water resistance is high and thus iron and sulphate ions can meet and form pyrite.

For foundation piles in service only pressure differences in groundwater between the bottom and the top of the pile can result in water flow inside a pile. Different groundwater pressures in the soil layers penetrated by the foundation piles have no effect on water flow in the pile, as radial water flow is very low (up to 100 times lower than axial).

In this study no attention was paid to the influence of branches or knots on the radial water flow in the wood. Although the effect of stem length on water flow was not studied in this investigation, this factor requires further research. If bordered pit closure plays an important role in the water flow through spruce wood, as suggested in this study, the amount of latewood could be a parameter explaining intraspecific variation. For both pine and spruce it is known that with increasing ring width the relative amount of late wood decreases. This could mean that foundation piles with wide annual rings are less susceptible to bacterial degradation. However, in pine this relationship is obscured by the fact that the amount of sapwood, which is most susceptible to degradation, also depends on ring width.

## 4. Conclusions

This study has explored the relationship between the hydrological environment around wood in the soil, and water movement in and through the wood. If a relationship is supposed between erosion bacterial wood degradation and water flow in the wood, the degradation will be either stimulated by an increase in water-pressure differences along the foundation pile or by dynamic changes in the water pressure between the bottom and top of the piles. All species with an open wood structure show a higher water flow and are more susceptible to decay by erosion bacteria. Therefore, it can be assumed that the bacterial degradation in the less sensitive spruce piles can be equal to that in pine piles when the water pressure difference in the spruce piles is up to four times higher than in the pine piles. Moreover, because in spruce both sapwood and the latewood tracheids in the heartwood are open for water flow, a whole stem can be degraded, whereas in pine the impermeable heartwood will resist bacterial degradation for much longer.

Erosion bacteria and bacterial wood degradation are considered to be ever present in the natural environment (Nilsson and Björdal, 2007b). However, if wooden piles are enclosed in water-saturated soils with no water-pressure gradient along the pile and hence no water flow through the stem, bacterial wood degradation should be (almost) inactive.

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