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SOME PHYSICAL AND MECHANICAL PROPERTIES OF PINE WOOD (*PINUS SYLVESTRIS* L.) FROM EXCLUDED ZONES AROUND THE CHERNOBYL POWER STATION

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SYNOPSIS. Wood samples collected from pines growing in excluded zones around the Chernobyl Nuclear Power Plant were investigated. It was studied whether the anatomical changes in wood structure due to irradiation might have any influence on mechanical and physical properties of investigated wood. The width of annual increments, density of wood and compression strength in longitudinal direction were analysed.

KEY WORDS: Chernobyl disaster, compression strength, density, pine wood

INTRODUCTION

The explosion of the Lenin nuclear reactor in Chernobyl in April 1986 caused serious radioactive pollution, especially in the surrounding area. Several dozen radioactive isotopes found their way into the atmosphere, their collective radioactivity was at the level of $3{\cdot}10^{18}$ Bq, 30% of this amount on the first day of the catastrophe. Thermal currents caused by explosion and fire took the substances to the height of approximately 2 km. From there they moved together with the air masses. Big aerosols fell lower while smaller ones floated for a decidedly longer time. The proportions between specific isotopes in the radioactive fall changed in relation to the distance from the place of catastrophe and, in the following days, in relation to changes of temperature of the reactor fire.

As far as radioactivity is concerned the area of Chernobyl is still one of the most dangerous places on Earth. The remains of the destroyed reactor, closed in a concrete tomb, contain leftover nuclear fuel whose radioactivity reaches $0.7{\cdot}10^{18}$ Bq. The threat is however much bigger. Within the 30-kilometre closed area around the power station there remain 800 makeshift storing places. Different radioactive waste was buried there, including trees which absorbed high amounts of dangerous isotopes from the atmosphere (Belli and Tikhomirov 1996). Forests are a very specific environment, where pollution remains very long in main elements of the ecosystem. Harmful substances are found mostly in forest litter (Rafferty et al. 1996).

The high level of radioactive contamination, undoubtedly, influences forest trees. The cambium as a meristematic tissue seems to be sensitive to irradiation but in the literature there is lack information concerning this phenomenon.

The effects of ionising radiation by gamma rays on vascular plants are, in general, unfavourable. Woodwel and Miller (1963) showed that effect of long term irradaiation of *Pinus rigida* Miller to low dosages of about 3 roentgen per day caused reduction of radial increment. The radial growth was reduced at all levels in stem, but in the most intensive degree it was seen at the stem base. The authors speculated whether cambium, in unfavourable conditions, might have been inactive for a period of years or continue dividing on the phloem side only. Conversely, Chandorkar and Dengler (1987) who observed the reaction of *Pinus sylvestris* L. seedlings on continuous low level exposure to gamma irradiation noted the stimulation of mitotic activity by cambium in comparision to control and it was resulted in increase the number of xylem and phloem cells. The studies of Hamilton (1963), Clark and Hamilton (1968) as well as Hamilton and Chesser (1969) showed that ionising radiation effected wood structure. In the annual increments formed after the irradiation the areas with changed xylem cells occurred. The tracheids on the transverse sections were more round in size and possessed thin cell wall and smaller diameter. The tracheids were also shorter in comparison to the tracheids formed prior to the irradiation. Quite similar abnormalities in wood structure were observed by Kozubov and Taskaev (1994), Skuterud et al. (1994), Schmitt et al. (2000), Tulik (2001 a, b) who investigated pine wood from 30 excluded zones around the Chernobyl power station. They were noted that among tracheids created the regular, radial files areas of abnormal xylem were presented. Such areas consisted of deformed tracheids and ray cells as well as parenchymatic cells with lignified walls. The abnormal xylem was deposited irregularly around the stem circumference and was found both in the early and late wood. Its surface was varied in shape and size as well.

In relation to the literature data, a working hypothesis of our research was to study whether the changes observed on the anatomical level might influence physical and mechanical properties of wood. The width of annual increments, density of wood and the compression strength in longitudinal direction were tested as a result of impact of irradiation after the Chernobyl disaster.

MATERIALS AND METHODS

For studies the wood samples collected from the stem at the breast height of two living Scots pine (*Pinus sylvestris* L.) trees were obtained in October 1997. Trees grew 5 km south from the Chernobyl power station in a Scots pine forest stand at a distance of about 100 m from each other on the flat terrain, where radioactive contamination at the time of collection was $3.7 \cdot 10^5$ kBqm^{-2}. The analysed samples possessed bark and all annual rings formed before and after the Chernobyl accident. Age of trees counted at breast height was 30 and 42 years. Further these trees will be named, in short, as 30- and 42-year-old pines respectively. For wood samples the contribution of sapwood and heartwood was calculated. From the sapwood zones the standard samples were cut to study the compression strength in longitudinal direction (shape and size according to PN-79/D-04102). Samples were cut in pairs regarding the main anatomical direction in wood. The natural faults in wood were

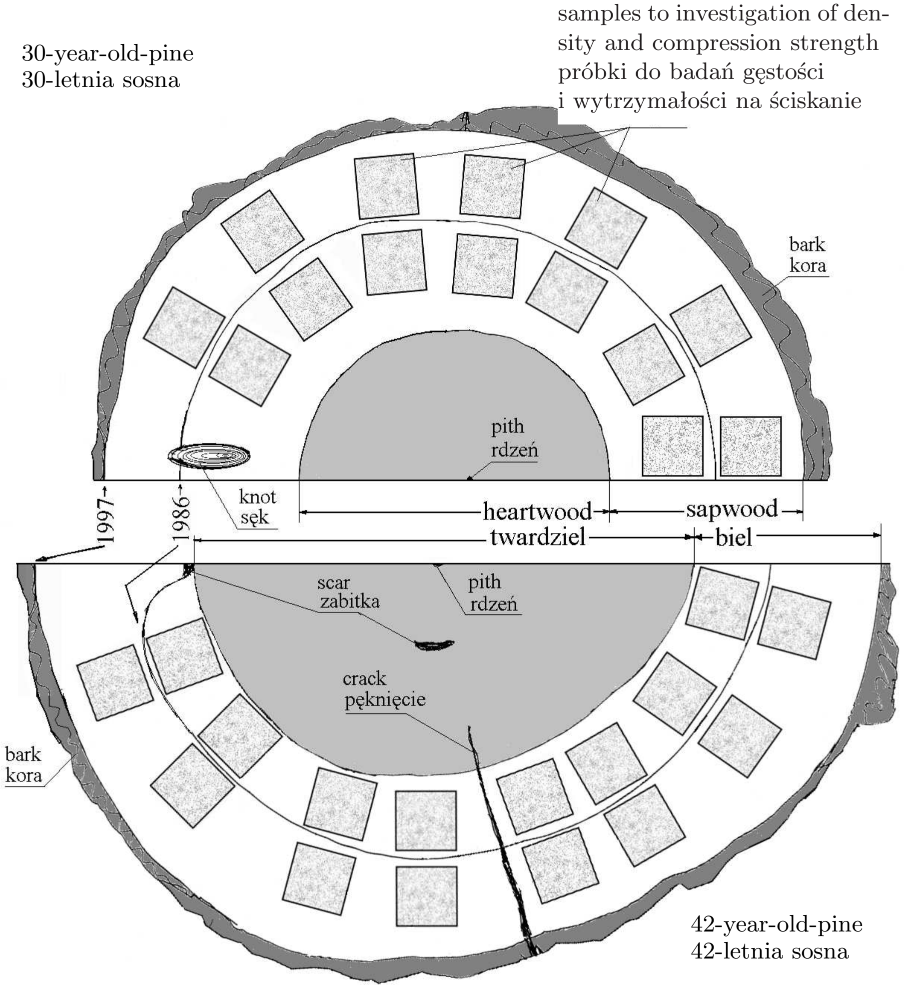


Fig. 1. Transverse sections from wood of 30-year-old (A) and 42-year-old (B) pine trees (showed half transverse section). Distribution (arrangement) of wood samples that were used to study of density and compression strength was marked

Rys. 1. Przekrój poprzeczny badanego drewna 30- i 42-letniej sosny (przedstawiono połowę przekroju). Zaznaczono rozmieszczenie próbek pobranych do badań gęstości i wytrzymałości na ściskanie wzdłuż włókien avoided as was shown on Figure 1. One sample was taken from annual rings just prior and the other just after the disaster in 1986. All samples were obtained from wood "above" 12 annual ring counting from the pith.

The wood samples for microscopic examinations were obtained from sapwood of 30-year old pines. The samples were boiled in a mixture of alcohol, glycerol and water for a few hours to soften wood. Next, the sections of wood, 20 µm thick, were cut with a sliding microtome, stained with 1% mixture of safranin and ethyl alcohol and embedded in Canada balsam. The sections were observed under light microscope equipped with digital imaging scanning system. Some samples were macerated for a few hours in a mixture of H_2O_2 (36%) and glacial acetic acid, 1:1 (v/w), at 100°C in a water bath. Pieces of macerated wood were watched and observed under light microscope equipped with Nomarski contrast.

The samples for investigation were stored in a heated closed room, where they dried to moisture content level of about 6-8%. To achieve the moisture content level of about 12% the wood samples were submitted to air conditioning process over a saturated solution of NaCl (Schneider 1960). Before performing destruction studies of wood samples the density of wood was calculated using stereoscopic measuring methods according to PN-77/D-04101 as well as the width of annual increments on the transverse section of samples. After the studies concerning the compression strength of wood the moisture content of samples was measured with the oven-dry method according to PN-77/D-04100.

The results were analysed statistically. The absolute error and the relative error were calculated by method of the total differential. Average result, standard deviation and variation coefficient were estimated for each tested characteristic. To determine the importance of differences between average results of tested characteristics of wood produced before and after 1986 the t-Student test was performed.

RESULTS AND ANALYSIS

On Figures 2, 3, 4 and 5 microscopic areas of pine wood with changed xylem elements are presented using the example of 30-year old pine. On transverse section (Fig. 2) an area of abnormal wood formed by tracheids is visible. The tracheids do not form regular radial rows. In such areas the direction of rays is also distorted. Intercellular spaces are often created where they are connected with the tracheids. Such intercellular spaces could appear secondarily as a result of wood drying, in places where desorption tensions were bigger than integrity of material. On radial section (Fig. 3) an area of irregular tracheids endings is presented. Untypical for pine clusters of rays, connected with their irregular shape and "stretching" parenchyma cells in tangentail direction are seen on tangential section (Fig. 4).

Observation of macerated wood showed that tracheids from abnormal wood were deformed. They were more or less round on the transverse sections and wider in comparison to tracheids from normal wood. The tips of tracheids from abnormal wood were quite often bifurcated, flattened or transversally elongated (Fig. 5).

Table 1. Diameter of stem and width of growth rings in sapwood and heartwood of pine trees form excluded zones around the Chernobyl nuclear power station
Tabela 1. Średnica pnia i szerokość przyrostów rocznych w drewnie bielu i twardzieli w sosnach ze strefy zamkniętej wokół elektrowni atomowej w Czarnobylu

Scots pine Sosna zwyczajna	Diameter of stem Średnica pnia [cm]	Part of sapwood Udział bielu [%]	Average width of growth rings in heartwood Średnia szerokość słojów w twardzieli [mm]	Average width of growth rings in sapwood Średnia szerokość słojów w bielu [mm]	Average width of growth rings in stem Średnia szerokość słojów w pniu [mm]
30-year-old 30-letnia	22.2	56	4.8	2.7	3.7
42-year-old 42-letnia	26.9	42	6.5	1.9	3.2

Moreover, the tracheids from abnormal wood possessed pits on cell walls, but way of pitting was irregular, instead of regular unilateral pitting, typical for pine trees, the irregular arrangement of pits occurred. Sometimes in the cell wall of tracheids the structure that were neither bordered nor window-loke pits appeared (Fig. 5).

Abnormal wood was deposited randomly on the whole girth of the analysed pines in sapwood that was formed after disaster in 1986. Abnormalities were found in earlywood as well as late wood – the biggest amounts in annual ring formed two years after radiation occurred, i.e. in 1988. The size of those areas is differed – from a few cells to several dozen.

Average moisture content of wood from four groups of samples intended to test physical-mechanical properties was similar and was measured with t-Student test at confidence interval level 95%. The samples achieved an air-dry stage (moisture content approximately 12.4%).

The tested pine wood from Chernobyl is a product with altering width of annual rings. The sapwood of 30-year-old pine formed before 1986 has wide rings (s = 4.8 mm), after 1986 the increments are narrow (s = 2.5 mm). The transition from wide to narrow rings is gradual. The width of growth decreases steadily in the direction from pith to girth. This change appears to be natural (in accordance with age trend of pine) and not connected with the serious radioactive pollution after the reactor's explosion in 1986. In a 42-year-old pine width of annual increments is different and untypical. Wide rings close to the pith in heartwood area quickly become narrow. Unlike in the 30-year-old pine, in the 42-year-old the rings of sapwood formed prior 1986 are narrow (s = 2.1 mm) and after 1986 wide (s = 3.4 mm). Narrowing of annual growth between approximately 1976-1986 in 42-year-old pine took place at the expense of late wood and probably resulted from weakening of cambium activity in the second part of vegetation season. The factor which caused such a phenomenon could have been some individual impulse affecting the tree's growth, e.g. mechanical damage of the trunk (in the section tested two clusters were noticed at the breast height: one in heartwood and second, much bigger, starting in the annual growth from 1975).

Table 2. Some physical and mechanical properties of sapwood in stem of 30 and 42-year-old pine trees from excluded zones around the Chernobyl nuclear power station

Tabela 2. Wybrane właściwości fizykomechaniczne drewna bielastego z pni 30- i 42-letnich sosen rosnących w zamkniętej strefie wokół elektrowni atomowej w Czarnobylu

Property of wood Właściwość drewna		30-year-old pine – sapwood Sosna 30-letnia – biel before 1986 przed 1986	30-year-old pine – sapwood Sosna 30-letnia – biel after 1986 po 1986	42-year-old pine – sapwood Sosna 42-letnia – biel before 1986 przed 1986	42-year-old pine – sapwood Sosna 42-letnia – biel after 1986 po 1986
Moisture content Wilgotność	average value (W) [%] wartość średnia (W) [%]	12.38	12.44	12.39	12.46
	standard deviation (s) [%] odchylenie standardowe (s) [%]	0.45	0.05	0.50	0.21
	coefficient of variation (v) [%] współczynnik zmienności (v) [%]	3.60	0.41	4.03	1.71
Width growth rings Słoistość	average value (sł) [mm] wartość średnia (sł) [mm]	4.8	2.5	2.1	3.4
	standard deviation (s) [mm] odchylenie standardowe (s) [mm]	0.66	0.27	0.56	0.49
	coefficient of variation (v) [%] współczynnik zmienności (v) [%]	13.7	11.0	26.4	14.5
Density Gęstość	average value (g_{12}) [kg/m^3] wartość średnia (g_{12}) [kg/m^3]	501	565	489	512
	standard deviation (s) [kg/m^3] odchylenie standardowe (s) [kg/m^3]	37.2	21.2	24.6	20.3
	coefficient of variation (v) [%] współczynnik zmienności (v) [%]	7.4	3.8	5.0	4.0
Compression strength in longitudinal direction Wytrzymałość na ściskanie wzdłuż włókien	average value (R_{s12}) [MPa] wartość średnia (R_{s12}) [MPa]	39.4	46.9	36.3	38.4
	standard deviation (s) [MPa] odchylenie standardowe (s) [MPa]	4.1	3.9	3.2	1.5
	coefficient of variation (v) [%] współczynnik zmienności (v) [%]	10.5	8.4	8.9	3.9

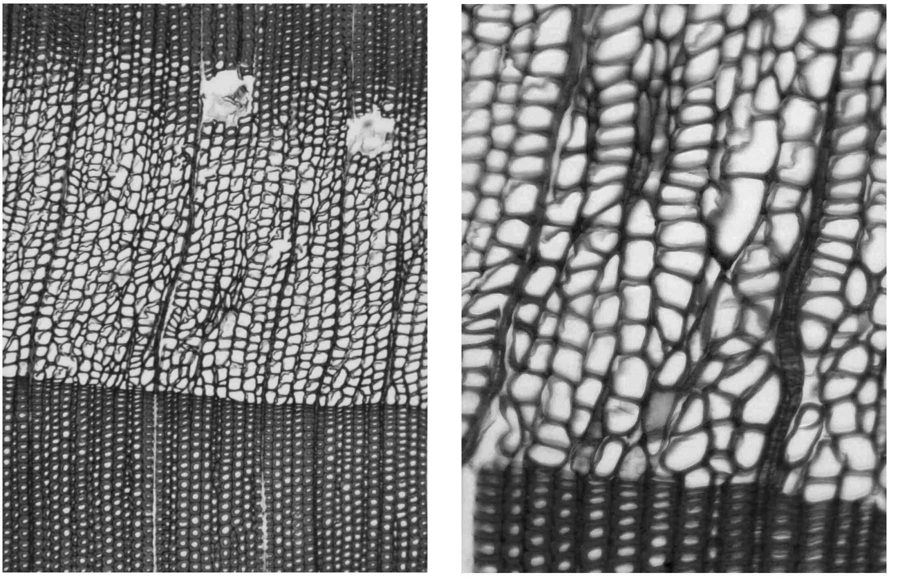


Fig. 2. Microscopic structure of sapwood in stem of 30-year-old pine that was formed after the Chernobyl accident in 1986 – transverse section
Rys. 2. Budowa mikroskopowa drewna bielastego z pnia 30-letniej sosny, powstałego po awarii w Czarnobylu w 1986 roku – przekrój poprzeczny

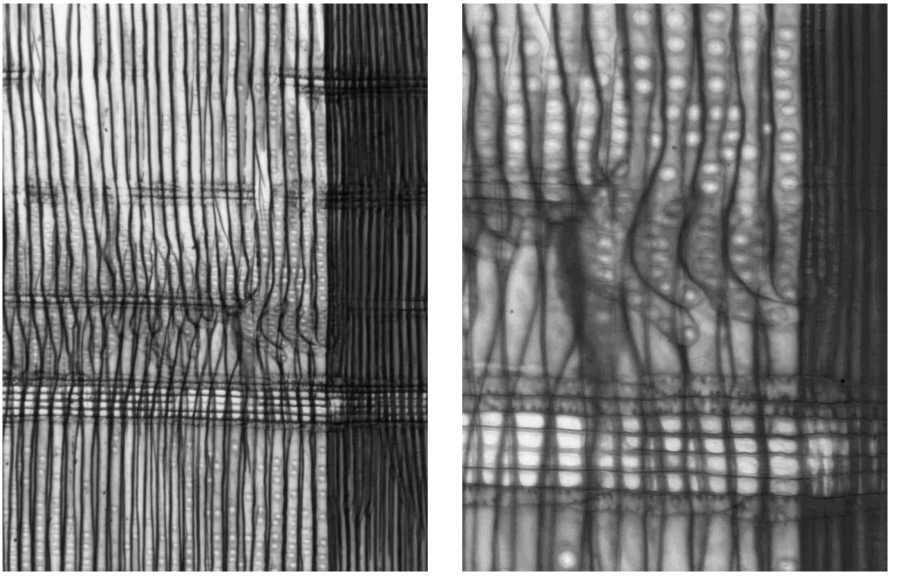


Fig. 3. Microscopic structure of sapwood in stem of 30-year-old pine that was formed after the Chernobyl accident in 1986 – radial section
Rys. 3. Budowa mikroskopowa drewna bielastego z pnia 30-letniej sosny, powstałego po awarii w Czarnobylu w 1986 roku – przekrój promieniowy

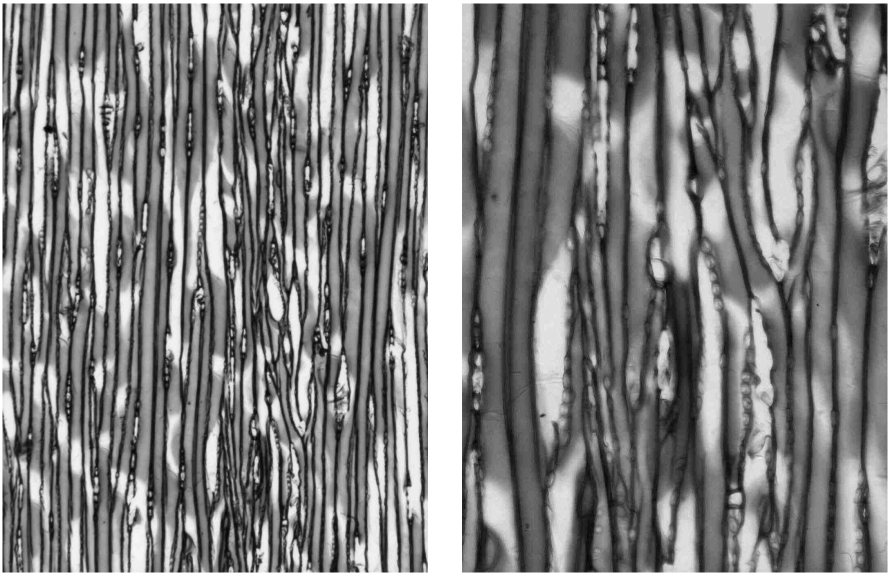


Fig. 4. Microscopic structure of sapwood in stem of 30-year-old pine that was formed after the Chernobyl accident in 1986 – tangential section
Rys. 4. Budowa mikroskopowa drewna bielastego z pnia 30-letniej sosny, powstałego po awarii w Czarnobylu w 1986 roku – przekrój styczny

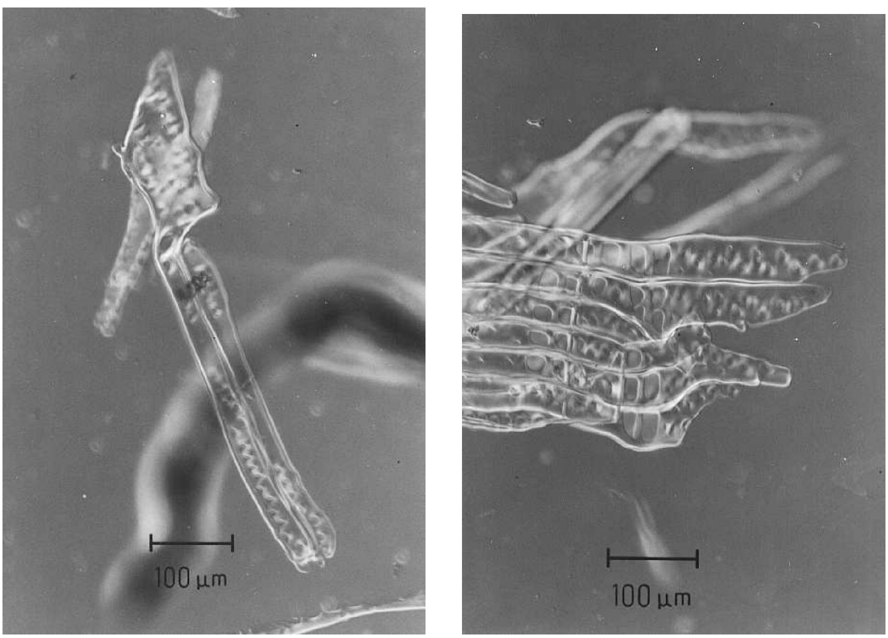
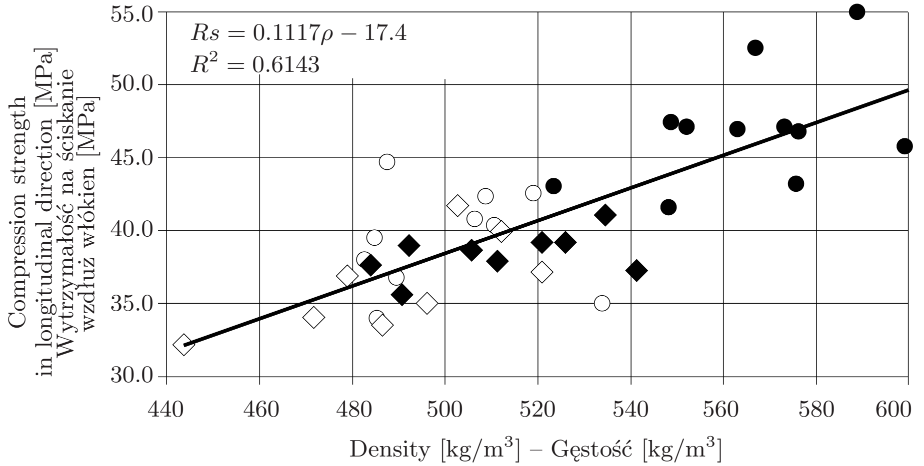


Fig. 5. Microscopic structure of sapwood in stem of 30-year-old pine that was formed after the Chernobyl accident in 1986 – abortive tracheids of early wood
Rys.5. Budowa mikroskopowa drewna bielastego z pnia 30-letniej sosny, powstałego po awarii w Czarnobylu w 1986 roku – zniekształcone cewki drewna wczesnego

In the wood of both analysed pines the borders of annual growth are clear and regular – typical for this kind of wood. Average width of annual growth of sapwood is considerably different at confidence level 95%.

The density of the tested pine wood remains at a level known from literature, (Krzysik 1978). In 30-year-old pine the sapwood with wider rings (before 1986) containing a lower percentage of late wood has lower density ($\rho \sim 500$ kg/m^3) in comparison to the narrow rings form after 1986 ($\rho \sim 565$ kg/m^3). In 42-year-old pine the narrow increments of sapwood next to heartwood has a low density in its relation to rings ($\rho \sim 490$ kg/m^3), lower than that of wide rings of sapwood formed after 1986 ($\rho \sim 510$ kg/m^3).

Considerable differences in average density of the tested wood areas were reflected in big differences between average resistance along fibres. The connection between wood density and resistance to compresion strength along fibres is a direct and proportional one (Krzysik 1978, Dzbeński et al. 2000). The density decides about the wood's resistance (for the wood tested over 60% determination factor R^2 on Fig. 6). The connection analysed for Chernobyl pine is typical and shows no differences when compared with wood from other places, e.g. pine from Rogów (Dzbeński et al. 2000).



30-year-old pine – sosna 30-letnia

○ – wood formed before 1986 – drewno powstałe przed 1986 rokiem

● – wood formed after 1986 – drewno powstałe po 1986 roku

42-year-old pine – sosna 42-letnia

◇ – wood formed before 1986 – drewno powstałe przed 1986 rokiem

◆ – wood formed after 1986 – drewno powstałe po 1986 roku

Fig. 6. Relation between wood density and compression strength in longitudinal direction of wood in moisture content 12%

Rys. 6. Zależność między gęstością a wytrzymałością na ściskanie wzdłuż włókien drewna o wilgotności 12%

Small number of samples makes it more difficult to analyse independently the connection between density and resistance to compression strength along fibres for particular areas of wood. Nevertheless, this connection is the strongest for the wood of 42-year-old pine grown before the explosion in 1986 and the weakest for the wood of 30-year-old pine from after 1986.

CONCLUSION

At microscopic level one can observe changes in the structure of pine wood from Chernobyl formed after the reactor explosion and severe radioactive pollution of trees. Next to typical, unchanged wood irregular areas of deformed wood are found. There a partial damage to structure occurred. Those areas are placed randomly and do not represent a high percentage of the section.

The changes do not appear to have a considerable influence on physical-mechanical properties of wood, tested macroscopically. As far as width of annual increments and density are concerned, wood formed after 1986 is typical for pine (*Pinus sylvestris* L.). Similarly, resistance to compresion strength is at a level usual for pine, and depending on wood density.

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WYBRANE WŁAŚCIWOŚCI FIZYKOMECHANICZNE DREWNA SOSEN (*PINUS SYLVESTRIS* L.) Z OKOLIC ELEKTROWNI W CZARNOBYLU

Streszczenie

Różnorodne czynniki środowiskowe mają wpływ na aktywność kambium w roślinach drzewiastych i tym samym na właściwości powstającego drewna. W pracy zbadano wpływ silnego napromieniowania jonizującego związanego z awarią elektrowni atomowej w Czarnobylu na wybrane właściwości fizykomechaniczne drewna z dwóch sosen (ze strefy zamkniętej wokół elektrowni). Obserwowane na poziomie mikroskopowym lokalne, losowo rozmieszczone strefy zmienionego drewna nie wpłynęły znacząco na słoistość, gęstość i wytrzymałość na ściskanie. Drewno wytworzone po napromieniowaniu w 1986 roku pod względem zbadanych właściwości fizykomechanicznych jest typowe dla sosny zwyczajnej (*Pinus sylvestris* L.).

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