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Abstract

The main task of VTT in this EU project was to test and improve the reliability and performance of wood moisture content meters. A total of 16 resistance type and 6 capacitance type hand-held moisture meters were included in the test series.

Test samples of the most important European species (pine, spruce, birch, oak, beech, alder, larch) were obtained from all over Europe. Altogether a total of about 2,700 specimens were used for comparative testing. The specimens were conditioned to three different moisture content levels (8 - 10%, 12 - 14% and 16 - 18%). The moisture gradients of the test materials were low due to the extensive conditioning period of at least 1 year.

The effects of various factors such as moisture content, species, and temperature on the electrical resistance of conditioned wood were studied. The resistance – moisture content curves for different species from different countries were determined for the conditioned wood material in the laboratory. The regression model used for the resistance – moisture content curves in this work was as follows:

$$\log\log(R+1) = a \times u + b$$

where a and b are constants for the given type of wood.

The species-specific corrections (resistance curves) are quite similar for different countries. Only the resistance curve of Maritime Pine differs clearly from the other resistance curves for the pine species originating from the different countries.

In the temperature test, measurement of the electrical resistance was performed at temperatures of –10 °C, +5 °C, +20 °C, +40 °C, +60 °C and +70°C. Resistance (R) as a function of moisture content (u) and wood temperature (T) was determined by regression analysis as follows:

$$\log(\log(R)+2) = -0.00147\times T - 0.0262\times u - 0.000158T\times u + 1.075$$

From the above mentioned equation, the equation for temperature correction can be calculated when the resistance curve at a constant temperature (20 °C) is known from the following equation:

$$u_{corr} = -\frac{0.00147T1n(10) + 1n(\exp(au_{meas}1n(10) + b1n(10)) + 1) - 1.0751n(10)}{1n(10)(0.000158T + 0.0262)}$$

where

u_{corr} is temperature-corrected moisture content (%)

u_{meas} is moisture meter reading (%)

T is wood temperature (ºC)

a, b is constants for given wood type.

The wood temperature corrections are about 0.1 - 0.15%-units/°C which has to be considered when the moisture content of wood is measured at temperatures other than 20 °C.

The other properties of wood such as sapwood/heartwood and density does not have a significant impact on the resistance values. There were no significant resistance differences due to type of the electrodes, distances between electrodes and the different measuring directions.

The commercial instruments for the determination of wood moisture content were tested with respect to accuracy, reliability and ergonomy. The moisture meters were tested both under laboratory and industrial conditions. Most of the resistance meters showed a systematic deviation from the actual moisture content because of incorrect MC-resistance curves. When the MC was lower than 10%, the readings of all the resistance meters tended to creep. The accuracy of the MC meters (95% confidence interval) in laboratory tests with well-conditioned test material is about ±1.5 … ±2.5% units for the resistance meters and about ±2.5% … ±4.0% units for the capacitance meters. The corresponding accuracy of MC meters in industry test is about ±2.0% … ±5.0% units for the resistance meters and about ±3.0% … ±5.0% units for the capacitance meters. Other factors affecting the accuracy of the moisture meters were also studied for this report. Resistance type moisture meters have to be compensated for variation caused by wood species and wood temperature. The readings of capacitance type moisture meters have to be compensated for wood species and are influenced by the varying density of the wood species.

Preface

The project "Testing and improvement of the performance of MC measuring instruments for drying quality control" is a part of the EU project IMCOPCO "Improvement of Moisture Content Measuring Systems and Testing Strategies to Enable Precise Process and Quality Control of Kiln Dried Timber", which belongs to EC's 4th framework programme (SMT4-CT95-2023). The research work has been financed by EC and Centre for Metrology and Accreditation (MIKES) and Technical Research Centre of Finland (VTT). Their financial support is gratefully acknowlegded.

The EC contact person was Mrs. I. de Froidmont-Görtz. The participants in the IMCOPCO-project were follows:

Partner 1	Johannes Welling (project coordinator)	Bundesforschungsanstalt für Forst- und Holzwirtschaft	(D)
Partner 2	Jan Buchter	Danish Technological Institute	(DK)
Partner 3	Sverre Tronstad Sjur H. Fløtaker	Norwegian Institute of Wood Technology	(N)
Partner 4	Björn Esping	Swedish Institute for Wood Technology	(S)
Partner 5	Holger Forsén Veikko Tarvainen	Technical Research centre of Finland, Building Technology	(FIN)
Partner 6	Daniel Aleon	Centre Technique du Bois et de L'Ameublement	(F)
Partner 7	Wolfgang Gard Michel Riepen	TNO Centre for Timber Research	(NL)
Partner 8	Helmuth Resch	Institut für Holzforschung der Universität für Bodenkultur	(A)
Parner 9	Arnold Brookhuis Pieter Rozema	Brookhuis Micro-Electronics	(NL)

The Imcopco project is subdivided into 5 task programmes. This report deals with task 3 of the IMCOPCO-project.

The most common commercial moisture content meters that are available and used by the European woodworking industry and timber trade were tested in this project. All partners in the IMCOPCO Group have sent test specimens for the project from their respective countries. The tests were performed both at VTT's laboratory and at sawmills.

We wish to express our sincere thanks to all the persons involved in this project.

Espoo September 5, 2000

Holger Forsén Veikko Tarvainen

Contents

1. Introduction and aim of the task

Two different types of hand-held moisture meters for wood are available on the market. Resistance type moisture meters determine the electrical resistance of wood. Capacitance type moisture meters employ the large difference in the dielectric constant between wood and water. While wood moisture content directly influences electrical resistance, the electrical capacity of a piece of wood is determined by the mass of the water within the reach of the scan plates of the capacitance type meter. Resistance type moisture meters have to be compensated for wood species and wood temperature. The readings of capacitance type moisture meters have to be compensated for wood density. With these reservations, both types of instruments produce fairly reliable results if certain limitations are accepted (Skaar 1988).

Commercial instruments for the determination of wood moisture content were to be tested with respect to accuracy, reliability and ergonomy. The scope of the survey covers the performance of hand-held moisture content meters, both resistance and capacitance type moisture content meters. Hand-held moisture content meters were tested both under laboratory and industrial conditions.

In this report all the results achieved with commercial MC meters are presented anonymously. The aim of the project is to establish the state of the art for the accuracy, reliability and performance of the meters available on the market and used in normal industrial conditions and to seek to improve them in response to the results obtained.

2. Instruments, test material and measuring conditions

2.1 Measuring instruments

2.1.1 Resistance measuring instruments

The electrical resistance of wood was measured with Hewlett Packard´s high resistance meter model 4329A with a resistance measuring range of 5 x 10^5 … 2 x 10^16 ohm. The measuring specifications were as follows:

- Electrode type: insulated steel needles (type Gann)
- Measuring voltage: 10 Volts
- Measuring temperature: 20 °C (excluding point 3.2)
- Measuring delay: about 3 - 5 seconds depending on the the resistance stability time
- Measuring depth: 10 - 25 mm (a third of the thickness of the wood)
- Measuring direction: mostly parallel to the grain.

The moisture content – resistance curves of the different resistance moisture meters for different species at 20 °C were determined using a Calibration Reference box delivered by Brookhuis. This checkbox had the following resistance values (see Table 1).

Table 1. Calibration of the reference resistances in the Calibration Reference box (checkbox).

Nominal values	Measured values
10 KOhm	9.9409 KOhm
100 KOhm	100.159 KOhm
1 MOhm	0.99849 KOhm
10 MOhm	9.9826 MOhm
100 MOhm	102.013 MOhm
1 GOhm	1.04018 GOhm
10 GOhm	
100 GOhm	

2.1.2 Moisture content meters

Most European suppliers of moisture content measuring instruments were invited to participate in the test program. More than 15 companies have provided us with their moisture meters. All in all, VTT tested 22 different commercial hand-held MC meters (16 resistance meters and 6 capacitance meters). The following instruments were sent to VTT for testing:

Resistance meters:

- Aqua – Boy
- BES Bollmann combo 200
- CSA electronic, Delta - 8N
- Delmhorst RDM-2S
- FMD moisture meter
- FME moisture meter
- Gann Hydromette RTU600
- Gann Hydromette M2050
- Protimeter Timbermaster S
- Protimeter Timberlogger
- Timber Test FM510
- WALTTERI
- Vanicek VIVA 12
- WSAB Lignomat mini X
- WSAB Lignomat (pocket)
- WSAB Lignomat TESTER

Capacitance meters:

- CSA electronic, Delta 2000H
- CSA electronic, Delta 2000S
- FMW moisture detector
- HYGROTEST FM600
- Merlin HM8 - WS13
- Wagner L612

All the resistance meters were checked with the checkbox (see Table 1) every 2nd month to ensure the repeatability of the measurements. All resistance MC meters have their own (built-in) resistance curves for different species. The resistance curves are different for different species depending on the electrical properties of wood. Figure 1 shows an example of the built-in resistance curves for different wood species for one of the MC-meters.

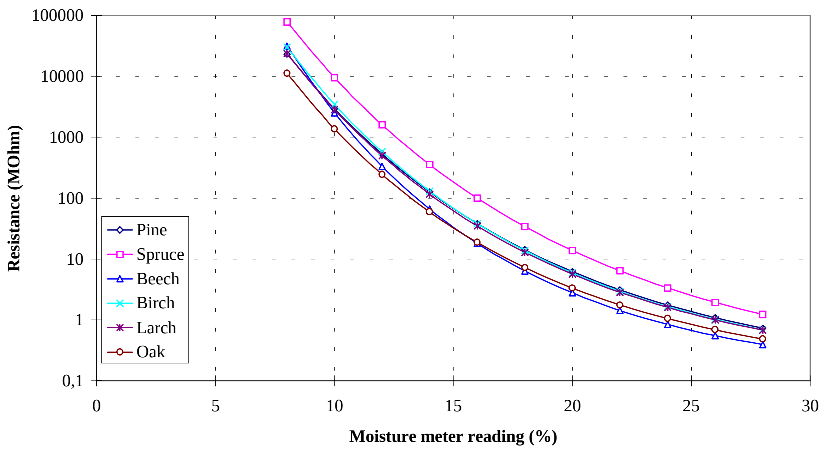

Figure 1. Resistance curves for different species by one MC-meter.

Due to the different built-in resistance curves, instruments from different manufacturers show different readings when used on the same wood material (see Figure 2).

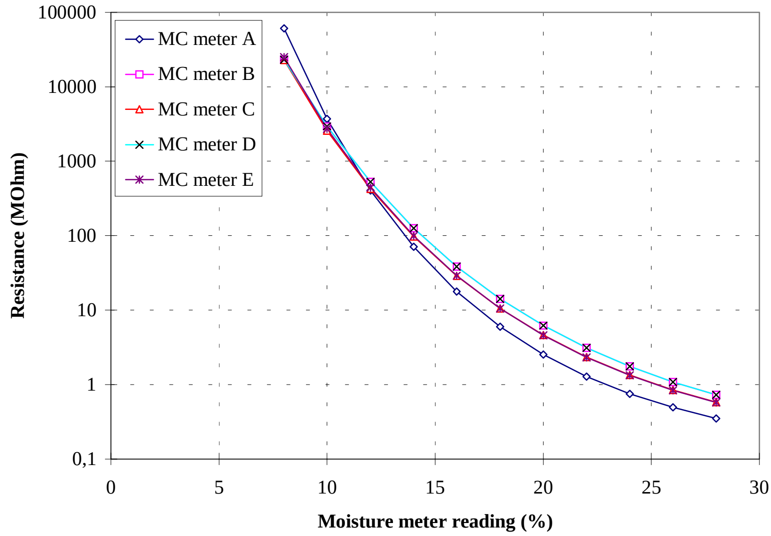

Figure 2. Resistance curves for pine by different MC-meters.

Only two of the capacitance MC meters provided for the tests could be calibrated. They were calibrated according to the manufacturer's instructions using calibration blocks supplied with the instruments.

2.2 Test material and conditioning

2.2.1 Procuring of the test material

Test samples of the most important European species (pine, spruce, birch, beech, oak, alder and larch) were collected from different places all over Europe in order to include different provenances for each species. The participating countries delivered samples as follows:

- Austria; spruce (*Picea abies*)
- Denmark; Douglas (*Pseudotsuga menzisii*), spruce (*Picea abies*), beech (*Fagus sylvatica*), oak (*Quercus petraea*), larch (*Laris decidua, Laris leptolepis*)
- Finland; Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*), birch (*Betula pubescens, Betula verrucosa*)
- France: Maritime pine (*Pinus pinaster*), oak (*Quercus robur*)
- Germany; pine (*Pinus sylvestris*), spruce (*Picea abies*), beech (*Fagus sylvatica*), oak (*Quercus robur*)
- Norway: Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies*)
- Sweden; Scots pine (*Pinus sylvestris*), Norway spruce (*Picea abies),* birch (*Betula pubescens*, *Betula verrucosa*), alder (*Alnus glutinosa*).

The test material was collected from different places in the said countries. A total of about 3000 pieces of wood were used for testing. The test material was conditioned to three different moisture content levels (8 - 10%, 12 - 14% and 16 - 18%). Table 2 presents the number of specimens of the different species according to the origin. All the instruments were tested with the different species.

Table 2. Species, origin, number and target moisture content of the test specimens.

Species	MC %	Origin: Germany	Denmark	Norway	Sweden	Finland	Austria	France	Total
Pine	8	90		38	80	80		30 *	288
	12	90		38	80	80		30 *	288
	16	90		38	80	80		30 *	288
Spruce	8	30	41	30	80	103	22		306
	12	30	41	30	80	103	22		306
	16	30	41	30	80	103	22		306
Birch	8				40	58			98
	12				40	58			98
	16				40	58			98
Beech	8	19	20						39
	12	19	20						39
	16	19	20						39
Oak	8	50	20					30	100
	12	50	20					30	100
	16	50	20					30	100
Alder	8				40				40
	12				40				40
	16				40				40
Larch	8		21						21
	12		21						21
	16		21						21
Total		567	306	204	720	723	66	90	2676

* Maritime pine

2.2.2 Preparation and conditioning

The tested species were pine, spruce, birch, oak, beech, alder and larch. The wood samples were divided into three parallel groups which were conditioned to 8 - 10%, 12 - 14% and 16 - 18% moisture content levels. All test material was green or previously air dried. At first all the test material was dried at a temperature of 40 °C close to the target moisture contents. Then the test material was conditioned in different climate rooms. The conditions were 20 °C/RH 40 % ± 5 %, 20 °C/RH 65 % ± 5 % and 20 °C/RH 85 % ± 5 %. The moisture gradients of the test materials were low due to the long conditioning period of at least 1 year. The average moisture contents and standard deviations for different moisture classes are presented in Table 3.

Table 3. Moisture contents and moisture gradients of the test specmens after conditioning.

Origin of test specimen	Moisture class 8 - 10 %				Moisture class 12-14 %				Moisture class 16 - 18 %			
	Moisture		Moisture gradient		Moisture		Moisture gradient		Moisture		Moisture gradient	
	AVE	Stdev	AVE	Stdev	AVE	Stdev	AVE	Stdev	AVE	Stdev	AVE	Stdev
Pine												
Finland	9.5	0.3	0.41	0.29	12.8	0.3	0.53	0.49	17.5	0.8	0.71	0.38
Sweden	9.6	0.3	0.22	0.14	13.1	0.5	0.29	0.23	17.3	0.5	0.73	0.42
Norway	9.5	0.2	0.48	0.26	12.8	0.3	0.60	0.43	17.4	0.8	0.49	0.29
Germany	9.7	0.2	0.32	0.31	13.3	0.4	0.51	0.33	17.6	0.9	0.36	0.27
France	9.9	0.5	0.56	0.31	13.5	0.3	0.63	0.32	17.8	0.5	0.69	0.35
Nordic	9.5	0.3	0.34	0.25	12.9	0.4	0.43	0.39	17.4	0.7	0.69	0.39
Spruce												
Finland	9.9	0.2	0.38	0.31	13.4	0.3	0.56	0.50	18.0	0.4	1.10	0.56
Sweden	10.0	0.2	0.28	0.53	13.6	0.3	0.27	0.26	18.0	0.3	0.80	0.39
Norway	9.8	0.1	0.29	0.18	13.2	0.4	0.70	0.30	18.1	0.7	0.89	0.85
Denmark	9.7	0.2	0.34	0.24	14.0	0.5	0.28	0.24	18.4	0.8	0.63	0.42
Germany	10.0	0.2	0.19	0.17	14.2	0.2	0.56	0.25	18.2	0.3	0.45	0.29
Austria	9.4	0.1	0.41	0.21	13.6	0.2	0.89	0.29	18.4	0.7	0.80	0.54
Nordic	9.9	0.2	0.33	0.40	13.4	0.4	0.44	0.41	18.0	0.4	0.96	0.54
Central Europe	9.9	0.2	0.32	0.22	13.4	0.4	0.48	0.34	18.0	0.4	0.63	0.42
Birch												
Finland	9.1	0.3	0.21	0.12	12.3	0.3	0.26	0.18	18.2	1.2	0.82	0.71
Sweden	9.0	0.2	0.28	0.21	12.4	0.4	0.49	0.33	19.1	0.6	1.82	0.61
Nordic	9.0	0.3	0.24	0.17	12.3	0.3	0.38	0.28	18.6	1.1	1.24	0.71
Oak												
Denmark	9.8	0.3	0.34	0.22	13.1	0.6	0.16	0.12	17.6	0.9	0.58	0.40
Germany	9.7	0.3	0.32	0.15	13.5	0.3	0.46	0.21	17.3	0.2	1.02	0.30
France	9.9	0.2	0.40	0.18	13.0	0.2	0.19	0.07	17.2	0.3	0.58	0.30
Central Europe	9.8	0.3	0.35	0.18	13.3	0.4	0.27	0.20	17.3	0.5	0.73	0.38
Beech												
Denmark	9.1	0.1	0.31	0.19	13.1	0.3	0.21	0.19	17.9	0.4	0.73	0.38
Germany	9.4	0.1	0.26	0.22	13.8	0.3	0.27	0.15	17.4	0.3	0.89	0.31
Central Europe	9.3	0.2	0.28	0.20	13.4	0.4	0.24	0.17	17.6	0.4	0.81	0.34
Alder												
Sweden	8.9	0.2	0.44	0.18	12.1	0.2	0.39	0.31	16.4	0.4	0.50	0.34
Larch												
Denmark	9.9	0.3	0.28	0.16	13.5	0.3	0.51	0.41	17.3	0.4	0.63	0.48

The standard deviation for all test specimen groups was mostly very low. The average moisture gradients, the MC difference between the surface and centre of a test sample, are less than 0.5%.

The average density of all test specimens was measured. Both weight and volume were determined at the same MC (actual density). Then the actual density was recalculated into other densities. The following density expressions were used (Kollman & Côté 1968):

- Density (12, 12) = weight at 12% MC /volume at 12% MC (commonly used in Central Europe)

- Density (0, 28) = oven dry weight/green volume (Nordic countries)

- Density (0, 12) = oven dry weight/volume at 12% MC (USA).

The average densities of each species by country in the different moisture conditions are presented in Table 4.

Table 4. Density of the test specimens in different moisture conditions.

Species	Country	Density (12, 12) (kg/m³)		Density (0, 28) (kg/m³)		Density (0, 12) (g/cm³)	
		Average	Standard deviation	Average	Standard deviation	Average	Standard deviation
Pine	Finland	520	62	433	51	0.464	0.055
	Sweden	496	62	413	51	0.443	0.055
	Norway	458	58	381	48	0.391	0.049
	Germany	511	68	425	57	0.456	0.061
	France	624	61	519	51	0.557	0.054
	Nordic	500	65	416	54	0.443	0.060
Spruce	Finland	463	49	387	41	0.413	0.044
	Sweden	477	40	399	33	0.426	0.035
	Norway	448	42	374	35	0.400	0.038
	Denmark	449	68	376	57	0.401	0.060
	Germany	461	68	385	57	0.411	0.061
	Austria	452	39	378	32	0.404	0.035
	Nordic	465	46	389	38	0.416	0.041
	Central Europe	454	62	379	52	0.405	0.056
Birch	Finland	629	38	517	31	0.562	0.034
	Sweden	649	48	533	39	0.580	0.043
	Nordic	638	43	524	36	0.569	0.039
Oak	Denmark	680	36	564	30	0.607	0.032
	Germany	656	51	544	42	0.586	0.046
	France	749	30	621	25	0.669	0.027
	Central Europe	689	59	571	49	0.615	0.053
Beech	Denmark	706	35	569	28	0.630	0.031
	Germany	678	40	547	32	0.606	0.036
	Central Europe	693	40	558	32	0.618	0.035
Alder	Sweden	512	35	422	29	0.457	0.031
Larch	Denmark	485	52	405	44	0.433	0.047

Variations in density in the one and same piece of sawn timber can by quite high due the unhomogeneity of wood. The standard deviation was about 50 kg/m^3 which is quite normal.

2.2.3 Conditions in laboratory and industrial testing

Electrical resistance was measured in laboratory conditions. All the moisture meters, resistance and capacitance type meters alike, were tested under both laboratory and industrial conditions. The test material in the laboratory tests was conditioned wood and in the industrial tests unconditioned wood.

2.2.4 Laboratory tests

The effect of different factors on the electrical resistance of wood was studied with conditioned test material. The "basic" resistance measurement at a constant temperature (20 °C) was performed on all test specimens. The "special" resistance measurement (temperature, sapwood/heartwood, type of electrodes, distances between electrodes, measuring direction, density) was performed on Scots pine using at least 16 specimens for every moisture class (8 - 10%, 12 - 14% and 16 - 18%).

In the laboratory, the accuracy and reliability of all moisture meters (both resistance and capacitance type moisture meter) were tested with conditioned test material. With the resistance moisture meters, at least 20 measurements were made in every origin, species, and moisture class group. The capacitance meters were tested with all the test materials because this method is very quick. Moisture meter readings were compared with the actual moisture content of wood which was determined by oven dry method. The measuring temperature of both the moisture meters and the test material was 20 °C. The electrodes were inserted in the direction of the grain. The measurements were conducted in complieance with the manufacturer's instructions.

2.2.5 Industrial tests

All moisture content meters were tested also under industrial conditions. The material for this test (a total of 300 pieces) was provided in the form of 10 packages supplied by sawmills. The measurement position was chosen on the outer face of the sawn timber. The measurement depth with resistance MC meters should be 0.3 times the thickness of sawn timber, at a distance of 0.3 meters from either end and at a distance of 0.3 times the width from one edge according to prEN 13183-2 (European standard prEN 13183-2). With the capacitance MC meters, the moisture content measurement was made according to the manufacturer's instructions. Under industrial conditions, the variables were as follow:

- Species: Pine and spruce
- Thickness of sawn timber: 25 mm - 75 mm
- Width of sawn timber: 100 mm - 250 mm
- Moisture content: 7% - 25%
- Wood temperature +5 °C - +20 °C
- Kiln types: Progressive and batch

The test material was unconditioned. Different ranges of moisture content and temperatures were considered. The storage time from drying to moisture measurement varied from 1 day to 3 month.

3. Effect of different factors on the electrical resistance of wood

3.1 Effect of the species and species correction

The resistance – moisture content curves for different species from different countries were determined in the laboratory according point 2.1.1. In order to determine the relationship between electrical resistance and moisture content of the wood, curve fitting was carried out with the measured values. The regression model used in this study was (Samuelsson 1990):

$$\log(\log R + 1) = a \times u + b \tag{1}$$

or rewritten

$$R = 10\hat{}\,(10\hat{}\,(a \times u + b) - 1 \tag{2}$$

where R is the resistance (MOhm) and u the moisture content (%).

Curve fitting was carried out with the SPSS software package, which calculated the coefficients a and b. By setting the coefficients a and b in the equation (2), the moisture content value can be calculated using the measured resistance. Figures 3a, 3b and 3c show, by way of an example, the resistance curves and measuring points for pine from Nordic countries, for spruce from Central Europe, and for oak from Central Europe. The resistance curves for pine, spruce, birch, beech, alder and larch from different countries are presented in Appendix A and summarised in Table 5.

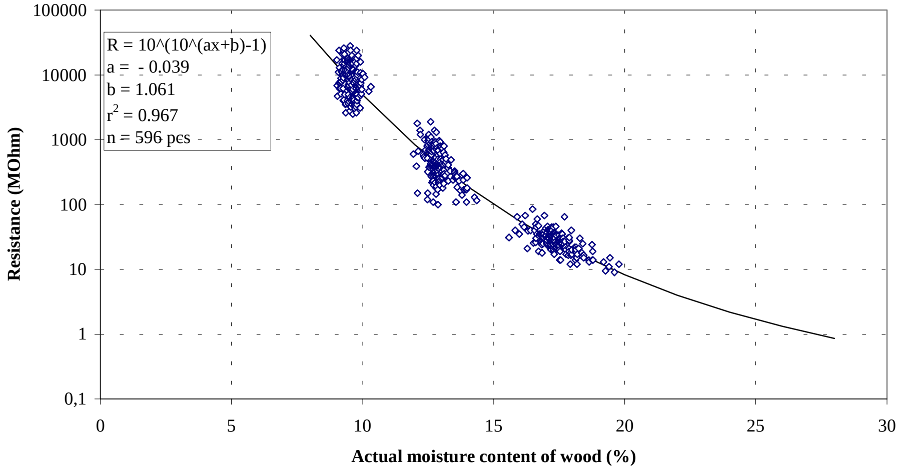

Figure 3a. Resistance curve for Nordic pine.

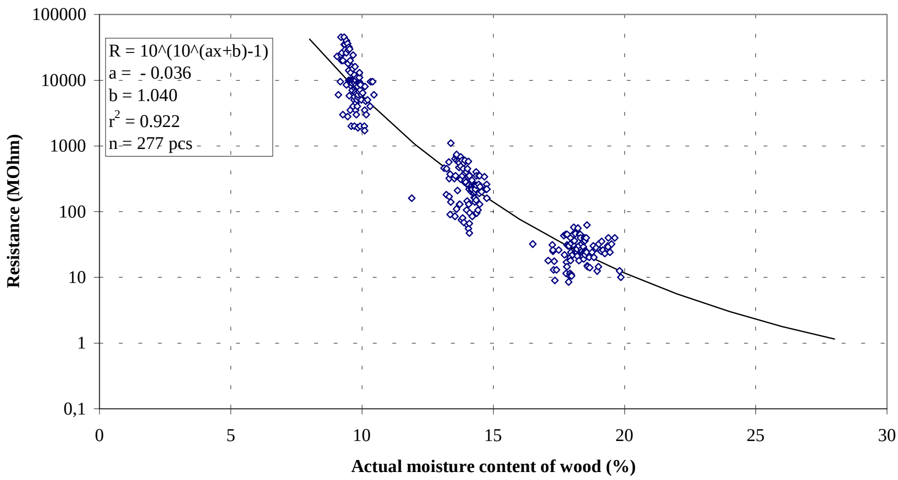

Figure 3b. Resistance curve for spruce from Central Europe.

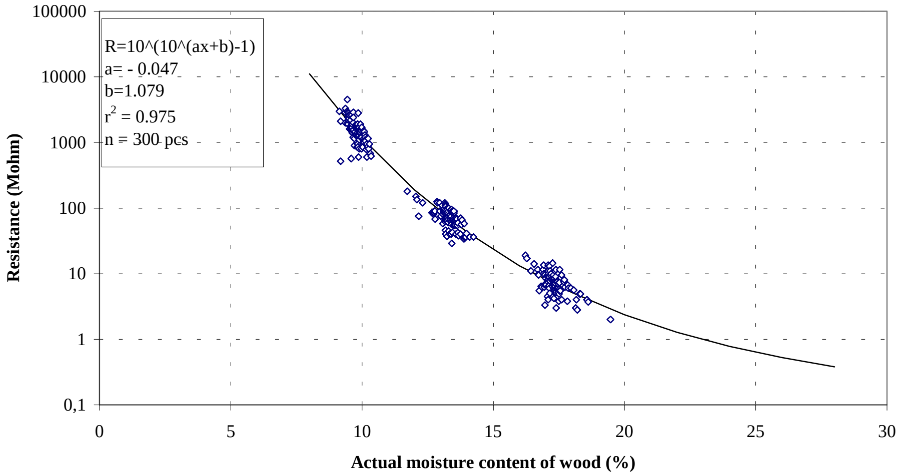

Figure 3c. Resistance curve for oak from Central Europe.

In all regression curves the coefficient of determination r^2 is very high, over 0.9. The deviation of the measured resistance values around the regression curve is considerable because of the large variation in the electrical properties of wood. At higher moisture contents of wood the deviation decreases.

In Table 5, the resistance curves for pine and spruce seem to be identical for different countries whereas Maritime pine (France) clearly stand out. When comparing resistance curves calculated by VTT with the curve from Trätek (Samuelsson 1990), a minor difference can be detected. In practice, the difference means that when the resistance is 10 MΩ the moisture content difference is about 1.0% while at 10 000 MΩ the difference is 0.6%.

Table 5. Resistance curves for wood.

Species	Country	Pieces	Resistance curves			Resistance		
			a	b	r^2	10 MOhm	1 000 MOhm	10 000 MOhm
Pine	Finland	240	-0.038	1.052	0.958	19.8	11.8	9.3
	Sweden	240	-0.039	1.062	0.981	19.5	11.8	9.3
	Norway	116	-0.040	1.079	0.964	19.4	11.9	9.5
	Germany	270	-0.036	1.015	0.951	19.8	11.5	8.8
	France	90	-0.045	1.147	0.973	18.8	12.1	10.0
	by Trätek		-0.040	1.055		18.8	11.3	8.9
	Nordic	596	-0.039	1.061	0.967	19.5	11.8	9.3
Spruce	Finland	309	-0.038	1.080	0.980	20.5	12.6	10.0
	Sweden	240	-0.037	1.047	0.985	20.2	12.0	9.4
	Norway	90	-0.038	1.072	0.987	20.3	12.4	9.8
	Denmark	123	-0.035	1.004	0.891	20.1	11.5	8.7
	Germany	90	-0.036	1.043	0.974	20.6	12.2	9.6
	Austria	66	-0.039	1.100	0.977	20.5	12.8	10.3
	by Trätek		-0.039	1.063		19.5	11.8	9.3
	Nordic	639	-0.038	1.067	0.981	20.2	12.2	9.7
	Central Europe	279	-0.034	1.014	0.892	21.0	12.1	9.3
Birch	Finland	176	-0.039	1.035	0.961	18.8	11.1	8.6
	Sweden	120	-0.038	1.029	0.976	19.2	11.2	8.7
	Nordic	296	-0.039	1.032	0.968	18.7	11.0	8.5
Oak	Denmark	60	-0.048	1.085	0.975	16.3	10.1	8.0
	Germany	150	-0.047	1.081	0.978	16.6	10.2	8.1
	France	90	-0.046	1.069	0.979	16.7	10.2	8.0
	Central Europe	300	-0.047	1.079	0.975	16.6	10.1	8.1
Beech	Denmark	60	-0.045	1.116	0.963	18.1	11.4	9.3
	Germany	57	-0.047	1.123	0.965	17.5	11.1	9.0
	Central Europe	117	-0.046	1.119	0.962	17.8	11.2	9.1
Alder	Sweden	120	-0.044	1.131	0.971	18.9	12.0	9.8
Larch	Denmark	63	-0.042	1.112	0.976	19.3	12.1	9.8

3.2 Effect of temperature

The electrical resistance of wood decreases when its temperature increases (Skaar 1988). The resistance curves for Pine were determined at temperatures of –10 °C, +5 °C, + 20 °C, +40 °C, +60 °C and +70 °C. The temperature of the wood specimen was changed in such a way that the moisture content of the wood remained unchanged by placing the specimen in plastic bags in a freezer, in a cold room and in a climate chamber where the temperature and the relative humidity can be adjusted without the MC of the specimens being affected. The measured resistance values are plotted in Figure 4. the resistance was calculated as a function of the real MC and temperature as follows using regression analysis (r^2 = 0.97):

$$\log(\log(R) + 2) = -0.00147 \times T - 0.0262 \times u - 0.000158 T \times u + 1.075 \qquad (3)$$

where

R is resistance in MOhm

u is moisture content (%)

T is wood temperature (°C).

The MC-resistance curves for Pine at the test temperatures are shown in Figure 4.

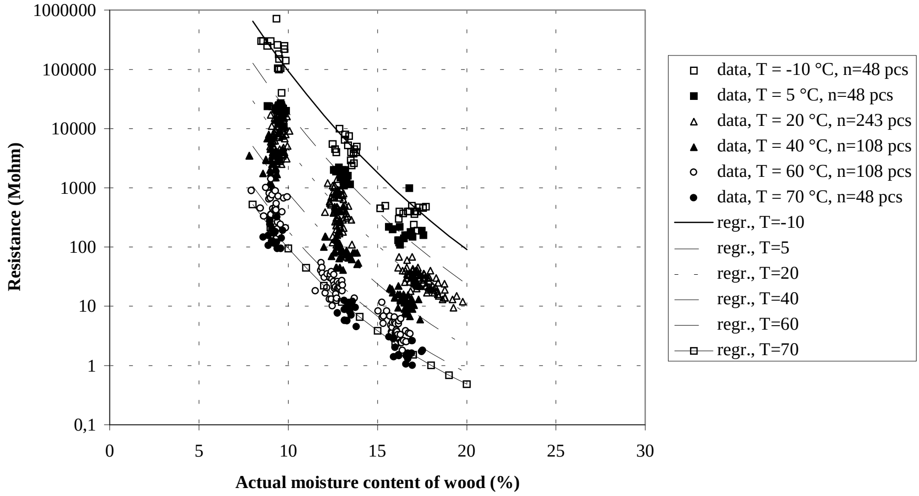

Figure. 4. The moisture content - resistance curves for Pine at different temperatures.

The temperature correction, which should be used when making measurements with resistance type MC meters, is calculated from Figure 4. The temperature corrections are about 0.1 - 0.15% units / °C which has to be noticed when the moisture content of wood is measured at temperatures other than 20 °C. The results compare well with those given by James (1975) and cited by Skaar (1988). Most resistance MC meters have an adjustable wood temperature compensation.

By substituting R from the regression equation (1) for the resistance curve at constant temperature (20 °C) in the regression equation (3) and solving that for u, the equation for temperature corrected moisture content is obtained as follows:

$$u_{corr} = -\frac{0.00147T(1n(10) + 1n(\exp(au_{meas}1n(10) + b1n(10)) + 1) - 1.0751n(10)}{1n(10)(0.000158T + 0.0262)} \quad (4)$$

where

u_{corr} is temperature-corrected moisture content (%)

u_{meas} is moisture meter reading (%)

T is wood temperature (ºC)

a = – 0.039 (coefficient for Nordic pine, see Table 5)

b = + 1.061 (coefficient for Nordic pine, see Table 5).

3.3 Resistance values of sapwood and heartwood

Resistance values of sapwood and heartwood (Pine) were measured with conditioned wood specimens. The resistance values and regression curves for sapwood and heartwood are shown in Figure 5.

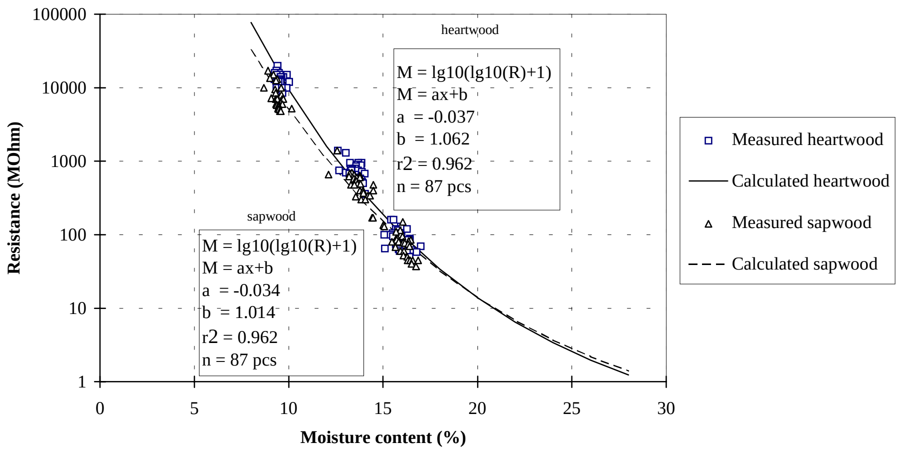

Figure 5. Measured MC resistance values and calculated regression curves for Pine sapwood and heartwood.

Figure 5 illustrates the relationship between the resistance values of sapwood and heartwood. The moisture content difference, when the measured resistance is the same, is only about 0.5% units (see Table 6), although the resistance values at an MC of 8% are twice as high for heartwood than sapwood. At high moisture contents, the differences in resistance are insignificant.

Table 6. Calculated moisture (a) and resistance values (b) for Pine sapwood and heartwood.

Resistance	a) Moisture content, %	
	Sapwood	Heartwood
10 MOhm	21.0	20.6
1000 MOhm	12.1	12.4
10000 MOhm	9.3	9.8

Moisture content	b) Resistance, MOhm	
	Sap wood	Heart wood
8 %	33200	68300
12 %	1100	1400
16 %	90	90

3.4 Effect of the type of electrodes

The effect of the type of electrode used was tested with 5 different commercial electrode types. For this test, conditioned Pine heartwood specimens were used. The tested electrode types are shown in Figure 6.

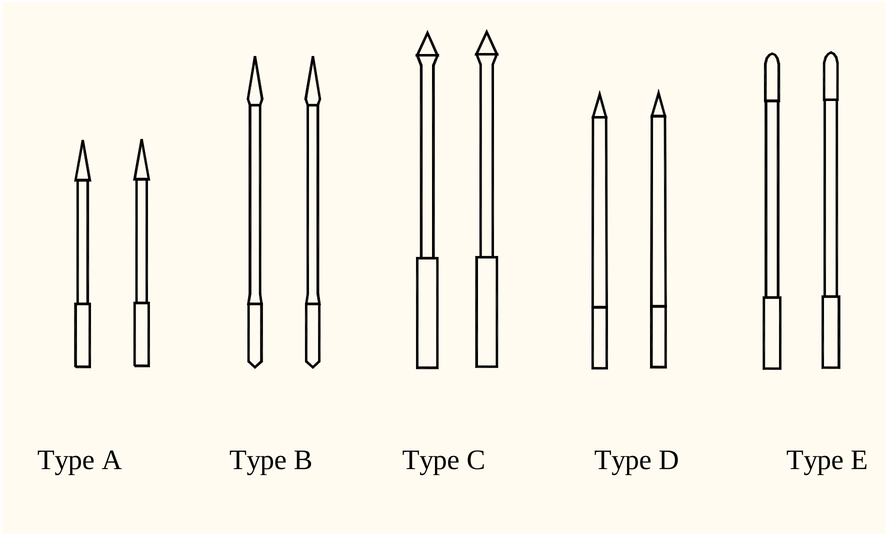

Figure 6. Different electrode types used in commercial MC meters.

Figure 6 shows the most usual types of electrodes. All the tested electrodes were insulated. The top of the different electrode types seems to have the strongest effect on the resistance values. The measurement results are shown in graphic form in Figure 7.

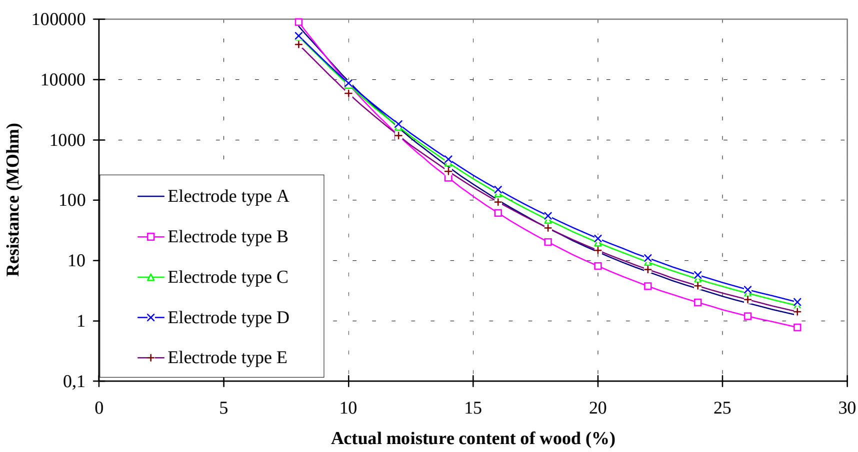

Figure 7. Effect of type of electrodes on resistance.

The B electrodes with a long and sharp top differ most from the other electrodes in Figure 7. The biggest difference between the different electrodes is about 3% points at highest tested MC (16 - 18%). With high resistance values at lower moisture contents the difference decreases. For the other electrodes the differences are not significant. Because the shape of the electrodes has the same effect on the measured resistance value, it is highly recommended that a MCmeter only be used with the electrode type provided by the supplier of the meter.

3.5 Resistance values at different distances between the electrodes

The distance between electrodes varies with different moisture meters. The effect of the distance between the electrodes was studied using the following distances: 20 mm, 30 mm, 60 mm, and 120 mm. The measuring direction was parallel to grain. The results are shown in Figure 8.

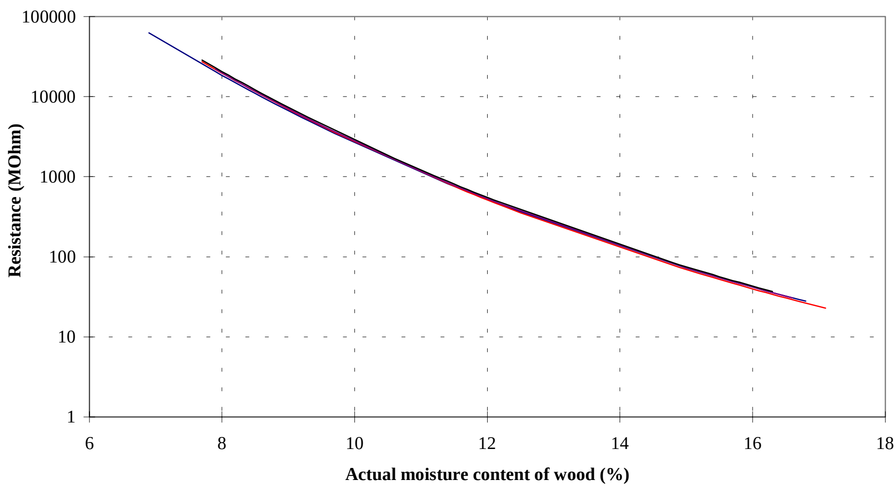

Figure 8. Effect of measuring distance between electrodes 20 mm, 30 mm, 60 mm, and 120 mm.

The distance had no effect on the moisture content value (see Figure 8). The four calculated regression curves do not differ from one another. The results are equivalent to NTI (Apneseth & Hay 1992). In principle, the distance between the electrodes can theoretically be as large as technically feasible. Of course, with normal pin distance, the MC is measured only locally. As the MC in the wood varies, the measured value is somewhere between the minimum and maximum MC value in the wood between the electrodes.

3.6 Resistance values in different measuring directions

The resistance measurements were performed parallel with and perpendicular to grain. The electrode type was Gann. The effect of the measuring direction can be seen from the calculated MC resistance regression curves shown in Figure 9.

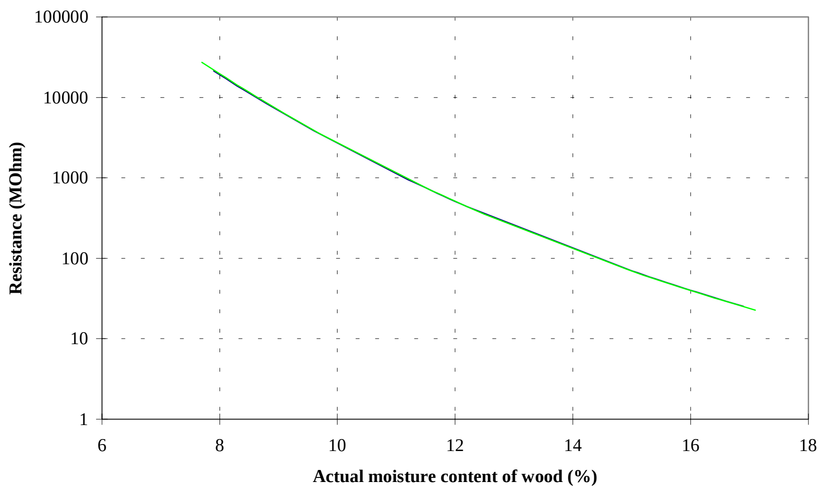

Figure 9. Resistance curves by measuring in two directions: parallel and perpendicular to grain.

There was no difference between the measuring directions. The resistance curves are identical in both directions: parallel with and perpendicular to grain. This corresponds to the findings of Trätek (Samuelsson 1990) and NTI (Apneseth & Hay 1992).

3.7 Effect of the density on electrical resistance

The effect of density on the electrical resistance of wood is shown in Figure 10 for three different density classes. Nordic Pine was divided into three density (12.12) groups (<450 kg/m^3, 450 - 550 kg/m^3, >550 kg/m^3). The MC resistance curves were calculated separately for each group.

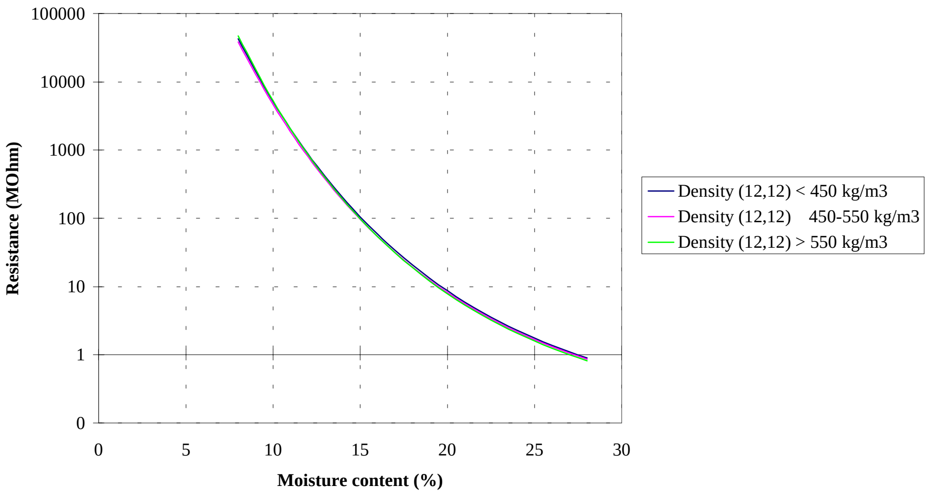

Figure 10. Resistance curves for Nordic Pine in different density classes.

Density had no significant influence on resistance values. All the three resistance curves are virtually identical. Similar results were obtained by Keylwerth and Noack (cited by Vermaas 1982).

4. Confidence intervals for MC resistance regression curves

Due to the large variations in properties within the same species and even in the same piece of wood, the electrical resistance of wood varies at constant wood moisture content as well. Wood moisture content, too, varies slightly in a single piece of wood despite extended conditioning in constant climate. Thus the variation in MC resistance values around the calculated regression curves may be quite large.

For the analysis of confidence intervals, the SPSS Statistical Package was used. The 95 % confidence intervals were defined for the MC resistance curves. The assumptions used in the regression analysis were as follows:

- the observations are independent
- the distribution of the residuals is approximately normal with constant variance
- the relationship between the dependent (transformed) and the independent variable is linear.

The assumptions concerning the distribution and the variance of the residuals are particularly important for the calculation of the confidence intervals.

The variable used, $x = \log(\log R + 1)$, satisfies these assumptions. One deviation curve is shown by way of an example in Figure 11.

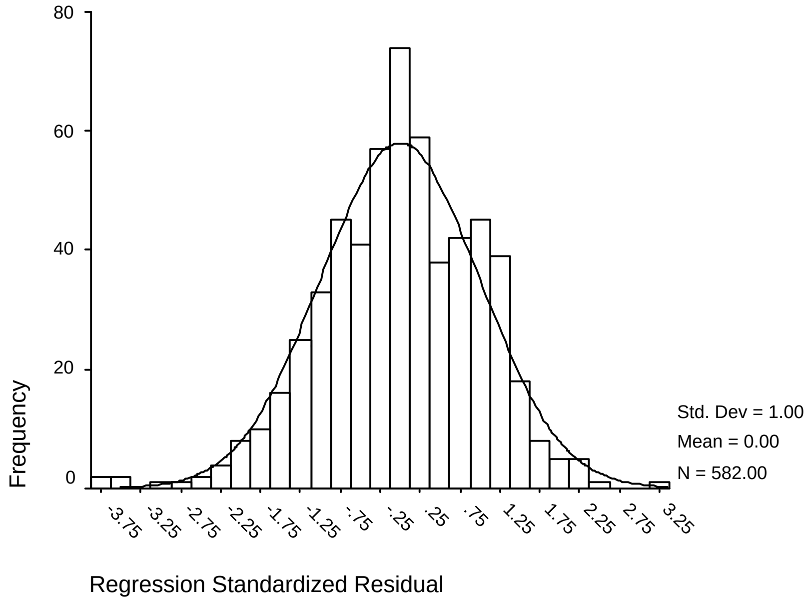

Figure 11. Deviation of standardized residuals in the regression model used for Nordic Pine at a moisture content of 8 - 20 %. Resistance values are transformed by using the transformation x = log(log(R)+1).

To ensure that the calculated confidence intervals are acceptable, a residual analysis was also performed. Figure 12 shows the residuals for Scots pine.

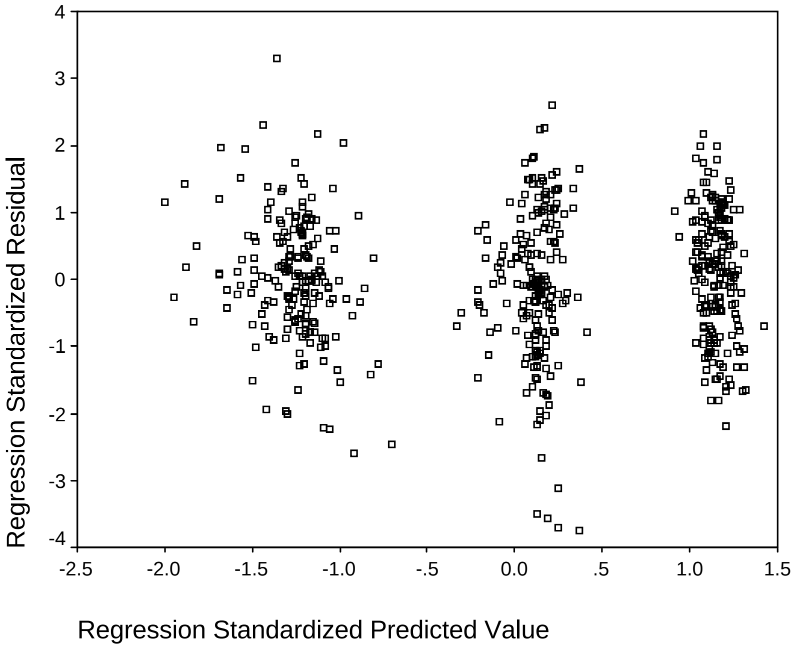

Figure 12. Residual scatter for MC – electrical resistance regression curve for Nordic Scots Pine when x = log(log(R)+1) is used as a variable.

The scatter of residuals is not fully perfect, but good enough too make it possible to use the calculated confidence intervals for the accuracy analysis of MC resistance values.

On the basis of the measured MC-resistance values, the upper and lower limit curves of a confidence level of 95 % for the calculated resistance curves were calculated and plotted for some species in Figures 13a - 13c. The confidence intervals for all the resistance curves given in Table 5 are presented in Table 7.

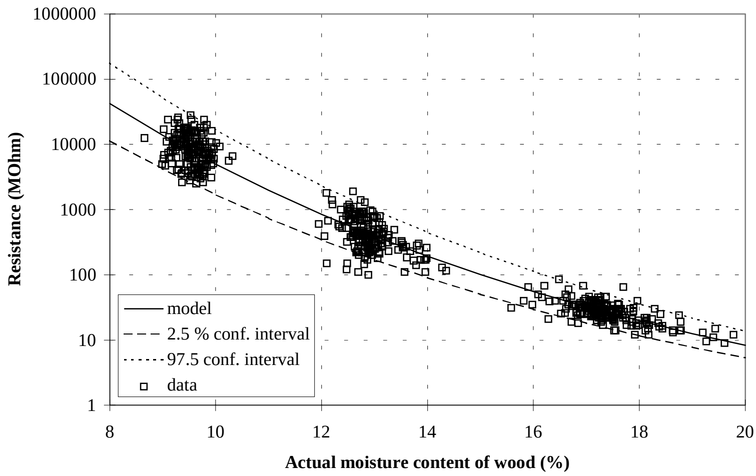

Figure 13a. Relationship between moisture content and wood resistance for Nordic Pine at 95% confidence limits.

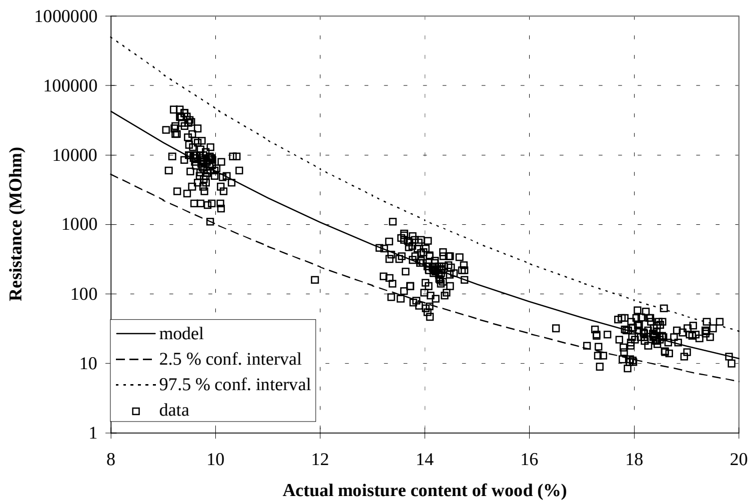

Figure 13b. Relationship between moisture content and wood resistance for Central European Spruce at 95% confidence limits.

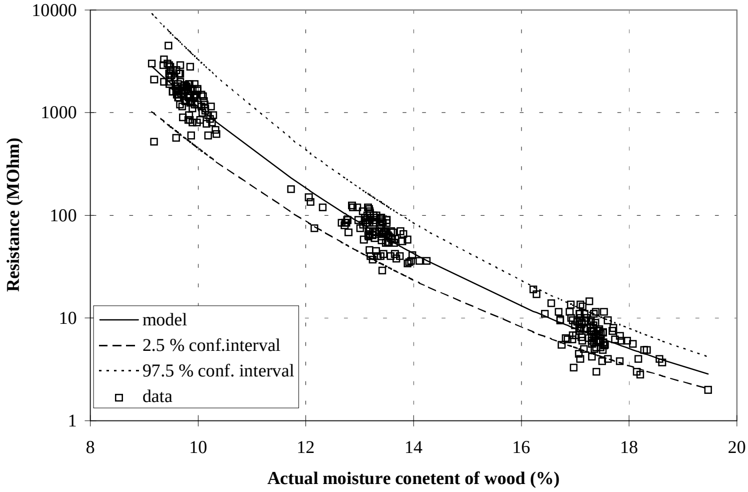

Figure 13c. Relationship between moisture content and wood resistance for Central European Oak at 95% confidence limits.

Table 7. Confidence intervals for the MC resistance curves (Table 5) of the tested species.

Species	Origin	95 % confidence intervals, % units
Pine	Nordic Germany France	± 1.2 ± 1.4 ± 1.1
Spruce	Nordic Central Europe	± 0.9 ± 2.0
Birch	Nordic	± 1.4
Oak	Central Europe	± 1.0
Beech	Central Europe	± 1.3
Alder	Sweden	± 1.1
Larch	Denmark	± 1.0

The confidence intervals indicate only one aspect of the “accuracy” of MC measurements. The difference between the real and measured moisture content is not included in these confidence intervals.

These confidence intervals can be used when the wood to be measured is well conditioned, its temperature is accurately known and the resistance curve programmed into the MC-meter is highly suitable for the material to be measured, i.e. deviation from real MC value is zero. Normally, it is not possible to measure the wood MC more accurately than indicated in Table 7. But when the regression curves are determined more locally, for instance for Scots pine from Eastern Finland, a higher degree of accuracy can be achieved. The confidence interval in Table 7 is about ± 1.2% for most species. The spread was biggest (±2.0 %) for spruce from Central Europe, where the wood properties vary very much.

The measurement accuracy of all the tested instruments with conditioned and unconditioned sawn timber is presented in Section 6.

5. Capasitance type moisture content meter

This chapter is a resume from the text book Skaar pp. 237 - 262 (Skaar 1988).

The capacitance type hand-held MC meters use the relationship between moisture content and the dielectric properties of wood and the water contained in it. The dielectric properties of wood change in propertion to its moisture content. They are normally measured using alternating current (AC) techniques. The dielectric properties are also affected by other parameters such as wood density, temperature, grain orientation, and AC frequency.

5.1 Dielectric principles

The static dielectric constant of an insulating material such as wood can be defined by considering Figure 14 a. This shows two thin parallel plates, each with an area A and separeted by a distance d, which is small compared with the value A.

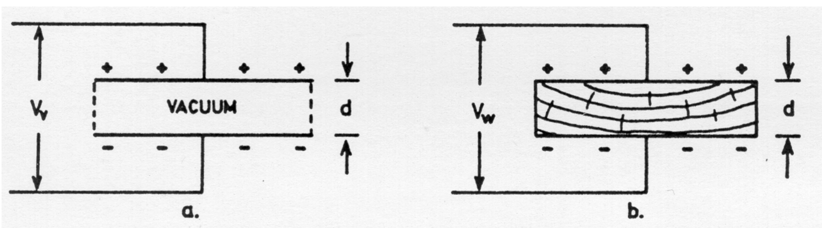

Figure 14. Schematic diagram illustrating charge accumulation on two plates each with an area A, and distance d apart showing: a) a voltage V_v in vacuum, b) a lower voltage V_w with a wood dielectric (Skaar 1988).

The capacitance C_w of the wood in Figure 14 b can be expressed as follows (Skaar 1988)

$$C_w = (Ae_w/(11.3d))\times 10^{-12} \ \ farads \qquad (5)$$

where

A is area of the plates
d is distance between the plates
e_w is dielectric constant of wood.

The dielectric constant e_w of a wood specimen can be calculated from equation (5) if C_w can be measured. It is difficult to measure C_w for wood using direct current techniques, and therefore alternating current measurements are generally used.

The dielectric constant is a measure of the polarization of atoms and molecules in the wood under the influence of an applied voltage V or voltage gradient E. At least four different kinds of polarization may occur in wood, each of which may contribute to the dielectric constant, depending on the frequency f of measurement. These are electronic, atomic, dipole and interfacial polarizations. The first two are of interest primarily from the viewpoint of optical and infrared spectroscopy, respectively. The last two are generally measured using electrical methods. The dipole mechanism involves the use of permanent dipoles while the other three are caused by induced polarization.

Figure 15 shows how the dielectric constant of an idealized material varies with the frequency (log scale). The two regions of most importance for measuring the moisture content of wood, and also for heating wood electrically, are those in which the dipole and interfacial mechanisms are dominant.

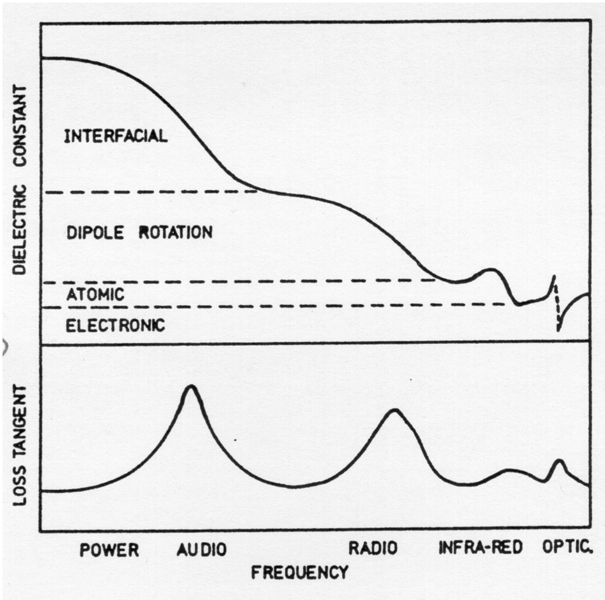

Figure 15. Diagram showing the dielectric constant and loss tangent as functions of applied frequency (log scale) from power to optical frequencies, for a dielectric material (Skaar 1988).

5.2 Dielectric properties of wood

5.2.1 Effect of moisture content

The dielectric constant of wood increases with moisture content. When moisture content increases the frequency of the electric field decreases. Figure 16 shows that both ε' and tan δ generally increase strongly with increasing moisture content at a given frequency at 20 °C.

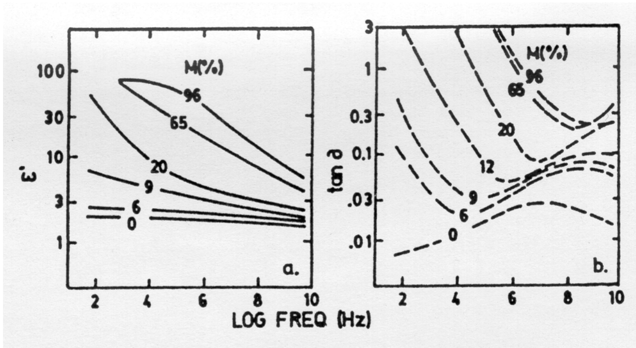

Figure 16. Dielectric constant (ε') and loss factor (tan δ), of European spruce at 20 °C, as a function of frequency (log scale) at several wood moisture contents (Skaar 1988).

5.2.2 Effect of temperature

The dielectric constant for wood increases with increasing temperature except at very high moisture contents where the reverse can occur. Figure 17 shows curves of electric constant (ε') and loss factor (tan δ) against frequency for Tanagi (*Salix jessonensis*) wood at 15% moisture content and several temperatures.

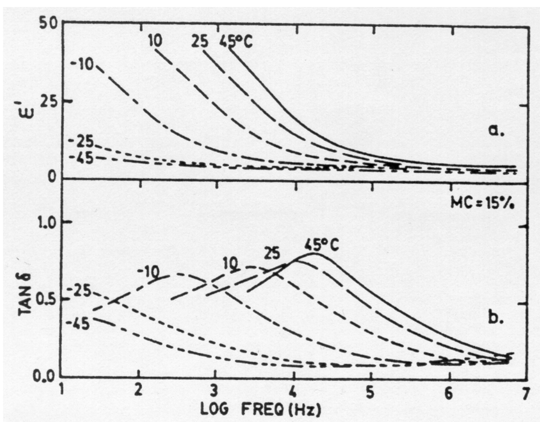

*Figure 17. Curves of dielectric constant ε' and of tan δ in relation to the logarithm of frecuency at several temperatures, for wood of Tanagi (*Salix jessoensis*) at 15% moisture conent (Skaar 1988).*

It is clear that the dispersion peaks shift to higher frequencies with an increase in temperature. The loss factor is not a simple function of temperature. It can both increase and decrease with increasing temperature depending on the frequency and moisture content.

5.2.3 Effect of density

The dielectric constant of the gross wood also increases with moisture content, but not to the same extent as that of the cell wall. The increase is greater for more dense than for less dense woods, as Figure 18 indicates. For example, from Figure 18, ε' doubles between 0% and 25%. moisture content for wood whose oven-dry specific gravity G_0 is 0.1, but quadruples over the same moisture range for wood G_0 = 0.6, at 1 MHz. This is because the cell wall volume is greater for the more dense woods, and therefore the relative contribution of the cell wall is greater than for the low density woods.

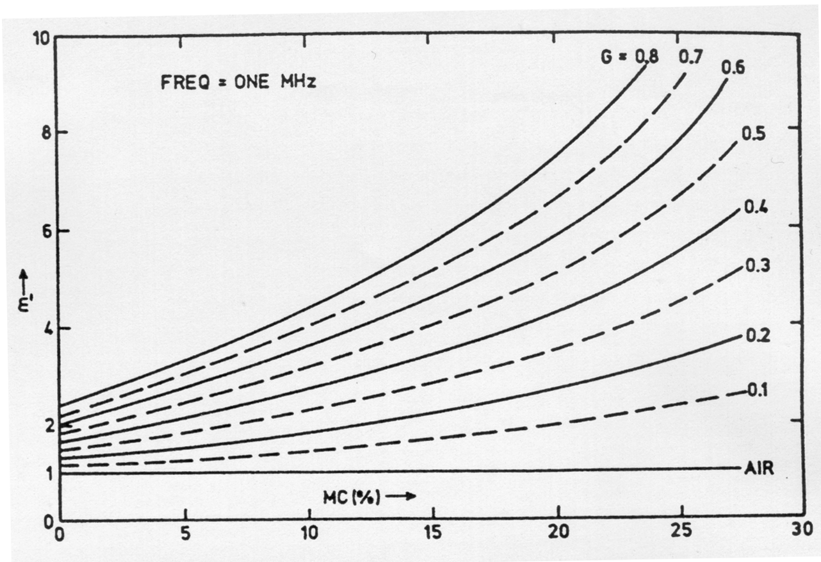

Figure 18. Curves showing increase of dielectric constant ε' with increasing wood moisture content and specific gravity (Skaar 1988).

It has been established that the loss tangent (tan δ) of wood also increases with increasing wood density. Its variation with wood moisture content is more complex, however, as Figure 19 indicates. This shows that tan δ increases with wood moisture content in general. However, at 16 MHz, it peaks near the 12% moisture content before resuming the normal increasing pattern. This is probably due to the proximity of a region of anomalous dispersion at this combination of frequency, moisture content, and temperature.

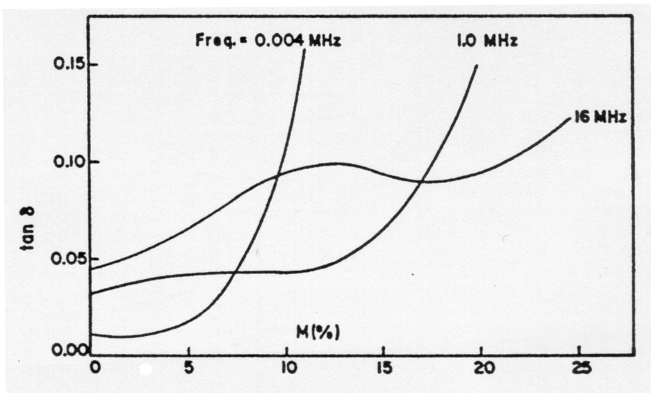

Figure 19. Loss tangent (tan δ) curves in relation to wood moisture content M for three different frequencies (Skaar 1988).

5.3 Dielectric moisture meters

There are two basic types of dielectric moisture meters, the capacitance type which essentially measures the dielectric constant and the power-loss type which measures the combined effect of dielectric constant and loss factor.

The capacitance type of moisture meter responds primarily to the capacitance between the electrodes, which is a function of the electrode configuration and the dielectric constant of the wood. Usually there is an air gap between the electrodes and the wood surface which reduces the sensitivity of the instrument to moisture content changes in the wood.

The power-loss type of dielectric moisture meter responds to increases in both the electric constant and loss factor with increasing wood moisture content. In other words, it measures the rate of electrical energy dissipation in the wood for a given input energy. This depends on the electrode configuration, which determines the electromagnetic coupling between the meter and the wood, as well as on the characteristics of the wood itself. The latter are complex functions of wood moisture content, temperature, density, stuctural orientation, frequency, etc.

Despite the many factors, in addition to wood moisture content, that affect dielectric moisture meter readings, dielectric meters are commonly used for estimating wood moisture content. They are often used in the wood industry to indicate wood moisture content during prosessing operations under reasonably standard conditions of species.

The capacity range of power-loss types moisture meters is from 0 to 25% moisture content. Unfortunately, the readings depend on the density of the specimen. Since density varies considerably within a species, and the meters are calibrated for the average specific gravity of each species, an error may occur. This error is directly proportional to the difference between the density of the wood being tested and the value used for calibration. Density determinations of every sample (so that reading could be corrected) would be too cumbersome for general use.

Surface moisture greatly affects the readings obtained. Consequently, lumber with a significant moisture gradient or a wet surface will produce erroneous results.

Temperature corrections charts or tables are not provided by the manufacturers of capacitance type meters.

6. Comparison of the accuracy and reliability of existing moisture content meters

The following tests were designed to evaluate how accurately the moisture content can be determined by the producers and users of dried timber for quality control purposes when using MC meters. Different ranges of moisture content and temperatures were considered. The tests were made both with conditioned wood in the laboratory and unconditioned wood at sawmills.

6.1 Moisture content measurement of conditioned and unconditioned wood

6.1.1 Laboratory tests with conditioned wood

In connection with the resistance measurements (section 3.1), the accuracy and the reliability of all hand-held moisture meters (both resistance and capacitance type moisture meters) were tested with conditioned test material. The tests were carried out at a room temperature of 20 °C.

Figure 20 shows an example, the regression line between the actual MC (oven dry method) and the MC results obtained with one MC meter. In this example the species is birch.

Figure 21 shows the moisture content – resistance curve obtained with the same resistance meter for birch. The other curve is the moisture content – resistance determined by VTT for this study.

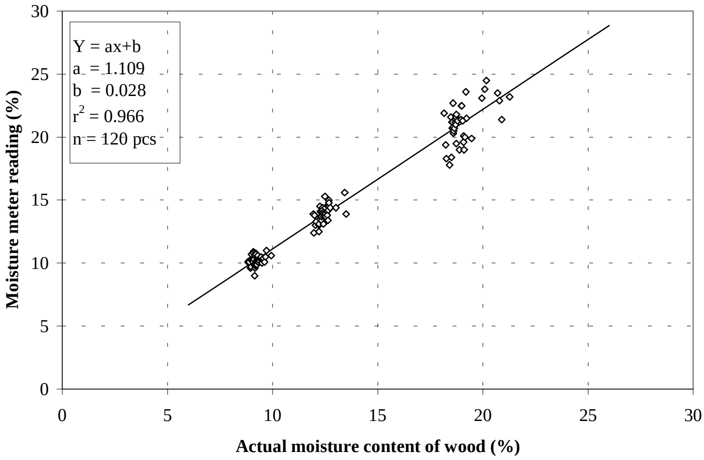

Figure 20. Regression between actual moisture content and values measure with a moisture meter.

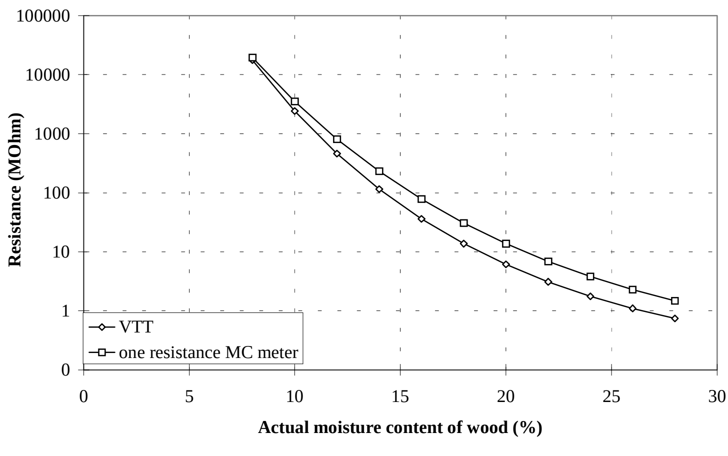

Figure 21. Moisture content – resistance curves for birch according to VTT's measurements and a resistance type MC meter.

Most meters show a systematic deviation from the actual moisture content. Many resistance type meters generate incorrect MC resistance curves. For example, when comparing the resistance curve for birch produced by one moisture meter with the resistance curve for birch determined by VTT (see Figure 21), we see that the moisture meter readings is 1 - 2% points higher than the actual values.

With capacitance type MC meters, the effect of wood density is very high. Thus the biggest problem with the capacitance meters is that the correct density of the wood to be measured is not known. For one capacitance type meter, the meter readings were corrected with the measured wood densities. Figures 22 and 23 show the correlation between the actual MC and moisture meter readings with and without density compensation.

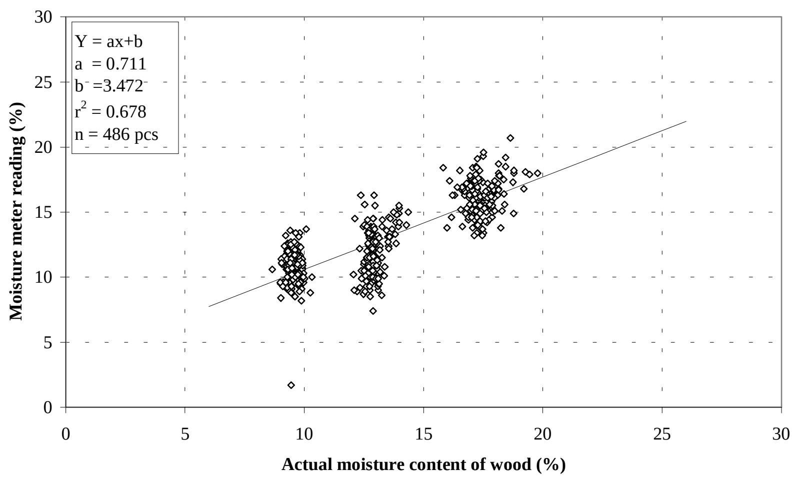

Figure 22. Moisture meter readings of a capacitance type meter without density compensation compared with the actual moisture content values.

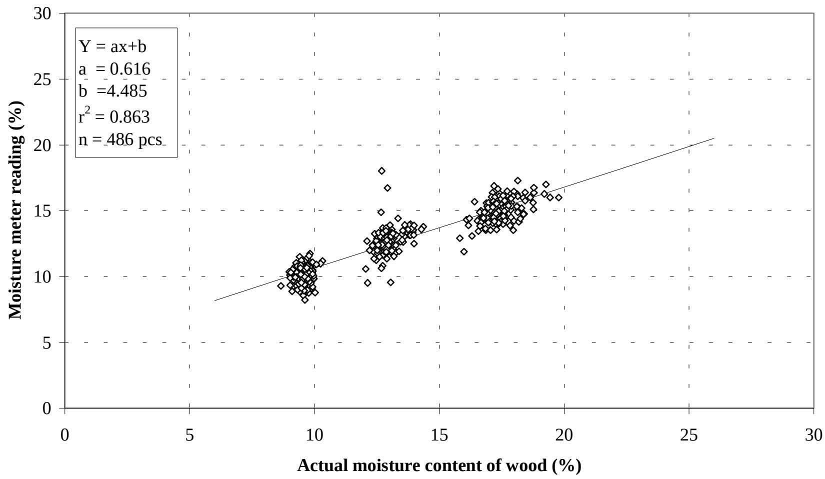

Figure 23. Moisture meter readings of a capacitance type meter with density compensation compared with the actual moisture content values.

A comparison of Figures 22 and 23 shows the effect of density compensation. The test results with density compensation are much better than without it.

The quality (planed/unplaned) and deformation (cupping) of sawn timber affects capacitance type measurements. If there is an airgap between the meter and the surface of sawn timber the meter shows lower values than if the contact is good.

The following comments are made:

A. Resistance type meters:

1. When the MC is lower than 10%, the readings of all the resistance meters tend to creep. The electronics and programming code of MC meters are vital for getting exact results. When MC is measured with two different MC meters, the results can be different despite identical programmed resistance curves.

2. In most of the meters the resistance curves should be changed (re-programmed).

3. Temperature compensation is very important for accurate measurements (see section 3.2).

B. Capacitance meters:

1. The readings are affected by the density of wood.

2. The contact between the meter and wood surface should be good.

3. For some meters the measuring method has an effect on the results. For example, when MC-meters with exposed electrodes are pressed harder against the wood surface, the MC values obtained are higher.

4. There was a big difference between the best and worst capacitance meters.

6.1.2 Industrial tests with unconditioned wood

All the moisture content meters were tested at sawmills. The test material was dried to normal industrial schedules at temperature levels of 60 - 75 °C. The moisture content of 10 sawn timber packages (representing a total of about 300 pieces of sawn timber) was measured. The background information on the sawn timber packages such as kiln type, drying schedule, drying date and storage time was recorded.

The measurement results were analysed separately for every MC meter. Two examples of the measurements (one resistance and one capacitance type moisture meter) are presented in Figures 24 and 25, where all the results of measurements with different variables (see section 2.2.5) are considered.

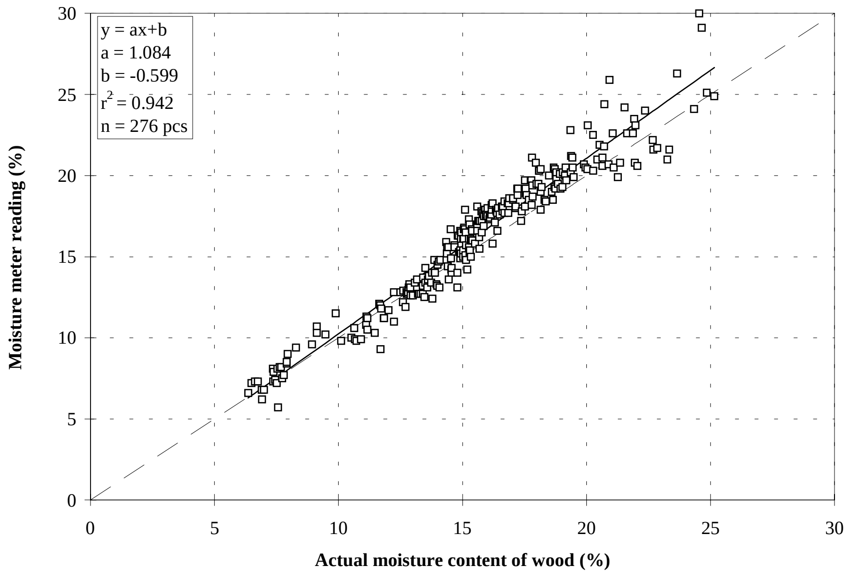

Figure 24. Regression line between actual MC and MC measured with a resistance type MC meter in industrial test.

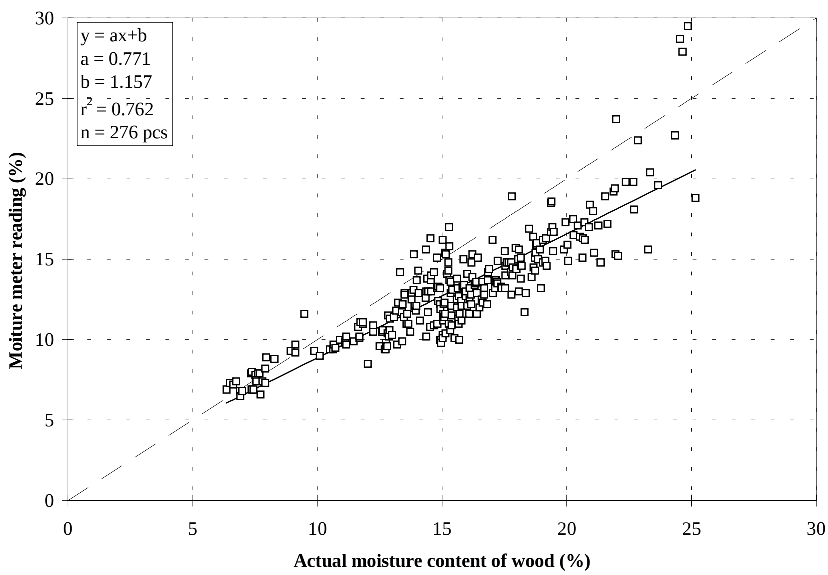

Figure 25. Regression line between actual MC and MC measured with a capacitance meter in industrial test.

Figures 24 and 25 from industry tests show a typical spreading of the measurement results with both types of MC meters. The measurements were made with great care. The measuring point (depth = 0.3 x thickness; distance from edge = 0.3 x width) and wood temperature for resistance MC meters were determined and the wood temperature taken into consideration. Most of the resistance meters are equipped with a temperature correction device. If this is not the case, the results have to be corrected with the aid of the temperature correction table provided by the manufacturer of the MC meter involved. The effect of temperature on capacitance measurement is very small. The big spreading of the result (up to ± 3.0%) for resistance the MC meter is caused by the MC gradient and MC level. The inaccuracy (up to ± 5.0%) of the capacitance type meters is caused by the density variation of the wood. The accuracy of measurement varies very much, particularly with capacitance MC meters. The difference between the best and poorest resistance MC meters is not so big as between the best and poorest capacitance type meters. The best capacitance MC meters can achieve nearly the same accuracy as an “average” resistance MC-meter.

All the industry tests were analysed to determine the percentage of readings that were within a certain interval around the oven-dry readings (ODMC). The results of measurements were analysed separately for every MC meter. The following graph shows the comparison of accuracy (expressed as percentage of readings within 0.5% and 1.0% of ODMC) of the meters subjected to the industrial test.

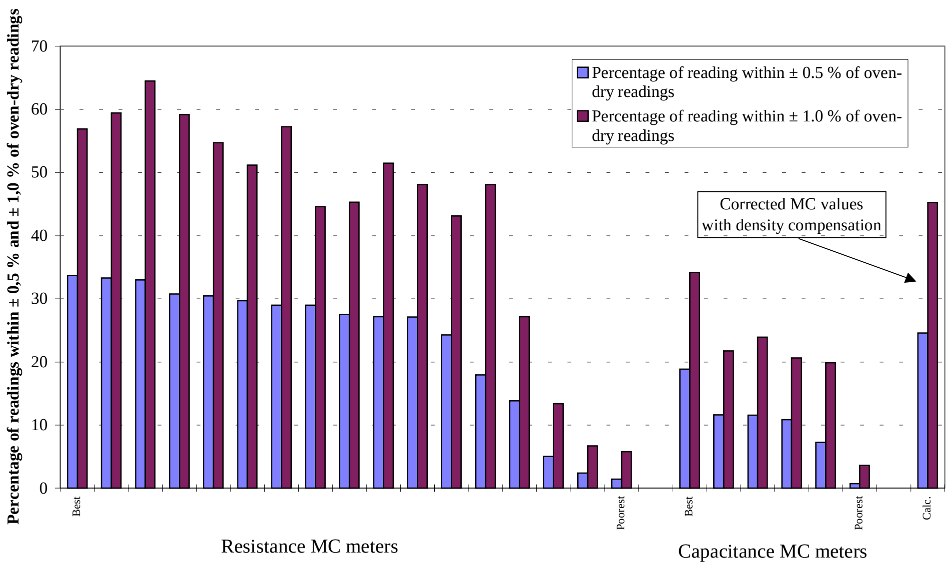

Figure 26. Comparison of accuracy of MC meters in industrial test.

In practice the best accuracy that can be expected is about 60% of the readings within ± 1.0% of ODMC. The typical accuracy of a resistance MC meter was actually about 45 to 50% of readings within ± 1.0% ODMC. Most of the capacitance MC meters fall short of these levels by a wide margin. When the values measured with the best capasitance meters (best in Figure 26) were corrected with the measured density values, the calculated accuracy came close to the average level of performance of resistance meters.

The following comments are made:

- Major differences between individual MC-meters exist
- Capacitance type MC-meters show a much wider variation compared to electrical resistance type meters
- Correct temperature setting is very important for resistant type meters
- Correct density setting is essential for capacitance type meters

- Other major factors affecting the accuracy of measurements are the dimensions of the sawn timber, the MC level and moisture gradient

- Consequently, the “correct” place (depth, width) where to measure the average MC varies

- Resistance MC meters are most accurate within the range of 8 - 20%

- Many capacitance type meters often indicate too low moisture contents because of low measuring depth and the moisture gradient.

6.1.3 Statistical analysis of the accuracy and reliability of MC meters

All measurement results obtained both in the laboratory and industrial tests were analysed statistically. In the statistical evaluation procedure every measuring result has been corrected with the average divergence (meter reading – true value) before the limits for 95% confidence interval are calculated. The used regression model is linear. An example of the results is given for Nordic pine and spruce in Table 8. Similar tables for other species are presented in Appendix B.

Table 8. Confidence intervals for different MC-meters. Species tested: Nordic pine and spruce (MC level 9 - 17 % for laboratory tests and 7 - 25 % for industry tests).

Types of hand-held moisture meters	Laboratory tests		Industry tests	
	95 % confidence intervals, % units	average divergence (reading – true)	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:				
Meter 1	± 1.2	-0.7	± 2.1	+1.3
Meter 2	± 1.2	-0.7	± 2.1	+1.2
Meter 3	± 1.2	-0.8	± 2.0	+1.2
Meter 4	± 1.3	-1.1	± 1.7	+0.8
Meter 5	± 1.3	-0.7	± 2.1	+0.7
Meter 6	± 1.3	-0.9	± 1.8	+0.6
Meter 7	± 1.3	-0.7	± 1.9	+0.7
Meter 8	± 1.3	-1.1	± 2.4	+1.0
Meter 9	± 1.4	-1.4	± 1.9	+0.1
Meter 10	± 1.4	+0.5		
Meter 11	± 1.4	-1.7	± 3.5	-1.6
Meter 12 (new set point)	± 1.5	-1.0	± 1.9	+1.0
Meter 12 (old set point)	± 1.5	+0.3	± 2.4	+2.8
Meter 13	± 1.5	-2.3	± 3.3	-0.8
Meter 14 (old set point)	± 1.6	-0.7	± 2.2	+2.0
Meter 14 (new set point)	± 2.1	-1.3	± 2.7	+1.5
Meter 15	± 1.8	-0.3	± 4.5	+2.3
Meter 16	± 1.8	-0.8	± 2.3	+0.1
Meter 17	± 1.9	-1.3	± 3.9	-3.6
Capacitance MC-meters:				
Meter 18 (dens. comp. calc.)	± 2.5	-0.5	± 1.6	-0.9
Meter 19	± 2.9	-0.6	± 3.8	-2.4
Meter 20	± 3.2	+1.2	± 4.7	-2.4
Meter 21	± 3.4	+1.4	± 4.6	-2.0
Meter 22	± 3.5	-2.7	± 5.3	-4.7
Meter 23	± 3.7	+0.0	± 2.0	-0,1
Meter 24	± 4.2	+0.3	± 4.7	-2.8

The accuracy of the MC meters (95% confidence interval) in laboratory test with well conditioned material was about ±1.5 … ±2.5% units for the resistance meters and about ±2.5% … ±4.0 % units for the capacitance meters. The corresponding accuracy of the MC meters in industry test was about 2.0% … ±5.0% units for the resistance meters and about ±3.0% … ±5.0% units for the capacitance meters. The average divergence (reading – true), i.e. systematic error, was much lower in the laboratory tests than in the industry tests because of the constant temperature and the negligible MC gradients in the conditioned laboratory specimens.

6.2 Effect of the MC meter and wood temperature on the moisture content readings

The moisture content meters were tested at different temperatures. The tested wood temperatures were –10 °C, +5 °C, +20 °C, +40 °C, 60 °C and +70 °C. The meter temperatures were same as the wood temperatures, i.e. –10 °C, +5 °C and +70 °C. For other wood temperatures, the temperature of the meters was 21 °C. The temperature correction of the resistance type meters was carried out according to the instructions given by the manufacturers.

Figures 27 and 28 show examples of the accuracy of the temperature compensation for one resistance type and Figure 29 for one capacitance type meter. Figures 27 and 29 indicate the temperatures of the wood specimens and meters as stated above. In the case shown in Figure 28, the resistance type meter temperature is equal to room temperature while the wood is placed in the freezer (–10 C).

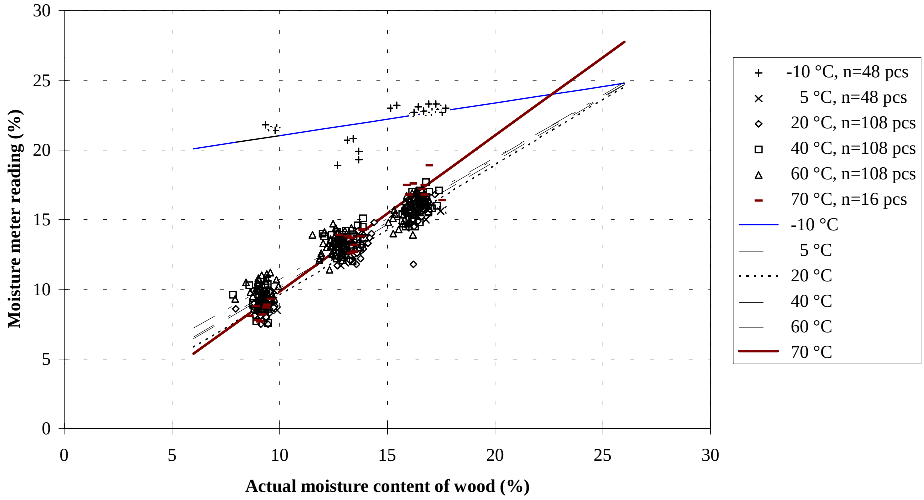

Figure 27. Temperature test with a resistance MC meter (MC meters temperature according to text on page 59).

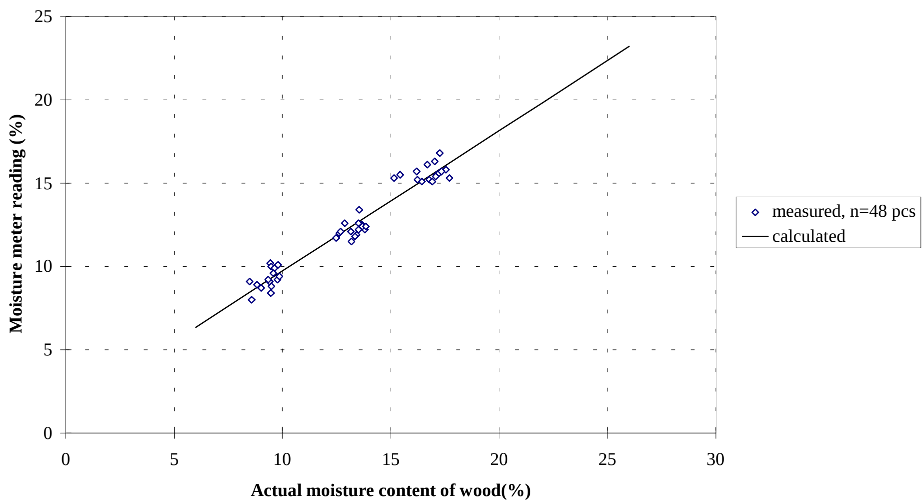

Figure 28. Freeze test with a resistance type MC meter when T(wood) = –10 °C and T(meter) = +15 °C.

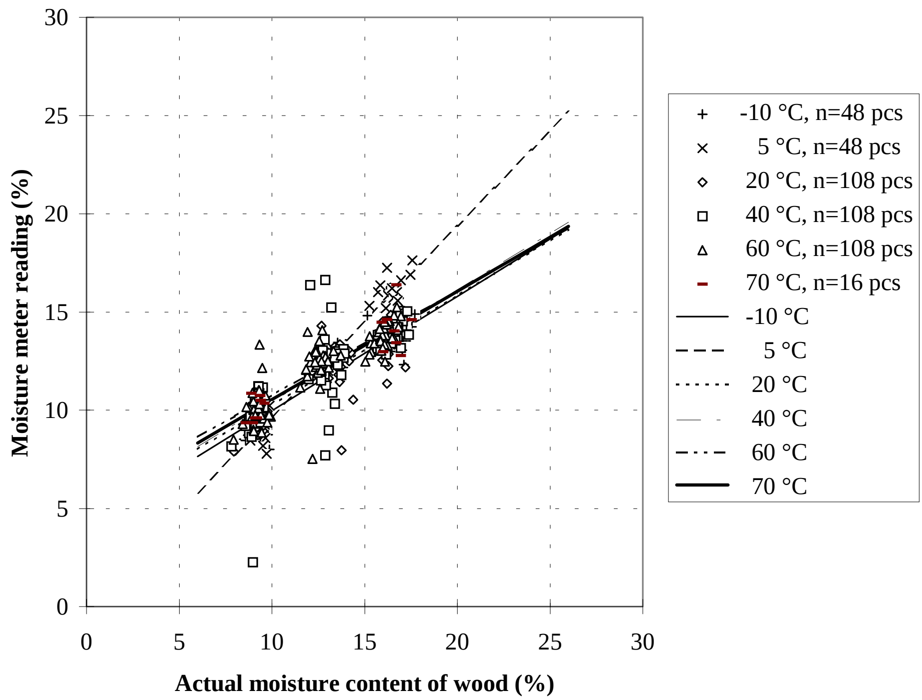

Figure 29. Temperature test with a capacitance MC meter (MC meters temperature according to text on page 59).

In the temperature test the resistance moisture meters showed lower accuracy and reliability than in room temperature test. In the temperature test at –10 °C the meters gave inaccurate readings. In cold weather, the meters often become sluggish. When the meters are at room temperature and test materials at –10 °C, the meters work much better (Figure 28). The temperature tests showed that the measurement accuracy is reduced when the meters are explosed to low or high temperatures. This means that the pre-programmed temperature corrections do not apply at extreme temperatures.

Temperature compensation works quite well, but the best results were achieved at room temperature.

The tests proved that the effect of temperature on the capacitance measuring is very small. It would also appear that operating a capacitance type instrument at extreme temperatures (–10 °C, +70 °C) does not affect its accuracy.

6.3 Effect of wood density on the moisture content reading of the MC meter

Both the resistance and capacitance type MC meters were tested with materials of different densities. The test materials, conditioned in the laboratory, was Scots pine from Sweden, Norway and Finland. The total number of 582 specimens were divided into three density classes. In the test with the resistance MC meters, the resistance of the wood was determined. The moisture meter readings were calculated from the measured resistance values with aid of the resistance curve of one meter. The results are shown in Figure 30.

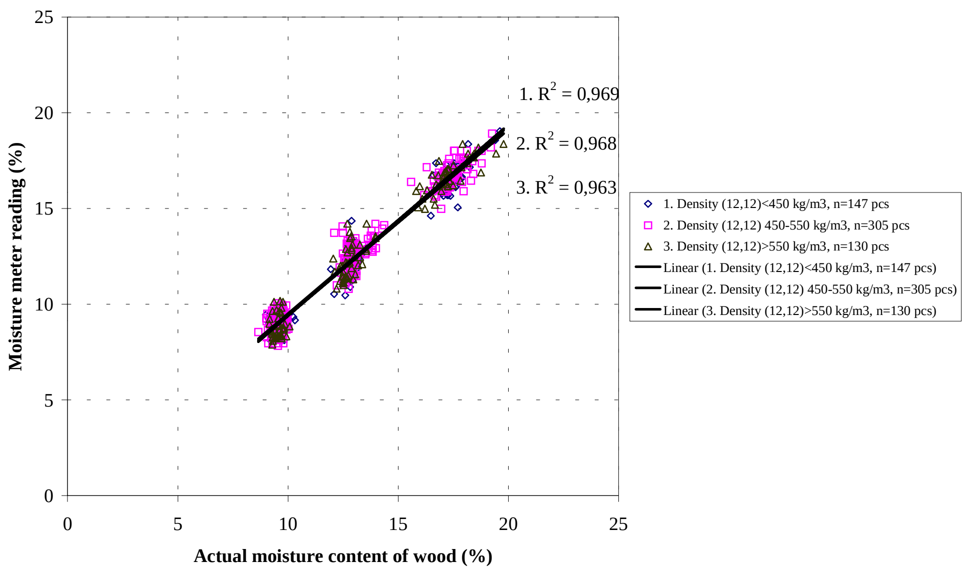

Figure 30. Effect of density level on MC values calculated from measured resistance values with aid of resistance curve of one meter.

The results confirm that, in the case of electrical resistance type MC meters, the density of wood has no significant impact on the measured wood moisture content (see section 3.7).

The effect of density (Scots pine) on the readings of one capacitance meter was studied. The measured values are plotted in Figure 31. Following regression analysis the meter reading is presented as a function of real MC and density ($r^2 = 0.91$).

$$u_{meas} = -0.309 \times u + 0.0482 \times u^2 + 0.0157 \times \rho_{12.12} + 0.6 \quad (6)$$

where

u_{meas} is moisture meter reading

u is actual moisture content of wood

$\rho_{12,12}$ is density (weight at 12% MC /volume at 12% MC).

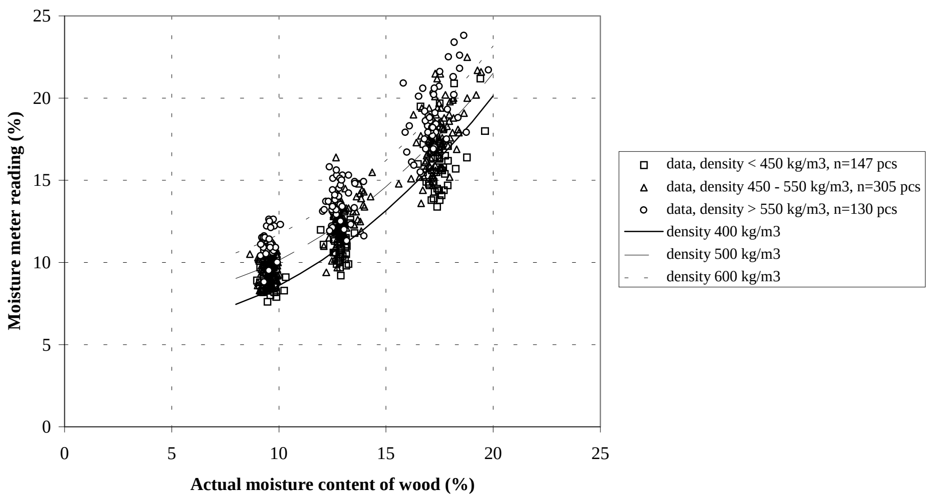

Figure 31. Regression curves calculated for three density values (400, 500 and 600 kg/m³). Scots pine from Finland, Norway and Sweden.

Figure 31 shows that density has a very strong effect on the meter readings. Normal standard deviation of density in a single kiln load is about 30 kg/m^3 and the variation range between minimum and maximum about 100 kg/m^3, which means a MC difference of 1.5 - 2% depending on MC level. The results confirm that, in order to obtain accurate MC values, it is essential to know the wood density.

6.4 Effect of sapwood and heartwood on the meter reading

The effect of sapwood and heartwood on the accuracy of both resistance and capacitance type meters was tested in connection with resistance measurements on sapwood and heartwood (see section 3.3). The readings for one MC meter were calculated with the aid of the measured resistance values obtained for wood. The measurement results with regression lines for sapwood and heartwood are shown in Figure 32.

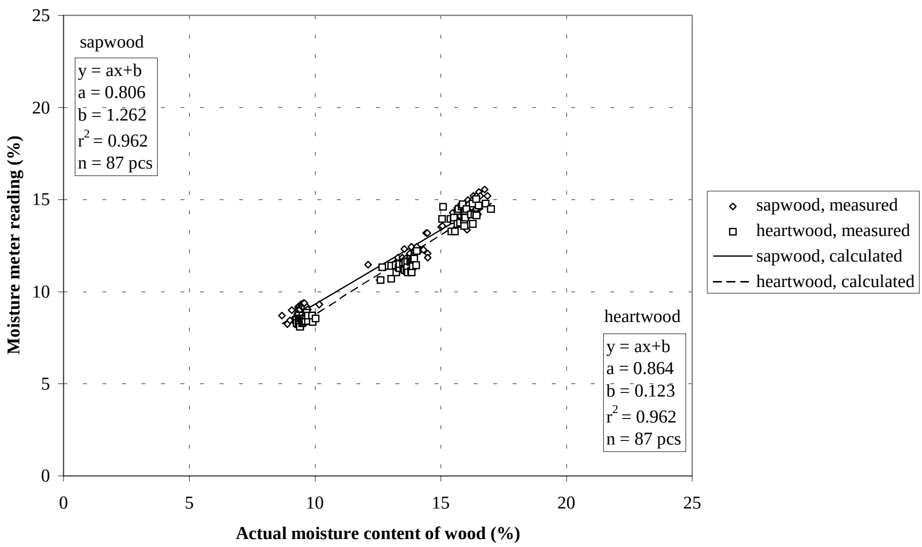

Figure 32. Effect of sapwood and heartwood of Nordic pine on moisture meter readings of one resistance type MC meter.

At low moisture contents, the difference in meter readings between sapwood and heartwood is about 0.5 MC % point. At higher moisture content level, the difference becomes smaller.

The results of capacitance measurements are shown in Figure 33.

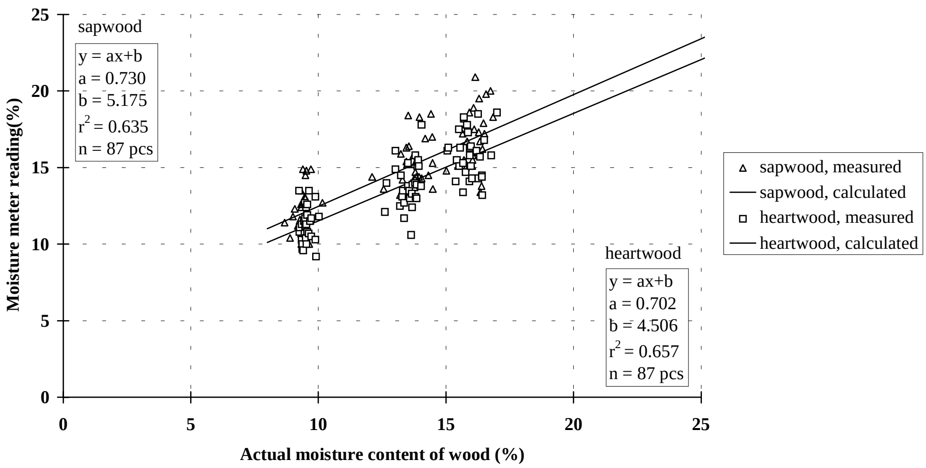

Figure 33. Effect of sapwood and heartwood of Nordic pine on moisture meter readings of one capacitance type MC meter.

The capacitance meters indicated significantly different moisture contents for sapwood and heartwood, even though the MC in sapwood and heartwood was the same. The finding can probably be explained by the difference in density between sapwood and heartwood. The density of sapwood of the test specimens was about 6% (30 kg/m^3) higher than that of heartwood. The meters indicated higher moisture values for sapwood than for heartwood when the same density value setting was chosen for them. Some meters use a plate measuring about 4 cm x 4 cm, which helps to average out any "sapwood/heartwood effect".

Actually, there is no reason whatsoever why sapwood should have a higher density than heartwood. If this was the case sapwood density would have to decrease when it is transformed into heartwood. The "sapwood/heartwood effect" is purely caused by density differences. In softwood trees, the annual rings in the sapwood are smaller than in the heartwood. In softwoods small annual rings have normally a higher density than wide rings.

7. Ergonomic test on moisture content meters

All hand-held moisture meters were tested for their ergonomic properties. Seven test persons all with some experience of MC measuring with hand-held moisture meters were chosen for the test. A questionnaire (see appendix C) was used for the evaluation. The purpose of the test was to determine the practical properties of the different meters. Because the MC meters cannot be identified by name in this report, the results of the ergonomic tests are evaluated from a more general point of view. All ergonomic characteristics were analysed to determine both positive and negative aspects. A summary of the results is shown in Table 9.

No individual meter possessed solely positive characteristis. Every meter can be ergonomically improved.

The ergonomics of all MC meters were evaluated by the test persons on a scale from 1 (poor) to 5 (excellent). No MC meter received the best marks for all the ergonomic properties evaluated in the test. Many meters were graded high (4 = very good or 5 = excellent) on a number of properties but there was always something that could be improved. Weighted average marks varied between 2.6 - 3.6. From the point of view of ergonomics, major improvements are required before a MC meter with excellent ergonomic properties is available.

Table 9. Results of ergonomic tests.

Erconomic properties	Properties	
	Positive	Negative
Cable connections	• easy to connect cables to meter • cable is protected against damage • ease of manufacture because of common parts	• no standard connectors
Changing parameters	• short and clear instructions on meter panel	• having to find the “right” parameter by trial and error
Display	• most important information • large enough font • background light	• too small font
Keyboard	• audible click on measurement • ease of use	• no user instructions • buttons too sensitive
Hammer design	• heavy enough for easy penetration and withdrawal of nails • easy and quick nail change • nail guide system to prevent breakage • adjustable penetration depth • hand well protected against injury • hammer does not turn	• too weak • too heavy/light • too short/long
Damage to wood	• no marks with capacitance meters	• severe marks (large holes) • breakage of wood (cracks)
Overall design	• correct dimensions	• too large to hold
Ease of reading	• easy to read even when inclined	• cumbersome reading position
Stability of meters	• stable	• creeping
Other comments	• proper electrode material: no bow, long service life • Isolated nails recommended	

8. Standard method for the use and calibration of hand-held moisture meters

The method proposed here gives guidelines for the use and calibration of hand-held moisture meters. To achieve reliable results, it is important that the MC meters are in good condition. Resistance and capacitance meters are not necessarily equal in performance under identical conditions. Both types of meters are to be calibrated with respect to moisture content on an oven-dry mass basis as determined by the European standard prEN 13183-1.

Timber is a natural raw material with considerable variations in terms of properties. Chemical constituents and extractives and wood density vary significantly in the trees from different areas and from one site to another also in an individual tree. The variations in the density of wood have no significant effect on the resistance values or measured wood moisture content (readings of the resistance MC meters). In contrast, the readings of capacitance meters are strongly influenced by the varying density of wood.

The meters should be tested and calibrated periodically in respect of the wood material used, either in the laboratory or in the field. Laboratory calibration procedures are intended to provide reference data under controlled conditions that include wood and ambient variables. The procedure is designed for full-scale calibration of the meter. Field calibration tests on resistance type meters for individual species shall be performed only with a meter that has been standardised and properly compensated for temperature and pin configuration. Field calibration tests on capacitance type meters shall be performed only with a meter that has been calibrated against the manufacturer's calibration standard. The procedure is modification from the ASTM D-standard 4444-92.

The test sample should have the following minimum dimension: thickness 20 mm, width 100 mm, and length 100 mm with the grain. The specimens must be free from visible irregularities such as knots, decay, reaction wood and resin concentrations. In laboratory calibration, the specimens shall be divided into at least 3 groups of 15 each and conditioned at 20 ± 1 °C while relative humidity selected for each of the three EMC levels should be between 7 and 21%. In each group, the moisture meter reading should be compared with the actual moisture content of wood measured using the oven dry method according to standard prEN 13183-1.

When moisture meters are tested, it is recommended that the meter manufacturer's instructions regarding the measurement direction and period are followed. All measurements should be recorded in a protocol, which also should indicate the following:

- type of meter, type of electrode and configuration
- reference temperature
- applied voltage
- wood species and setting for species correction
- wood temperature
- measuring time
- all individual results
- arithmetic mean of all measurements.

The moisture meter scale reading must be regressed against the corresponding moisture content for each specimen in the sample using the linear regression analysis. The equation for the regression line (Y = a x X + b) shall be used to establish the correction factor (Y - X) for the meter scale reading (Y) of 7 to 21 inclusive.

In field calibration, the procedure should be used to develop a meaningful relationship between a meter reading and the actual MC. All field calibrations must be referenced to oven dry tests to determine precision and bias. Special care must be taken to minimise errors caused by the effect of wood temperature on readings. Specimen size for field testing may be full size or sections thereof. Additionally, it should be noted that electrodes never indicate the average moisture content but rather local moisture content.

8.1 Resistance type MC meters

The moisture content measuring instruments have to be periodically checked using a control box with known resistances. The formula 7, rewritten from the equation (1), gives the relationship between resistance and moisture content of the wood as follows:

$$u = (\log(\log(R) + 1 - b) / a \qquad (7)$$

where
u is wood moisture content
R is known resistance values
a is species coefficient
b is species coefficient.

The coefficients for different species (based on VTT's measurements) are given in Table 5. A control box with a resistance range from 1 MOhm to 100 GOhm is very useful. As an example in Table 10 is MC values for Pine, Spruce, and Oak.

Table 10. Check box with known resistance values. Calculated calibration values for Nordic Pine (Pinus sylvestris), Spruce (Picea abies) in Central Europe and Oak (Quercus spp.) in Central Europe.

Resistance Position	Pine Nordic a = -0.039 b = 1.061 Control box value	Spruce Central Europe a = -0,034 b = 1,014 Control box value	Oak Central Europe a = -0.047 b = 1.079 Control box value
1 MOhm	27.2	29.8	23.0
10 MOhm	19.5	21.0	16.6
100 MOhm	15.0	15.8	12.6
1 GOhm	11.8	12.1	10.1
10 GOhm	9.3	9.3	8.1
100 GOhm	7.3	6.9	6.4

The deviation between the meter readings and control box values is almost linear. Adding the deviation to the meter reading gives the correct moisture content value.

Moisture meters are often used in a wide range of climatic conditions. The reliability of resistance moisture meters can be checked with a series of simple tests (Instructions for the Brookhuis MC meter). In the first test, a constant resistance (such as 10 MΩ) is connected to the measuring probe (hammer) and the moisture content is measured at room temperature (approx. 20 °C). The measured value is entered in Table 11. In the second test, the instrument without the measuring probe and resistance is placed in a freezer (for example at –10 °C) for 1 to 2 hours. Then the instrument is taken out and re-connected to the measuring probe and resistance. The moisture content is measured and the value entered in the table. In the third test, the instrument without measuring probe and resistance is placed in a oven (for example at +50 °C) for 1 to 2 hours, taken out and re-connected to the measuring probe and resitance. Again, the moisture content is measured and the value is recorded in the table.

Table 11. Temperature stability test according to the instructions for the Brookhuis MC meter (see text).

Test	Temperature	Measured value
First	+ 20 °C	%
Second	- 10 °C	%
Third	+ 50 °C	%

By comparing the results of these test runs it should show that all the three measuring values should be same. Otherwise the instrument is influenced by the temperature and therefore not reliable enough.

8.2 Capacitance type meters

Unlike resistance meters which all operate on the same basic principle of measuring resistance, the manufacturers of capacitance meters use different frequencies, sensor shapes and other technical features, which precludes the use of standard regression according to species.

Field calibration should be carried out on meters calibrated against the manufacturer's calibration standard and steps should be taken to develop a meaningful relationship between meter readings and the actual MC.

The samples should be chosen in the same way as for the resistance meters. The samples should be accurately weighed and measured with a calibrated meter using the manufacturer's recommended setting for the species being measured. The meter readings should be recorded for each sample and the samples then oven-dried according to the standard prEN 13183-1.

If the manufacturer has given the regression formula from base voltage to meter reading, the user can create a simple spreadsheet for reducing the meter reading at the used setting to the base voltage. Different meter settings can then be applied in the spreadsheet to give the optimum relationship between the meter setting and the actual oven-dry MC.

If the manufacturer has not given the formula, then several readings at different settings around the manufacturers recommended setting must be taken before oven drying the sample to ensure that the optimum setting can later be calculated.

Thus, the meter can be tuned for the local timber conditions.

8.3 Checklist for hand-held MC meters

All hand-held MC meters should be checked for correct operation before use. The checking procedure should be clear and easy to use. It is recommended that the checklist include the following items:

Checklist for hand-held MC meters

1. Checking the operating condition of MC meters
    - 1.1 check battery voltage
    - 1.2 carry out the checks recommnded by the manufacturer
    - 1.3 check the stability of the meters at different temperatures

2. Calibrating MC meters
    - 2.1 use reference resitances with resistance meters (Calibration Resistance box)
    - 2.2 use calibration blocks with capacitance meters

3. Checking with well-conditioned wood specimens
    3.1 use three different moisture classes
    3.2 make comparisions with the oven-dried method

Factors to be considered when performing measurements

1. wood temperature
2. moisture gradient in wood
3. the purpose of the measurement
    - average moisture content
    - surface moisture content
    - moisture distribution in wood
    - maximum moisture content
4. the number of measurements
    - in accordance with an approved standard (e.g. EN-standard).

9. Proposals for improving hand-held MC meters

9.1 Resistance type MC meters

To get a correct mean MC values with resistance MC meters, it is necessary to located the right measuring point in the timber. The MC level and moisture gradient affect the measuring accuracy. To eliminate the effect of the MC gradient, MC meters should automatically calculate the mean MC value when the pins are at different depths. The MC curve in the cross section of the timber is often parabolic in form.

Correct measurement of the wood temperature is also very important. Only two of the resistance meters tested here provided any means for measuring wood temperature. All resistance meters used for contractual or quality control purposes should have a built-in temperature measuring device or should be used in conjunction with an external temperature measuring device.

9.2 Capacitance type MC meters

What causes problems with capacitance meters is that density in the wood varies very much. Normal standard deviation of density in a single kiln load is about 30 kg/m^3. Wood density has a significant impact on the measured moisture content. Too high a density value gives too low an MC value, and vice versa. The density of individual pieces is very difficult to measure in normal operation, but this problem can be overcome as shown by one manufacturer.

In many cases, the meter manufacturer has chosen an incorrect adjustable factor value for species density. One manufacturer has come up with a solution to improve the accuracy of the capacitance MC meter.

On the basis of the results of the industry tests, one manufacturer of capacitance MC meters has been able to improve the accuracy and reliability of his meter. New species corrections for pine and spruce were determined based on the known correct MC and the correction equation as a function of specific gravity and the meter reading. Using these new species corrections, the MC meter reading values were calculated. However, these new meter readings must be further corrected with a correction factor that depends on the target MC. The idea is that the correction factor will be built into the meter. The following Table 12 shows the accuracy of the readings in the industrial tests before and after correction.

Table 12. Comparison of the accuracy of readings in the industrial tests before and after correction.

Correction	Percentage of readings within ± 0.5% of oven-dry readings	Percentage of readings within ± 1.0% of oven-dry readings
Before	19%	34%
After	35%	64%

The meter readings on the "After" row were calculated, not measured. This example shows how the accuracy of meter readings can be improved if the manufacturer can only determine the right species correction factor.

10. Discussion and summary

The conclusions of this study are as follows:

- the species corrections (resistance curves) are quite similar for different countries

- wood temperature has a significant effect on the moisture content measured with resistance type MC-meters (temperature corrections 0.1 - 0.15% units / °C) but no effect on the best capacitance type MC meters

- the differences between the properties of sapwood and heartwood have no significant effect on the moisture content values measured with resistance meters but some effect on those measured with capacitance meters (a difference of about 1 % unit) because of the higher density of sapwood.

- the type of electrodes used on MC meters have an effect on the resistance values that correspond to the maximum moisture content deviation of about 1.5% units at a moisture content of 16 - 18%

- the distance between electrodes has no effect on the moisture content measured with resistance type MC meters

- measuring directions (parallel or perpendicular to grain) have no effect on the moisture content measured with either resistance or capacitance meters

- wood density has no effect on moisture content measured with resistance type MC meters but has significant effect on moisture content measured with capacitance type MC meters.

The accuracy and reliability of the meters depends on the following factors:

- measuring temperature (acceptable range is +5…60 °C both for resistance and capacitance MC meters),

- moisture content limits (acceptable range for resistance meters 8 - 24% and for capacitance meters 5 - 30%)

- measuring accuracy of the MC-meters (95% confidence interval) in laboratory tests with well-conditioned material was about ±1.5% … ±2.5% units for the resistance meters and about ±2.5% … ±4.0% units for the capacitance meters. The corresponding accuracy of MC-meters in industry tests was about 2.0% … ±5.0 % units for the resistance meters and about ±3.0% … ±5.0% units for the capacitance meters.

- Ease of use and speed are important in industry. Using resistance meters correctly to obtain maximum potential accuracy is a slow process. Capacitance meters are much quicker and easier to use and, if an accurate meter is chosen, they will provide an accuracy equal to that of a resistance meter in industrial use.

- For contractual and quality control purposes, it is recommended that a test procedure for industrial conditions would be adopted. This should cover the range of MC, temperature, species, piece thickness, drying processes and other such parameters commonly encountered in industry. Only meters that can offer sufficient accuracy (for example over 55% of readings within 1% of oven-dry) should be used for contractual or quality control purposes.

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Instructions for the MC meters.

Resistance meters:

- Aqua - Boy
- BES Bollmann combo 200
- CSA electronic Delta - 8N
- Delmhorst RDM-2S
- FMD moisture meter
- FME moisture meter
- Gann Hydromette RTU600
- Gann Hydromette M2050
- Protimeter Timbermaster S
- Protimeter Timberlogger
- Timber Test FM510
- WALTTERI
- Vanicek VIVA 12
- WSAB Lignomat mini X

Capacitance meters:

- CSA electronic, Delta 2000H
- CSA electronic, Delta 2000S
- FMW moisture detector
- HYGROTEST FM600
- Merlin HM8 - WS13
- Wagner L612

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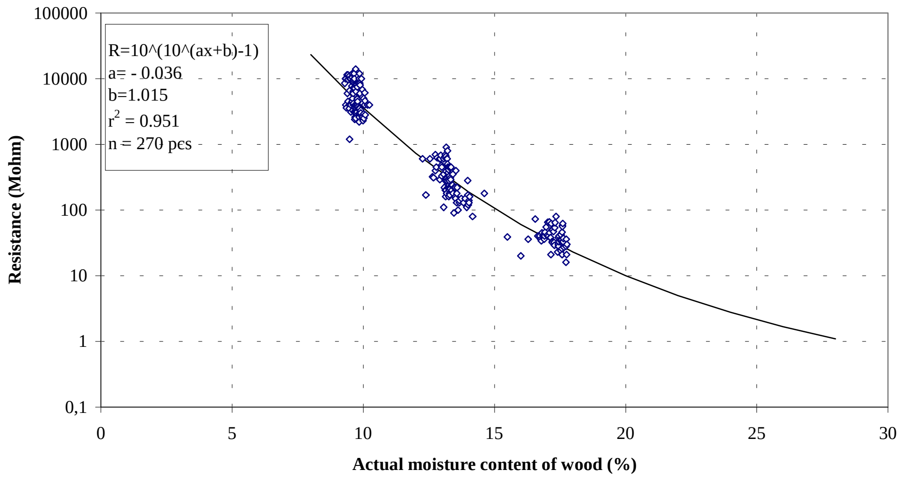

Figure 1. Resistance curve for pine (Germany).

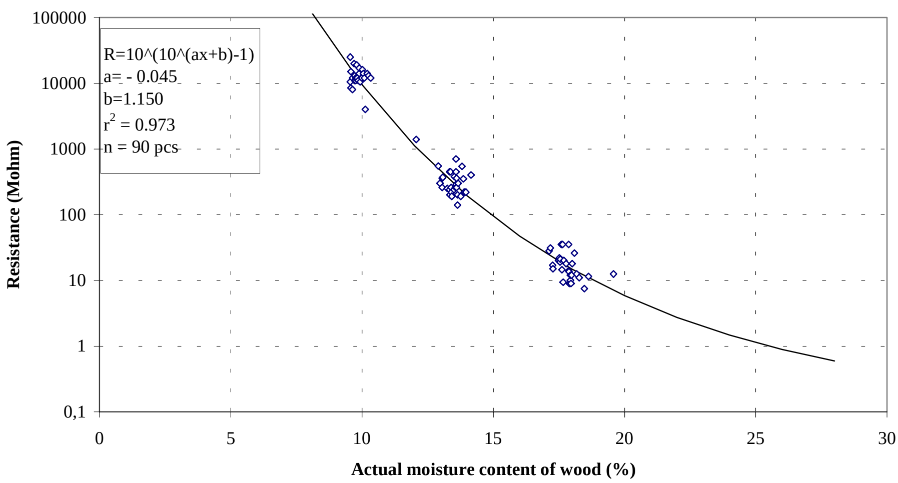

Figure 2. Resistance curve for maritime pine (France).

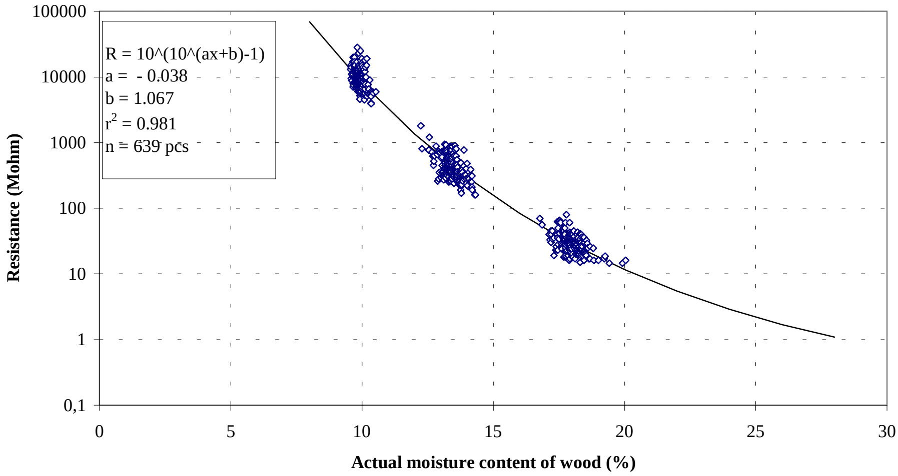

Figure 3. Resistance curve for spruce (Finland, Norway and Sweden).

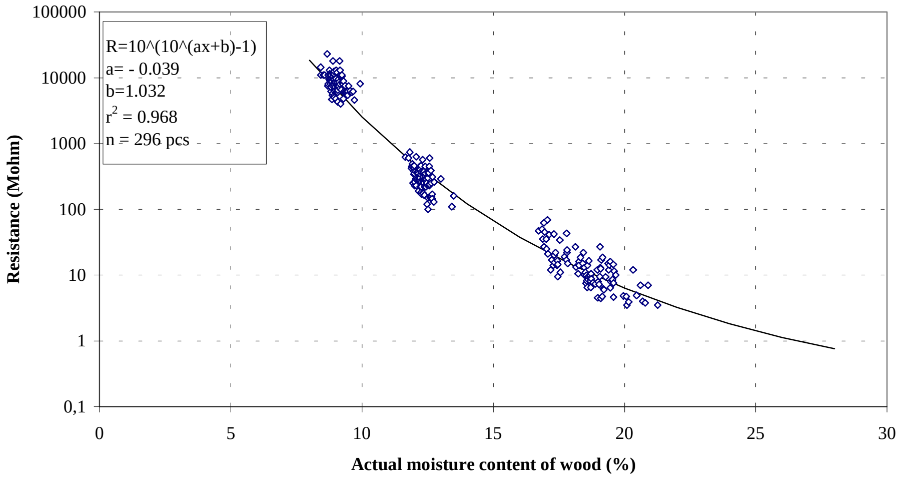

Figure 4. Resistance curve for birch (Finland and Sweden).

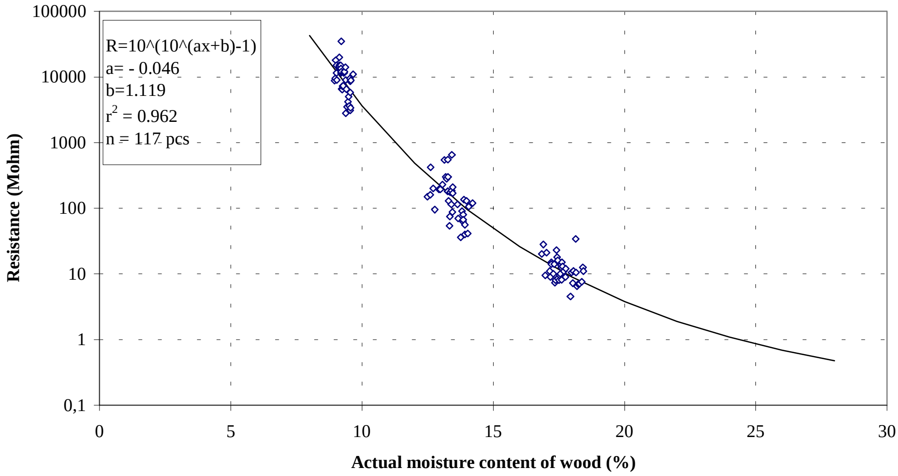

Figure 5. Resistance curve for beech (Denmark and Germany).

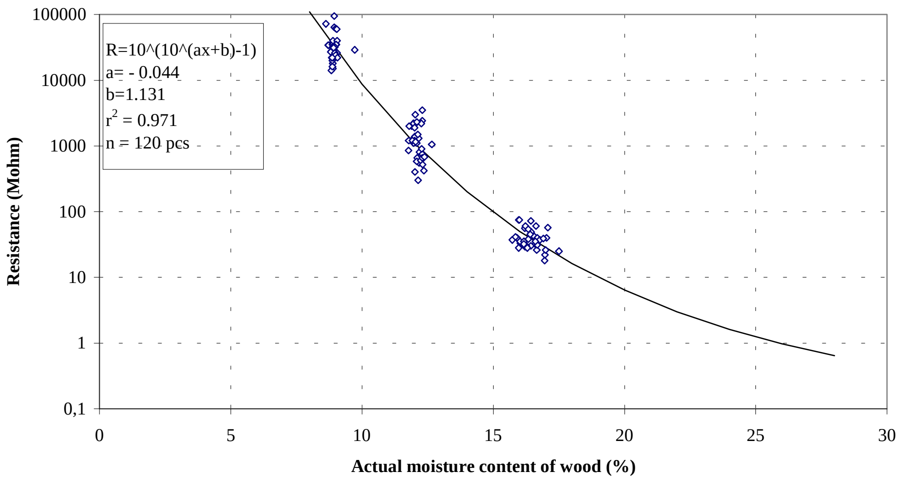

Figure 6. Resistance curve for alder (Sweden).

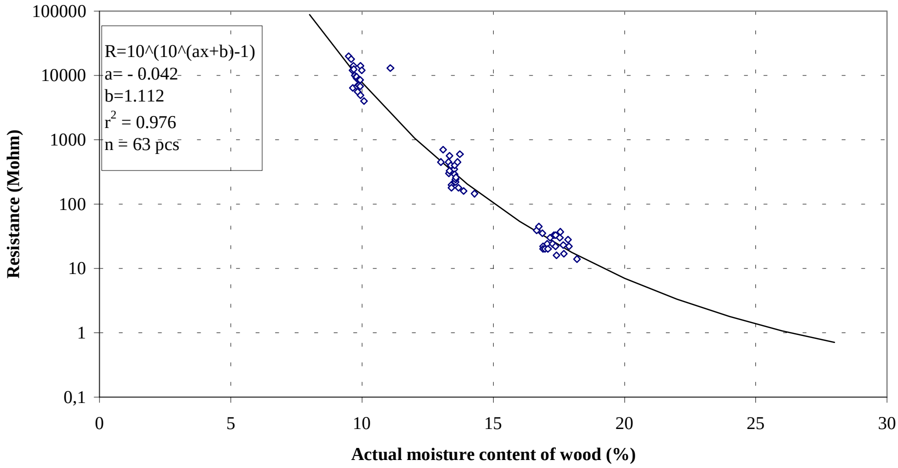

Figure 7. Resistance curve for larch (Denmark).

Table 1. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Pine from Finland. Norway and Sweden.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.1	-1.1
Meter 2	± 1.1	-1.0
Meter 3	± 1.2	-1.3
Meter 4	± 1.2	-1.0
Meter 5	± 1.2	-0.8
Meter 6	± 1.2	-1.1
Meter 7	± 1.2	-0.5
Meter 8	± 1.3	-1.3
Meter 9	± 1.3	-0.9
Meter 10	± 1.3	-1.2
Meter 11 (new set point)	± 1.3	-0.2
Meter 11 (old set point)	± 1.3	-1.2
Meter 12	± 1.3	-0.9
Meter 13	± 1.3	-0.3
Meter 14 (old set point)	± 1.4	+0.9
Meter 14 (new set point)	± 1.5	-0.5
Meter 15	± 1.4	+0.2
Meter 16	± 1.4	-1.8
Meter 17	± 1.9	-1.0
Capacitance MC-meters:		
Meter 18 (dens. comp. calc.)	± 2.6	-0.4
Meter 19	± 2.7	+0.0
Meter 20	± 3.3	+0.4
Meter 21	± 3.4	-2.4
Meter 22	± 3.5	+0.7
Meter 23	± 3.5	-0.3
Meter 24	± 4.4	+0.9

Table 2. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Pine from Central Europe.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.3	-0.2
Meter 2	± 1.3	-0.7
Meter 3	± 1.3	-0.6
Meter 4	± 1.3	-0.5
Meter 5	± 1.3	-0.5
Meter 6 (new set point)	± 1.3	-0.2
Meter 6 (old set point)	± 1.4	+1.2
Meter 7	± 1.3	-0.9
Meter 8	± 1.4	-0.5
Meter 9 (old set point)	± 1.4	-0.7
Meter 9 (new set point)	± 1.4	+0.3
Meter 10	± 1.4	-0.8
Meter 11	± 1.5	-0.7
Meter 12	± 1.7	-0.4
Meter 13	± 1.7	-0.3
Meter 14	± 2.1	-0.9
Capacitance MC-meters:		
Meter 15 (dens. comp. calc.)	± 2.9	-1.1
Meter 16	± 3.0	-0.4
Meter 17	± 3.1	-0.2
Meter 18	± 3.3	+0.0
Meter 19	± 3.4	+0.0
Meter 20	± 3.5	+0.3
Meter 21	± 3.8	-2.7

Table 3. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Maritime pine from France.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals. % point	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 0.9	+0.6
Meter 2	± 1.0	+0.1
Meter 3	± 1.0	-0.3
Meter 4	± 1.0	+0.2
Meter 5	± 1.0	-0.4
Meter 6	± 1.1	-0.1
Meter 7	± 1.1	+0.1
Meter 8	± 1.1	+0.5
Meter 9	± 1.1	+0.3
Meter 10	± 1.1	-1.8
Meter 11	± 1.1	-0.2
Meter 12	± 1.1	+0.3
Meter 13	± 1.2	-0.9
Meter 14	± 1.2	+0.4
Meter 15 (new set point)	± 1.2	+0.4
Meter 15 (old set point)	± 1.2	+1.9
Meter 16	± 1.3	-0.4
Meter 17	± 2.0	-1.0
Capacitance MC-meters:		
Meter 18	± 2.0	+2.0
Meter 19	± 2.6	+2.3
Meter 20	± 2.7	+1.8
Meter 21	± 2.7	+1.8
Meter 22	± 2.9	+1.5
Meter 23 (dens. comp. calc.)	± 2.9	-1.1
Meter 24	± 3.1	-2.5

Table 4. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Spruce from Finland, Norway and Sweden.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 0.8	+1.0
Meter 2	± 0.9	-0.4
Meter 3	± 0.9	-0.5
Meter 4	± 1.0	-0.5
Meter 5	± 1.0	-0.5
Meter 6	± 1.0	+0.0
Meter 7	± 1.1	-1.9
Meter 8	± 1.1	-2.1
Meter 9	± 1.1	-0.8
Meter 10 (new set point)	± 1.1	-2.3
Meter 10 (old set point)	± 1.2	-0.2
Meter 11 (new set point)	± 1.1	-1.5
Meter 11 (old set point)	± 1.2	-0.2
Meter 12	± 1.2	-0.2
Meter 13	± 1.2	-0.5
Meter 14	± 1.2	-0.7
Meter 15	± 1.2	-1.7
Meter 16	± 1.3	-2.7
Meter 17	± 1.7	-1.6
Capacitance MC-meters:		
Meter 18 (dens.comp.calc.)	± 2.5	-0.5
Meter 19	± 2.6	-1.1
Meter 20	± 3.1	+1.8
Meter 21	± 3.2	+2.0
Meter 22	± 3.4	-2.9
Meter 23	± 3.5	-0.3
Meter 24	± 3.8	+0.4

Table 5. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Spruce from Central Europe.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 2.0	+0.5
Meter 2	± 2.0	+0.9
Meter 3	± 2.0	-1.0
Meter 4	± 2.0	-1.3
Meter 5	± 2.0	+0.6
Meter 6	± 2.0	+0.6
Meter 7	± 2.0	+0.6
Meter 8	± 2.1	-1.2
Meter 9 (new set point)	± 2.1	-1.4
Meter 9 (old set point)	± 2.1	+0.7
Meter 10 (new set point)	± 2.1	-0.6
Meter 10 (old set point)	± 2.2	+0.8
Meter 11	± 2.2	+0.3
Meter 12	± 2.3	+1.0
Meter 13	± 2.3	-2.5
Meter 14	± 2.3	+0.2
Meter 15	± 2.3	+0.4
Meter 16	± 2.3	+0.1
Meter 17	± 3.0	+0.5
Capacitance MC-meters:		
Meter 18 (dens. comp. calc.)	± 2.2	-1.0
Meter 19	± 3.3	-1.6
Meter 20	± 3.7	+0.4
Meter 21	± 3.7	-0.7
Meter 22	± 4.0	+1.4
Meter 23	± 4.0	+1.2
Meter 24	± 4.4	-3.2

Table 6. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Birch from Finland and Sweden.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.7	+1.4
Meter 2	± 1.7	-0.2
Meter 3	± 1.8	+1.7
Meter 4	± 1.9	+1.0
Meter 5	± 1.9	+1.3
Meter 6	± 2.0	+1.3
Meter 7	± 2.0	+0.4
Meter 8	± 2.0	+1.3
Meter 9	± 2.0	+0.3
Meter 10	± 2.0	+1.3
Meter 11	± 2.0	+0.4
Meter 12	± 2.1	+0.9
Meter 13	± 2.1	+1.0
Meter 14	± 2.2	+0.3
Capacitance MC-meters:		
Meter 15	± 2.5	-0.9
Meter 16	± 2.7	+1.6
Meter 17	± 2.8	-1.4
Meter 18	± 2.8	+2.1
Meter 19	± 2.9	-1.8
Meter 20 (dens.comp. calc.)	± 2.9	-1.8
Meter 21	± 3.1	-1.0

Table 7. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Beech from Denmark and Germany.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.2	-0.3
Meter 2	± 1.3	+0.4
Meter 3	± 1.3	-1.6
Meter 4	± 1.4	+0.8
Meter 5	± 1.4	+0.4
Meter 6	± 1.4	-0.4
Meter 7	± 1.5	+1.5
Meter 8	± 1.5	+0.5
Meter 9	± 1.5	+0.7
Meter 10	± 1.5	-0.1
Meter 11	± 1.5	-1.3
Meter 12	± 1.5	+1.3
Meter 13	± 1.6	-0.7
Meter 14	± 1.6	+0.3
Meter 15	± 1.6	+0.6
Meter 16	± 2.0	-2.1
Capacitance MC-meters:		
Meter 17 (dens. comp. calc.)	± 2.0	-2.1
Meter 18	± 2.3	-0.9
Meter 19	± 2.4	-1.0
Meter 20	± 2.5	-0.4
Meter 21	± 2.5	-1.9
Meter 22	± 2.8	+2.5
Meter 23	± 2.8	+2.4

Table 8. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Oak from Denmark, France and Germany.

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.0	-0.3
Meter 2	± 1.0	+0.8
Meter 3	± 1.0	+0.7
Meter 4	± 1.0	+0.7
Meter 5	± 1.0	+0.8
Meter 6	± 1.0	+0.9
Meter 7	± 1.1	+1.1
Meter 8	± 1.2	+1.7
Meter 9	± 1.2	+0.5
Meter 10	± 1.2	+1.5
Meter 11	± 1.2	+0.3
Meter 12	± 1.2	+0.7
Meter 13	± 1.3	+0.8
Meter 14	± 1.4	+0.0
Meter 15	± 1.6	+1.6
Meter 16	± 1.9	+1.1
Capacitance MC-meters:		
Meter 17	± 2.1	-1.3
Meter 18 (dens. comp. calc.)	± 2.2	-2.2
Meter 19	± 2.3	-1.3
Meter 20	± 2.8	-0.9
Meter 21	± 2.9	+2.3
Meter 22	± 3.0	+1.8
Meter 23	± 3.1	-2.2

Table 9. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Alder from Sweden.

Alder

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 0.8	+0.3
Meter 2	± 0.8	+0.0
Meter 3	± 0.9	+0.4
Meter 4	± 0.9	+0.1
Meter 5	± 0.9	-0.3
Meter 6	± 1.0	-0.4
Meter 7	± 1.0	+0.1
Meter 8	± 1.0	-1.5
Meter 9	± 1.1	-0.5
Meter 10	± 1.1	+1.3
Meter 11	± 1.1	-1.3
Meter 12	± 1.1	+0.1
Meter 13	± 1.1	-0.5
Meter 14	± 1.2	-0.8
Meter 15	± 1.3	-0.8
Meter 16	± 2.0	-3.1
Capacitance MC-meters:		
Meter 17	± 2.0	-0.8
Meter 18	± 2.1	+0.7
Meter 19	± 2.2	-0.4
Meter 20	± 2.2	+0.5
Meter 21 (dens. comp. calc.)	± 2.7	-1.2
Meter 22	± 2.7	-1.4
Meter 23	± 3.1	-1.8

Table 10. Confidence intervals (MC level 9 - 17 %) for different MC-meters. Species tested: Larch from Denmark.

Larch

Types of hand-held moisture meters	Laboratory tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 0.9	-0.7
Meter 2	± 1.0	+0.3
Meter 3	± 1.0	-0.1
Meter 4	± 1.0	-1.5
Meter 5	± 1.1	-0.0
Meter 6	± 1.1	-0.5
Meter 7	± 1.1	-2.1
Meter 8	± 1.1	-0.2
Meter 9	± 1.1	-0.6
Meter 10	± 1.1	+0.5
Meter 11	± 1.1	-0.8
Meter 12	± 1.2	+0.2
Meter 13	± 1.3	-0.7
Meter 14	± 2.2	-1.8
Capacitance MC-meters:		
Meter 15 (dens. comp. calc.)	± 1.8	-1.0
Meter 16	± 3.1	-1.7
Meter 17	± 3.1	-2.5
Meter 18	± 3.9	-3.0
Meter 19	± 4.0	-2.6
Meter 20	± 4.2	-2.2
Meter 21	± 4.5	-2.2

Table 11. Confidence intervals (MC level 7 - 25 %) for different MC-meters. Species tested: Pine from Finland and Sweden.

Types of hand-held moisture meters	Industry tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 1.4	+1.2
Meter 2 (new set point)	± 1.5	+1.4
Meter 2 (old set point)	± 2.6	+3.2
Meter 3	± 1.9	+0.4
Meter 4	± 2.1	+0.4
Meter 5	± 2.2	+0.7
Meter 6	± 2.2	+0.6
Meter 7	± 2.4	+0.9
Meter 8	± 2.4	+1.1
Meter 9	± 2.5	-0.2
Meter 10	± 2.5	+1.1
Meter 11	± 2.6	-0.7
Meter 12 (old set point)	± 2.6	+1.7
Meter 12 (new set point)	± 2.7	+2.5
Meter 13	± 2.8	+1.0
Meter 14	± 3.4	-1.8
Meter 15	± 4.3	-4.1
Meter 16	± 5.4	+2.7
Capacitance MC-meters:		
Meter 17 (dens. comp. calc.)	± 1.9	+0.3
Meter 18	± 1.9	-0.2
Meter 19	± 4.2	-1.9
Meter 20	± 5.2	-2.9
Meter 21	± 5.2	-2.5
Meter 22	± 5.3	-2.7
Meter 23	± 5.9	-4.2

Table 12. Confidence intervals (MC level 7 - 25 %) for different MC-meters. Species tested: Spruce from Finland and Sweden.

Types of hand-held moisture meters	Industry tests	
	95 % confidence intervals, % units	average divergence (reading – true)
Resistance MC-meters:		
Meter 1	± 0.7	+1.2
Meter 2	± 0.8	+1.5
Meter 3 (new set point)	± 0.9	-0.3
Meter 3 (old set point)	± 0.9	+2.5
Meter 4	± 0.9	+0.3
Meter 5 (new set point)	± 0.9	+0.5
Meter 5 (old set point)	± 1.0	+2.2
Meter 6	± 1.1	+0.4
Meter 7	± 1.1	+1.3
Meter 8	± 1.2	+0.9
Meter 9	± 1.4	+1.6
Meter 10	± 1.5	+1.5
Meter 11	± 1.5	-0.4
Meter 12	± 1.6	+1.3
Meter 13	± 1.7	+0.8
Meter 14	± 2.0	-2.7
Meter 15	± 3.0	-1.1
Meter 16	± 3.6	-1.3
Capacitance MC-meters:		
Meter 17 (dens. comp. calc.)	± 1.4	-1.4
Meter 18	± 1.7	-0.4
Meter 19	± 2.0	-3.3
Meter 20	± 2.6	-1.3
Meter 21	± 2.8	-1.6
Meter 22	± 3.0	-5.5
Meter 23	± 3.1	-3.1

APPENDIX C

Qualification of the properties of moisture meters

Surveyor: ______________________

Meter: ______________________

Date: ______________________

Grading system: 1 = poor, 2 = adequate, 3 = good, 4 = very good, 5 = excellent

Property	**Grade**	**Explanation** **Good/bad aspects**
Cable connections		
Changing parameters		
Display		
Keyboard		
Hammer design		
Pin marks		
Overall design		
Readability		
Stability of meters		

Comments

____

____

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Title

Accuracy and functionality of hand held wood moisture content meters

Abstract

The main task of VTT in this EU project was to test and improve the reliability and performance of moisture content meters. A total of 16 resistance type and 6 capacitance type hand-held moisture meters were included in the test series.

Test samples of the most important European species (pine, spruce, birch, oak, beech, alder, larch) were obtained from all over Europe. The total survey included about 2,700 pieces for comparative testing. The test material was conditioned to three different moisture contents (8 - 10%, 12 - 14% and 16 - 18%). The moisture gradients in the test specimens were small due to the long conditioning time lasting at least 1 year.

The effects of various factors, such as moisture content, species, and temperature, on the electrical resistance of conditioned wood were studied. In the laboratory tests, the resistance – moisture content curves for different species from different countries were determined using conditioned wood material.

The species corrections (resistance curves) are quite similar for different counties. Only the resistance curve for Maritime Pine differs clearly from the other resistance curves for the pine species originating from the different countries.

The wood temperature corrections are about 0.1 - 0.15% units/°C which has to be considered when the moisture content of wood is measured at temperatures other than 20 °C.

The other properties of wood, such as as sapwood/heartwood and density, do not have a significant effect on resistance values. There were no significant resistance differences related to the type of electrodes, distances between electrodes, and different measuring direction.

The commercial instruments for the determination of wood moisture content were tested with respect to accuracy, reliability and ergonomy. The moisture meters were tested both under laboratory and industrial conditions. Most of the resistance meters show a systematic deviation from the actual moisture content because of incorrect MC resistance curves. When the MC was lower than 10%, the readings of all the resistance meters tended to creep.

The measuring accuracy of the MC meters (95 % confidence interval) in laboratory tests with well conditioned material was about ±1.5 … ±2.5% units for the resistance meters and about ±2.5% … ±4.0% units for the capacitance meters. The corresponding accuracy of MCmeters in industry test was about 2.0 % … ±5.0% units for the resistance meters and about ±3.0% … ±5.0% units for the capacitance meters.

Keywords

wood, timber, moisture meters, moisture content, measuring instruments, reliability, tests, electrical resistance, temperature, species correction, pine, spruce, birch, oak, beech, alder, larch

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