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Characterization of the mechanical properties of saturated spruce (*Picea abies*) and pine (*Pinus sylvestris*) foundation piles

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A R T I C L E I N F O

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A B S T R A C T

The lack of strength values for wooden foundation piles in the design standards for timber (Eurocode 5) hinders their proper engineering design and assessment. In order to fill this gap, an extensive experimental campaign was conducted to characterize the mechanical properties of large-scale, water-submerged spruce (*Picea abies* L.) and pine (*Pinus sylvestris* L.) piles. This was achieved through the execution of axial compression tests on 253 full-scale pile segments. Wet compressive strength and stiffness values were derived for both spruce and pine piles, applicable to the whole pile and/or its parts: head, middle-part, and tip. The quality variables that most influenced the wet compressive strength of the piles were density, knot ratio (KR), number of annual rings (age), and growth rate. Based on this, characteristic strength values were derived for piles with the following grading limits: KR < 0.5, age between 20 and 100 years, and a growth rate <5 mm/year. These variables were used as key parameters to develop prediction models for the wet compressive strength of spruce and pine piles. The saturated compressive strength values and grading boundaries presented in this study contribute to the engineering design of timber piles and support the integration of reliable design values into future versions of Eurocode 5.

1. Introduction

1.1. Background

Round timber has always played an important role in engineering construction, particularly in the past, as timber foundation piles in soft, waterlogged soils. In Europe, many historic buildings and strategic infrastructures, such as bridges and quay walls, are founded on wooden piles. In particular, the application of wooden foundations is widespread in cities with weak soils, such as Amsterdam (NL) and Rotterdam (NL), as well as in other cities like Venice (IT) and Hamburg (DE) where similar timber foundations can be found [1–3, 44,[45]]. During the construction of wooden pile foundations, softwoods such as spruce (*Picea abies* L.), pine (*Pinus sylvestris* L.) and fir (*Abies Alba*) were commonly used due to their cost-effectiveness and availability in Europe. In the Netherlands, the majority of wooden foundation piles comprises softwoods, while hardwood piles, such as Oak and Alder, were used in only a limited number of cases [4]. Nowadays, many of these structures have been in service for up to 500 years, making the assessment of the remaining service life of

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timber foundation piles a critical issue [5–9]. However, since the behaviour of timber foundation piles has not been extensively studied [10], little or no design guidance can be found in the design standards. In the current Eurocode 5 [11] wooden piles are not addressed. In the Netherlands, the National Annex to Eurocode 5 (NEN-EN 1995-1-1/NB:2013 [12]) and NEN 5491 Timber Piles (2010) [13] provide design values and grading rules for wooden piles and their application in the soil. However, these standards provide only a single strength value for the dry compressive strength ($f_{c,0,k} = 19.8$ N/mm^2) at 12 % moisture content (MC), derived from a statistical analysis of historical test data conducted in Ref. [14]. This results in a lack of saturated strength values in the standards, in contrast to the fact that most wooden piles remain submerged below the water level throughout their entire service life. To address this, the draft of the new Eurocode 5, prEN 1995-1-1/NB:2023 [15], proposes to directly use wet compressive strength values in the design calculations of wooden foundation piles. Presently, the available literature on saturated round wood [14,16], is not sufficiently comprehensive for the accurate design or assessment of wooden piles, since it is based on a limited database and lacks grading boundaries and strength parameters that cover the entire length of the pile, from head to tip. The tip is especially critical as, depending on soil conditions, it corresponds to the critical cross section of the pile during service, primarily due to the high stresses associated with its smaller cross section. The knowledge gaps on saturated strength and stiffness parameters for wooden foundation piles pose significant uncertainties in their design and assessment. In this context, the results of an extensive experimental test program are reported in this paper, with the purpose of characterizing the mechanical properties of saturated wooden foundation piles.

1.2. State of the art

Axial compression tests on saturated spruce, pine, and fir pile heads were conducted in Buiten [16]. Based on this data, a statistical analysis was carried out in Ref. [14], leading to the derivation of wet mean and characteristic compressive strength values. In particular, wet compressive strength values were reported for 57 European spruce (*Picea abies* L.), 18 Douglas fir (*Pseudotsuga menziesii*), and 20 larch (*Larix decidua Mill.*) debarked pile segments. The specimens had an average diameter of 140 mm, a length of 900 mm (ratio 1:6:4, close to 1:6 in accordance with EN 408 [18] and EN 1425 [19]), and an average MC = 110 %. Maximum knot diameters ranging from 5 mm to 60 mm, and a knot ratio (KR) between 0.2 and 0.6, were measured. The knot ratio was calculated as the ratio between the sum of knot diameters over a pile section of 150 mm and the circumference of the pile. However, the testing procedures adopted in Ref. [16] were not reported. Differently from literature, the expected inverse correlation between KR and the wet compressive strength of the piles was not found. To this end, particular attention is paid in Section 3.2 for the measurement of the KR. Depending on the grade requirements listed in NEN 5491, which provides a limit of 50 mm for the biggest knot and a limit of 0.5 for KR, 37 specimens should have been excluded from strength grading in Ref. [14], leaving 58 standardized specimens. However, all the samples were included in the statistical analysis in Ref. [14], since no significant difference in mean strength values was measured between the 58 standardized wooden piles and all the 95 piles. The difference in strength values among the three wood species was reported in Ref. [14] to be not large enough for strength sorting by wood species. Moreover, in order to prevent the batch of spruce piles from being assigned to a too high strength value, the characteristic value was derived based only on the strength of the 57 spruce piles. Thus, from the mean wet compressive strength of the spruce samples ($f_{c,0,mean,wet} = 20 \pm 2.2$ MPa), a corresponding characteristic wet compressive strength ($f_{c,0,k,wet} = 16.3$ MPa) was derived in Ref. [14]. The mean wet compressive strength values for all the three species tested in Ref. [14] are, in any case, reported in Table 2 $f_{c,0,k,wet} = 16.3$ MPa served as a basis to standardize the design and the 'dry' compressive strength for a single wooden pile. The valid design code for Timber Structures (in accordance with NEN 6760: 1997 [20]) was derived using the ratio of 0.85/0.7 for short term strength in dry/wet conditions, respectively. By applying the multiplication factor of 0.85/0.7 = 1.21 to the $f_{c,0,k,wet} = 16.3$ MPa, a 'dry' characteristic compressive strength value $f_{c,0,k,dry} = 19.8$ MPa was determined for MC = 12 %. Subsequently, for the long-term compressive strength, that includes long-term load and the effect of high moisture content, a design wet compressive strength value $f_{c,0,d} = 9.8$ MPa was incorporated in the Dutch National Annex NEN-EN 1995-1-1/NB (2013), and reported as applicable to spruce, fir, and larix foundation piles.

As part of a joint European (FAIR) project, started in 1996 for small diameter round wood for structures in service class 1 and 2 (not applicable to wooden piles), a strength grading of round timber for structural systems was developed in Ranta-Maunus [21]. In this project, the compression properties of 150 British and Finnish pine (*Pinus sylvestris*), 180 Douglas fir (*Pseudotsuga menziesii*) and 200 spruce (*Picea abies*) small round pile sections were determined. The specimens had diameters between 80 mm and 150 mm, a length of

Table 1
Correlation matrix (R) for all compression material (from Boren 2000).

	$E_{c,0}$	$f_{c,0}$	a	d	ks	KAR	mk	ρ_{12}	r	S
$E_{c,0}$	1.00									
$f_{c,0}$	0.79	1.00								
a	0.72	0.66	1.00							
d	−0.15	0.02	0.22	1.00						
ks	−0.70	−0.73	−0.63	0.22	1.00					
KAR	−0.65	−0.72	−0.72	−0.15	0.91	1.00				
mk	−0.60	−0.64	−0.63	0.26	0.87	0.76	1.00			
ρ_{12}	0.57	0.50	0.43	0.11	−0.23	−0.24	−0.16	1.00		
r	−0.72	−0.64	−0.75	0.18	0.72	0.66	0.63	−0.29	1.00	
S	0.31	0.20	0.34	−0.31	−0.45	−0.38	−0.45	−0.37	−0.51	1.00
MC	−0.25	−0.67	−0.17	−0.07	0.39	0.36	0.41	−0.10	0.23	−0.03

Table 2
Mechanical properties in compression parallel to the grain in dry (MC ≈ 12 %) and wet (MC > 30 %) conditions for round pine (*Pinus sylvestris),* spruce (*Picea abies*), Douglas fir (*Abies alba*) and larch (*Larix decidua*) reported in literature (Van de Kuilen 1994 [14]; Boren 2000 [22]; Ranta-Maunus 2000 [21]; Aicher 2016 [23]).

									Dry (MC ≈ 12 %)						Wet (MC > 30 %)					
Category	Reference	Sample size	age (years)		diameter (mm)		KAR (%)		$E_{c,0}$ (GPa)		$f_{c,0}$ (MPa)		$f_{c,0,k}$ (MPa)	$\rho_{12,k}$ (kg/m^3)	$E_{c,0,wet}$ (GPa)		$f_{c,0,wet}$ (MPa)		$f_{c,0,k,wet}$ (MPa)	$\rho_{k,wet}$ (kg/m^3)
			mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	x_{05}	x_{05}	mean	SD	mean	SD	x_{05}	x_{05}
Pine (FIN + UK) (*Pinus sylvestris*)	Boren (2000) [22]	150	17	6	120	20	19.9	8.9	9.9	–	28.6	3.4	19.1	404	–	–	–	–	12.4[a]	–
Spruce (*Picea abies*)	Van de Kuilen (1994) [14]	57	–	–	113	28	32.4	7.7	–	–	–	–	–	–	–	–	20.0	2.2	16.3	–
	Boren (2000) [22]	200	26	5	105	21	13.9	5.8	11.5	–	30.7	4.2	20.8	332	–	–	–	–	13.5[a]	–
	Aicher (2016) [23]	34[b]	–	–	200	–	21.0	–	12.1	1.9	30.8	6.1	20.3	370	10.7	1.6	17.6	2.3	13.4	387
Douglas Fir (*Pseudotsuga menziesii*)	Van de Kuilen (1994) [14]	18	–	–	148	22	24.8	8.5	–	–	–	–	–	–	–	–	22.9	2.8	17.3	–
	Ranta-Maunus (2000) [21]	180	–	–	120	–	24.0	–	11.0	–	33.0	–	26.0	367	–	–	–	–	16.9[a]	–
Larch (*Larix decidua*)	Van de Kuilen (1994) [14]	20	–	–	141	26	25.1	10	–	–	–	–	–	–	–	–	24.0	3.9	17.1	–

[a] calculated value according to the reduction factor dry to wet $k_{moist} = 0.65$ based on Aicher (2016) [23].
[b] 17 samples tested in dry conditions and 17 samples tested in wet conditions (MC > 80 %).

6 times the smallest diameter of the conical log sections according to EN 408 [18] and 10 % < MC < 20 %. The quality of the tested timber was characterized by determining the diameter, number of annual rings (age), annual ring width, and knot dimensions. These parameters were correlated with the compressive strength ($f_{c,0}$), stiffness ($E_{c,0}$), density (ρ_{12}), and MC in the correlation matrix in Table 1, presented in Boren [22], limited to 150 pine and 200 spruce round samples. Moreover, a regression model ($R^2 = 0.82$) for the compressive strength parallel to the grain (Eq. (1)) was also reported in Boren (2000). Spruce piles had 10 % lower $f_{c,0}$ than pine piles. Furthermore, spruce exhibited roughly 35 % lower KR than pine, average 10 % lower ρ_{12}, and 10 % smaller mean diameter than pine. No correlation between the mechanical properties and the diameter was found. The effect of the age of the piles was studied, by investigating new piles with an age between 10 and 40 years, where pine was on average 5 years younger than spruce. For both spruce and pine, piles younger than 20 years had 25 % lower $f_{c,0}$ and $E_{c,0}$ values than older specimens, potentially attributed to the larger portion of juvenile wood, inherently less dense and strong than mature wood [24,28], The results of all the characterized mechanical properties of the piles tested in Refs. [21,22], as well as the characteristic values adjusted to moisture content MC = 12 % (in accordance with EN 384 2016 [17]), were listed in Table 2.

$$f_{c,0} = 18.35 – 0.05127d – 4.58f_4 – 0.0898KAR + 0.02676\rho_{12} + 0.00226\rho_{12}S – 21.131\log(MC/a) \quad (1)$$

Where:

d diameter of the specimen (mm)
f_4 variable: 1 for pine, 0 for other wood species
KAR knot area ratio (%)
ks sum of the diameters of the knots in a knot cluster (mm)
mk diameter of the thickest knot (mm)
ρ_{12} density at 12 % moisture content (kg/m^3)
S tree species (pine = 0, spruce = 1)
MC moisture content (%)
a age, annual rings (years)
r annual ring width (mm), measured at or close to the failure point

The compressive strength of wood is influenced by changes in MC, increasing with decreasing MC [24,28]. Many studies in literature cover the relationship between the mechanical properties of wood with MC ranging from oven-dried material (MC = 0 %) to high MC values at and above fiber saturation (30 %–80 %), summarized in Ref. [28]. Although the variability of the fiber saturation range, reported in textbooks such as [28] and in the Eurocode 5 [11], the transition value from dry to water saturated status of softwoods (as spruce and pine), is taken as MC ≈ 25 %, after which the compressive strength and stiffness properties of timber do not change anymore. In case of timber foundation piles, mainly comprising softwoods [3–10], it was demonstrated in Kollmann [24] from tests of spruce and fir that the fiber saturation point ranges at 30–34 %. The findings in Ref. [24], suggested that reduction factors related to fiber saturation extend beyond the chosen fiber saturation limit of MC ≈ 25 %. In addition, it was highlighted in Ref. [23] from fits to literature data, that the moisture modification factor $k_{moist} = 0.82$ adopted in the Eurocode 5 [11] might not be appropriate for considering the reduction for the compression strength parallel to the fiber of softwoods in wet conditions. In order to determine an adequate k_{moist}, the mechanical properties of 17 full-scale 'new' spruce round wood with high moisture content (avg. MC = 89 %) were characterized in Aicher [23]. The piles had an average mid-length diameter of 197 mm and a length of 6 times the smallest diameter of the conical log sections in accordance with EN 408 (2010) and EN 14251 (2003). The grade of the pile segments complied with NEN 5491 (1999), with maximum knot diameters of 19 mm–42 mm and knot area ratios of 0.11–0.31. In addition, 17 dry full-scale 'new' spruce piles were tested in Ref. [23], with average MC = 12 %, in order to derive a dry compressive strength value for spruce piles. From the dry and wet compressive strength (on the 5 % quantile level), a reduction factor $k_{moist} = 0.65$ was derived, confirming the findings in Kollmann [24], who suggested that reduction factors related to fiber saturation extend beyond the chosen fiber saturation limit of MC ≈ 25 %. This showed that $k_{moist} = 0.82$, provided in Ref. [12] might not be adequate to account for the reduction for the compression strength parallel to the fiber of softwood foundation piles in wet conditions. This issue, which is especially relevant for the design of water-saturated piles, is presently not addressed in the Eurocode 5 [11]. Therefore, deriving saturated compressive values of wooden piles, as suggested in the draft of the new Eurocode 5 [15], reveals to be a more adequate method for the design and assessment of wooden foundation piles, since the effect of moisture is already included in the saturated compressive strength ($f_{c,0,k,sat}$). The results of the dry and wet characterization of the 34 piles tested in Ref. [23] were presented in Table 2 $k_{moist} = 0.65$ determined in Ref. [23], was applied in Table 2 to the dry characteristic strength values determined in Refs. [21,22]. The calculated wet characteristic strength values for spruce, applying a $k_{moist} = 0.65$, resulted in ca. 20 % lower strength compared to the spruce piles tested in Ref. [14]. For the other tested species, the calculated wet compressive strength values were in line with the tested wet piles from the literature. It should be noted that the results and descriptions presented regarding the state-of-the-art strength properties of the piles are entirely derived from literature sources [14,16,21–23].

1.3. Research scope

The saturated mechanical and material properties of the piles in the literature are based on a limited database, mainly involving piles with small average diameters (120 mm), without providing grading boundaries and strength parameters covering the entire length of the tapered pile, from the head to the tip. In order to overcome the lack of strength values for saturated wooden piles in the literature and in the design standards (Eurocode 5), research is conducted with the purpose of characterizing the mechanical properties of 70 water-saturated full-sized round spruce (*Picea abies*) and pine (*Pinus sylvestris*) piles. The mechanical properties are investigated by performing axial compression tests on pile segments extracted from head, middle-part, and tip of full-length tapered piles, with average total length of 12 m. Pile segments with different diameters are tested (ranging from 130 mm to 280 mm), spanning the most common wooden-pile dimensions used in practice, as indicated in Ref. [13]. The research aims to provide mean and characteristic values for compressive strength, modulus of elasticity parallel to the grain, and density in saturated conditions. These values are proposed for inclusion in the new draft of Eurocode 5 (prEN 1995-1-1/NB:2023) [15], as timber foundation piles are primarily used in saturated conditions. To this end, the updated draft of Eurocode 5 (2023) introduces a revised approach, requiring saturated compressive strength values for timber piles. Differently from the previous version, the specified k_{mod} values no longer account for high moisture content but they are only used for load duration effects in a newly defined Service Class 4, since saturated conditions are already accounted in the compressive strength values. This research further investigates the visually detectable characteristics of timber, such as diameter, knot-related parameters, annual rings, rate of growth, slope of the grain, and tapering, and their potential influence on saturated strength and stiffness. These properties are visually graded to establish grading limits and correlations between compressive strength, stiffness, and visually graded parameters. These findings improve the knowledge on the mechanical behaviour of saturated wooden foundation piles and their relationship with quality variables of timber that could possibly affect the strength. The results provide a basis for the engineering assessment and design of wooden foundation piles and they complement the provisions outlined in prEN 1995-1-1/NB:2023 [15].

2. Materials

The test material comprised 253 pile segments sawn from full-scale logs subdivided in:

- 38 spruce (*Picea abies* L.) piles from a forest in Holterberg, The Netherlands;
- 32 pine (*Pinus sylvestris* L.) piles from a forest in Nuremberg, Germany.

When tapered timber piles are employed in foundations, there are two parameters used for the selection of the piles in the forest: the tip diameter and length (Fig. 1). These parameters are chosen in relation to the foundation design project and soil stratigraphy. The piles used in this study were selected based on an average tip diameter (ca. 130–140 mm, measured on the top part of the tree trunk), and pile length (ca. 15 m), as showcased in Fig. 1a. The timber piles were cut at the lower section of the tree trunk ("butt log") close to the base [35] (Fig. 1b). This specific portion is generally favoured due to its characteristics of being broader, straighter, and having a more consistent diameter compared to the upper part of the tree [35,36], also ensuring the optimal utilization of the material during

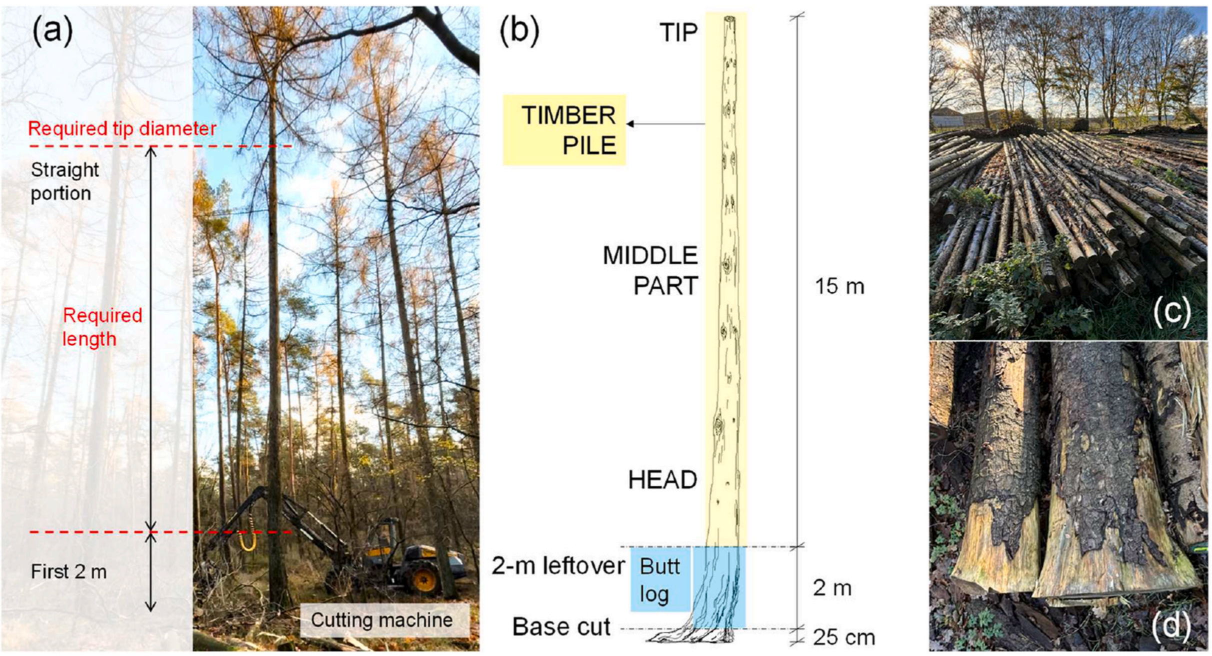

Fig. 1. Sourcing process of a timber pile from a tree: (a) example of selection and cutting of a (pine) tree in the Holterberg forest (NL) depending on the tip diameter and required pile length; (b) Cutting positions of a ca. 15-m-timber pile from a debranched tree trunk; (c) timber piles after cutting; (d) fiber deviation at the bottom part of a tree trunk.

harvesting, minimizing material waste. More specifically, the trees were cut approximately 25 cm from the ground, as close as possible to the soil level. In addition, the first 2 m of the trunk were cut off, since this part is typically considered as low quality material due to the natural growing deviation of the grain of the trunk at the base as observable in Fig. 1b and d (Director of RHS Rondhout, Hierden (NL); personal communication, November 28, 2023). Thus, the remaining 15-m portion of the tree was taken for the spruce and pine piles tested in this study.

The timber piles were extracted from the trees in 2019. They had a mean length of 15 m, a mean head diameter (D_{head}) of 290 mm, and a mean tip diameter (D_{tip}) of 135 mm (see Fig. 1b for the location of head and tip). Out of a total of 70 piles, 27 piles (18 spruce and 9 pine) were driven into the soil in 2019 in a test field in Overamstel, Amsterdam (NL), as part of a geotechnical project handled by the city of Amsterdam. A pile driver machine was used with an impact hammer of 800 kg. The data regarding the forces used for the pile insertion was not available. However, the in-situ pile driving was carried out according to EN 12699:2015 [25] and prEN 1995-1-1/NB:2023 [15], so that the maximum stress during driving should not exceed 0.8 times the characteristic compressive strength of the piles. Subsequently, 18 of these piles (13 spruce and 5 pine), named DL (Driven and Loaded), were subjected to short-term in-situ loading with the goal of assessing the maximum geotechnical failure load, correspondent to a maximum displacement of the head of the pile equal to 10 % of the head diameter, in accordance with NEN 9997–1+C2:2017 [26]. The loading procedure was carried out within a day, with a maximum stress of 6.9 MPa recorded on the pile head. It should be noted that the failure did not correspond to the material failure, but to the failure with respect to the soil settlement. After this, the load was removed from the 18 piles, except for 2 spruce piles (DL-1) that were loaded to 80 % of the failure load for 22 days. The other 9/27 piles (5 spruce and 4 pine), named D (Driven), were driven but never loaded. After this, all the piles were extracted from the soil in 2020 and treated in the same manner as the 43 other piles (named ND, Never Driven), which involved cutting each pile into three parts (head, middle-part, and tip), and submerging all the parts under water in containers. Fig. 2 shows the workflow and the different categories of piles used in this research. Table 3 lists the preliminary data of each pile category and the average maximum stress levels reached on the pile head during the loading operation. The average tapering of the pile from the head to the tip is also reported: possible taper variations along the length could occur if considering pile-sections where the diameter could be influenced by natural growth patterns of the tree.

3. Methods

3.1. Preparation of the pile segments

During 2021 and 2022, all piles were transported from the storage location of the city of Amsterdam to the TU Delft Stevin 2 laboratory for mechanical testing. Upon the arrival of every batch of piles, the full-scale piles were cut into head, middle, and tip segments (Fig. 3) with a length of approximately 6 times the smallest diameter of the conical pile sections according to EN 408 [18]. During handling and cutting procedures, the piles were kept submerged in large water tanks to avoid drying and consequent cracking. Three length categories were established: 900 mm ($D < 160$ mm), 1350 mm ($160 \text{ mm} \leq D \leq 240$ mm), and 1800 mm ($D > 240$ mm). This was done to investigate the compressive strength profile over the length of the tapered piles. This was done to recreate the same in-soil conditions where the piles were fully under the water level, in order to obtain comparable mechanical and physical properties during testing. MC was determined with the oven-dry method, according to EN 13183 2002 [27], by analysing two 30-mm-thick discs taken from both sides of each pile segment. The discs were oven-dried at a temperature of 103 °C, until a constant mass was achieved. MC was determined from the ratio between the difference between wet and dry mass, and dry mass of the discs. The dry density ρ_{dry} (at MC = 0 %) of the segments was calculated from the ratio between the dry mass of the pile segment and the dry volume of the pile segment. In some cases, the dry volume of the pile could not be accurately determined due to large cracks after testing and drying. In this case, a 12 % volumetric shrinkage from green to ovendry moisture content was assumed for both spruce and pine, according to the Wood Handbook [28]. MC was calculated with input values of dry and wet mass of each pile segment; therefore, any variation of the wet mass of the pile could be related to a precise MC value. After this, the pile segments were weighted and subsequently submerged in water to achieve the fully saturated condition for the compression test. During mechanical testing, all the samples had 50 % ≤ MC ≤

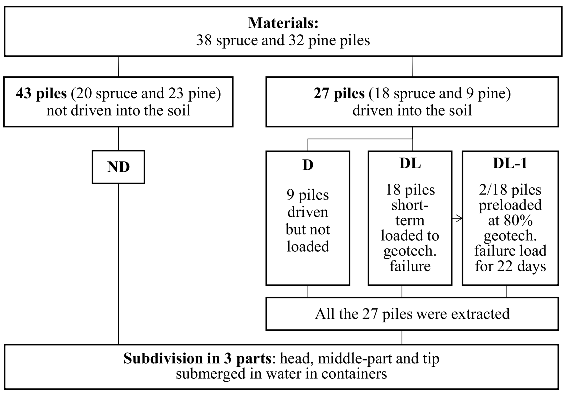

Fig. 2. Workflow of the materials used in this research.

Table 3
Preliminary data of full-scale piles and in-situ applied stress (standard deviation reported in brackets).

Pile Categories	No.	Length mean	D_{head} mean	D_{tip} mean	Avg. tapering	Max stress on pile head
		m	mm	mm	mm/m	MPa
ND	20[a] 23[b]	15.1 (0.16)	290 (27)	135 (13)	8.6 (2.5)	-
D	5[a] 4[b]	15.1 (0.12)	290 (30)	135 (12)	10.1 (2.7)	-
DL	13[a] 5[b]	15.1 (0.11)	300 (26)	135 (13)	10.6 (2.1)	6.9
DL-1[c]	2[a]	15.1 (0.06)	310 (8)	130 (9)	11.9 (1.1)	4.5

[a] Spruce piles (*Picea abies*).
[b] Pine (*Pinus sylvestris*).
[c] Piles DL-1 are a sub-category of 2/18 piles included in DL.

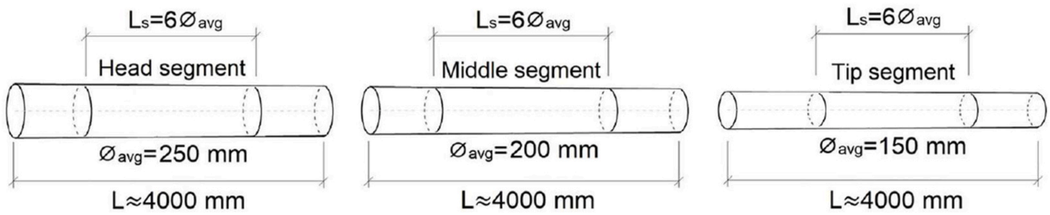

Fig. 3. Cutting scheme and subdivision of the full-scale pile into head, middle, and tip segments.

135 %, well above fiber saturation point. The distribution of MC between heartwood and sapwood was not measured; instead, the global MC of the entire cross-section was considered. The global MC values were related to global large-scale mechanical testing performed on the saturated pile segments, where the mechanical properties were determined in relation to the full cross-section of the pile. The global MC was therefore assumed to be comparable to that of the in-situ piles fully submerged under water, as also noted in the draft of the new Eurocode 5 [15], where MC of softwood logs in fully water-saturated condition is considered to be above 50–60 %.

3.2. Visual grading

The quality of the tested timber was characterized by measuring visual characteristics that could possibly relate to its strength and stiffness properties. These included diameter, age, rate of growth (RoG), knot-related parameters, slope of the grain (SoG), and tapering. The diameter was studied in relation to head, middle-part, and tip of the pile, in order to assess how the compressive strength varied along the length. The relationship between strength, stiffness, and visually graded wood properties such as age (number of annual rings) and rate of growth (average width of the growth rings) observable in the cross section of head, middle-part, and tip of the pile, was investigated. The width and number of the growth rings give important information on the percentage of juvenile wood and age of the pile, respectively [[30]39,40,[32]]. RoG was calculated by counting the number of growth rings over the outer 75 % of the representative radius of the cross section in accordance with NEN-EN 1309–3, 2018 [29]. An example is provided in Fig. 4, where the pith is eccentric: the length equal to 75 % of the radius was divided by the number of growth rings counted, the RoG was expressed in millimeters. After this, the age was calculated over the radius R, by counting the annual rings. In some cases it was difficult to count all the rings, especially close to the outer side of the cross section, leading to a potential measurement error of 5 %.

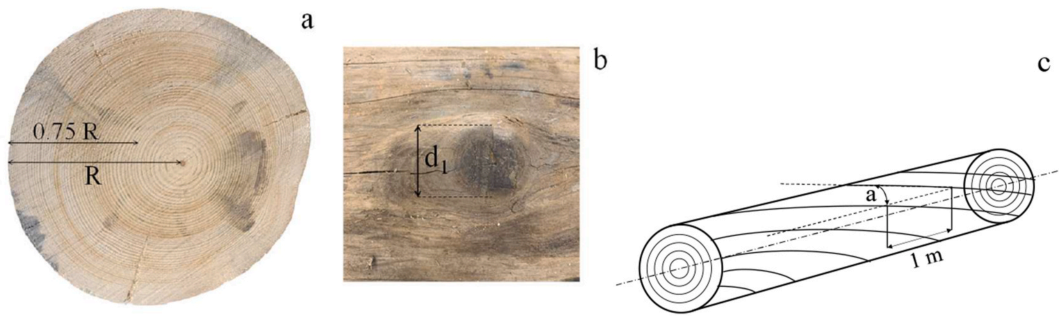

Fig. 4. (a) Rate of growth calculation over 0.75 R, and annual rings over R, for a cross section where the pith is eccentric; (b) measurement of the diameter d_1 of a knot perpendicular to the longitudinal direction of the log; (c) slope of the grain measurement over a distance of 1 m.

The knot ratio (KR) was measured according to NEN 5491 (2010), which defines KR as the ratio between the sum of the knot diameters perpendicular to the longitudinal axis of the log, over a 150 mm length, and the circumference of the log in that section. In order to comply with the strength grading requirements provided in NEN 5491 (2010), KR must not exceed 0.5, while the largest knot must not exceed 50 mm or 1/12 of the circumference of the pile.

Part of the piles investigated in this paper was already studied in Ref. [31], where the influence of knots on the compressive strength was estimated. A prediction equation for compressive strength was determined based on dry density (MC = 0 %) and KR. The results obtained in this research were used to implement the equation determined in Ref. [31]. In addition, the results regarding strength and knot dimensions for wet piles were available from Ref. [14].

The slope of the grain (SoG) was determined in accordance with NEN-EN 1309–3 (2018), as shown in Fig. 4c. The values were reported in the following increments (e.g. 1/4, 1/6, 1/8, 1/10, 1/12) to analyse the effect of SoG on the mechanical properties. SoG = 1/10 ($\alpha = 5.7^{\circ}$) is the current highest acceptable value for strength grading according to the new draft of the Eurocode 5 (prEN 1995-1-1/NB:2023). However, all the SoG values were considered to study their influence on the mechanical properties. Given the fact that is difficult to visually measure the SoG of wet piles, the measurements were conducted after drying when most of the specimens showed surface cracks.

The effect of tapering on the mechanical properties was analysed, by measuring the ratio between the difference in diameter of head and tip of the pile segment and its length. This was studied with the understanding that a constant taper, limited to a maximum of 15 mm/m over the entire length, complies with pile grade requirements specified in NEN 5491 (2010). Finally, the cutting of the piles was performed to ensure that the straightness of all pile segments did not deviate from the straight line by more than 1 % of the length. All these parameters were studied in relation to the compressive strength and stiffness parallel to the grain of the tested pile segments.

3.3. Compression tests parallel to the grain

Compression tests were performed to determine the wet compressive strength ($f_{c,0,wet}$) and modulus of elasticity ($E_{c,0,wet}$) of the pile segments in direction parallel to the grain. Prior to conducting full-scale mechanical testing on the pile segments, the wet density of each pile was determined by measuring wet mass and volume. For the mechanical tests, a displacement controlled set-up was used (Fig. 5), where the specimens were subjected to an axial load in direction parallel to the grain in accordance with EN 408 (2010) and EN 14251 (2003). The precise displacement between the two steel plates during the mechanical testing was monitored using four linear potentiometers ('S' sensors), which were placed on the four edges of the top plate and connected to the bottom plate. The deformation of the specimens was measured with four linear potentiometers that were attached to the surface of the pile ('P' sensors), positioned at 90° intervals on each side of the pile, with a variable length equal to two-thirds of the length of the specimen. Given the short stroke of the four 'P' sensors placed on the pile, they were removed right after the peak load to avoid damages. The post-peak softening was monitored only by the 'S' potentiometers attached to the top and bottom steel plates of the compression machine. In addition, a hinge, mounted on a steel plate, was placed on top of the specimen to have an uniformly distributed compression load on the pile. The compression test was carried out at a constant speed of 0.02 mm/s until the peak load was reached. After the peak load, the test continued at a higher speed until the cracks were visible, and to show the post-peak behaviour of the pile, aiming in total on a

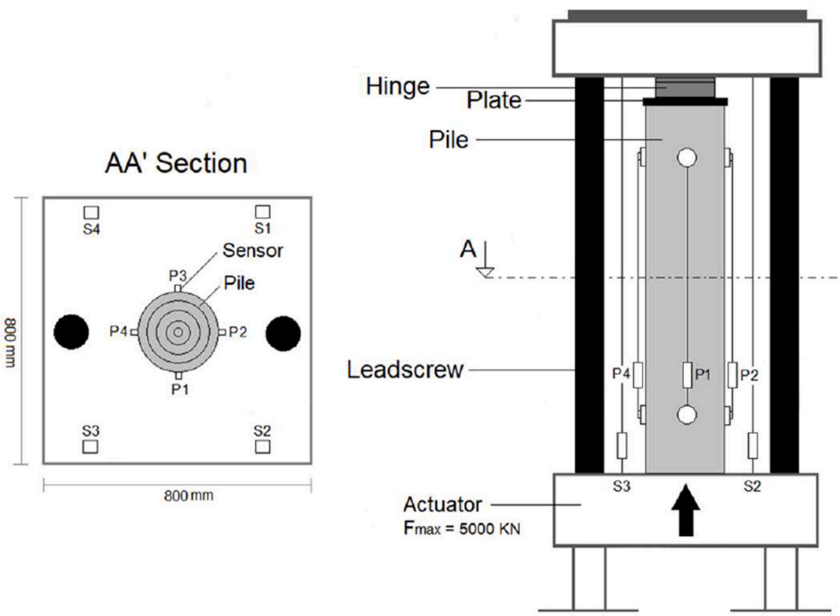

Fig. 5. Sensors positioning and set-up for the compression test of the pile segments.

test duration of 5 min. Upon completion of the test, $f_{c,0,wet}$ was calculated by taking the ratio of the maximum force achieved in compression by the specimen and the average cross-sectional area of the pile. The global behaviour of the piles was studied with the average stress-strain curve of the four linear potentiometers connected to the compression test machine; the strains were calculated considering the length of the specimen. $E_{c,0,wet}$ was calculated with the stress variation ($\Delta\sigma$) divided by the strain variation ($\Delta\varepsilon$), between 10 % and 40 % in the slope of the linear elastic portion of the stress-strain curve. In addition, the dynamic modulus of elasticity ($E_{c,0,dyn,wet}$) was determined through the frequency response method, using the timber grader MTG. This measurement was performed on every segment prior to testing.

3.4. Determination of the characteristic values

The values obtained from the mechanical testing were reported depending on the number of specimens from each category (ND, D, DL, and DL-1), and on the two different populations (spruce and pine). The characteristic values (mean $E_{c,0,wet}$ and the 5-percentile value of $f_{c,0,wet}$ and ρ_{wet}) were determined according to the parametric calculation in NEN-EN 14358 [[33]]. The density at MC = 12 % ($\rho_{k,12}$) was determined in Equation (2) from the calculated mass m_{12} (Eq. (3)) and the volume V_{12} at MC = 12 % (Eq. (4)). In order to determine V_{12}, the volumetric shrinkage at MC = 12 % was calculated on the basis of the following three assumptions according to Ref. [28]: shrinkage starts at the fiber saturation point (MC = 30 %); the dimensions of the pile decrease linearly with decreasing MC; variability in volumetric shrinkage can be expressed using a coefficient of variation of approximately 15 %, accounting for wood's intrinsic growth characteristics. Based on this, Equation (4) was used to calculate the volume V_{12} at MC = 12 %. The characteristic values of $f_{c,0,k,wet}$ and $E_{c,0,k,wet}$ were not adjusted to 12 % moisture content, as prescribed in EN 384 (2016). This because the European standard EN 384 (2016) sets a maximum threshold of MC = 18 % for saturated wood, far below the moisture content of the tested piles (MC > 70 %). Questions arise regarding the accuracy of the method for saturated piles, where moisture contents are well above 18 %, and it highlights the challenges in the design, where clearly design values for wooden piles are needed in wet conditions, as discussed in the prEN 1995-1-1/NB:2023.

$$\rho_k = m_{12} / V_{12} \quad (2)$$

$$m_{12} = m_{dry}\,(1 + u_{ref}) \quad (3)$$

$$V_{12} = V_{wet} \bullet (1 - S_0) \bullet (1 - u_{ref} / u_{30}) \quad (4)$$

Where:

V_{wet} volume at test moisture content.
u_{30} = 30 % moisture content at fiber saturation point (assumed equal to 30 % [28]).
u_{ref} = 12 % moisture content at 12 %.
S_0 = 12 % volumetric shrinkage from green (MC = 30 %) to ovendry (MC = 0 %) assumed to be 12 % [28] for both pine and spruce.

3.5. Statistical methods

A correlation analysis was carried out using the mechanical properties determined through compression tests at the test moisture content, and the visually graded parameters. Based on this, a multiple regression analysis was conducted. The independent variables were chosen based on their relationship with the mechanical properties, including the physical properties and wood characteristics of the pine and spruce specimens. The selection process for each variable was performed and based on its statistical significance, t-value, and correlation with other variables [34]. For both spruce and pine piles, two models were constructed: one based on the density and the visually graded wood properties; and the other based only on visual characteristics of wooden piles. In particular, this last model was constructed to provide a prediction of the wet compressive strength of a spruce or pine pile, only on the basis of parameters that could be visually measured, without the need of conducting experiments in a laboratory environment. All the pile segments tested in this research were considered, including all pile categories. Subsequently, the models with the highest correlation were combined into a single regression model applicable to both spruce and pine (Model S + P). Equation (5) describes the form of the regression equation used for the models, where y is the dependent variable, x_i are the independent variables, A_0 is the intercept (constant) and A_i are the multipliers of the independent variables. The model was based on the assumption that the dependent variable is normally distributed and the independent variables have equal variances.

$$y = A_0 + \Sigma\,(A_i \bullet x_i) \quad (5)$$

The model was computed by assessing the uncertainty associated with the regression coefficients. For both spruce and pine, 95 % confidence intervals were calculated to define the upper and lower limits, representing the range of predicted values that fall within 95 % confidence level. Probability plots (Q-Q plot) were reported for each model, as well as residual plots, to demonstrate the normal distribution of the residuals and to highlight the differences between the measured y-values and the predicted values derived from the regression model. Finally, the prediction equation for spruce and pine developed in the literature by Boren [22] was applied to the datasets of tested piles and compared with the regression equation from Model S + P. This comparison aimed to evaluate the applicability of a regression model developed for dry spruce and pine piles to saturated piles, and to identify common parameters that could influence the mechanical properties.

4. Test results

4.1. Mechanical properties of spruce and pine piles

The mechanical properties of 253 pile segments from 70 piles, divided into head, middle-part, and tip, are characterized in Table 4, including the characteristic wet compressive strength ($f_{c,0,k,wet}$) and wet density ($\rho_{k,wet}$). The cumulative distributions of the wet compressive strength and modulus of elasticity parallel to the grain are presented in Fig. 6 for spruce and pine segments (ND), and in Fig. 7 for spruce and pine segments (DL and D). The results of $f_{c,0,wet}$ and $E_{c,0,wet}$ are visually showcased with bar charts in Figs. 8 and 9. The load-displacement behaviour of the saturated spruce and pine specimens tested in compression exhibited linearity up to 70 %–80 % of the maximum compression load. Out of linearity, a nonlinearity phase was visible until peak load. As softening began, the load gradually decreased, showing a quasi-plastic load plateau. In approximately 70 % of the cases, a failure mechanism for local buckling was observed, where cracks initiated in the section with the highest KR. For the other cases, a failure due to crushing occurred, mostly in the top or bottom part of the pile, and it was typically observed in pile segments with KR $<$ 0.1.

4.2. Density adjusted to 12 % moisture content

Table 5 shows the mean and characteristic values for the density calculated at MC = 12 % according to Section 3.4. The 5-percentile characteristic value of density ($\rho_{k,12}$) was determined according to the parametric calculation in NEN-EN 14358 (2016).

4.3. Correlation among the mechanical properties

The correlation analysis was conducted for all the mechanical properties at test moisture content (50 % $\leq$ MC $\leq$ 135 %), well above fiber saturation, as well as for the visually graded parameters. All the tested pile segments had SoG <1:10, higher deviation of grain direction was not measured; hence, this parameter was not included in the correlation analysis. The density calculated at MC = 12 %

Table 4
Results of spruce and pine pile segments tested in compression parallel to the fiber in saturated conditions according to EN 408. The 5-percentile characteristic values correspond to the MC content at test time.

Category	Segment	Sample size (No.)	D (mm)		MC (%)		$f_{c,0,wet}$ (MPa)		$E_{c,0,wet}$ (MPa)		ρ_{wet} (kg/m^3)		$f_{c,0,k,wet}$ (MPa)	$\rho_{k,wet}$ (kg/m^3)
			mean	SD	mean	SD	mean	SD	mean	SD	mean	SD	x_{05}	x_{05}
spruce + pine (ND)	All	145	210	40	90	16	18.3	3.0	10300	1700	780	80	13.0	640
spruce + pine (D)	All	26	210	35	80	13	16.7	2.6	9900	1600	730	62	12.0	620
spruce + pine (DL)	All	82	210	35	80	14	16.0	3.1	9500	1700	710	63	10.2	590
spruce (DL-1)	All	6	230	30	80	12	14.8	1.3	9600	1000	690	56	11.8	560
spruce (ND)	All	64	210	38	80	16	17.2	2.6	10300	1500	740	75	12.5	600
	Head	20	260	20	80	10	18.9	2.3	11400	1300	740	75	14.5	600
	Middle	20	220	15	80	15	17.8	2.0	10500	1100	740	85	14.0	580
	Tip	24	180	15	90	20	15.4	2.0	9200	1200	760	70	11.6	630
spruce (D)	All	15	220	36	80	15	15.5	1.6	9900	1400	720	62	12.3	600
	Head	5	260	18	90	21	14.8	2.4	10400	1600	770	44	–	–
	Middle	5	230	10	80	11	16.6	1.0	10600	900	720	66	–	–
	Tip	5	180	6	80	3	15.1	0.3	8700	2800	680	51	–	–
spruce (DL)	All	53	220	37	90	15	14.6	2.0	9400	1500	690	61	10.9	580
	Head	15	260	22	90	14	15.6	1.9	10400	1500	730	65	11.9	600
	Middle	16	230	15	90	18	15.3	1.1	9600	1200	700	47	13.2	610
	Tip	22	180	18	80	13	13.4	2.1	8500	1200	670	61	9.4	550
spruce (DL-1)	All	6	230	30	80	12	14.8	1.3	9600	1000	690	56	11.8	560
	Head	2	250	24	100	10	15.0	2.0	10500	300	750	57	–	–
	Middle	2	230	3	70	3	15.2	1.2	9900	1000	680	20	–	–
	Tip	2	190	9	70	5	14.1	0.9	8500	40	640	0	–	–
pine (ND)	All	81	200	35	90	15	19.1	3.0	10200	1900	810	75	13.6	680
	Head	23	230	20	80	10	21.9	2.7	12100	1600	820	90	16.8	650
	Middle	25	200	20	90	10	19.4	2.5	10400	1300	780	80	14.8	630
	Tip	33	170	15	100	15	16.9	1.7	8700	1100	800	60	13.8	690
pine (D)	All	11	190	25	70	10	18.5	2.8	9900	2000	720	65	12.8	590
	Head	4	210	15	70	15	21.0	1.0	11600	900	740	90	–	–
	Middle	4	190	5	70	1	18.0	2.0	9700	1400	700	50	–	–
	Tip	3	160	10	80	10	15.7	2.6	7800	2100	690	40	–	–
pine (DL)	All	29	180	25	80	10	18.5	3.2	9800	1800	720	60	12.5	610
	Head	8	210	10	70	10	21.4	2.3	11200	1200	760	70	16.3	610
	Middle	8	190	15	80	10	18.9	2.1	10400	1400	750	50	14.3	640
	Tip	13	160	15	80	10	16.3	2.8	8600	1300	690	40	10.7	610

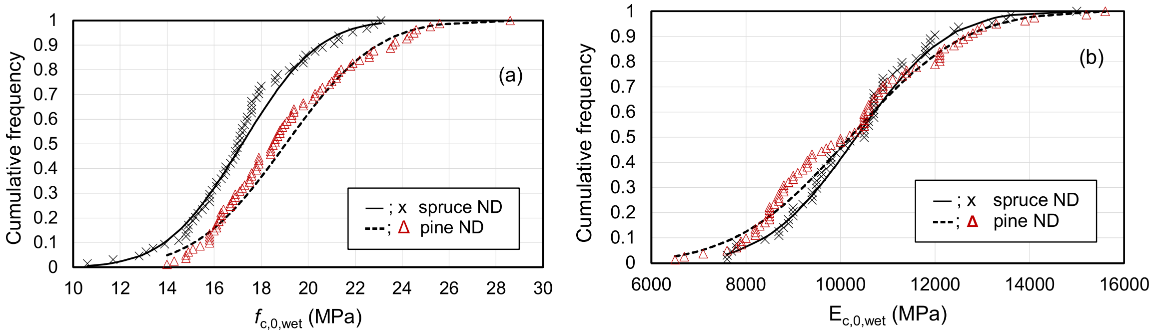

Fig. 6. Cumulative distributions of $f_{c,0,wet}$ (a) and $E_{c,0,wet}$ (b) parallel to the grain for spruce and pine pile segments ND tested according to EN 408 (2010) in wet status (MC_{mean} > 70 %). The lines show the normal distribution fitted to the data.

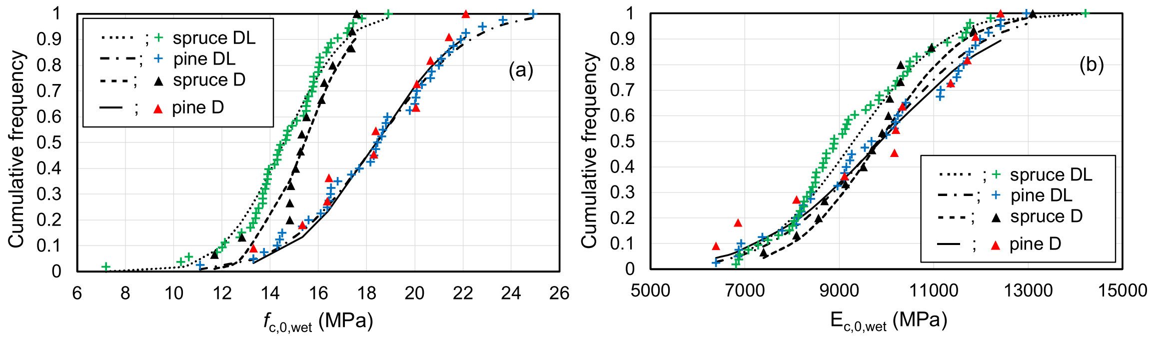

Fig. 7. Cumulative distributions of $f_{c,0,wet}$ (a) and $E_{c,0,wet}$ (b) parallel to the grain for spruce and pine pile segments DL and D tested according to EN 408 (2010) in wet status (MC_{mean} > 70 %). The lines show the normal distribution fitted to the data.

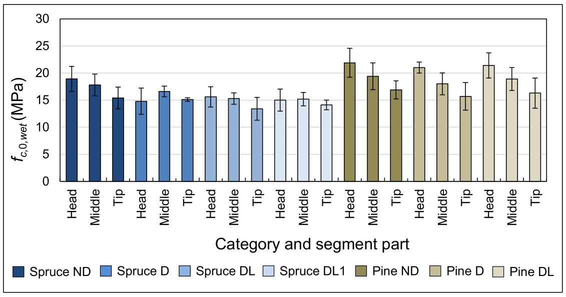

Fig. 8. Bar chart of saturated compressive strength ($f_{c,0,wet}$) of spruce and pine piles subdivided into head, middle part, and tip.

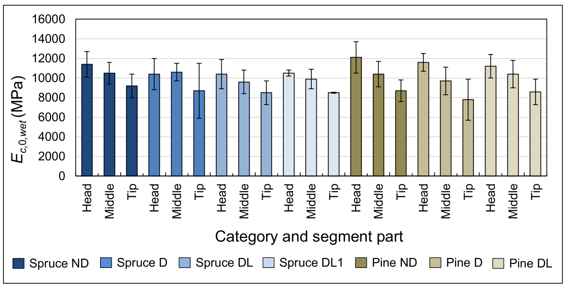

Fig. 9. Bar chart of saturated modulus of elasticity ($E_{c,0,wet}$) of spruce and pine piles subdivided into head, middle part, and tip.

Table 5
Mean and characteristic values for density according to NEN-EN 14358 (2016) adjusted to MC = 12 %.

Category	Segment	Sample size	MC = 12 %		
			ρ_{12} (kg/m^3)		$\rho_{k,12}$ (kg/m^3)
			mean	SD	x_{05}
spruce + pine (ND)	All	145	500	49	420
spruce + pine (D)	All	26	480	44	400
spruce + pine (DL)	All	82	460	47	380
spruce (ND)	All	64	500	49	410
spruce (D)	All	15	480	31	430
spruce (DL)	All	53	450	40	370
spruce (DL-1)	All	6	460	14	430
pine (ND)	All	81	500	49	420
pine (D)	All	11	490	60	380
pine (DL)	All	29	490	49	390

(ρ_{12}) was also considered, in order to have a standardized parameter for the density. The correlation matrix was presented both for spruce piles (Table 6) and for pine piles (Table 7). The density ρ_{12} had a moderate positive correlation with both $f_{c,0,wet}$ and $E_{c,0,wet}$, stronger than the wet density ρ_{wet}. Age demonstrated a clear positive correlation with the mechanical properties ($f_{c,0,wet}$, $E_{c,0,wet}$, and density), especially with $f_{c,0,wet}$. However, the knot-ratio (KR) had a strong negative correlations with the mechanical properties for spruce and pine. The same negative correlation was found between RoG and the mechanical properties, strong in the case of spruce piles and moderate for pine piles. MC and tapering of the piles exhibited in both spruce and pine a weak negative correlation with the mechanical properties. Finally, the diameter had a weak positive correlation with $f_{c,0,wet}$ and $E_{c,0,wet}$ in spruce piles, and positive moderate correlation in pine piles. In addition, the diameter exhibited a moderate negative correlation with the KR. In general, age was strongly correlated with KR and RoG in both spruce and pine, and a moderate positive correlation was observed between KR and RoG.

4.4. Relationship among strength, stiffness, and density

The wet compressive strength for all the category of tested piles was correlated with the density adjusted to MC = 12 % (ρ_{12}). A moderate correlation was found between $f_{c,0,wet}$ and ρ_{12} (Fig. 10a), as well as between $E_{c,0,wet}$ and ρ_{12} (Fig. 10b). This correlation is possibly attributed to the fact that ρ_{12} is significantly influenced by KR, age, and RoG, as discussed in the correlation analysis in Section 4.3. The relationship between $f_{c,0,wet}$ and $E_{c,0,wet}$ (Fig. 11a) exhibited a good correlation ($R^2 = 0.59$), indicating that the stiffness is a good indicator for the wet compressive strength. A very similar correlation was also found between $f_{c,0,wet}$ and $E_{c,0,wet,dyn}$ (Fig. 11b), determined through frequency response measurements. This suggests that $E_{c,0,wet}$ and $E_{c,0,dyn,wet}$ are strongly correlated, as shown in Fig. 12, with a $R^2 = 0.93$ between these two parameters. This implies that frequency response measurements can be efficiently employed to estimate the modulus of elasticity of wooden piles.

4.5. Relationship between mechanical properties and visually graded wood properties

The relationships between $f_{c,0,wet}$, $E_{c,0,wet}$, and visually graded parameters for both spruce and pine piles, are presented in Fig. 13. Moreover, the results for the visually graded parameters influencing the compressive strength and stiffness, categorized by head, middle-part, and tip for each tested pile, are shown in Table 8. The majority of the piles exhibited $0 \leq KR \leq 0.4$ (Fig. 13a). Spruce and pine tips had a $KR_{mean} > 0.2$, while middle-parts and heads had a $KR_{mean} < 0.2$ (Table 8). The trendline in Fig. 13a approaches a near-zero strength value when KR = 1 (i.e. when the pile section is completely filled with knots). This suggests that knots could be associated with zero-strength zones due to longitudinal fiber deviations. The relationship between $f_{c,0,wet}$ and age (Fig. 13c) shows that the age of all the pile segments ranged from 15 years to 100 years, with spruce piles averaging 20 years younger than pine piles. Generally, the number of annual rings (age) increased from tips to heads, with a difference of 10–15 years among each part: tip, middle-part, and head

Table 6
Correlation matrix for all spruce piles.

	$f_{c,0,wet}$	$E_{c,0,wet}$	ρ_{wet}	ρ_{12}	Age	KR	RoG	MC	Tapering	D
$f_{c,0,wet}$	1									
$E_{c,0,wet}$	0.76	1								
ρ_{wet}	0.41	0.37	1							
ρ_{12}	0.53	0.54	0.62	1						
Age	0.72	0.63	0.34	0.35	1					
KR	−0.60	−0.48	−0.24	−0.24	−0.66	1				
RoG	−0.68	−0.54	−0.28	−0.29	−0.86	0.53	1			
MC	−0.14	−0.19	0.36	−0.49	−0.02	0.02	0.00	1		
Tapering	−0.22	−0.34	0.01	0.04	−0.34	0.37	0.23	−0.05	1	
D	0.27	0.34	0.11	0.10	0.44	−0.48	−0.12	0.01	−0.26	1

Table 7
Correlation matrix for all pine piles.

	$f_{c,0,wet}$	$E_{c,0,wet}$	ρ_{wet}	ρ_{12}	Age	KR	RoG	MC	Tapering	D
$f_{c,0,wet}$ rowhead	1									
$E_{c,0,wet}$ rowhead	0.89	1								
ρ_{wet} rowhead	0.42	0.39	1							
ρ_{12} rowhead	0.64	0.70	0.70	1						
Age rowhead	0.76	0.74	0.24	0.49	1					
KR rowhead	−0.72	−0.66	−0.28	−0.46	−0.71	1				
RoG rowhead	−0.52	−0.47	−0.20	−0.32	−0.73	0.52	1			
MC rowhead	−0.24	−0.36	0.47	−0.28	−0.31	0.21	0.14	1		
Tapering rowhead	−0.31	−0.32	0.06	−0.17	−0.41	0.38	0.30	0.34	1	
D rowhead	0.46	0.46	0.06	0.29	0.64	−0.49	−0.09	−0.28	−0.32	1

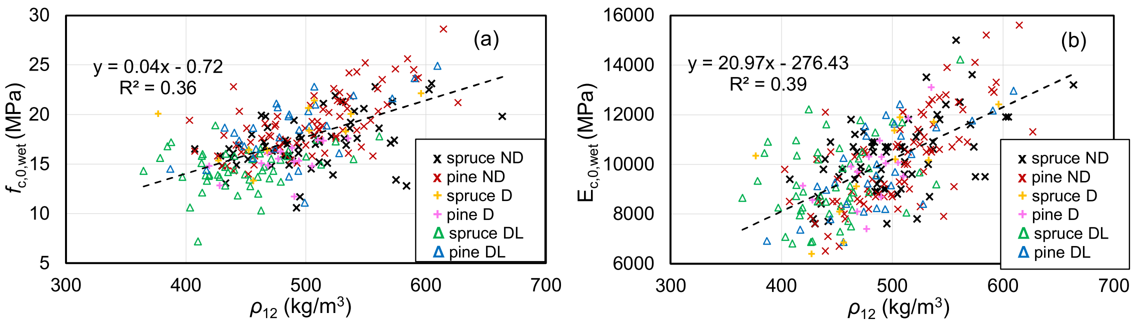

Fig. 10. Relationship between $f_{c,0,wet}$ and density ρ_{12} (a) and $E_{c,0,wet}$ and density ρ_{12} (b) for all the categories of tested pile segments.

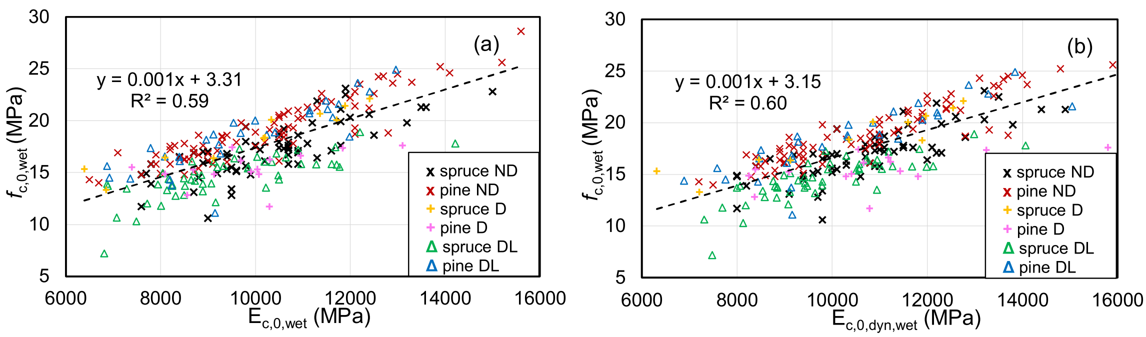

Fig. 11. Relationship between $f_{c,0,wet}$ and $E_{c,0,wet}$ (a) and $f_{c,0,wet}$ and $E_{c,0,dyn,wet}$ (b) for all the categories of tested pile segments.

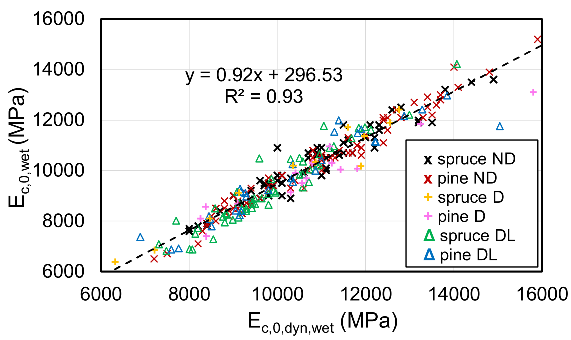

Fig. 12. Relationship between $E_{c,0,wet}$ and $E_{c,0,dyn,wet}$ for all the categories of tested pile segments.

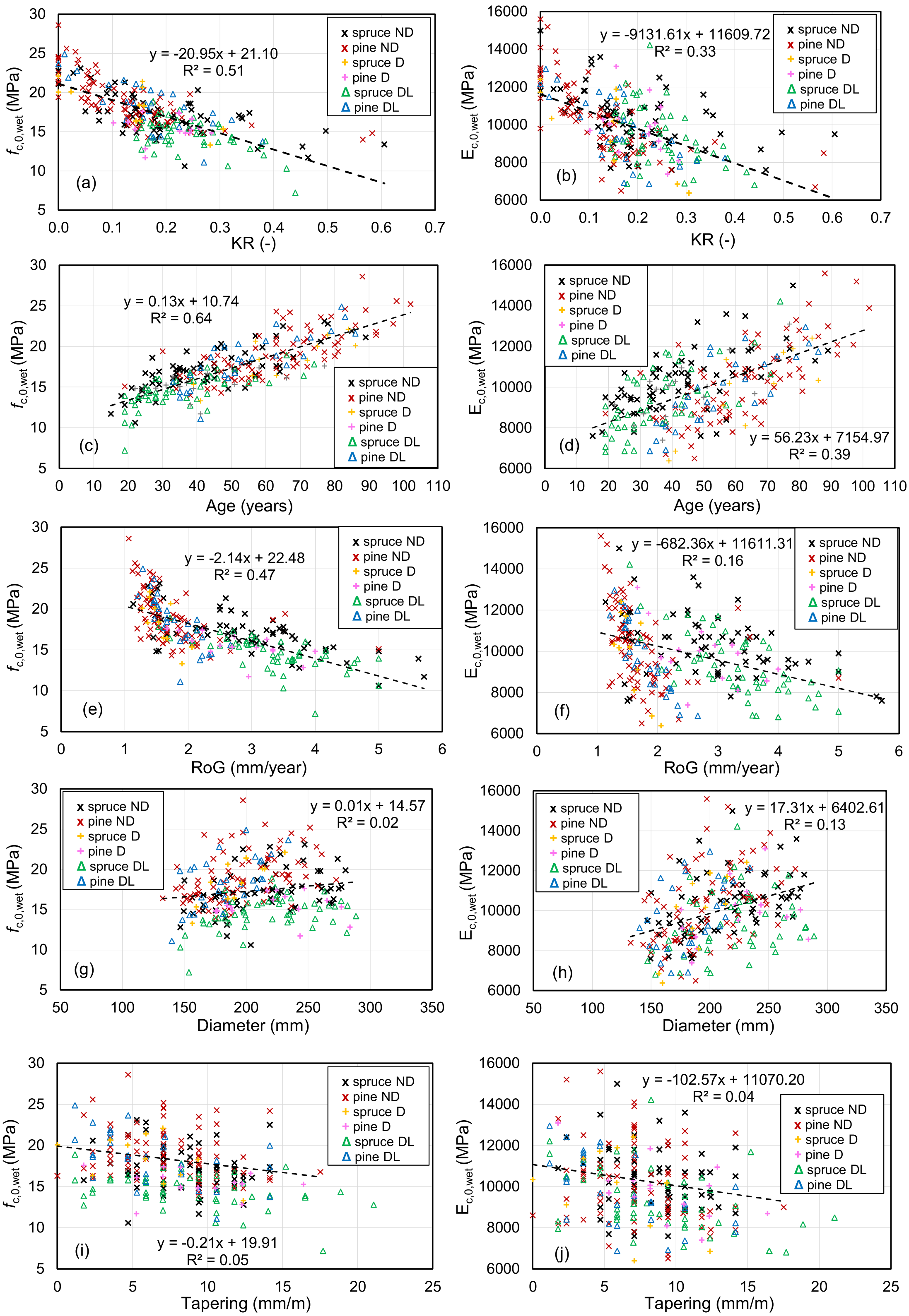

Fig. 13. Compressive strength $f_{c,0,wet}$ and modulus of elasticity $E_{c,0,wet}$ parallel to the fiber versus visually graded parameters: knot-ratio KR (a, b), annual rings (c, d), rate of growth (e, f), diameter (g, h), and tapering (i, j) of all the tested categories of spruce and pine pile segments.

Table 8
Mean $f_{c,0,wet}$ and ρ_{12} in relation to the influencing visually graded parameters determined for each category of spruce and pine piles for head, middle-part and tip.

Category	Segment	Sample size (No.)	$f_{c,0,wet}$ (MPa)		ρ_{12} (kg/m^3)		KR (−)		Age (years)		RoG (mm/year)	
			mean	SD	mean	SD	mean	SD	mean	SD	mean	SD
spruce + pine (ND)	All	145	18.3	3.0	500	49	0.16	0.12	54	20	2.2	1.0
spruce + pine (D)	All	26	16.7	2.6	480	44	0.25	0.12	52	18	2.3	0.8
spruce + pine (DL)	All	82	16.0	3.1	460	47	0.22	0.09	43	17	2.8	1.0
spruce (DL-1)	All	6	14.8	1.3	460	14	0.22	0.08	44	17	2.9	1.0
spruce (ND)	All	64	17.2	2.6	500	49	0.19	0.12	43	17	2.9	1.1
	Head	20	18.9	2.3	520	54	0.12	0.07	57	17	2.5	0.8
	Middle	20	17.8	2.0	500	39	0.16	0.07	43	13	2.8	1.0
	Tip	24	15.4	2.0	490	52	0.28	0.12	32	12	3.2	1.2
spruce (D)	All	15	15.5	1.6	480	31	0.20	0.06	43	15	2.8	0.7
	Head	5	14.8	2.4	480	39	0.14	0.02	55	17	2.6	0.8
	Middle	5	16.6	1.0	490	22	0.21	0.05	44	10	2.7	0.6
	Tip	5	15.1	0.3	470	32	0.25	0.02	31	7	3.1	0.7
spruce (DL)	All	53	14.6	2.0	450	40	0.25	0.08	36	14	3.3	0.8
	Head	15	15.6	1.9	470	47	0.19	0.04	51	11	2.7	0.6
	Middle	16	15.3	1.1	440	36	0.23	0.04	36	7	3.3	0.7
	Tip	22	13.4	2.1	440	34	0.31	0.07	26	7	3.8	0.7
spruce (DL-1)	All	6	14.8	1.3	460	14	0.22	0.09	44	17	2.9	1.0
	Head	2	15.0	2.0	460	12	0.16	0.01	56	22	2.6	1.2
	Middle	2	15.2	1.2	470	8	0.17	0.00	44	18	2.9	1.2
	Tip	2	14.1	0.9	440	13	0.34	0.03	34	15	3.2	1.3
pine (ND)	All	81	19.1	3.0	500	49	0.13	0.11	62	17	1.7	0.6
	Head	23	21.9	2.7	540	47	0.05	0.05	80	13	1.5	0.5
	Middle	25	19.4	2.5	500	43	0.10	0.06	64	11	1.7	0.5
	Tip	33	16.9	1.7	480	38	0.20	0.11	48	10	1.9	0.7
pine (D)	All	11	18.5	2.8	490	60	0.14	0.10	64	16	1.6	0.2
	Head	4	21.0	1.0	500	93	0.04	0.07	81	5	1.4	0.1
	Middle	4	18.0	2.0	490	36	0.15	0.01	62	7	1.6	0.2
	Tip	3	15.7	2.6	460	38	0.25	0.08	46	10	1.8	0.3
pine (DL)	All	29	18.5	3.2	490	49	0.17	0.09	55	16	1.8	0.4
	Head	8	21.4	2.3	530	52	0.09	0.07	76	7	1.4	0.1
	Middle	8	18.9	2.1	480	33	0.16	0.08	56	6	1.7	0.2
	Tip	13	16.3	2.8	460	35	0.22	0.07	41	6	2.1	0.3

(Table 8). Pine piles showed a consistently low RoG (ranging from 1 mm/year to 2.5 mm/year), while spruce pile segments showed a wider range from 1 mm/year to nearly 6 mm/year (Table 8). Fig. 13e highlights variations of roughly 10 MPa in $f_{c,0,wet}$ for similar RoG values, particularly for spruce and pine heads with RoG = 1.5. A very low correlation was observed between $f_{c,0,wet}$, $E_{c,0,wet}$, and the diameter (Fig. 13g; Fig. 13h), confirming that the diameter is not an influencing parameter for the wet compressive strength and stiffness of spruce and pine piles. Finally, the tapering of the pile segments showed almost no correlation with the mechanical properties (Fig. 13i; Fig. 13j). For almost all the segments, the taper was less than 15 mm/m, which corresponds to the maximum taper for wooden foundation piles according to prEN 1995-1-1/NB:2023.

5. Discussion

5.1. Influencing parameters on the compressive strength of the piles

The density (ρ_{12}), age, KR, and RoG were identified as the parameters having a significant influence on the wet compressive strength of the piles, as presented in Section 4.3. Age was positively correlated with ρ_{12}, with an age difference of 10–15 years was measured among heads, middle-parts, and tips (see Table 8). Older segments, such as heads, were characterized by a higher portion of mature wood in their cross section, correspondent to higher densities [39]. In contrast, younger segments, such as tips, had a higher portion of juvenile wood, characterized by a lower density than mature wood [40]. KR was negatively correlated with ρ_{12}, since higher KR values were mainly found in spruce and pine tips, which had lower density than middle-parts and heads, which were instead associated with lower KR values. However, the density of a pile could increase with a large presence and size of knots, as the density of a knot is roughly twice that of a knot-free area [41,42]. For example, between two piles with the same ratio of mature to juvenile wood and the same RoG, the one with a larger amount and size of knots could have higher density. RoG was also negatively correlated with ρ_{12}, since faster-growing trees exhibited higher RoG values associate with lower densities [43]. This relationship among ρ_{12}, age, and KR can be observed in Table 8. Both spruce and pine ND had equal mean density ($\rho_{12,mean}$), but pine piles ND had a 30 % lower KR_{mean} and were, on average, 20 years older than spruce ND, resulting in a RoG_{mean} approximately half that of spruce ND. This contributed to a scatter of 2 MPa between $f_{c,0,mean,wet}$ of pine ND and spruce ND. This scatter increased to 3 MPa in the heads, where pine heads ND were characterized by very low KR_{mean} = 0.05 and RoG_{mean} = 1.5 mm/year. Spruce exhibited a larger presence of knots compared to pine, especially in the heads and middle-parts. This is because the crown of pine trees develops mainly on the upper part, resulting in fewer and smaller branches on the lower part of the tree. In contrast, the crown of spruce trees begins already from the base of the trunk, leading to a greater number of knots throughout the log.

5.2. Effect of pile driving and in-situ loading on the mechanical properties

The group of piles DL was loaded in situ until a settlement of 10 % of the diameter of the pile head was reached, in accordance with NEN 9997–1+C2:2017. Pile driving was performed in situ under saturated soil conditions on spruce and pine piles D and DL. Although the data regarding the forces used for the pile insertion was not available, the pile driving was carried out according to the guidelines in Refs. [15,25], ensuring that the maximum stress during driving did not exceed 0.8 times the characteristic compressive strength of the piles. It is important to mention that after driving a pile, residual loads could develop in the pile after the driving force is removed [37,38]. Residual compressive stresses may be present, especially at the pile base, and balanced by the negative skin friction along the shaft. These residual stresses were not considered during in-situ preloading, and were therefore neglected during stress measurement on the pile. In addition, the confining pressure applied to the timber pile shaft was neglected, since the modulus of elasticity perpendicular to the grain of the pile is 30 times smaller than that parallel to the grain ($E_{c,90} = 1/30\ E_{c,0}$) as outlined in EN 338 (2016). The effects of the soil environment were not specifically studied in this research. Thus, possible minimal residual loads could have occurred in the pile.

The maximum stress on the pile head during the in-situ loading was recorded as 6.9 MPa for category DL. Although this value was associated with the failure with respect to the soil settlement rather than material failure, the measured stresses remained below the maximum design strength for short-term loading ($f_{c,0,d,short} = 11.5$ MPa) specified in NEN-EN 1995-1-1/NB:2013 [12]. For two of these piles (DL-1), the maximum stress on the head reached 4.5 MPa, after which 80 % of this stress (approximately 3.6 MPa) was maintained for 22 days. This constant load applied to DL-1 represented a possible real service condition of the piles, with stresses below the maximum design strength for long-term loading ($f_{c,0,d,long} = 9.8$ MPa) provided in NEN-EN 1995-1-1/NB:2013 [12]. Based on the average wet compressive strength determined for spruce and pine heads ND (see Table 4), the stress applied in situ was approximately one-third of the maximum wet compressive strength.

The middle-parts and tips of spruce D and ND had comparable mean density ($\rho_{12,mean}$), KR_{mean}, mean age, and RoG_{mean} (see Table 8), with no significant differences in $f_{c,0,wet,mean}$ among the pile segments, partly due to the limited number of spruce segments D. However, spruce heads D exhibited roughly 20 % lower $f_{c,0,wet,mean}$ than spruce pile heads ND. This difference could be attributed to the lower $\rho_{12,mean}$ of spruce heads D, although no significant differences in terms of KR, age, and RoG were observed in Table 8.

The spruce piles DL, which were loaded in-situ, exhibited lower $f_{c,0,wet,mean}$ than spruce D, possibly related to lower values of $\rho_{12,mean}$, especially in the middle-parts and tips. All the spruce segments DL were characterized by higher KRs than spruce D, and lower age, indicating a greater proportion of juvenile wood [40], with RoG_{mean} reaching up to 3.8 mm/year in the tips. Hence, the lower $f_{c,0,wet,mean}$ of spruce piles DL compared to spruce D could be attributed to a lower quality of the piles, suggesting that the in situ load applied to the piles did not significantly influence their wet compressive strength. Finally, the effect of the loading for 22 days on spruce DL-1 had no significant influence on $f_{c,0,wet,mean}$ of the piles, consistent with the results from spruce DL and D.

Among all the groups of segments of pine piles ND, D, and DL, no significant differences in $f_{c,0,wet,mean}$ were measured. In particular, no effect of pile driving was observed in $f_{c,0,wet,mean}$ among pine heads D/DL and ND. The quality of all pine heads (ND, D, and DL) was higher compared to spruce heads, with maximum KR values below 0.09, mean age of 80 years, and $RoG_{mean} = 1.4$ mm/year, despite variations in $\rho_{12,mean}$ were measured (see Table 8). Therefore, neither pile driving nor in situ loading had a significant effect on the wet mean compressive strength of the piles. Instead, the wet compressive strength was governed by density, KR, specimen age, and the rate of growth, as outlined in Refs. [22,40,43].

5.3. Comparison of the mechanical properties with data available from the literature

The influence of KR on $f_{c,0,wet}$ of all the specimens investigated in this paper was compared with the study by Van de Kuilen [14]. This comparison was based on KR values and the wet compressive strength of 57 spruce, 20 larch, and 18 Douglas fir saturated piles reported in Ref. [16], with $MC_{mean} = 100$ % (SD = 30 %). Fig. 14a shows the correlation between $f_{c,0,wet}$ and KR for all the spruce and pine segments ND, D, and DL, along with the superimposed results from Ref. [14]. In Ref. [14], a very weak correlation ($R^2 = 0.06$) was found between $f_{c,0,wet}$ and KR. The values of $f_{c,0,wet}$ in Ref. [14] ranged from 16 MPa to 29 MPa, with KR values distributed between 0.2 and 0.5. However, no data regarding age and/or RoG was provided, and the testing procedures adopted in Ref. [16] were not reported. The larch and Douglas fir piles studied in Ref. [14] exhibited, on average, $f_{c,0,wet}$ values 2 MPa higher than those of spruce piles for the same range of KR. The piles in Ref. [14] had an average diameter of 140 mm (SD = 10 mm), comparable to the tip segments of spruce and pine ND, D, and DL. However, for similar KR values and diameters, the piles in Ref. [14] delivered $f_{c,0,mean,wet} = 20$ MPa (SD = 2.2 MPa), corresponding to a $f_{c,0,k,wet} = 16.3$ MPa. In comparison, the spruce and pine tips ND, D, and DL delivered $f_{c,0,mean,wet} = 15.5$ MPa (SD = 1.9 MPa) and $f_{c,0,k,wet} = 11.7$ MPa. The differences in mean and characteristic wet compressive strength could be attributed to the higher quality of the piles studied in Ref. [14], which may have included older specimens with lower values of RoG, even for small diameters. This would lead to higher $f_{c,0,wet}$ values compared to spruce and pine tips ND, D, and DL. However, this assumption cannot be validated, since no data on the age and the RoG of the piles was available in Ref. [14]. Finally, it should be noted that the very weak correlation between $f_{c,0,wet}$ and KR in Ref. [14] could be attributed to the limited spread of KR values (mainly between 0.2 and 0.5), which limits the potential to establish a stronger correlation between wet compressive strength and KR.

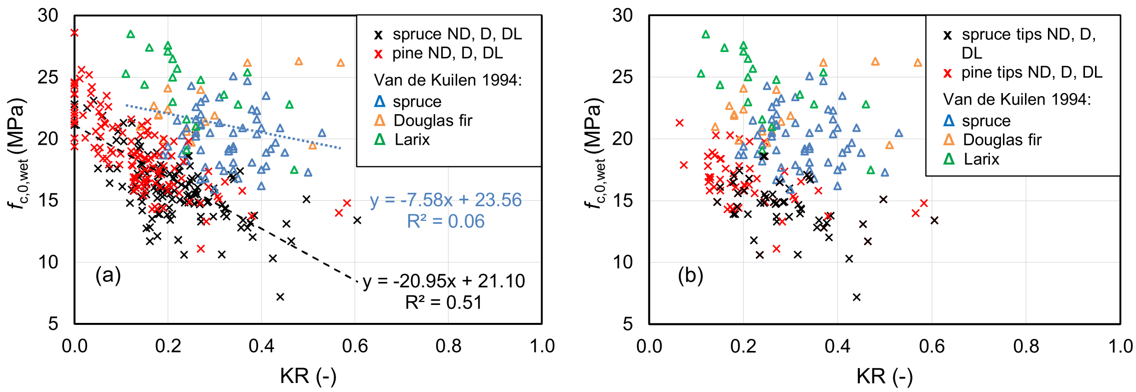

Fig. 14. Relationships between $f_{c,0,wet}$ and KR of (a) spruce and pine piles (ND, D, and DL) and spruce, larch and Douglas fir piles [14]; (b) spruce and pine tips (ND, D, and DL) and spruce, larch, and Douglas fir piles [14].

6. Analysis

6.1. Regression models for spruce piles

Two regression models were constructed for all spruce pile segments. Model S1 included knot ratio (KR) and rate of growth (RoG) as visual independent variables, and calculated density (ρ_{12}) at MC = 12 % (Table 9). The regression analysis for Model S1 resulted in the multiple regression Equation (6) for the predicted wet compressive strength ($f_{c,0,wet,pred}$). Model S1 presented a F-value = 76.1 (n = 132), a multiple coefficient of determination (adjusted R^2) of 0.63 and a standard error of 1.56.

$$f_{c,0,wet,pred} = 12.972 + 0.017\ \rho_{12} - 1.143\ \text{RoG} - 7.735\ \text{KR} \tag{6}$$

Model S2 considered only visually graded independent variables: KR, RoG, and annual rings (AR) listed in Table 10. For spruce piles, diameter, tapering, and MC were not included as relevant parameters (p-value >0.05). The prediction equation (7) represents $f_{c,0,wet,pred}$ for Model S2. Model S2 presented a F-value = 54.4 (n = 132), a multiple coefficient of determination (adjusted R^2) of 0.55 and a standard error of 1.73.

$$f_{c,0,wet,pred} = 17.429 + 0.052\ \text{AR} - 6.516\ \text{KR} - 0.718\ \text{RoG} \tag{7}$$

Figs. 15 and 16 show the relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$, the normal probability plot and the residuals for Model S1 and S2, respectively. All multipliers in Model S1 and S2 were significant and the residuals had relatively equal variances.

6.2. Regression models for pine piles

Similarly to spruce piles, two regression models were constructed for pine pile segments. Model P1 included knot ratio KR and annual rings (AR) as visual independent variables and density (ρ_{12}) at MC = 12 % (Table 11). The regression analysis for Model P1 resulted in the multiple regression Equation (8) for predicted wet compressive strength ($f_{c,0,wet,pred}$). Model P1 presented a F-value = 97.7 (n = 121), a multiple coefficient of determination (adjusted R^2) of 0.71 and a standard error of 1.65.

$$f_{c,0,wet,pred} = 6.318 + 0.019\ \rho_{12} + 0.072\ \text{AR} - 8.742\ \text{KR} \tag{8}$$

On the other hand, Model P2 was based on visually graded independent variables (KR and AR) listed in Table 12. Differently from spruce piles, where RoG was taken as independent variable for the regression, RoG of pine piles was not significant for $\alpha = 0.05$. Thus, RoG, diameter, tapering, and MC of pine piles were not included as relevant parameters (p-value >0.05) for the Model P2. The prediction Equation (9) represents $f_{c,0,wet,pred}$ for Model P2. Model P2 presented a F-value = 107.6 (n = 121), a multiple coefficient of determination (adjusted R^2) of 0.64 and a standard error of 1.83.

$$f_{c,0,wet,pred} = 14.862 + 0.09\ \text{AR} - 10.792\ \text{KR} \tag{9}$$

Table 9
Multipliers and statistical parameters for 95 % confidence interval in regression Model S1 for spruce.

Variables	Coefficients	Standard Error	t-stat	p-value	Lower 95 %	Upper 95 %
Intercept	12.972	1.565	8.291	1.33E-13	9.876	16.068
KR	−7.735	1.634	−4.734	5.74E-06	−10.968	−4.502
RoG	−1.143	0.172	−6.654	7.51E-10	−1.483	−0.803
ρ_{12}	0.017	0.003	6.003	1.86E-08	0.011	0.023

Table 10
Multipliers and statistical parameters for 95 % confidence interval in regression Model S2 for spruce.

Variables	Coefficients	Standard Error	t-stat	p-value	Lower 95 %	Upper 95 %
Intercept	17.429	1.906	9.143	1.19E-15	13.657	21.201
Annual rings	0.052	0.021	2.459	1.53E-02	0.010	0.094
KR	−6.516	2.029	−3.211	1.67E-03	−10.531	−2.501
RoG	−0.718	0.315	−2.282	2.42E-02	−1.340	−0.095

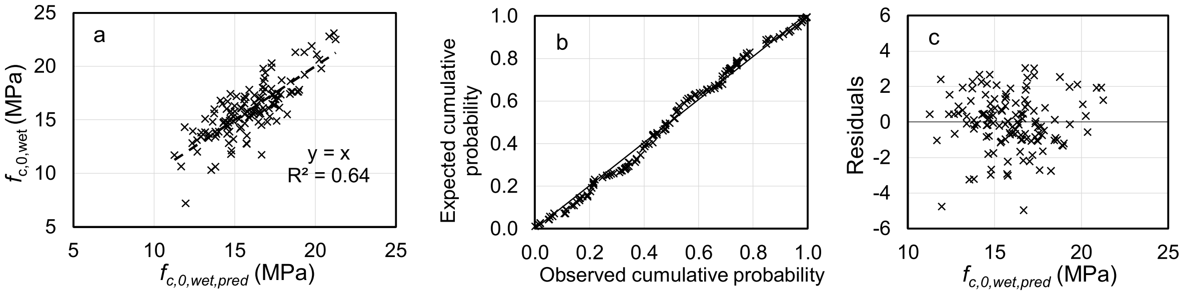

Fig. 15. Regression model S1 with relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ (a), normal probability plot (b) and residuals (c).

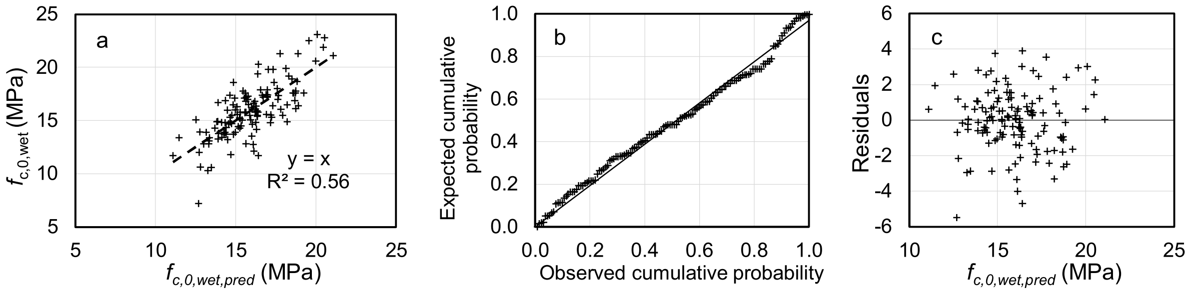

Fig. 16. Regression model S2 with relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ (a), normal probability plot (b) and residuals (c).

Table 11
Multipliers and statistical parameters for 95 % confidence interval in regression Model P1 for pine.

Variables	Coefficients	Standard Error	t-stat	p-value	Lower 95 %	Upper 95 %
Intercept	6.318	1.894	3.336	1.14E-03	2.568	10.068
Annual rings	0.072	0.013	5.538	1.91E-07	0.047	0.098
KR	−8.742	2.126	−4.113	7.30E-05	−12.952	−4.532
ρ_{12}	0.019	0.004	5.316	5.15E-07	0.012	0.026

Table 12
Multipliers and statistical parameters for 95 % confidence interval in regression Model P2 for pine.

Variables	Coefficients	Standard Error	t-stat	p-value	Lower 95 %	Upper 95 %
Intercept	14.862	1.111	13.379	2.10E-25	12.662	17.062
Annual rings	0.090	0.014	6.460	2.44E-09	0.063	0.118
KR	−10.792	2.319	−4.653	8.63E-06	−15.385	−6.199

Figs. 17 and 18 show the relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$, the normal probability plot and the residuals for Model P1 and P2, respectively. All multipliers in Model P1 and P2 were significant and the residuals had relatively equal variances.

6.3. *Regression model for spruce and pine: model S + P*

The regression models S1 and P1 revealed a higher correlation ($R^2 = 0.64$ and $R^2 = 0.71$, respectively) compared to the models that included only visually graded parameters (S2 and P2). Fig. 19 shows the comparison between Model S1 and P1, where spruce piles are

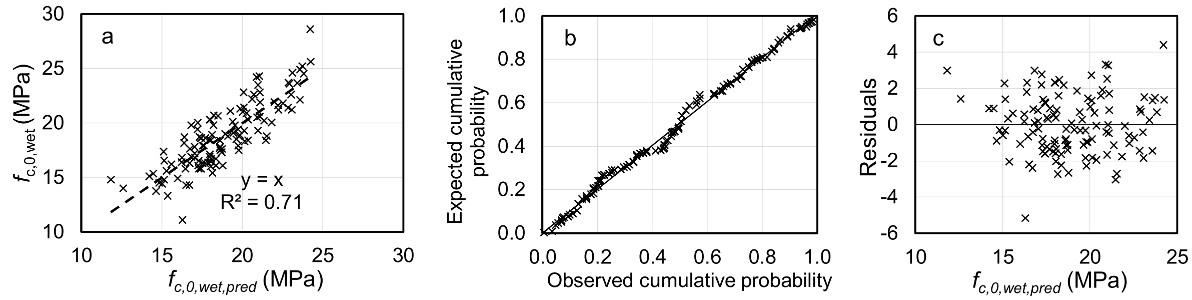

Fig. 17. Regression model P1 with relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ (a), normal probability plot (b) and residuals (c).

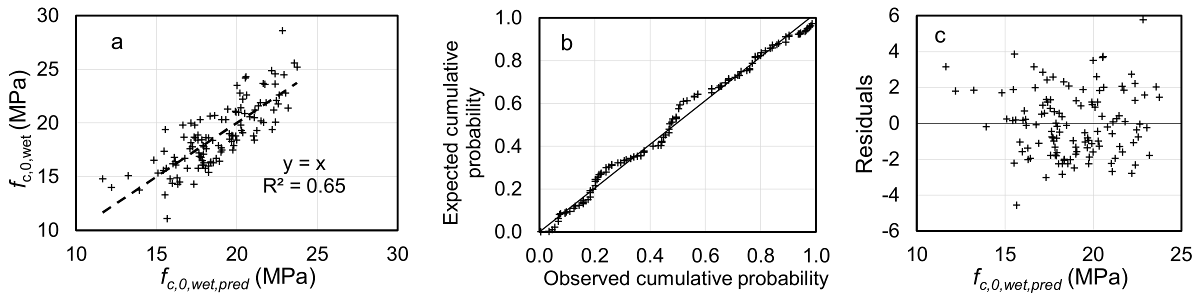

Fig. 18. Regression model P2 with relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ (a), normal probability plot (b) and residuals (c).

more distributed in the lower part of the graph, since they exhibited lower values of wet compressive strength compared to pine. However, the two models are well correlated to each other. Hence, a regression model (Model S + P) for both spruce and pine was constructed, based on the variables listed in Table 13. The regression analysis for Model S + P (Fig. 20) resulted in the multiple regression Equation (10) for the predicted wet compressive strength ($f_{c,0,wet,pred}$) based on ρ_{12}, annual rings (AR) and KR. Model S + P presented a F-value = 232.9 (n = 253), a multiple coefficient of determination (adjusted R^2) of 0.73 and a standard error of 1.63. All multipliers were significant and the residuals had relatively equal variances.

$$f_{c,0,wet,pred} = 6.206 + 0.017\,\rho_{12} + 0.081\,AR - 7.248\,KR \tag{10}$$

6.4. Comparison with the correlations in the literature

Fig. 21 illustrates the relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ obtained with Model S + P, for all the spruce and pine pile segments (ND, D, and DL), with the regression model predictions ($f_{c,0,wet,pred}$) from Boren [22] superimposed. $f_{c,0,wet,pred}$ determined with the regression model in Ref. [22] underestimated the wet compressive strength of the piles, particularly when the ratio between MC and age (a) exceeded 1.5 (See Eq. (1)). The ratio (MC/a) was observed to be above 1.5 primarily in young spruce heads, middle-parts, and tips, as well as in pine tips. This discrepancy can be attributed to the generally younger age of the spruce piles

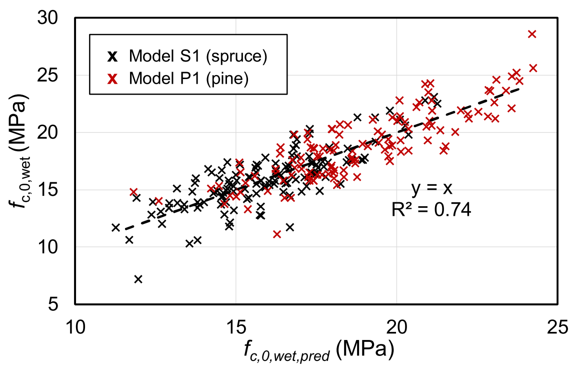

Fig. 19. Comparison between Model S2 and Model P2 for spruce and pine piles.

Table 13
Multipliers and statistical parameters for 95 % confidence interval in regression Model S + P for spruce and pine.

Variables	Coefficients	Standard Error	t-stat	p-value	Lower 95 %	Upper 95 %
Intercept	6.206	1.187	5.230	3.60E-07	3.869	8.544
Annual rings	0.081	0.008	9.868	1.34E-19	0.065	0.097
KR	−7.248	1.404	−5.161	5.03E-07	−10.014	−4.482
ρ_{12}	0.017	0.002	7.593	6.28E-13	0.013	0.022

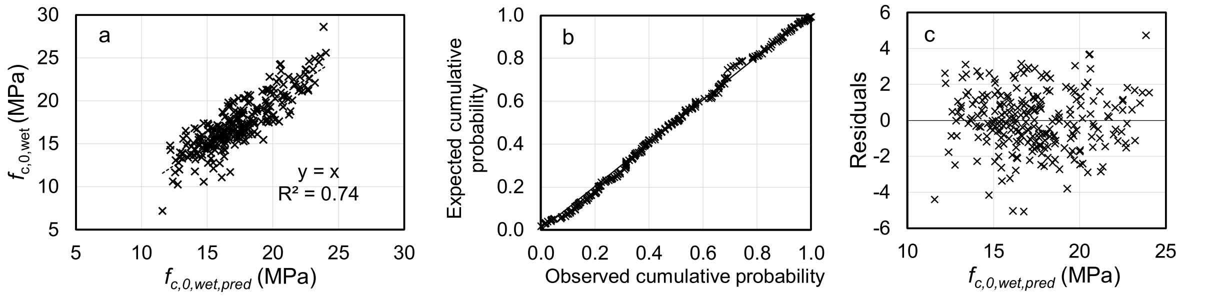

Fig. 20. Regression model S + P with relationship between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ and comparison with Model S1 and Model P1 (a), normal probability plot (b), and residuals (c).

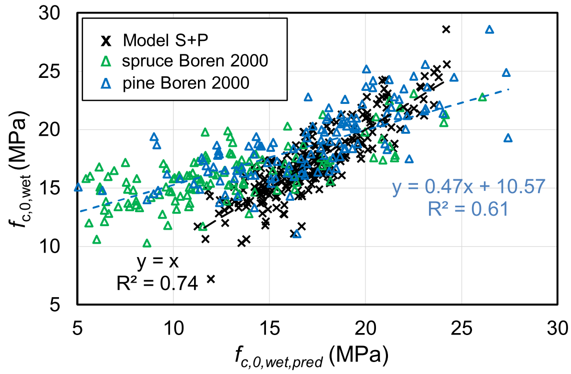

Fig. 21. Comparison between $f_{c,0,wet}$ and $f_{c,0,wet,pred}$ for all spruce and pine segments ND, D, and DL determined with Model S + P, and with the regression model for spruce and pine developed in Boren [22].

compared to the pine piles. The multiple regression model developed in Ref. [22] for spruce and pine piles cannot be directly applied to the datasets investigated in this study. This limitation is related to the fact that the model in Ref. [22] was based on dry specimens with MC_{mean} = 16.3 % (SD = 2.5 %) for spruce and MC_{mean} = 16.4 % (SD = 3.4 %) for pine. Moreover, the piles in Ref. [22] were about 20 years old and had an average diameter of approximately 110 mm–20 years younger and with diameters 100 mm smaller than the spruce and pine piles (ND, D, and DL) analysed in this study. These distinctions emphasize the unique focus of this study on the mechanical characterization of saturated wooden piles (with diameters up to 280 mm) and highlight the need for specific regression models for the wet compressive strength. These models have to incorporate key influencing parameters, such as density, knot ratio (KR), age, and rate of growth (RoG), as identified in this study. Both this work and the research in Ref. [22] found strong correlations (R) between compressive strength values and visually graded parameters (KR, RoG, and age). Moderate correlations between compressive strength and density ρ_{12} were also observed (see Table 6, and Table 7). In addition, the weak correlation between the compressive strength and the pile diameter in Ref. [22] aligns with the findings for the ND, D, and DL pile categories.

7. Conclusions

The conducted work characterized the mechanical properties of 38 spruce and 32 pine full-sized tapered piles, each averaging 12 m in length, tested in accordance with the draft of the new Eurocode 5 (prEN 1995-1-1/NB:2023). The mechanical properties were investigated in saturated conditions (MC_{mean} = 70 % ± 20 %), by performing axial compression tests on pile segments extracted from head, middle-part, and tip of each full-length pile. This approach allowed for the investigation of different pile diameters, ranging from 130 mm to 280 mm. The wooden piles were subdivided into three categories: piles never driven into the soil (ND); piles driven into the soil (D); and piles driven into the soil and subjected to in-situ loading, with a maximum stress of 6.9 MPa recorded at the pile head (DL). The mechanical properties determined in this study were analysed in relation to timber quality variables that could potentially influence the wet compressive strength.

The conclusions drawn from this experimental study can be summarized as follows:

- Characteristic wet values for compressive strength and modulus of elasticity of spruce and pine piles are reported in Table 14, for piles with a knot ratio (KR) < 0.5, age between 20 and 100 years, and rate of growth (RoG) below 5 mm/year. Good correlations were observed between wet compressive strength and these visually determined parameters, suggesting potential for grading into multiple strength classes, a promising topic for future research. The data in this paper was derived from an extensive experimental campaign involving 253 pile segments and are applicable to the entire pile or specific sections: head, middle-part, and tip. Moreover, the wet strength and stiffness values can be used for spruce and pine separately or for both species combined. The saturated compressive strength values and grading boundaries presented in this study contribute to the engineering design of timber piles and support the integration of reliable design values into future versions of Eurocode 5.
- The wet characteristic compressive strength values of spruce piles in Table 14 were lower than the $f_{c,0,k,wet} = 16.3$ MPa determined in the literature [14] for saturated spruce piles. This underscores the need to expand the limited database currently available, which is constrained by small sample sizes and limited grading parameters. This study contributes significantly to addressing this gap by enlarging the database for the saturated compressive strength of spruce and pine piles. Additionally, the strength properties were characterized along the length of the pile, revealing variations in saturated compressive strength that are relevant for design practices and grading criteria.
- The age of timber and its relation with the diameter (measured through the rate of growth) had a significant influence on the wet compressive strength. Older timber with lower RoG typically has a higher proportion of mature wood in the cross section, resulting in higher wet compressive strength values. For instance, pine specimens, which were on average 20 years older than spruce specimens, exhibited a mean RoG of 1.7 mm/year, compared to 2.9 mm/year for spruce. This trend was also observed across different pile sections (heads, middle parts, and tips), where the age gradually decreased, and the RoG increased. Consequently, the wet compressive strength decreased from heads to tips, with tips showing an average of 20 % lower strength than heads for both spruce and pine.
- The origin of wood affects the knot-ratio, with consequent influence on the wet compressive strength. In particular, pine pile heads were characterized by a very low $KR_{mean} = 0.05$, due to the crown's natural growth pattern, which develops mainly in the upper part of the log. In contrast, spruce trees, where the crown already starts closer to the bottom part of the log, exhibited higher KR values in their heads. This difference can be observed in Table 14, where spruce heads and middle-parts had no significant variations in the characteristic wet compressive strength ($f_{c,0,k,wet}$). Conversely, pine piles had a significant difference in strength between heads and middle-parts. For both species, KR increased progressively from heads to tips due to the tapering of the pile and the increased presence of knots, reducing the difference in KR values between spruce and pine in the tips.
- The effect of pile driving (piles D) and in-situ loading (piles DL), which subjected the pile heads to stress levels up to 6.9 MPa, had no significant influence on the mechanical properties of spruce and pine piles. The variations in the wet compressive strength across all pile categories (ND, D, and DL, as shown in Section 4.1), were attributed to differences in KR, age, and RoG in the respective pile sections (heads, middle-parts, and tips, as shown in Table 8). It should be noted that the effects of the soil environment were not taken into account in this study, since the research focused on the mechanical properties of spruce and pile piles.
- Two regression models were developed to predict wet compressive strength for spruce and pine piles, respectively. These models are based on density (ρ_{12}) and visually graded parameters such as KR, RoG, and age. The models can be used for both visual and machine grading for each wood species.

Table 14
Characteristic wet compressive strength and modulus of elasticity determined in accordance with NEN-EN 14358 (2016) along spruce and pine foundation piles.

Wood species (All categories - no distinction)	Segment	Sample size (No.)	$E_{c,0,k,wet}$ (MPa)	$f_{c,0,k,wet}$ (MPa)
			mean	x_{05}
spruce + pine	All	253	10000	11.7
	Head	75	11300	13.0
	Middle	78	10200	13.4
	Tip	100	8700	11.3
spruce	All	132	9800	11.3
	Head	40	10800	12.0
	Middle	41	10100	13.1
	Tip	51	8800	10.6
pine	All	121	10000	13.4
	Head	35	11800	17.1
	Middle	37	10300	14.8
	Tip	49	8600	12.9

- When softwood foundation piles are utilized in water-saturated conditions, their durability can be compromised over time due to biological decay, which may lead to a gradual reduction in their compressive strength and stiffness. This issue has been addressed in the literature [1–10] and it is crucial to consider in the design of timber piles.

CRediT authorship contribution statement

Giorgio Pagella: Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Geert Ravenshorst:** Visualization, Validation, Project administration, Funding acquisition. **Wolfgang Gard:** Project administration, Funding acquisition. **Jan-Willem van de Kuilen:** Supervision, Resources, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Delft university reports financial support and equipment, drugs, or supplies were provided by municipality of amsterdam.

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Data availability

Data will be made available on request.

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