COST ACTION E24

Final Report

Of

Short Scientific Mission

By

A.J.M. Leijten - TU-DELFT
J. Köhler - ETH

JUNE 2004

Evaluation of Embedment Strength Data for Reliability Analyses of connections with dowel type fasteners

1 Aim

In the European design standard, Eurocode 5 (EN1995-1-1) the Johansen model is presented to predict the strength of connections with dowel-type fasteners. This model contains besides a number of geometrical parameters two material parameters; the embedment strength of the timber and the yield moment of the fastener. This study focuses on the main influencing independent parameters of the embedment strength being; the timber density and diameter of the fastener. The embedment strength expressions in Eurocode 5 are based on a comprehensive study by Whale and Smith (1986b) and Ehlbeck and Werner (1992). The influence of the timber density and the fastener diameter was derived using regression analyses. Expressions for the lower 5%-Fractile were assumed to be the same as for the mean. This was achieved by simply exchanging in the regression formula the mean density by the lower 5%-Fractile of the density.
In the present study embedment test results from the above-mentioned research and test data from later investigations are considered to assess the lower 5%-Fractile based on probabilistic evaluation. This information can be used to be incorporated in model design codes and to feed probabilistic design models of timber connections.

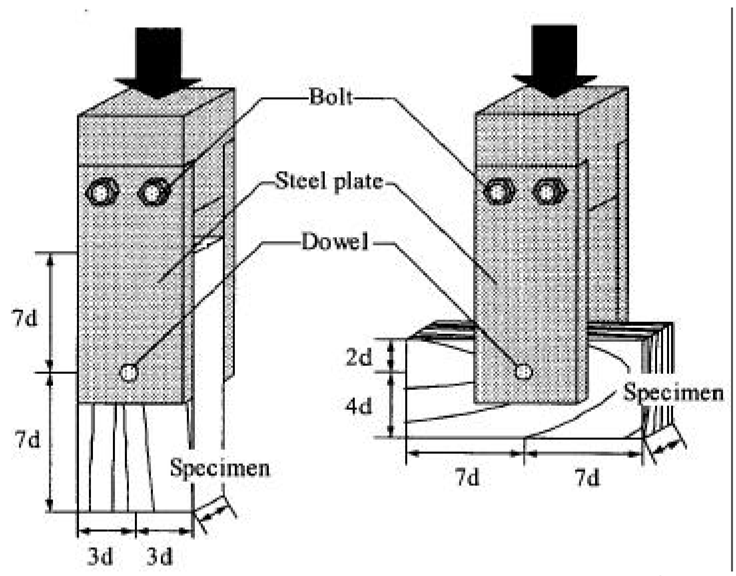


Figure 1: Embedment test according to EN 383 taken from Sawata and Yasumura (2002)

2 Parallel and perpendicular to grain embedment test results

Although in the past many embedment tests have been reported. For the purpose of this study only results are evaluated that follow the procedure and definition of the embedment strength laid down in EN 383. The standardised test set-up for parallel to grain tests as well as perpendicular to grain is given in Figure 1. This standard defines the embedment strength as the highest embedment stress within 5mm displacement for both parallel and perpendicular to grain tests. For the parallel to grain test the maximum load is usually reached within 2 or 3 mm displacement and the load-displacement curves show a typical linear and full plastic branch. The fibres directly underneath the dowel buckle locally. For the perpendicular to grain test the physical failure mechanism is completely different. The fibres are loaded perpendicular to the grain and due a chord or cable effect of the fibres a hardening branch appears in the load displacement diagram, Figure 2. The hardening is dependent of the diameter of the fastener. After some initial testing Whale and Smith (1986b) defined the embedment strength for both

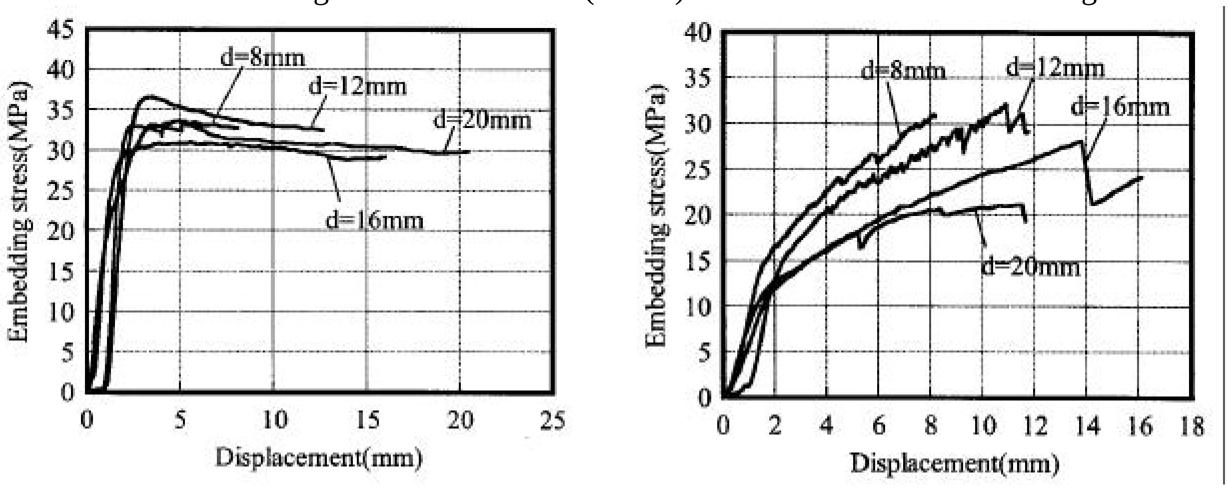


Figure 2: Difference in load-displacement behaviour parallel and perpendicular to grain test. Taken from Sawata and Yasumura (2002)

nails and dowels as the embedment stress at 2,1mm displacement in both directions. Sawata and Yasumura (2002) investigated the influence of the displacement limit. They compared two methods, the American 5% offset method and the EN383 method, Figure 3. In the first method a line parallel to the linear load displacement curve is off set by 0,05d and the intersection with the load displacement curve is taken as the embedment strength. For parallel to grain test both test methods appeared to be in good agreement, for linear full plastic behaviour no surprise. For the perpendicular to grain results Sawata and Yasmura reported the 5% off-set method to be less sensitive for the fastener diameter. In the evaluation of embedment test results this issue should be considered.

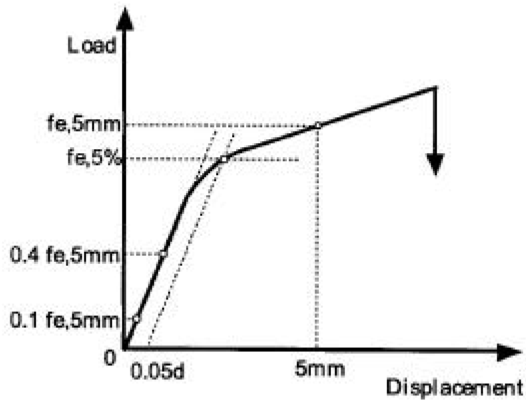


Figure 3: Two definitions of embedment strength

3 The Databases

To enable comparison databases are reviewed and are brought in line if necessary. Data from the following sources where considered and adopted for evaluation:

- Whale and Smith (1985a,b). They made a major contribution in the determination of the embedment strength of deciduous and coniferous wood species and other wood based products. They used dowel diameters ranging from nail sizes of 2,65mm to 7mm up to dowel diameters of 8 to 20mm. The test specimens comprised many wood species and at least 40 tests per wood species per fastener diameter, Table 1. After some preliminary tests with nails the perpendicular to grain embedment strength was defined as the maximum stress within a displacement of 2,1mm (for EN383 it is 5 mm). Having taken note of the research by Sawata and Yasumura (2002) and from some data analyses of the perpendicular to grain results it was concluded that this part of their database had to be discarded from the evaluation. Furthermore, the density of the embedment specimens was taken as the oven dry volume/weight at test. Other databases report the density as the ratio of weight and volume at test. Therefore the density of all specimens was modified using the method given by W.T. Simpson (1993). The coniferous specimens with nail

size holes were not pre-drilling but for the deciduous specimens these holes were pre-drilled to 80% of the nail diameter. They were all regarded as not-predrilled.
- Ehlbeck and Werner (1992) confined their research to deciduous wood species. The dowel diameter ranged from 8mm to 30mm diameter. Part of the test programme studied the influence of the angle between the load and grain direction. In his PhD-thesis Werner (1993) presents an overview of the parameters that influences the strength of connections with dowel type fasteners.
- Vreeswijk (2003) focused mainly on high-density wood species (11 tests Spruce).
- Mischler (not published) performed embedment tests exclusively with Spruce specimens focusing on small pre-drilled holes for 5 and 7mm diameter.
- Sawata and Yasamura (2002) made a comprehensive survey using exclusively Japanese pine. The equal number of experiments per dowel diameter (8, 12, 16 and 20 mm) parallel and perpendicular to the grain made this database very well- balanced. They evaluated the differences between the 5% off-set test method and EN383. In addition they also evaluated the strength of connections with dowel-type fasteners applying Monte Carlo simulations, with the experimental embedment data as input, Sawata and Yasumura (2000). In addition an attempt was made using a non-linear model based on Johansen theory to estimate the strength of bolted connections, Sawata and Yasumura (2003).

Table 1: Wood species and number of embedment tests

Whale & Smith (1985a,b)	Ehlbeck & Werner (1992)	Vreeswijk (2003)	Mischler (not publ.)	Sawata & Yasumura (2003)
Sitka Spruce n =357	Beech n = 55	Spruce n = 11	Spruce n = 130	Pine n = 1009
Scots Pine n =160	Oak n = 20	Oak n = 10	-	-
European redw. n =357	Teak n = 5	Massaranduba n = 10	-	-
Spruce Pine Fir n =160	Merbau n = 19	Angelim Vermelho n = 12	-	-
Keruing n =180	Afzelia n = 20	Azobé n = 10	-	-
Greenhart n =180	Bongossi n = 35	Cumaru n = 10	-	-

In Table 2 a general overview of the data is given. Since Whale and Smith (1986b) showed no significant difference between the results in tension and compression parallel to grain these sub sets were combined. Before evaluation and analyzing the data a number of overviews and checks were made. A summary of the mean and standard deviation of the specimen densities per wood species is given in Table 3.

Table 2: Review of source and sample size of the database.

NAILS (not-drilled)				
Source	Parallel to grain		Perp. to grain	Total
	tension	compression	compression	
Whale and Smith (1985a) Whale and Smith (1985b)	400	120	400	920
Nails	**520**		**400**	**920**
DOWELS				
Whale and Smith (1985a) Whale and Smith (1985b)	360	120	360	840
Ehlbeck and Werner (1992)	79	45	30	154
Sawata and Yasumura (2003)	-	503	506	1009
Mischler (not published)	-	80	50	130
Vreeswijk (2003)		62		62

Total Dowels	**1249**	**946**	**2195**
Total Nails + Dowels	**1769**	**1346**	**3115**

Table 3: Overview of the density per wood species

Coniferous	n	density			**Deciduous**	n	density		
		mean	st.d	COV			mean	st.d	COV
Sitka Spruce	357	393	39,1	10	Keruing	200	707	60,9	9
Scots Pine	119	458	59,0	13	Greenhart	120	905	35,9	4
European Redwood	358	460	46,6	10	Beech	56	717	33,1	5
European Whitewood	119	390	41,6	11	Teak	5	652	9,7	1
Spruce Pine Fir	119	411	36,8	9	Oak	30	718	36,7	5
Picea (Japan)	1009	398	44,2	11	Merbau	19	802	36,5	5
Spruce	151	446	51,7	12	Afzelia	20	714	24,0	3
					Bongossi	35	1086	56,3	5
					Massaranduba	10	972	27,3	3
					Angelim Vermelho	11	1104	40,0	4
					Azobe	10	1072	11,2	1
					Cumaru	10	1142	18,7	2

In Figure 4 the density distribution of all the specimens of all wood species excluding Picea Jezoerisis is presented. The large number of coniferous wood distinguishes itself clearly from the other deciduous species in that the densities concentrate between 200 and 550 kg/m^3. The density range of the deciduous wood species is much wider and apparently is well represented around 700, 900 and 1100 kg/m^3. The density distribution play a role in the assumptions of the theory applied below.

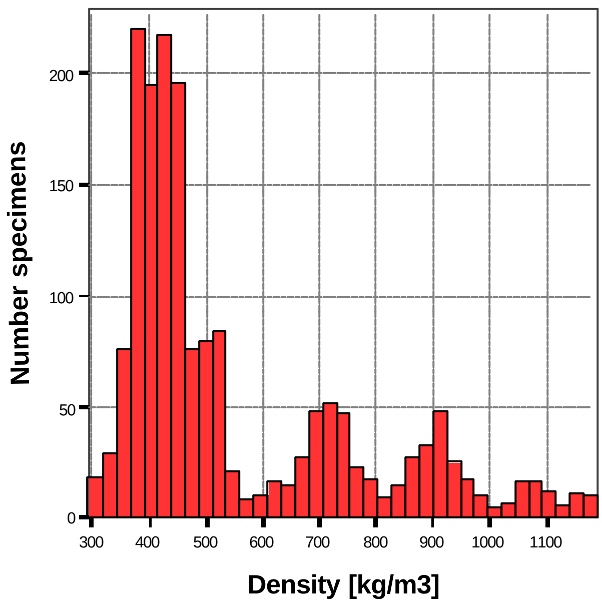


Figure 4: Density histogram

4 Data analysis

The individual data sub sets (wood species) are combined to virtual populations of unique loading mode and wood family. Therefore, eight groups were identified, namely, coniferous or deciduous wood species with nails or dowels loaded parallel or perpendicular to the grain. By testing if the sub data sets are statically similar it was observed that considerable differences exist. For that reason the use of multivariate models for the analysis of the populations is not possible. However, it is assumed that the mean values of an arbitrary subpopulation can be related through a regression model derived from the entire combined sub set. The best fit was found for the following expression:

$$f_h = A r^B d^C \tag{1}$$

where

f_h is the embedding strength,

r is the timber density and

d is the diameter of the fastener.

A, B and C are model parameters.

Considering the natural logarithms of the material properties involved a simple linear equation can be written and multiple linear regression analysis can be utilized to estimate the model parameters.

4.1 Regression Analysis

The regression analysis takes basis in n simultaneous observations of the embedment strength $f_h = \left(f_{h,1}, f_{h,2},..., f_{h,n}\right)^T$ as the dependent material property and the density $r = \left(r_1, r_2,..., r_n\right)^T$ and the diameter of the fastener $d = \left(d_1, d_2,..., d_n\right)^T$ as indicative properties. Assuming that at least locally a linear relationship between the natural logarithm $\ln\left(f_h\right) = f_h^*$, $\ln\left(r\right) = r^*$ and $\ln\left(d\right) = d^*$ exist the regression may be performed on the basis of

$$f_h^* = A^* + B r^* + C d^* + e \tag{2}$$

where $A^* = \ln\left(A\right)$, B and C are the regression coefficients and where e is an error term. Assuming that the error term e is normal distributed with zero mean and unknown standard deviation s_e the maximum likelihood method, see e.g. Lindley (1965) may be used to estimate the mean values and covariance matrix for the parameters A^*, B, C, s_e.

The likelihood is given as

$$L\left(A^*, B, C, s_e\right) = \prod_{i=1}^{n} \frac{1}{\sqrt{2p}\, s_e} \exp\left(-\frac{1}{2}\left(\frac{-f_{h,i} + A^* + B r^* + C d^*}{s_e}\right)^2\right)$$

The parameters are estimated by the solution $\mathbf{p}^*$ to the optimisation problem

$$\max_{\mathbf{p}} L(\mathbf{p}), \tag{3}$$

where $\mathbf{p} = \left(A^*, B, C, s_e\right)^T$.

It can be shown that for a sufficient large n the estimated parameters are normal distributed with mean values μ = p*. By considering instead of the likelihood function L the log-likelihood function l

$$l = \ln(L) \tag{4}$$

the covariance matrix for the parameters $\mathbf{p} = \left(A^*, B, C, s_e\right)^T$ may be obtained through the inverse of the Fischer information matrix with components given by

$$H_{ij} = -\frac{\partial^2 l}{\partial p_i \partial_j}\Big|_{p=p^*} \qquad (5)$$

The regression analysis results are summarized in Table 4 for nails (pre-drilled) and in Table 5 for dowels. Regarding Table 5 it should be noted that the Japanese data (n=1009) is very dominating for the coniferous wood species. Comparison with the European coniferous wood species shows significant differences. For this reason additional columns are provided in Table 5 including, excluding the Japanese data as shown at the bottom of the table..

Annex 1 contains a graphical representation of the data and the multiple linear regression curves.

Table 4: Regression parameters for (pre-drilled) Nails
$\ln(f_h)=A+B*\ln(r)+C*\ln(d)$

Nails	N = 397	N = 319	N = 120	N = 80
	Coniferous		***Deciduous***	
	Parallel	*Perpendicular*	*Parallel*	*Perpendicular*
μ_A	-4,562785	-3,085869	-5,533446	-7,904825
s_A	0,439676	0,390547	0,513015	0,533076
μ_B	1,345241	1,148261	1,506924	1,886664
s_B	0,071756	0,064172	0,076790	0,079256
μ_C	-0,272704	-0,419665	-0,181376	-0,418183
s_C	0,029885	0,026845	0,037282	0,038645
µsigeps	0,174512	0,140670	0,119008	0,100721
ssigeps	0,004379	0,003938	0,005432	0,005630
cov(A;B)	-0,995002	-0,994941	-0,993812	-0,993843
cov(C;B)	0,084639	0,039359	0,005608	0,004097
cov(C;A)	-0,181708	-0,137500	-0,114606	-0,112836
cov(C;sigeps)	0,000030	-0,000033	0,000034	0,000258
cov(A;sigeps)	0,000047	0,000580	0,000823	0,000177
cov(sigeps;B)	-0,000054	-0,000584	-0,000833	-0,000208

Table 5: Regression parameters for Dowels
$\ln(f_h)=A+B*\ln(r)+C*\ln(d)$

Dowels	N = 951	N = 448	N = 503	N = 506	N = 292	N = 37
	Parallel)[1]	*Parallel)*[2]	*Parallel)*[3]	*Perpend)*[4]	*Parallel*	*Perpend*
	Coniferous				***Deciduous***	
μA	-0,965556	-2,334036	-1,251187354	-2,547059	-2,441370	-2,244701
s A	0,196697	0,232486	0,196697217	0,308889	0,296084	0,655234
μB	0,812427	1,065760	0,837394995	1,099235	1,091321	1,127928
s B	0,031861	0,037509	0,032907101	0,051986	0,044068	0,097064
μC	-0,157257	-0,253238	-0,080890969	-0,431719	-0,252681	-0,454555
s C	0,011399	0,012179	0,01302657	0,020870	0,018130	0,038226
μsigeps	0,125654	0,107329	0,08047327	0,128749	0,129111	0,112074
ssigeps	0,002037	0,002535	0,001794063	0,002862	0,003824	0,010231
cov(A;B)	-0,988401	-0,991062	-0,984102213	-0,983571	-0,986150	-0,986761
cov(C;B)	0,091930	0,105251	-0,092401277	-0,125516	-0,115408	-0,129225
cov(C;A)	-0,240676	-0,235190	-0,084975621	-0,054692	-0,048929	-0,030300
cov(C;sigeps)	0,000010	-0,000086	-1,83111E-10	0,000018	-0,000021	-0,000017
cov(A;sigeps)	0,000000	0,000381	1,34281E-09	0,000227	0,000690	0,000558
cov(sigeps;B)	-0,000003	-0,000379	-1,40067E-09	-0,000224	-0,000681	-0,000550

)1 Including Japanese data
)2 excluding Japanese data
)3 Only Japanese data
)4 Only Japanese data

4.2 Prediction of 5%-Fractile

Using the information from the regression analysis, the embedding strength can be estimated for given mean value of the timber density and given diameter of the fastener. The mean values of the regression parameters are describing a surface in the three dimensional space. The uncertainties of the location and the shape of this surface are quantified through the covariance matrix of the parameters. Given logarithm of the mean value of the density r_m^* and given logarithm diameter d^* of the fastener the mean value of the logarithm of the embedding strength, M_f, can be estimated as a normal distributed random variable with mean value and standard deviation as follows:

$$m_{M_f} = m_{A^*} + m_B r_m^* + m_C d^* \tag{6}$$

$$s_{M_f} = \sqrt{s_e^2 + s_{A^*}^2 + s_B^2 r_m^{*2} + s_C^2 d^{*2} + r_{A^*B} s_{A^*} s_B r_m^* + r_{A^*C} s_{A^*} s_C d^* + r_{BC} s_B r_m^* s_C d^*} \tag{7}$$

Where m_{A^*}, m_B, m_C are the mean values and s_{A^*}, s_B, s_C are the standard deviations of the regression parameters. r_{A^*B}, r_{A^*C}, r_{BC} are the correlation coefficients between the regression parameters (the correlation coefficients between the parameters and the error term e equal to zero).

The standard deviation of the embedding strength s_f is assumed known. The probability distribution function of the embedding strength can be assessed through the integration of the uncertain mean M_f and the standard deviation s_f.

$$F_f\left(x \middle| M_f, s_f\right) = \frac{1}{s_{M_f}} \int_{-\infty}^{\infty} \Phi\left(\frac{x-x}{s_f}\right) j\left(\frac{x-m_{M_f}}{s_{M_f}}\right) dx \,. \tag{8}$$

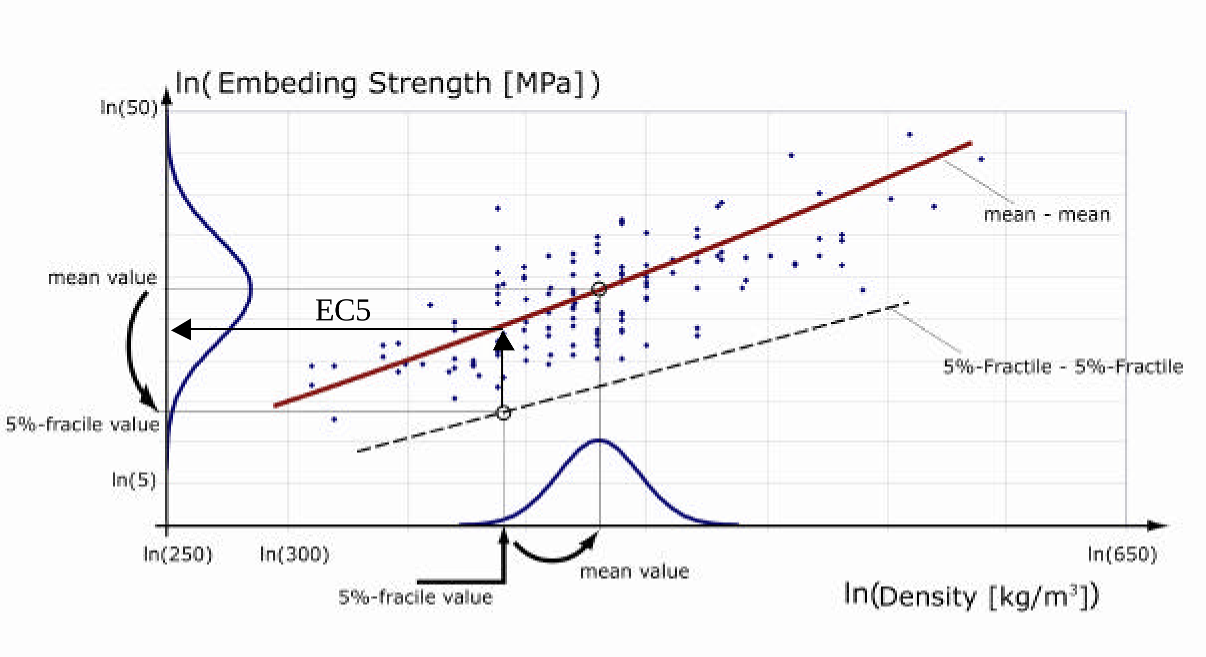


Figure 4: Logarithm of embedding strength over logarithm of density for a given diameter of the fastener. Scheme for the estimation of 5%-values.

For practical use it is often convenient to take the 5%-Fractile values of density and to find embedding strength directly for a given fastener diameter. Figure 4 shows how such a value can be deducted. The coefficients of variation of the embedding strength and the density are assumed to be constant along the (ln)y-axis and the (ln)x-axis respectively. The Eurocode 5 pragmatic adopted approach takes a vertical line from the point of the lower 5%-Fractile of density and the intersection with the mean regression curve gives the lower 5%-Fractile of the embedment strength.

In the application of the theory below the assumed coefficient of variation is 10% for density and 20% for the embedment strength for both coniferous and deciduous wood species. Table 3 shows that the cov for density is smaller for deciduous wood species, 5% instead of 10%, however, this did not affect the lower 5%-Fractile curve as position of this curve is governed by the uncertainty in the regression parameters A, B and C represented by $s_{A,}$ s_B and $s_{C.}$

In annex 2 an overview is presented of all lower 5%-Fractile curves.

4.2.1 Prediction of 5%-Fractile for Nails

In Figure 5 and 6 some examples are taken from annex 2. The graphs are given for (not pre-drilled) 3.35mm diameter nails parallel and perpendicular to the grain. The Eurocode 5 curve should represent the regression of the data mean.

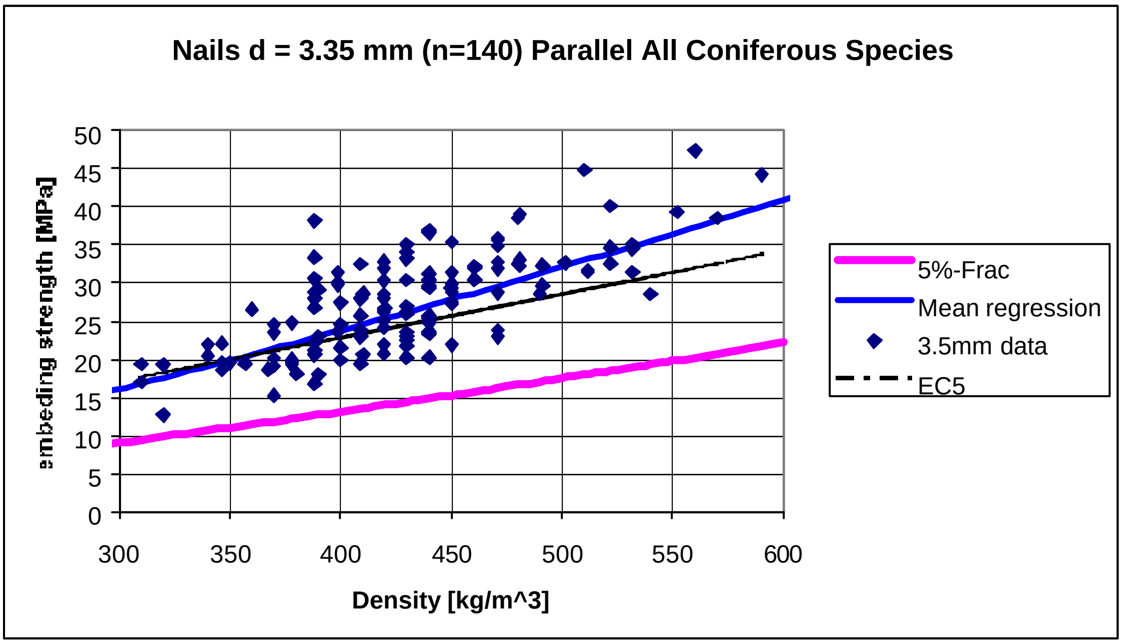


Figure 5: Result of analyses with 5%-Fractile curve and Eurocode 5

The difference between both curves is big. The low position of the 5%-Fractile curve is caused by the high value of the coefficient of variation s_A in Table 4. In Figure 6 the Eurocode 5 curve now drops below the mean regression curve but still results in considerable higher lower 5%-embedment values compared with the 5%-Fractile estimate curve. The low position of the lower 5%-Fractile curve is consistent for all data sets evaluated.

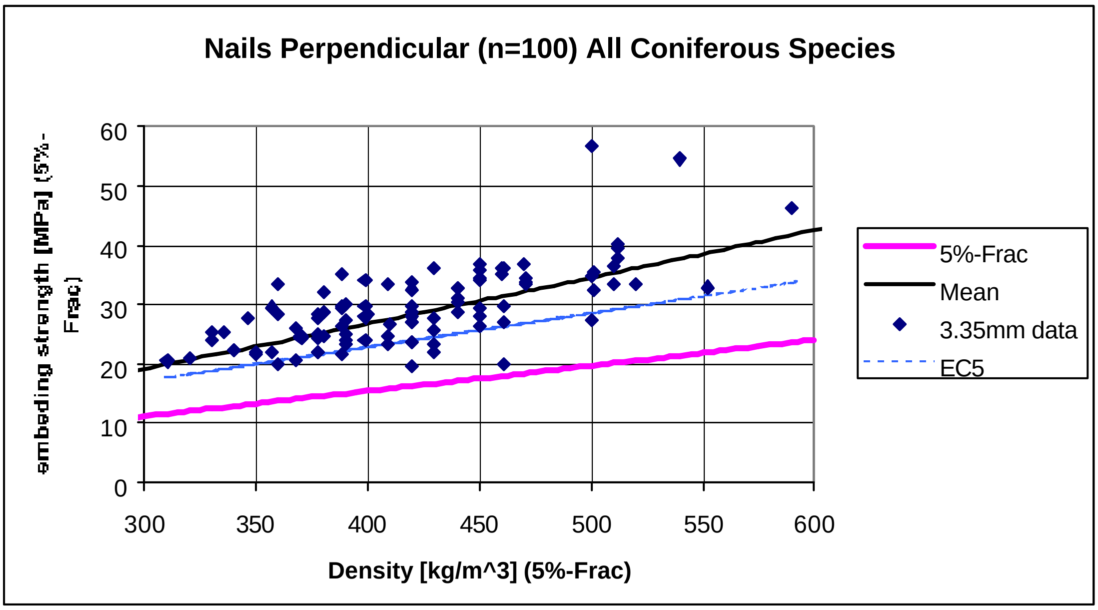


Figure 6: Comparing of the perpendicular to grain 5%-Fractile prediction and Eurocode 5 (d=diameter)

4.2.2 Prediction of 5%-Fractile for Dowels

Below graphs show the results for some of the dowel sizes. More details are provided in Annex 2. The Japanese Pine data sub set is so dominating in this part of the database that it will be evaluated separately as well in combination with the European wood species. Figure 7 shows the

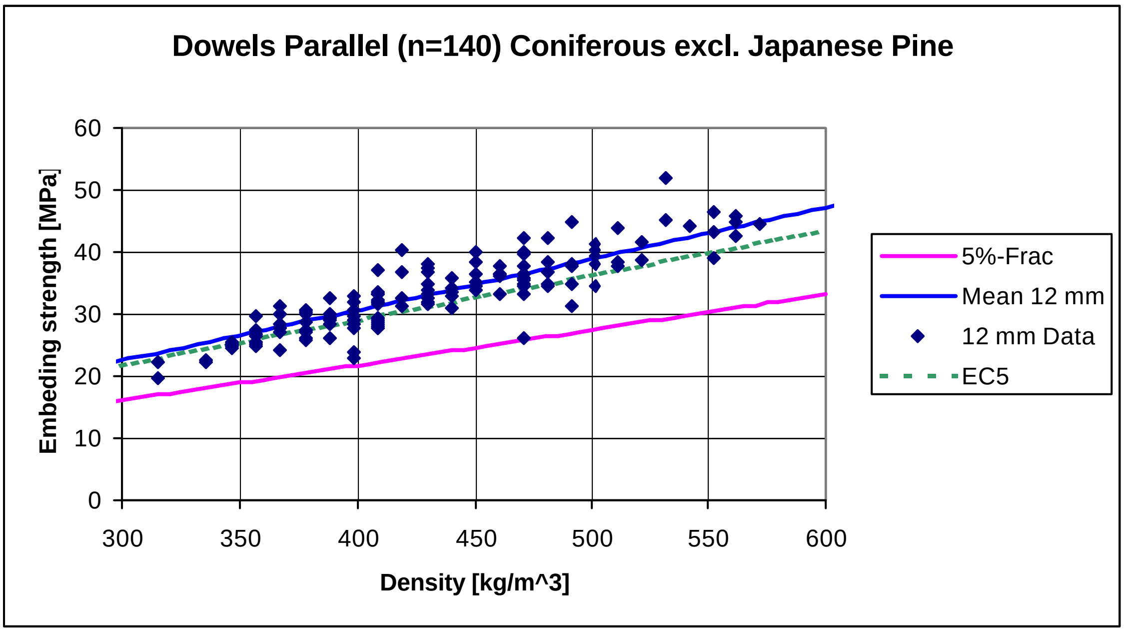


Figure 7: Comparing of the parallel to grain 5%-Fractile prediction and Eurocode 5 (d=diameter)

result of the analyses as well as the Eurocode 5 curve for dowels with 12 mm diameter disregarding the Japanese data. The EC5 curve is close to mean regression. However, assuming a lower 5% density of 350 kg/m^3 the difference in lower 5% embedment strength estimate of both curves is still big, approximately 20%.

The advantage of the Japanese tests is the large quantity of data per dowel diameter using only two Japanese Pine wood species. In Figure 8 the data of the 12mm diameter dowel and the 5%-Fractil estimates are given. The 5%-Fractile estimate curve now compare better with the Eurcode5 curve than previously. Reason being the embedment strength is higher over the whole density range as well as the 5%-Fractile estimate while the Eurocode 5 curve stays on the same position. The perpendiculars to the grain results are given in Figure 9 for the same dowel diameter of 12mm as well. Here the differences in 5% embedment strength are again considerable

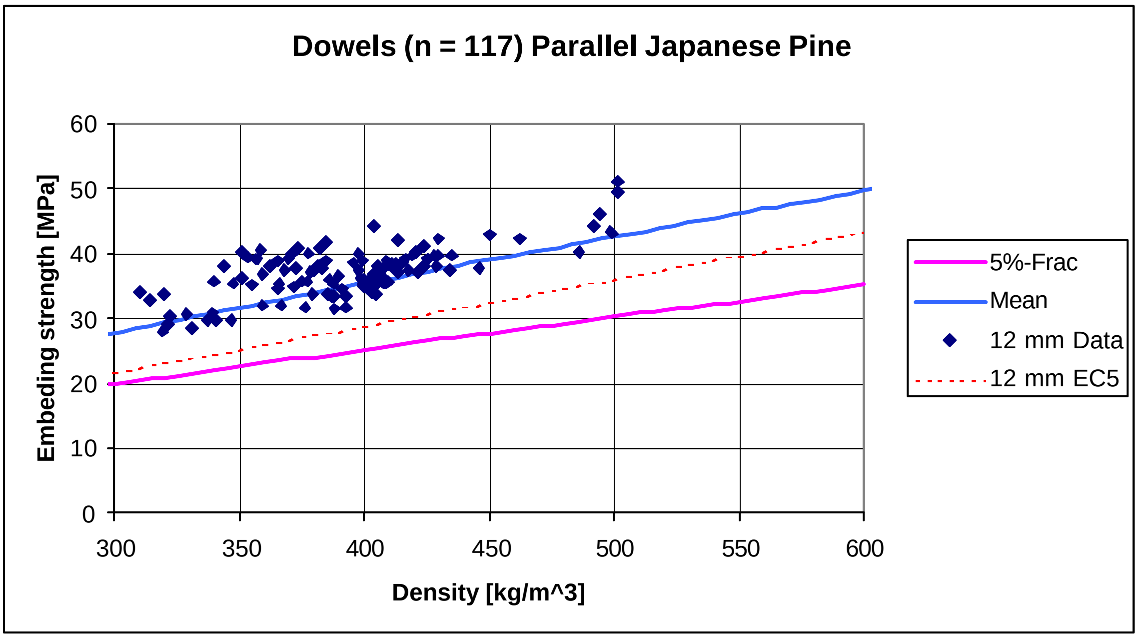


Figure 8: Comparing of the parallel to grain 5%-Fractile prediction and Eurocode 5 (d=diameter)

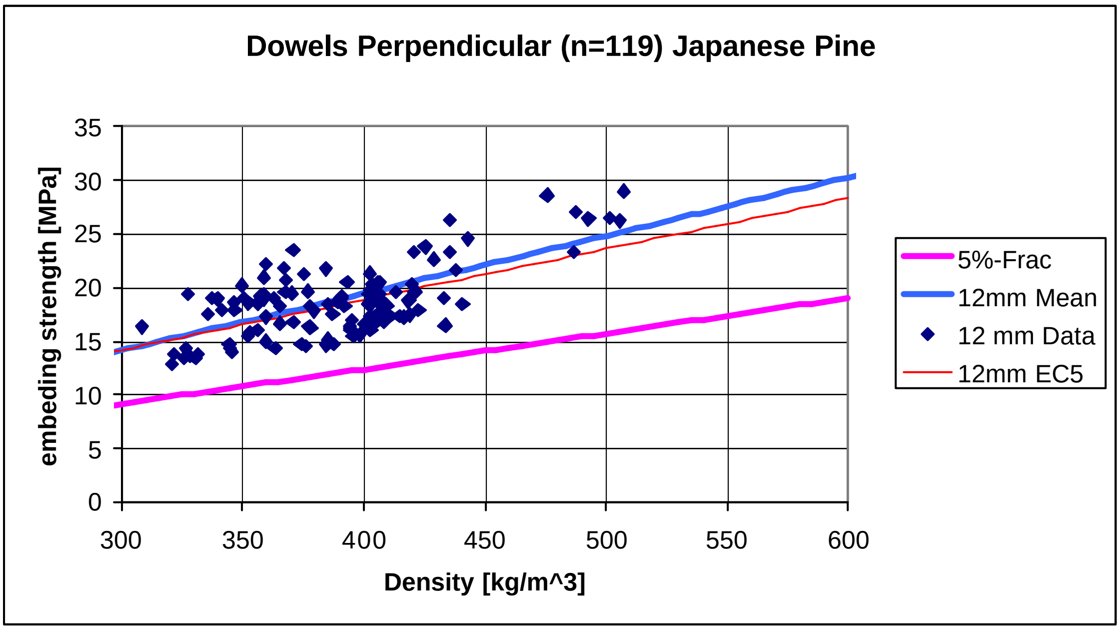


Figure 9: Comparing of the perpendicular to grain 5%-Fractile prediction and Eurocode 5 (d=diameter)

The results with 16 mm dowel diameters and deciduous wood species are presented in Figures 10. As reported by Ehlbeck and Werner (1992) the Eurocode 5 curve is conservative with respect to the mean regression curve. Still the lower 5%-Fractile curve is way below the data for high density values. On the other hand the theory applied assumes the density to be log normal distributed, which clearly is not the case for the deciduous specimens, Figure 4. This indicates that the lower 5%-Fractile curve of Figure 10 has no meaning.

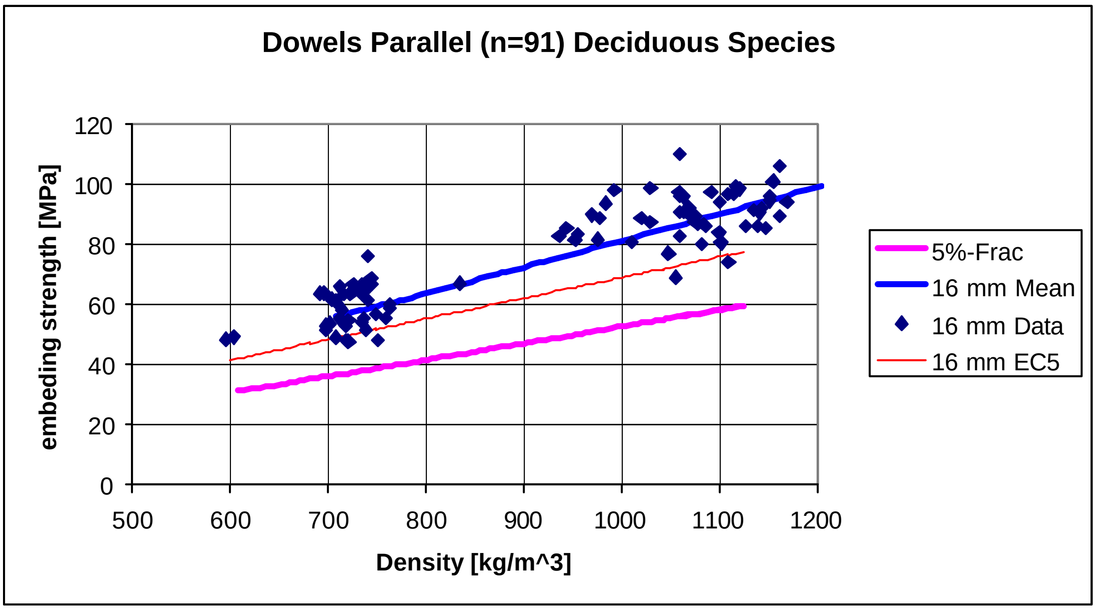


Figure 10: Comparing the parallel to grain 5%-Fractile prediction of 16 mm dowels and Eurocode 5 (d=diameter)

As was mentioned at the beginning of 4.2.1 the low position of the 5%-Fractile curves is presumably caused by the high coefficient of variation of the parameter A. The coefficient A represents the intersection of the regression curve with the vertical ln(embedment) axis. In the Tables 4 and 5 this values varies between 19 to 65%. The high uncertainty is probably caused by

the uncertainty in the slope of the regression curve, which is not very stable due to the small density range of the data.
To check this assumption an effort was made to reduce the variability of the slope by expanding the data density range. This was achieved by combining coniferous and deciduous wood species thereby violating the theory of lower 5%-Fractile prediction. For this case the position of the lower 5%-Fractile has no meaning but it indicates how the variability of the regression parameters is affected. The result is shown in Figure 11 and shows a 5%-Fractile curve much closer to the data than in previous graphs. In Annex 3 more details are given. The cov of the parameter A,B and C, now are reduced to 7, 1 and 1%, respectively.

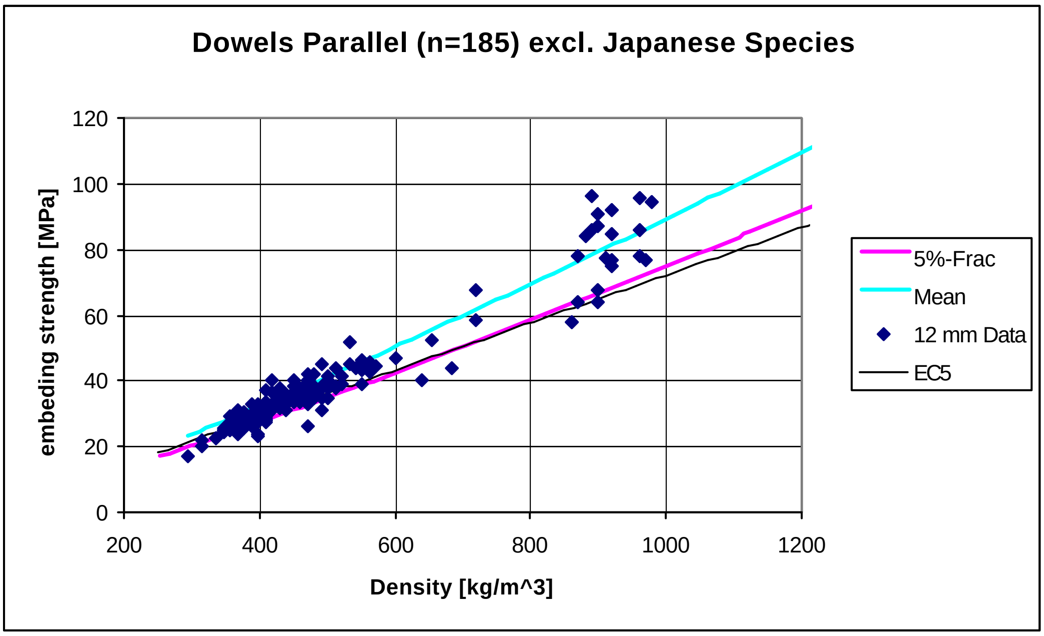


Figure 11: Influence of cov regression parameter A and B

5 Conclusions regarding the results

From the evaluation of the analyses results it can be concluded that:

- Caused by differences in definition of the embedment strength perpendicular to grain a large portion of the available database was unsuitable for evaluation.
- The applied theory to derive the lower 5%-Fractile curves taking into account all uncertainties in the regression parameters result consistently in lower values for both coniferous as well as deciduous wood species compared to current Eurocode 5.
- The position of the lower 5%-Fractile curves is strongly affected by the uncertainty in the regression parameters.

6 Acknowledgement

The authors would like to thank Prof. M. Faber (ETH) for the spontaneous co-operation in the realization of this study. Furthermore, the EC sponsored COST Action E24 is acknowledged providing financial support of this short scientific mission. This study could only be accomplished by the grateful contributions of the researchers that carried out and reported the experiments. In particular Prof. Ian Smith from the University of New Brunswick, Canada, is mentioned who retrieved half of the TRADA database that was almost lost. Furthermore, Luke Whale of Timber Solve UK, Hans Blass for sending the research report of Ehlbeck and Werner, Karlsruhe Technical University Germany, as well as Kei Sawata and Motoi Yasumura of Shizuoka University, Japan, who granted us the use of their extensive data base.

7 Literature references

Ehlbeck, J. and Werner, H., 1992, Coniferous and deciduous embedding strength for dowel-type fasteners, *In*: *Proceedings of CIB-W18*, Paper 25-7-2.

Lindley, D. V. (1965). "Introduction to Probability & Statistics" Cambridge University Press.

Sawata, K., Yasumura, M. 2000, Evaluation of yield strength of bolted timber joints by Monte-Carlo simulation, *In*: Proceedings of the *World Conference on Timber Engineering*, July-August 2000, Whistler, University of British Columbia, Vancouver, BC, Canada,

Sawata, K., Yasumura, M. 2002, Determination of embedding strength of wood for dowel-type fasteners, Journal of Wood Science, 48:138-146, 2002

Sawata, K., Yasumura, M. 2003, Estimation of yield and ultimate strengths of boltsed timber joints by nonlinear analysis and yield theory, Journal of Wood Science, 49:383-391, 2003

Simpson, W. T., 1993, *Specific gravity, moisture content and density relationship for wood*, Gen. Tech. Report. FPL-GTR-76, Madison WI, USA Department of Agriculture, Forest Services, Forest Products Laboratory, 13p.

Vreeswijk, B., Verbindingen in hardhout, Master Thesis, Faculty of Civil Engineering TU-Delft, 2003.

Werner, H., 1993, Tragfähigkeit von Holz-Verbindungen mit Stiftförmige Verbindungsmitteln unter Berücksichtigung streuender Einfluß größen, PhD-thesis, Universität Karlsruhe.

Whale, L.R.J. and.Smith, I., 1985a, *Mechanical timber joints, embedment tests*, Annex to Final report of DOE-project, April 1983 – September 1985, TRADA

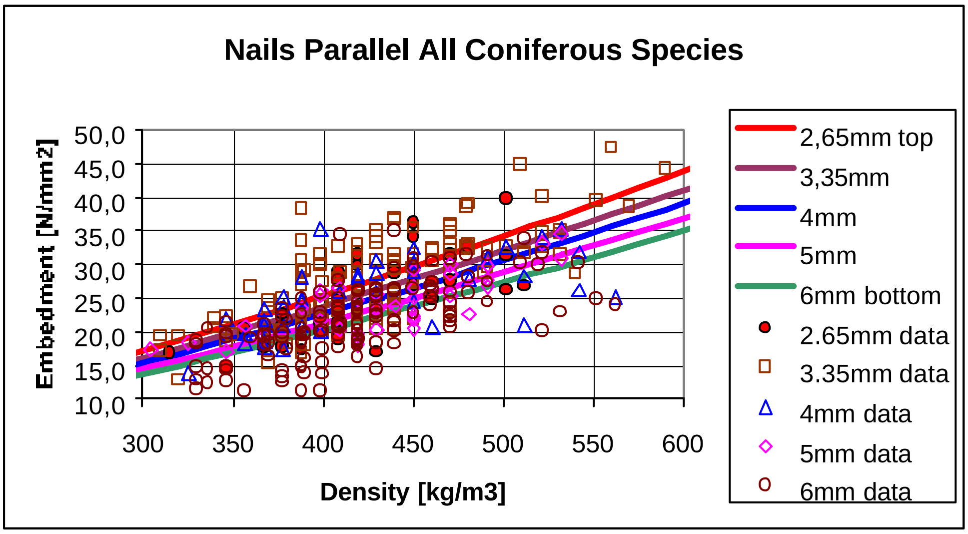
Whale, L.R.J. and.Smith, I., 1985b, *Mechanical timber joints, embedment tests*, Report to DOE-project, April 1983 – September 1985, TRADA

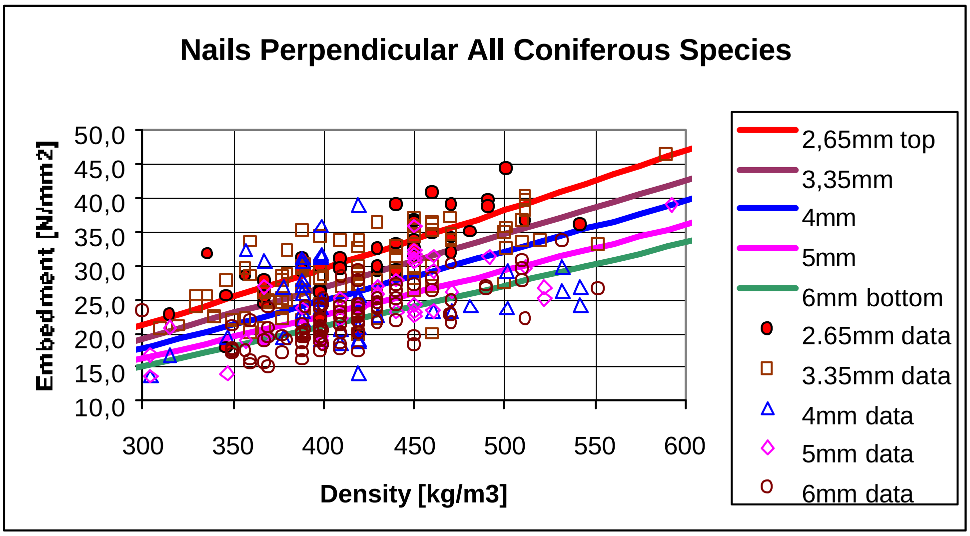
Whale, L.R.J. and Smith, I., 1986a, *Mechanical joints in structural timberwork*, information for probabilistic design, Annex to research report, CEC-project, TRADA, research report 17/86.

Whale, L.R.J. and Smith, I., 1986b, The derivation of design clauses for nailed and bolted joints in Eurocode 5, *In*: *Proceedings of CIB-W18*, Paper 19-7-6.

Whale, L. R.J. and Smith, I., Hilson, B.O. 1986c, Behaviour of nailed and bolted joints under short-term lateral load – conclusions from some recent research, *In*: *Proceedings of CIB-W18*, Paper 19-7-1.

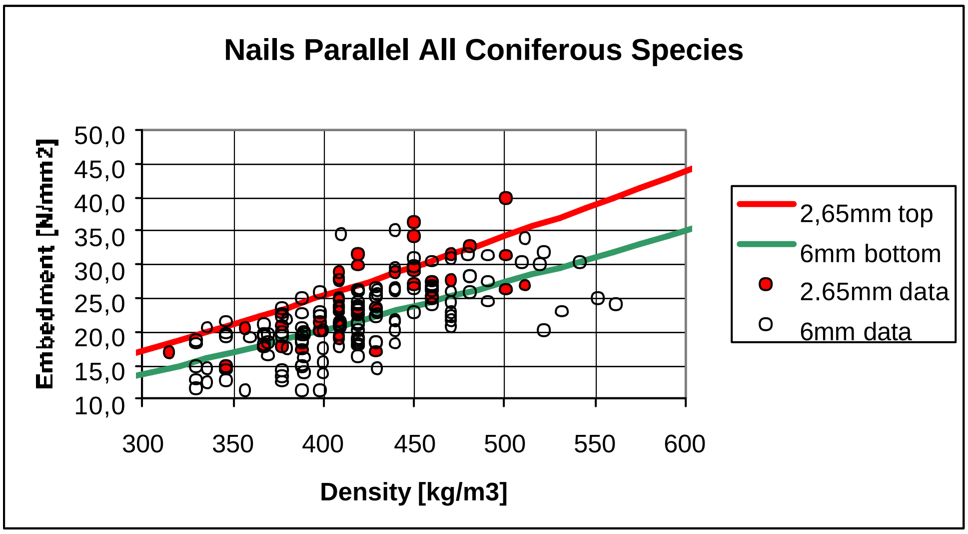
ANNEX 1

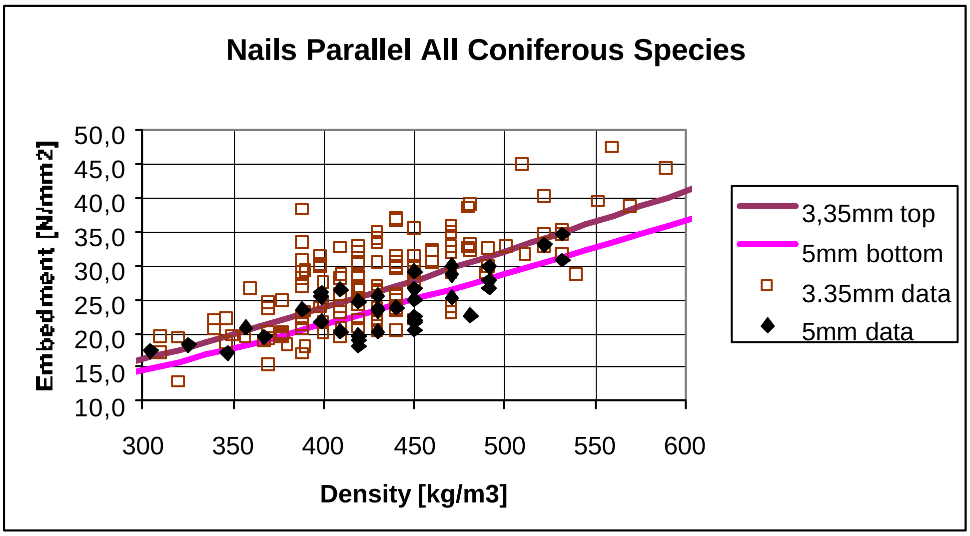


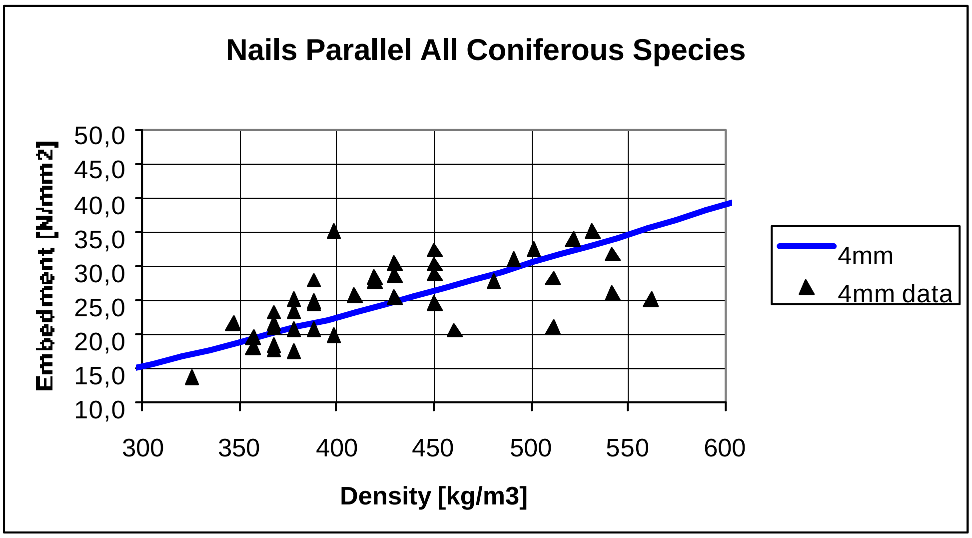


The graphs on the next two pages show in a more detail what is presented above.

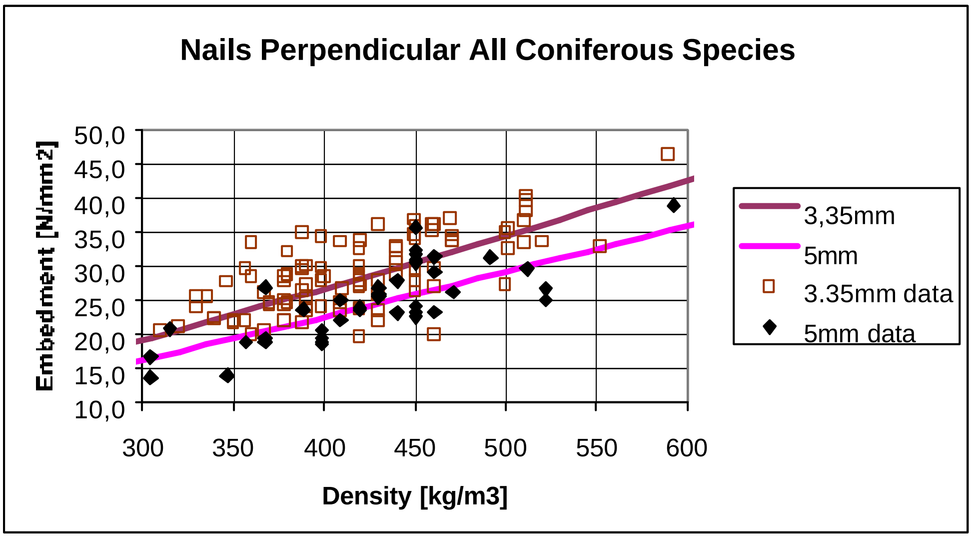
ANNEX 1

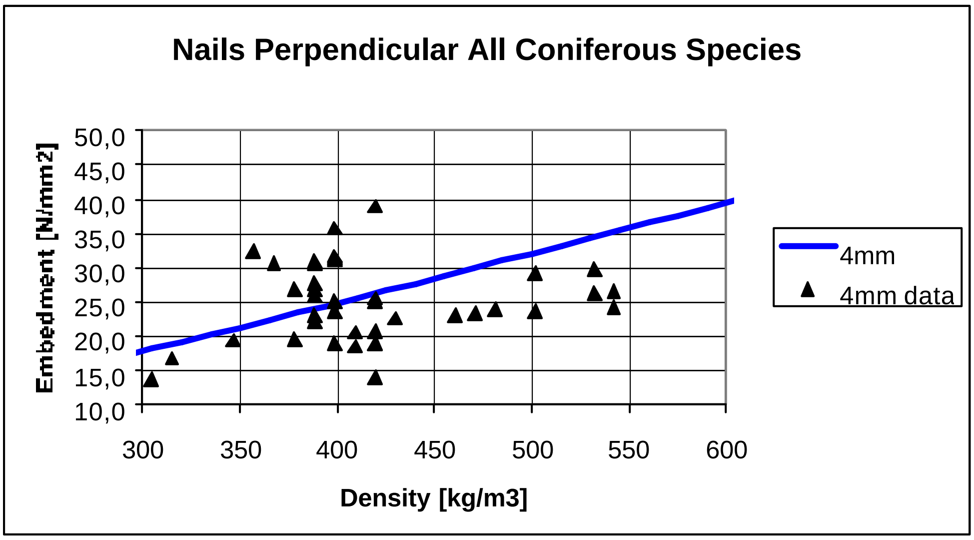

Nails Parallel All Coniferous Species
Embedment [N/mm2]
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
Density [kg/m3]
2,65mm top
6mm bottom
2.65mm data
6mm data


Nails Parallel All Coniferous Species
Embedment [N/mm2]
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
Density [kg/m3]
3,35mm top
5mm bottom
3.35mm data
5mm data

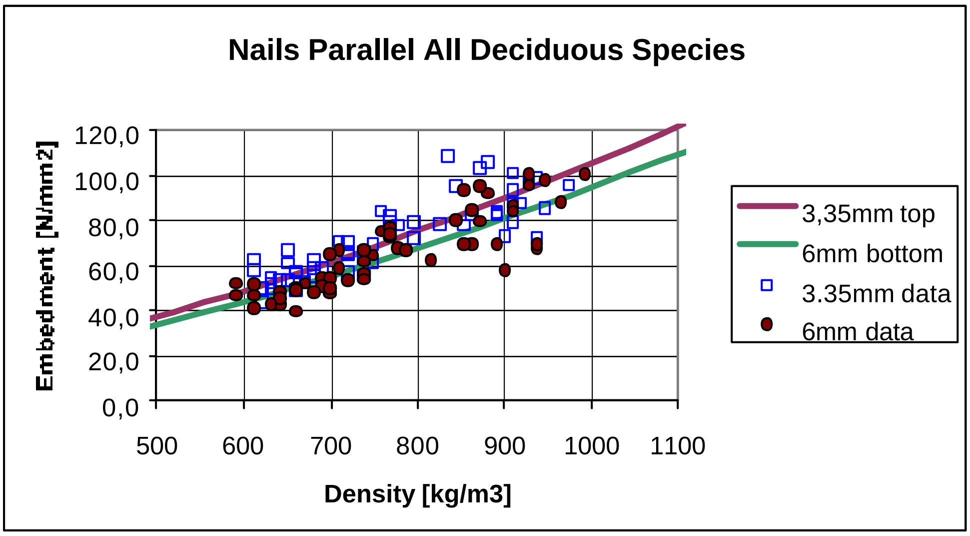

Nails Parallel All Coniferous Species
Embedment [N/mm2]
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
Density [kg/m3]
4mm
4mm data

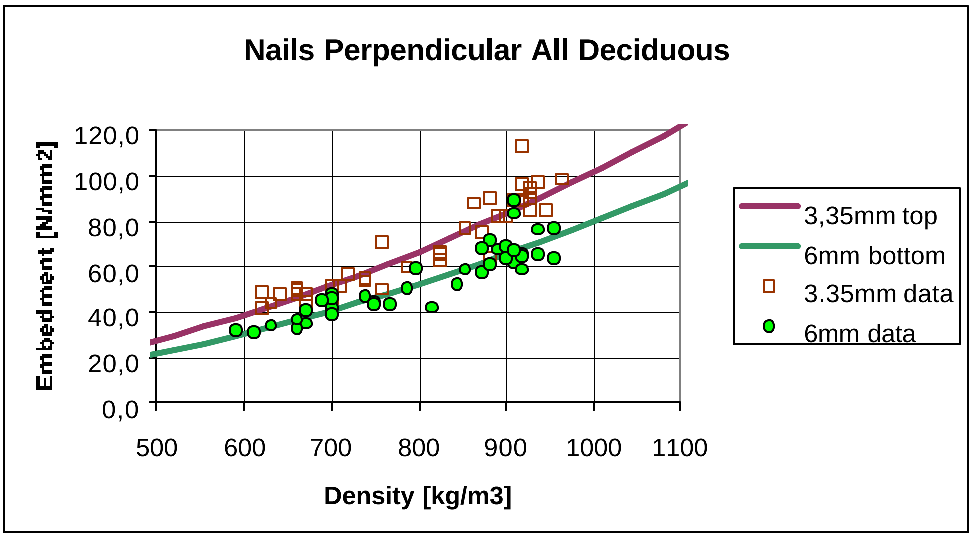
ANNEX 1


Nails Perpendicular All Coniferous Species
Embedment [N/mm2]
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
Density [kg/m3]
3,35mm
5mm
3.35mm data
5mm data

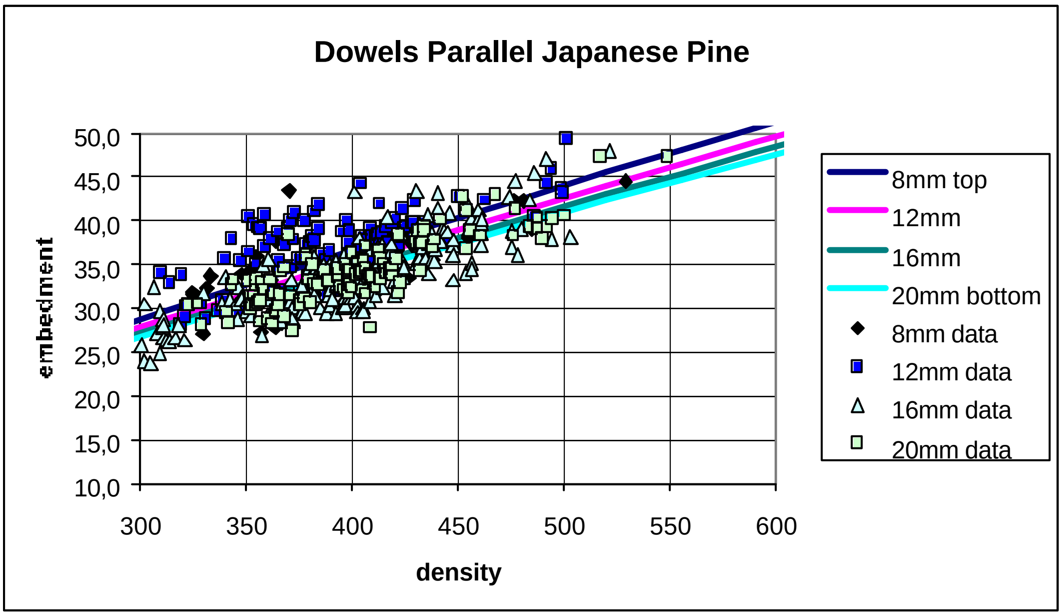

Nails Perpendicular All Coniferous Species
Embedment [N/mm2]
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
Density [kg/m3]
4mm
4mm data

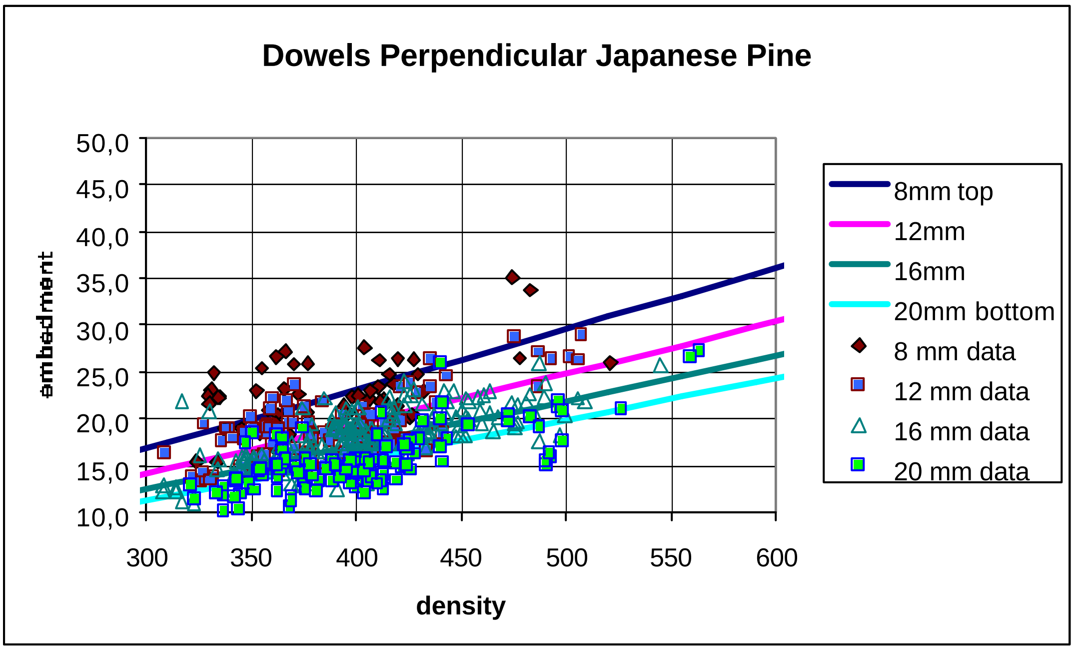
ANNEX 1


Nails Parallel All Deciduous Species
Embedment [N/mm2]
120,0
100,0
80,0
60,0
40,0
20,0
0,0
500
600
700
800
900
1000
1100
Density [kg/m3]
3,35mm top
6mm bottom
3.35mm data
6mm data

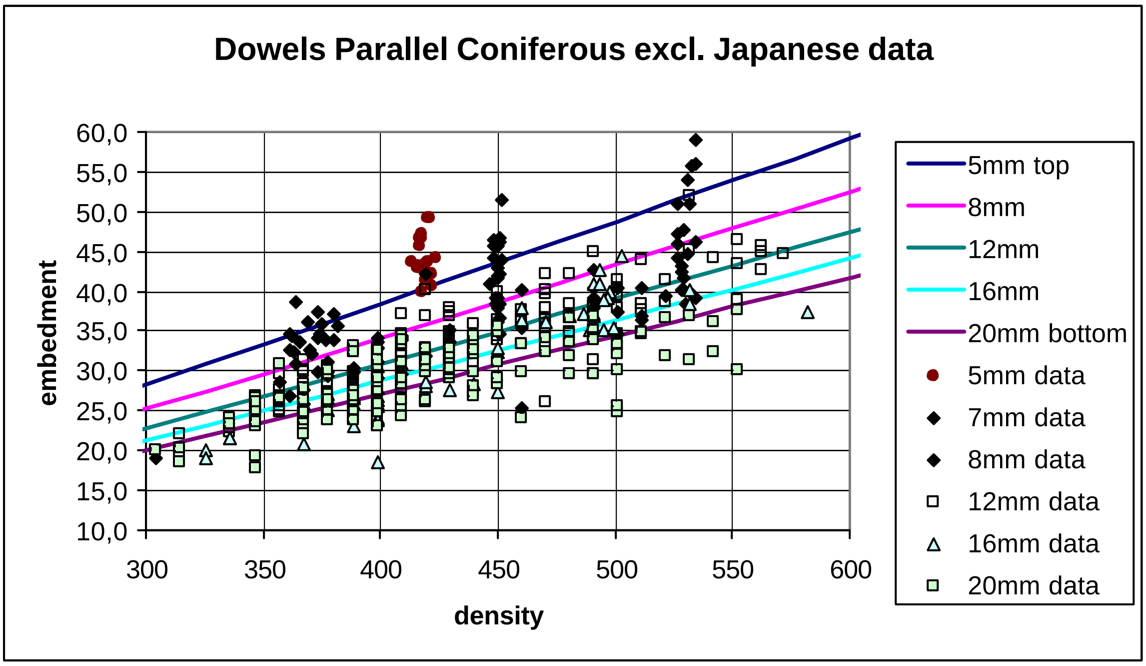

Nails Perpendicular All Deciduous
Embedment [N/mm2]
120,0
100,0
80,0
60,0
40,0
20,0
0,0
500
600
700
800
900
1000
1100
Density [kg/m3]
3,35mm top
6mm bottom
3.35mm data
6mm data

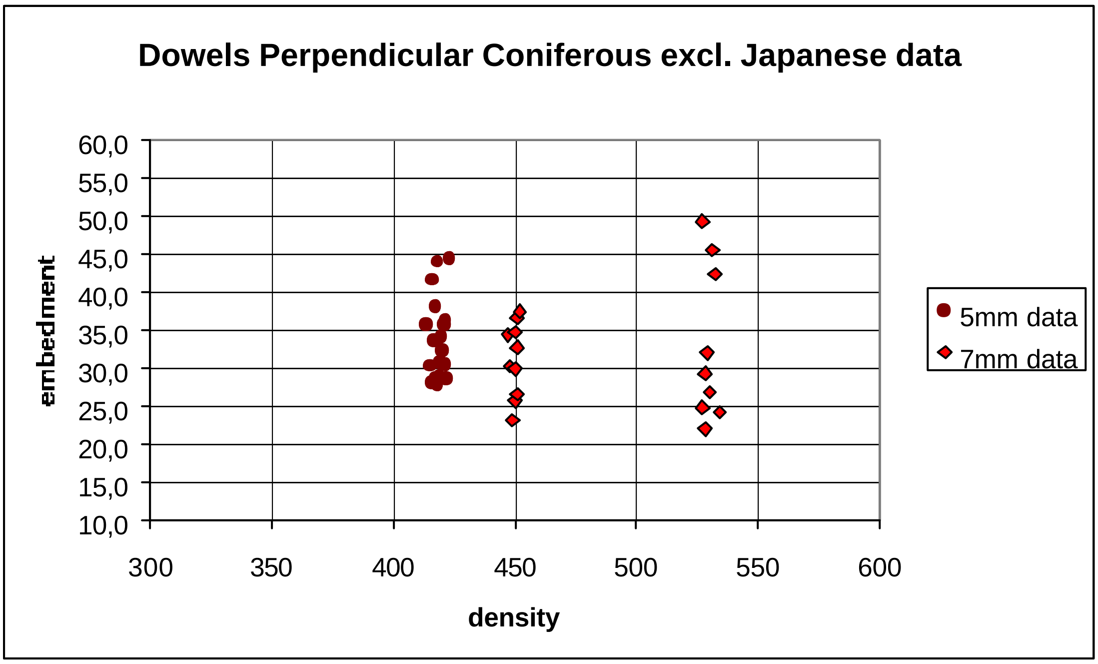
ANNEX 1


Dowels Parallel Japanese Pine
embedment
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
density
8mm top
12mm
16mm
20mm bottom
8mm data
12mm data
16mm data
20mm data

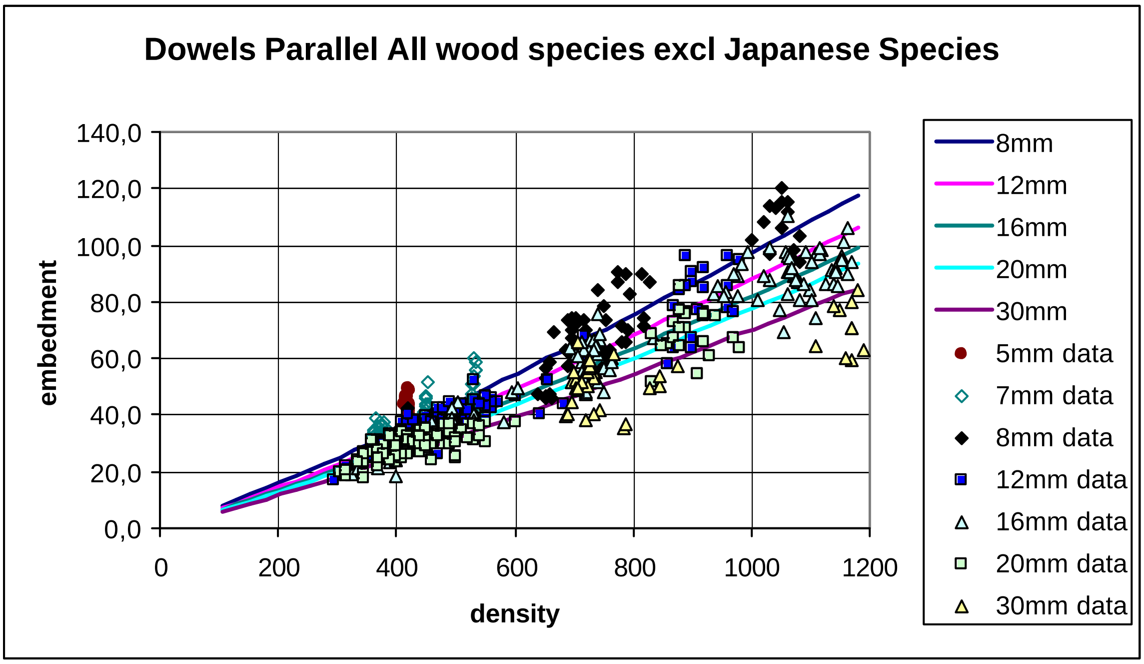

Dowels Perpendicular Japanese Pine
embedment
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
300
350
400
450
500
550
600
density
8mm top
12mm
16mm
20mm bottom
8 mm data
12 mm data
16 mm data
20 mm data

ANNEX 1

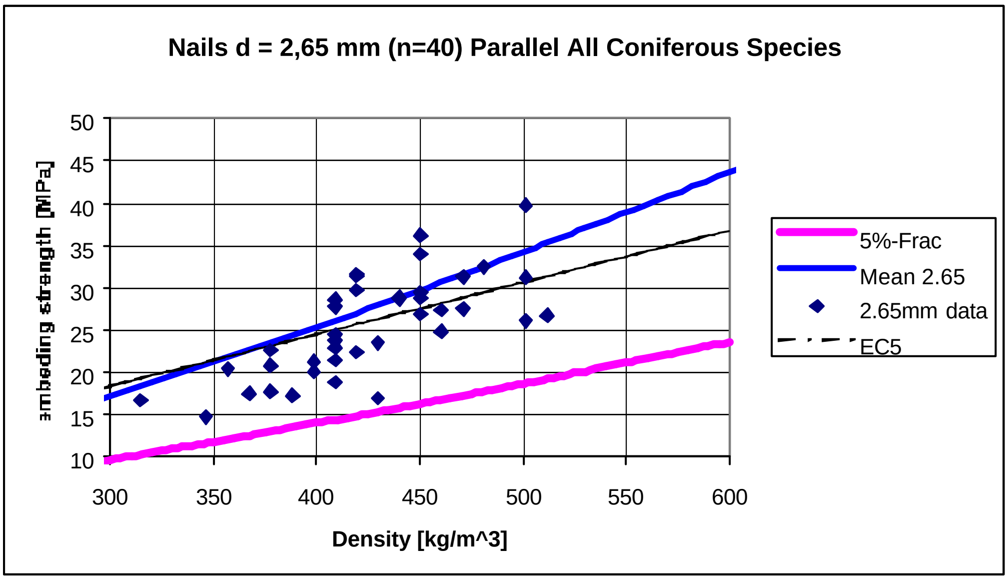

Dowels Parallel Coniferous excl. Japanese data
60,0
55,0
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
embedment
300
350
400
450
500
550
600
density
5mm top
8mm
12mm
16mm
20mm bottom
5mm data
7mm data
8mm data
12mm data
16mm data
20mm data

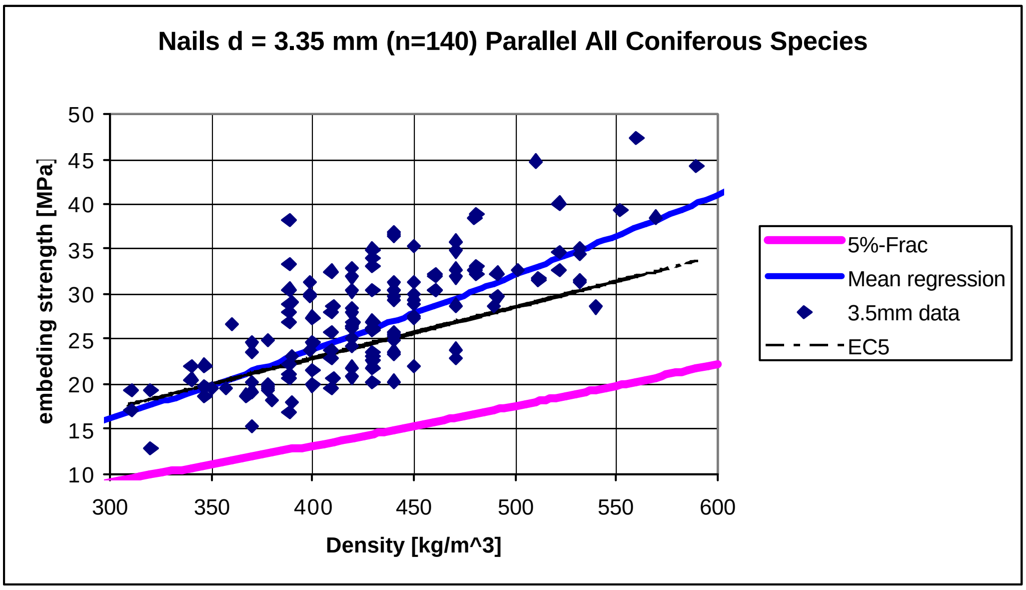

Dowels Perpendicular Coniferous excl. Japanese data
60,0
55,0
50,0
45,0
40,0
35,0
30,0
25,0
20,0
15,0
10,0
embedment
300
350
400
450
500
550
600
density
5mm data
7mm data

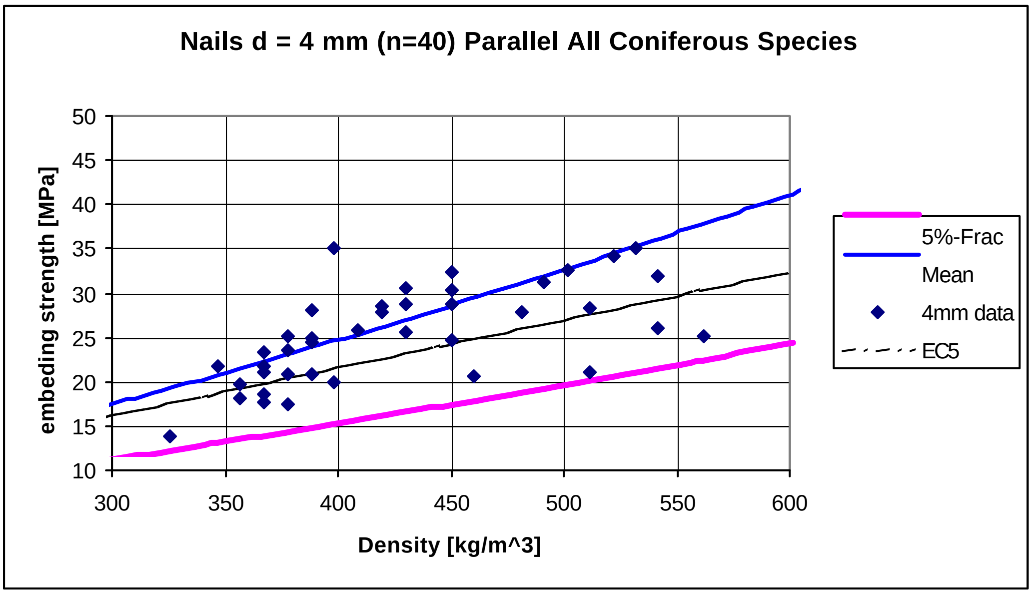
ANNEX 1


Dowels Parallel All wood species excl Japanese Species
embedment
140,0
120,0
100,0
80,0
60,0
40,0
20,0
0,0
0
200
400
600
800
1000
1200
density
8mm
12mm
16mm
20mm
30mm
5mm data
7mm data
8mm data
12mm data
16mm data
20mm data
30mm data

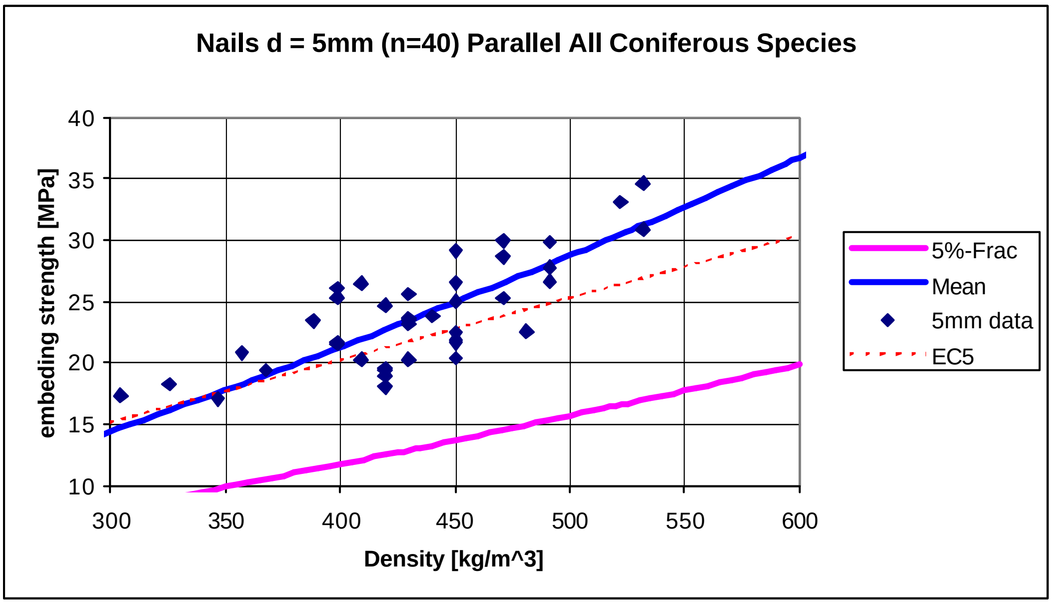
ANNEX 2

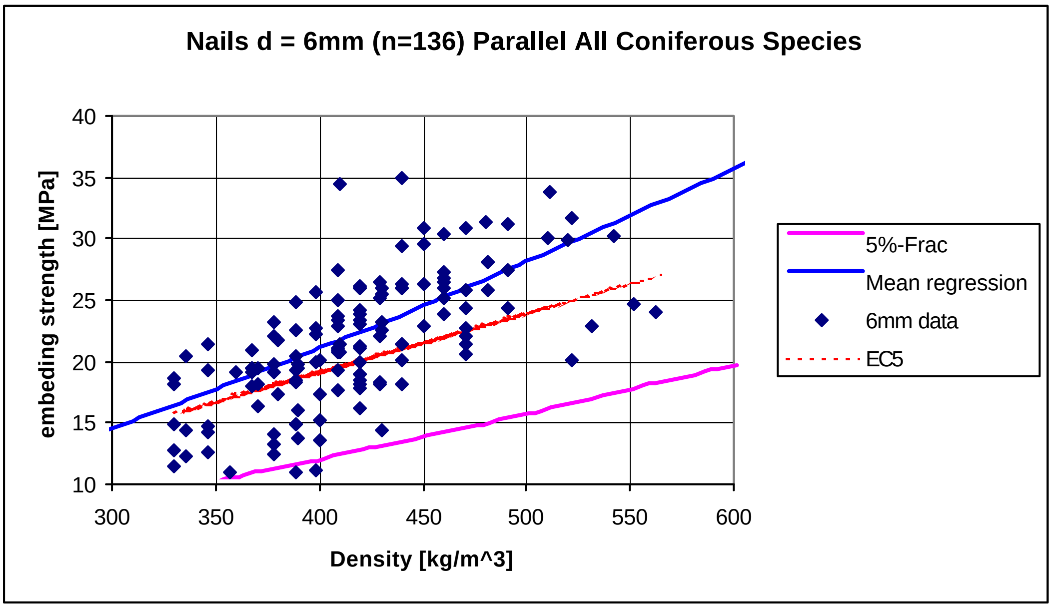

Nails d = 2,65 mm (n=40) Parallel All Coniferous Species
embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean 2.65
2.65mm data
EC5


Nails d = 3.35 mm (n=140) Parallel All Coniferous Species
embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean regression
3.5mm data
EC5

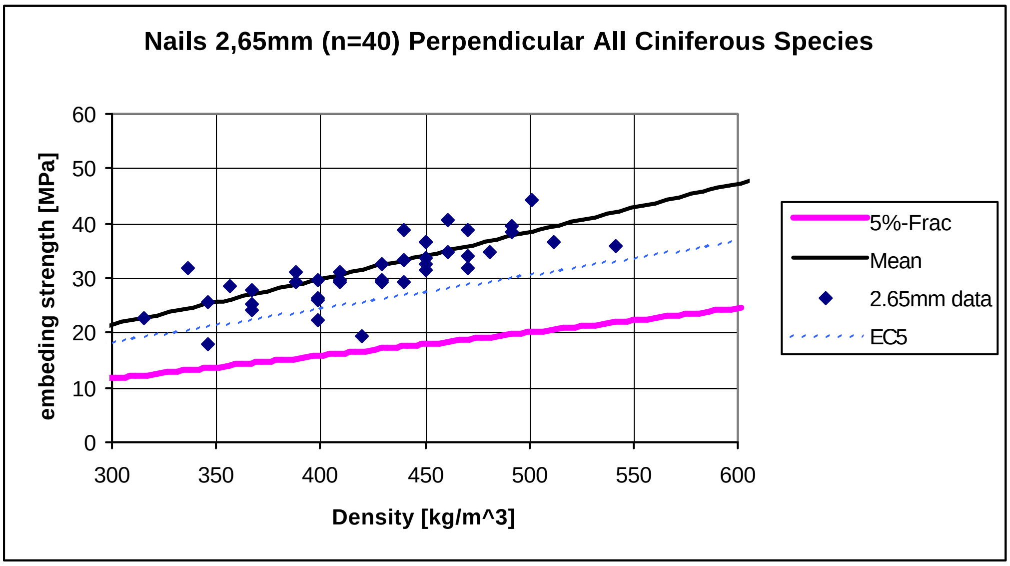

Nails d = 4 mm (n=40) Parallel All Coniferous Species
embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
4mm data
EC5

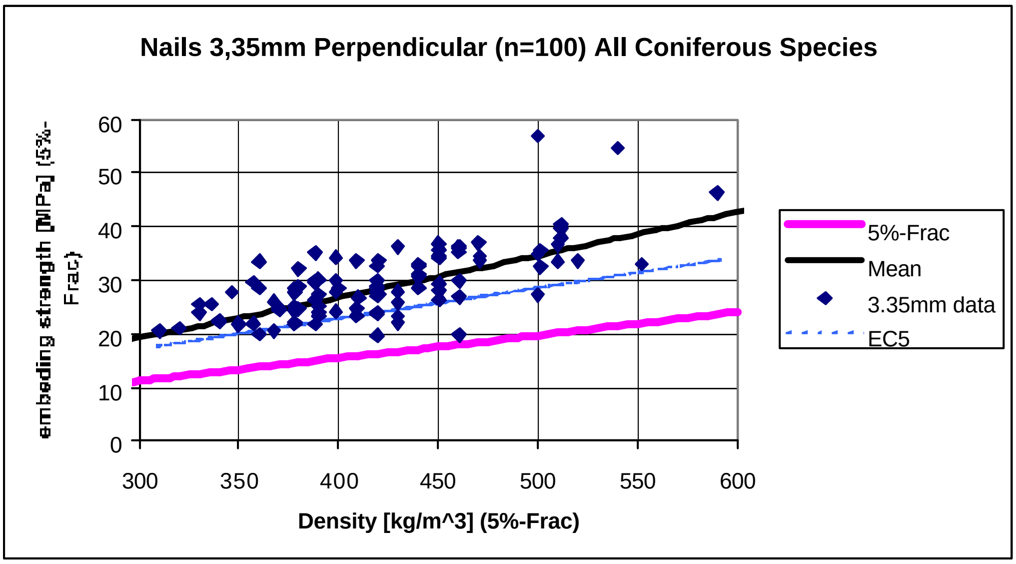
ANNEX 2

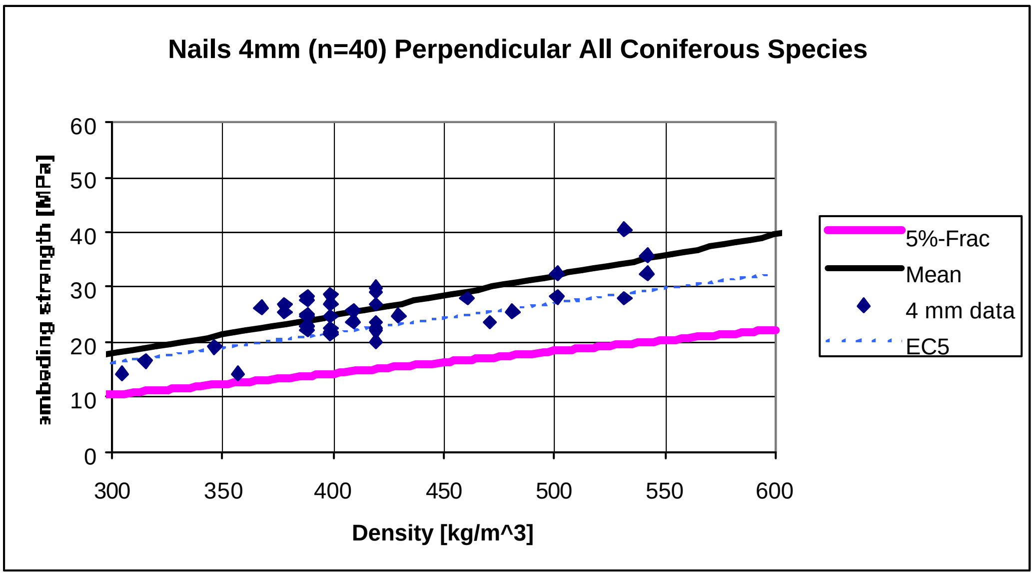

Nails d = 5mm (n=40) Parallel All Coniferous Species
embeding strength [MPa]
40
35
30
25
20
15
10
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
5mm data
EC5


Nails d = 6mm (n=136) Parallel All Coniferous Species
embeding strength [MPa]
40
35
30
25
20
15
10
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean regression
6mm data
EC5

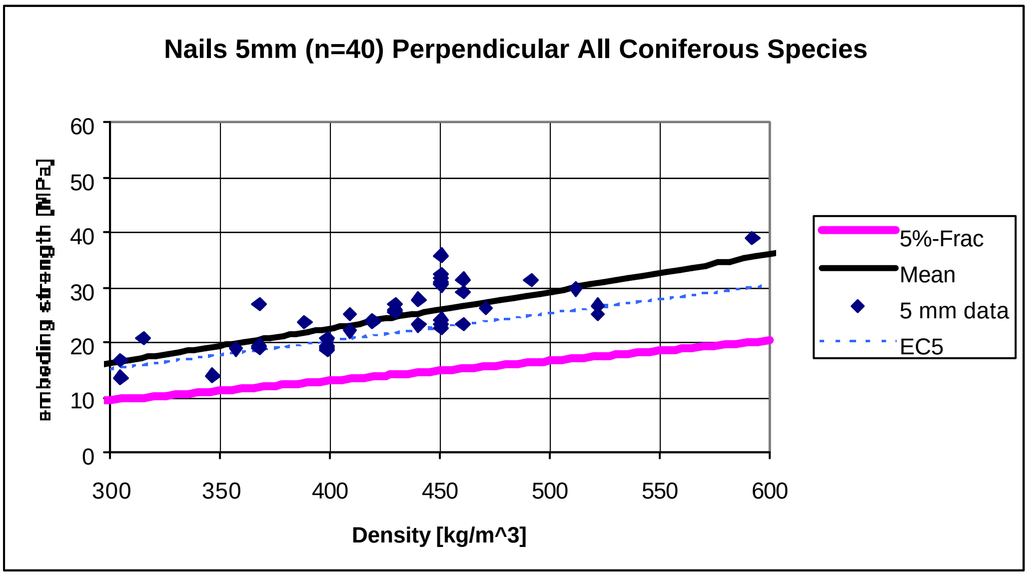
ANNEX 2

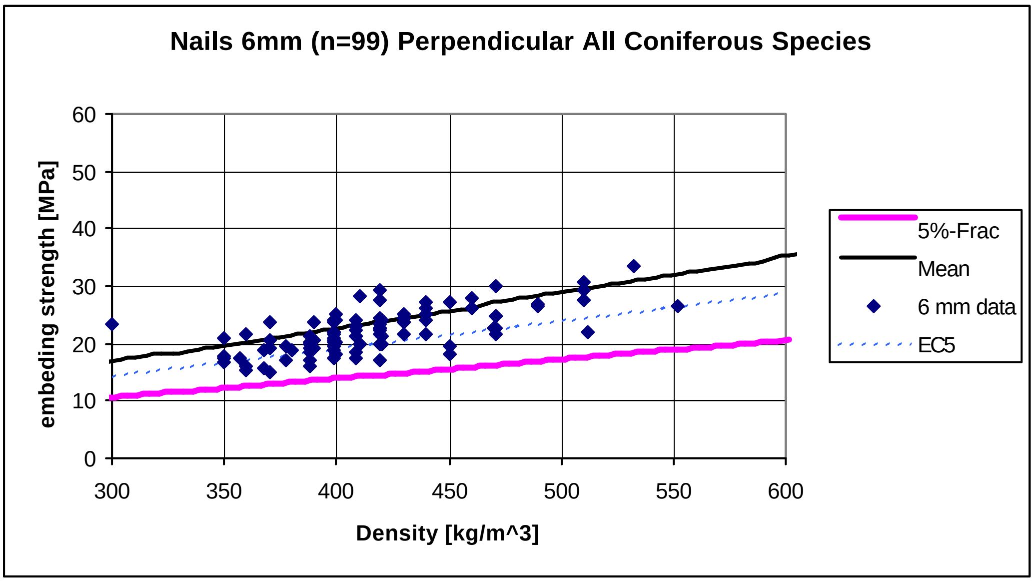

Nails 2,65mm (n=40) Perpendicular All Ciniferous Species
embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
2.65mm data
EC5


Nails 3,35mm Perpendicular (n=100) All Coniferous Species
embeding strength [MPa] (5%-Frac)
Density [kg/m^3] (5%-Frac)
5%-Frac
Mean
3.35mm data
EC5

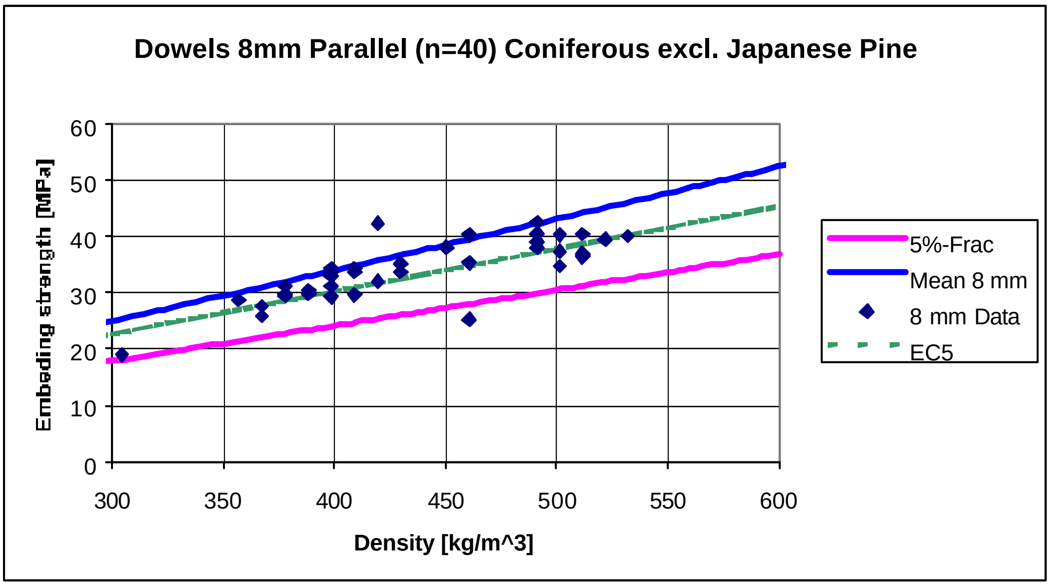

Nails 4mm (n=40) Perpendicular All Coniferous Species
embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
4 mm data
EC5

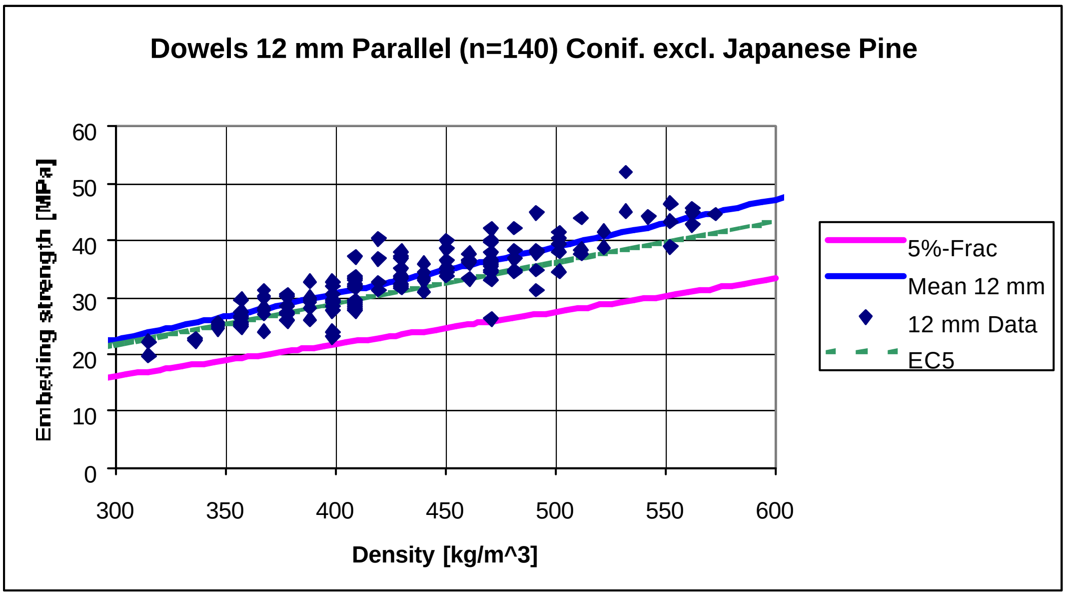
ANNEX 2

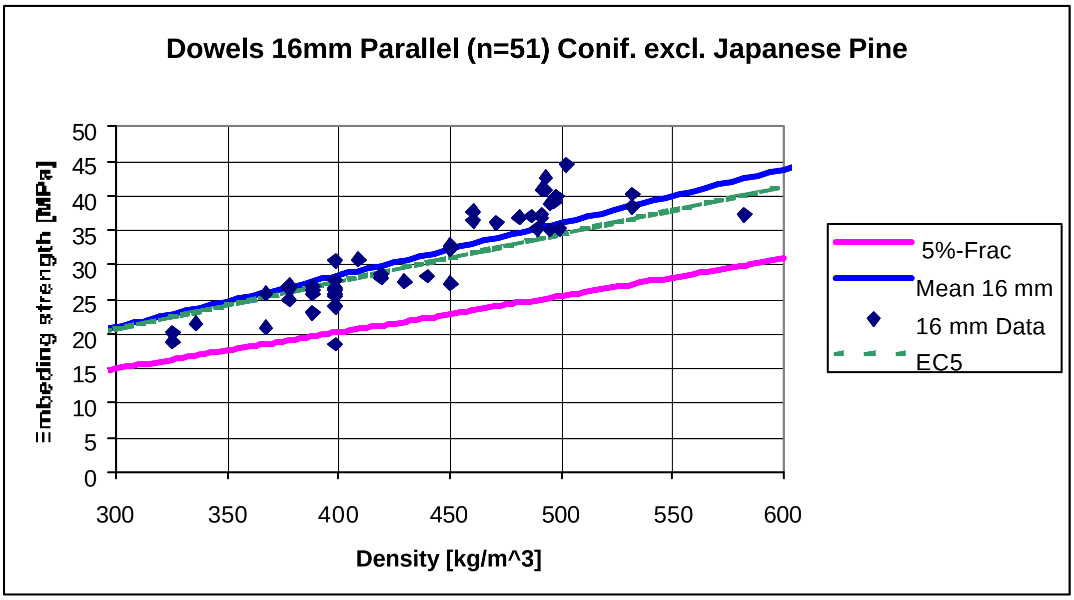

Nails 5mm (n=40) Perpendicular All Coniferous Species
embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
5 mm data
EC5


Nails 6mm (n=99) Perpendicular All Coniferous Species
embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
6 mm data
EC5

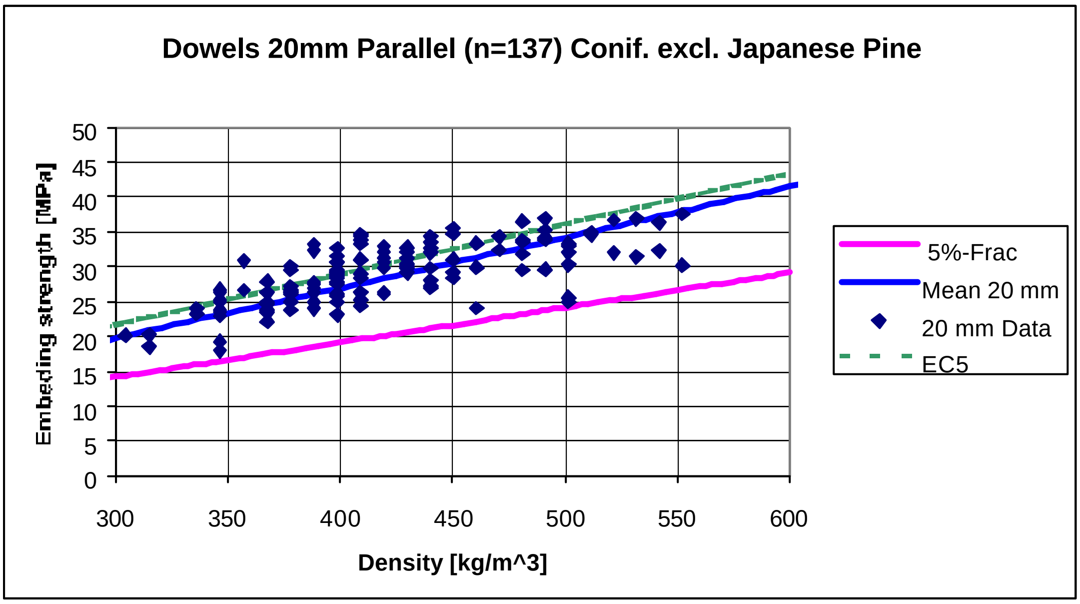
ANNEX 2


Dowels 8mm Parallel (n=40) Coniferous excl. Japanese Pine
Embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean 8 mm
8 mm Data
EC5


Dowels 12 mm Parallel (n=140) Conif. excl. Japanese Pine
Embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean 12 mm
12 mm Data
EC5

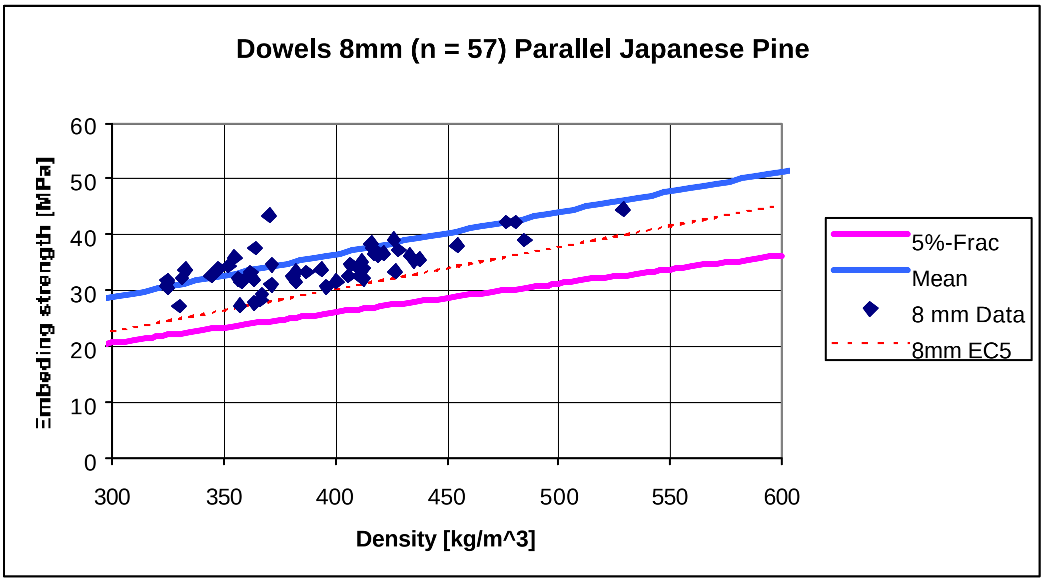

Dowels 16mm Parallel (n=51) Conif. excl. Japanese Pine
Embeding strength [MPa]
50
45
40
35
30
25
20
15
10
5
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean 16 mm
16 mm Data
EC5

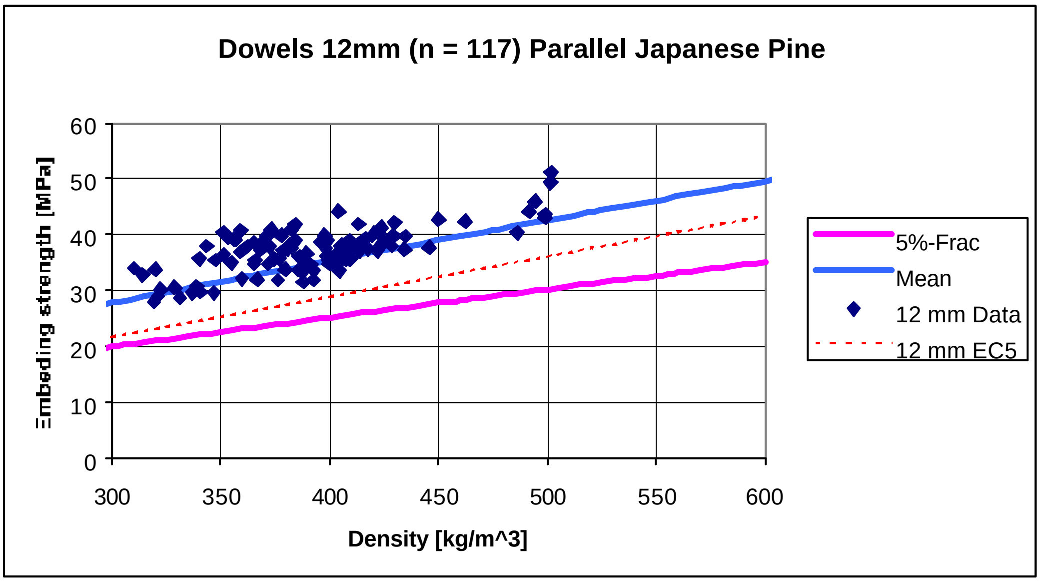
ANNEX 2

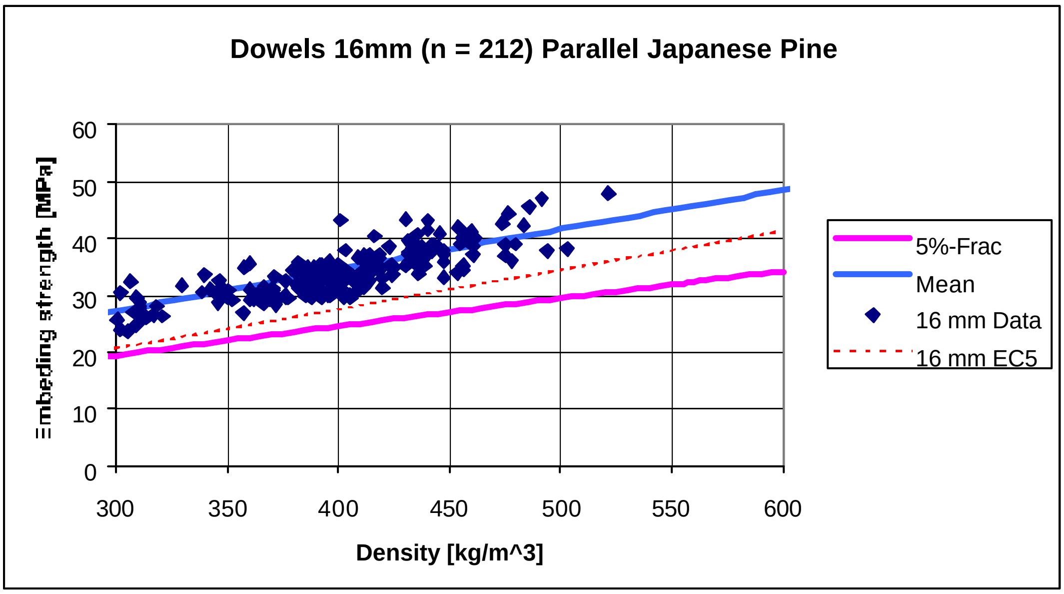


Dowels 20mm Parallel (n=137) Conif. excl. Japanese Pine
Embeding strength [MPa]
50
45
40
35
30
25
20
15
10
5
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean 20 mm
20 mm Data
EC5

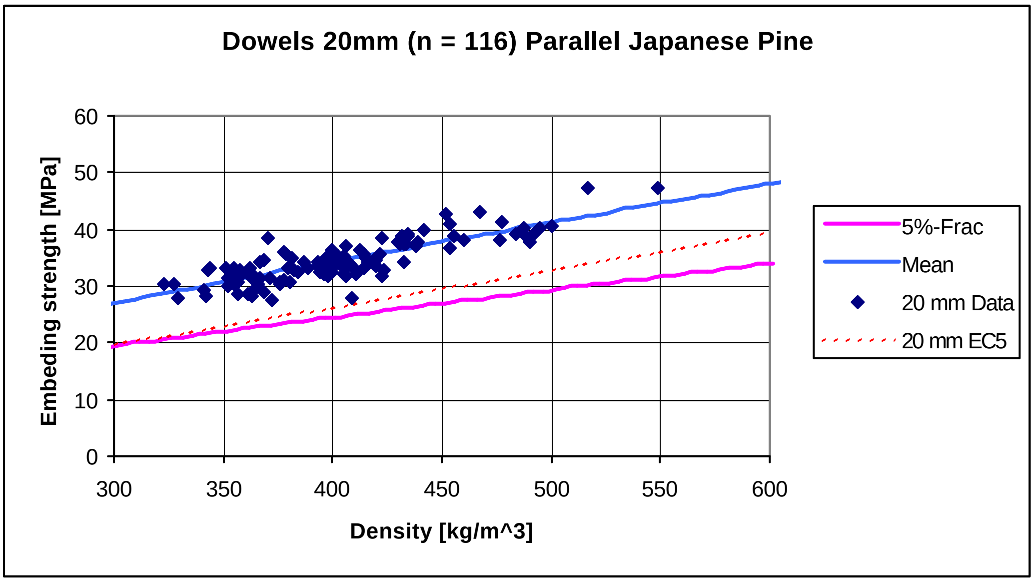
ANNEX 2

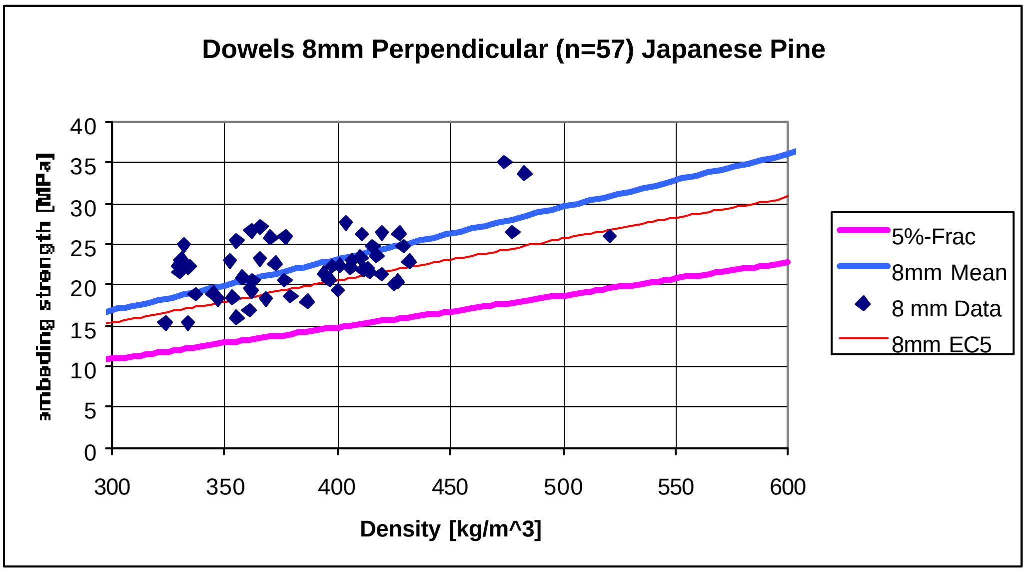

Dowels 8mm (n = 57) Parallel Japanese Pine
Embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
8 mm Data
8mm EC5

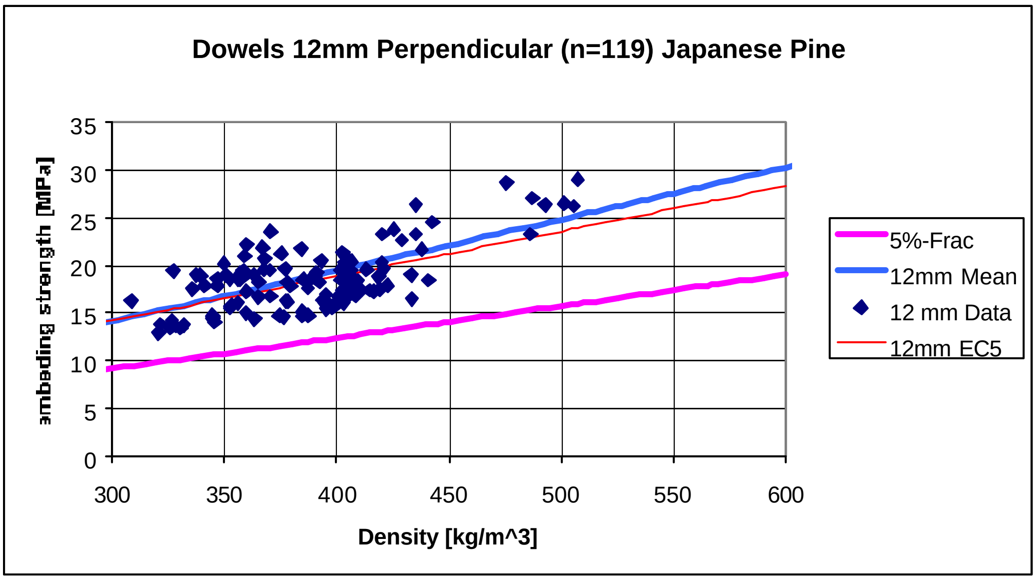

Dowels 12mm (n = 117) Parallel Japanese Pine
Embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
12 mm Data
12 mm EC5


Dowels 16mm (n = 212) Parallel Japanese Pine
Embeding strength [MPa]
Density [kg/m^3]
5%-Frac
Mean
16 mm Data
16 mm EC5

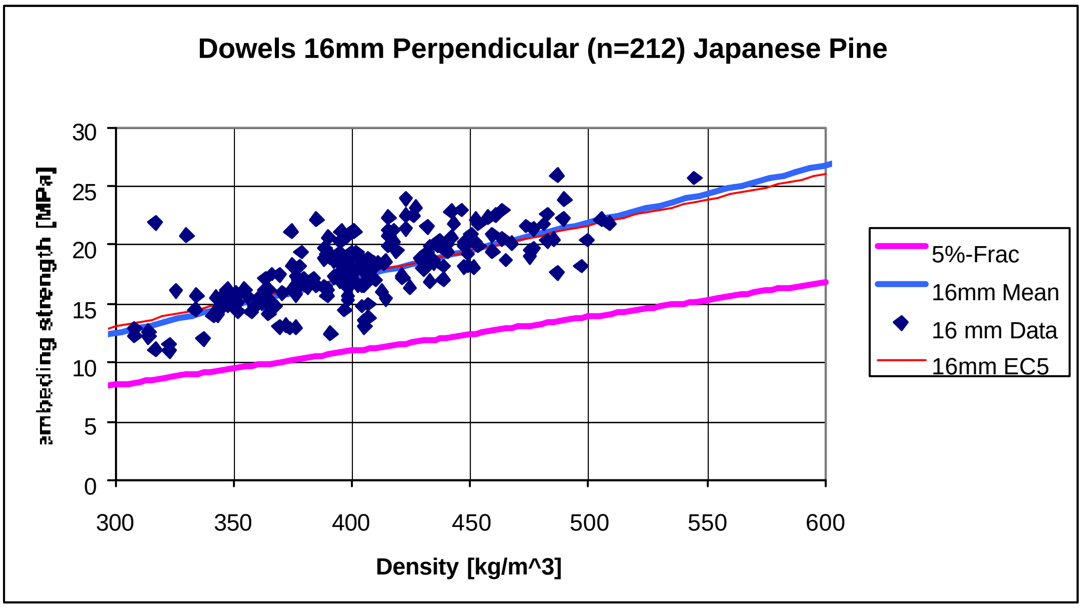
ANNEX 2

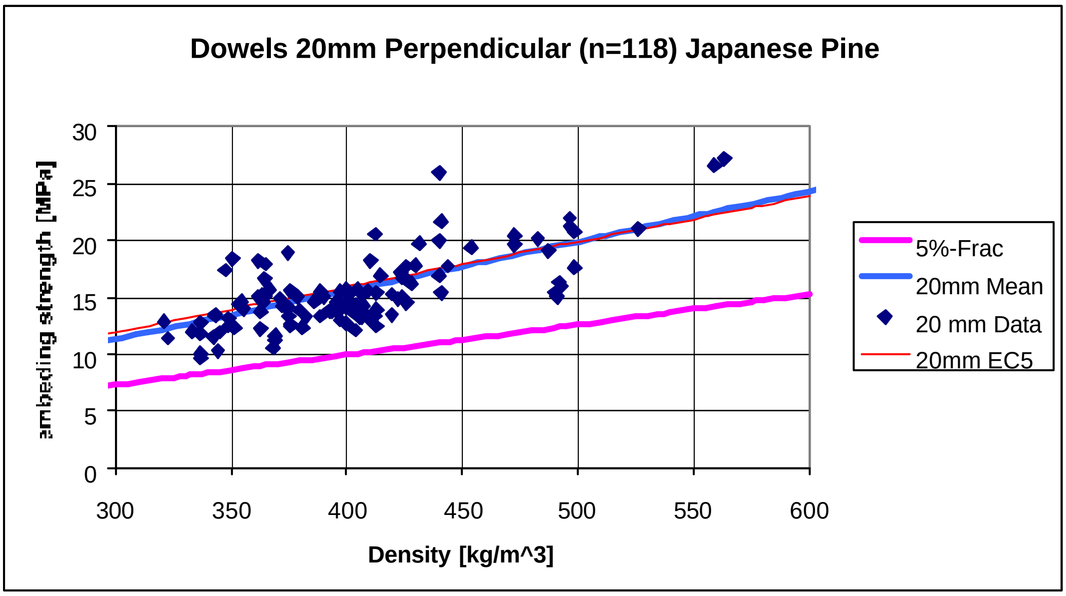

Dowels 20mm (n = 116) Parallel Japanese Pine
Embeding strength [MPa]
0
10
20
30
40
50
60
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
20 mm Data
20 mm EC5


Dowels 8mm Perpendicular (n=57) Japanese Pine
mbeding strength [MPa]
0
5
10
15
20
25
30
35
40
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
8mm Mean
8 mm Data
8mm EC5

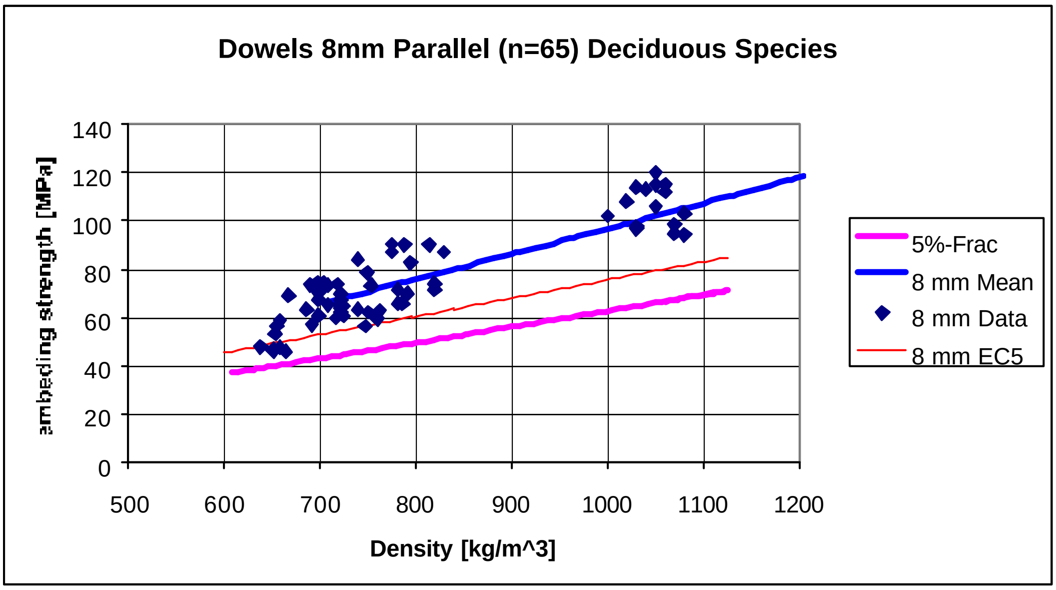

Dowels 12mm Perpendicular (n=119) Japanese Pine
mbeding strength [MPa]
0
5
10
15
20
25
30
35
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
12mm Mean
12 mm Data
12mm EC5

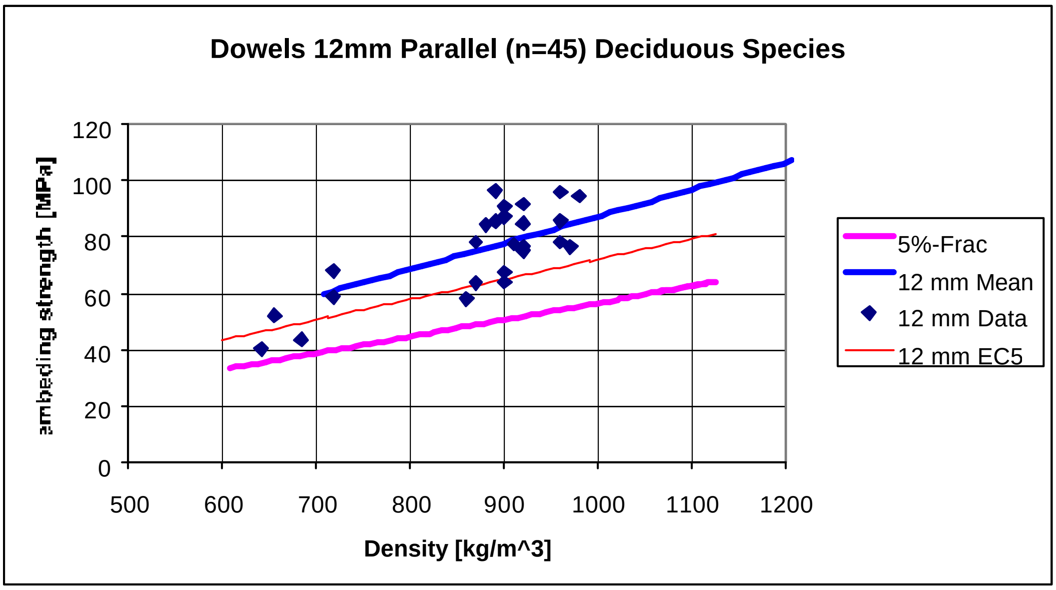
ANNEX 2

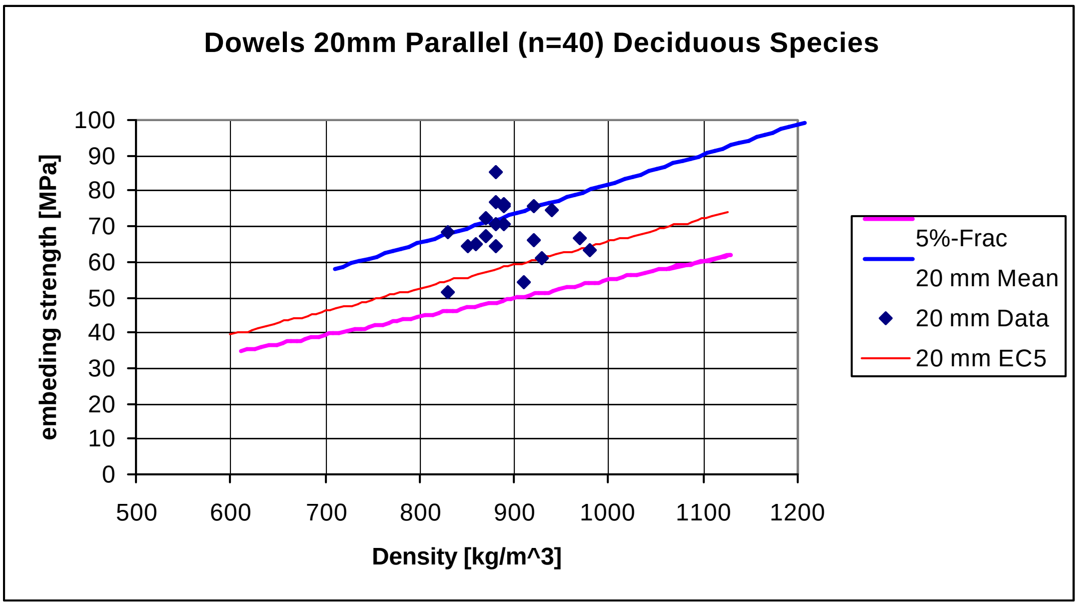

Dowels 16mm Perpendicular (n=212) Japanese Pine
embeding strength [MPa]
30
25
20
15
10
5
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
16mm Mean
16 mm Data
16mm EC5


Dowels 20mm Perpendicular (n=118) Japanese Pine
embeding strength [MPa]
30
25
20
15
10
5
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
20mm Mean
20 mm Data
20mm EC5

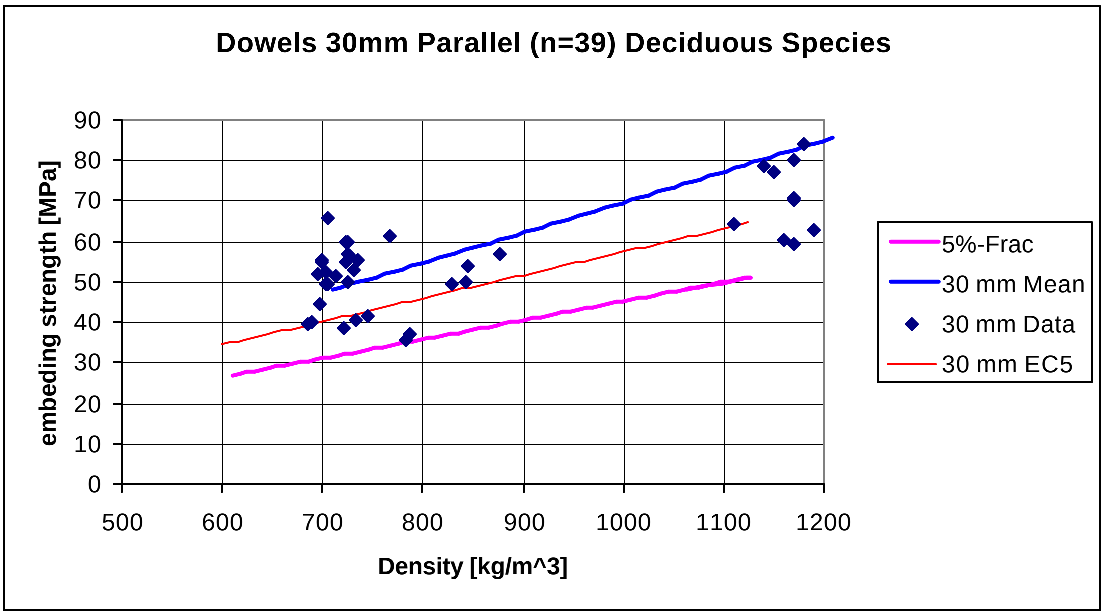
ANNEX 2

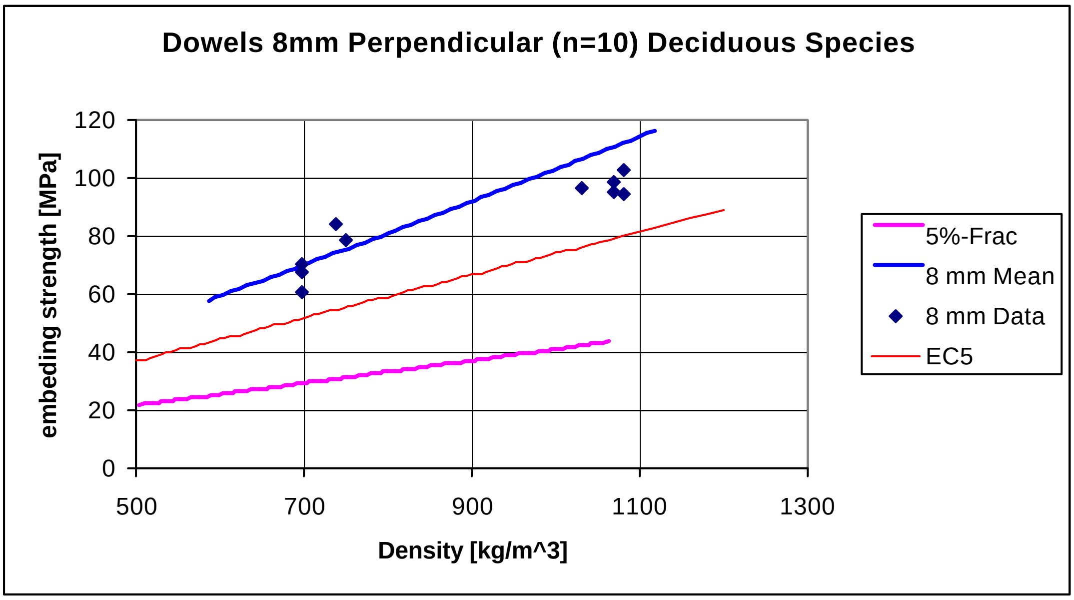

Dowels 8mm Parallel (n=65) Deciduous Species
embeding strength [MPa]
140
120
100
80
60
40
20
0
500
600
700
800
900
1000
1100
1200
Density [kg/m^3]
5%-Frac
8 mm Mean
8 mm Data
8 mm EC5

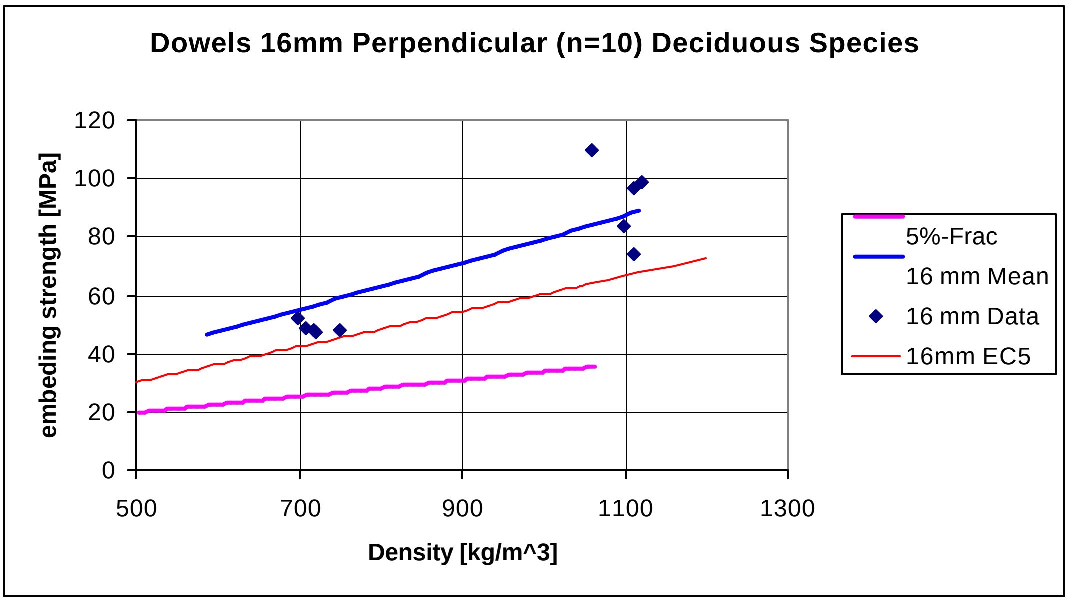

Dowels 12mm Parallel (n=45) Deciduous Species
embeding strength [MPa]
120
100
80
60
40
20
0
500
600
700
800
900
1000
1100
1200
Density [kg/m^3]
5%-Frac
12 mm Mean
12 mm Data
12 mm EC5


Dowels 20mm Parallel (n=40) Deciduous Species
embeding strength [MPa]
100
90
80
70
60
50
40
30
20
10
0
500
600
700
800
900
1000
1100
1200
Density [kg/m^3]
5%-Frac
20 mm Mean
20 mm Data
20 mm EC5

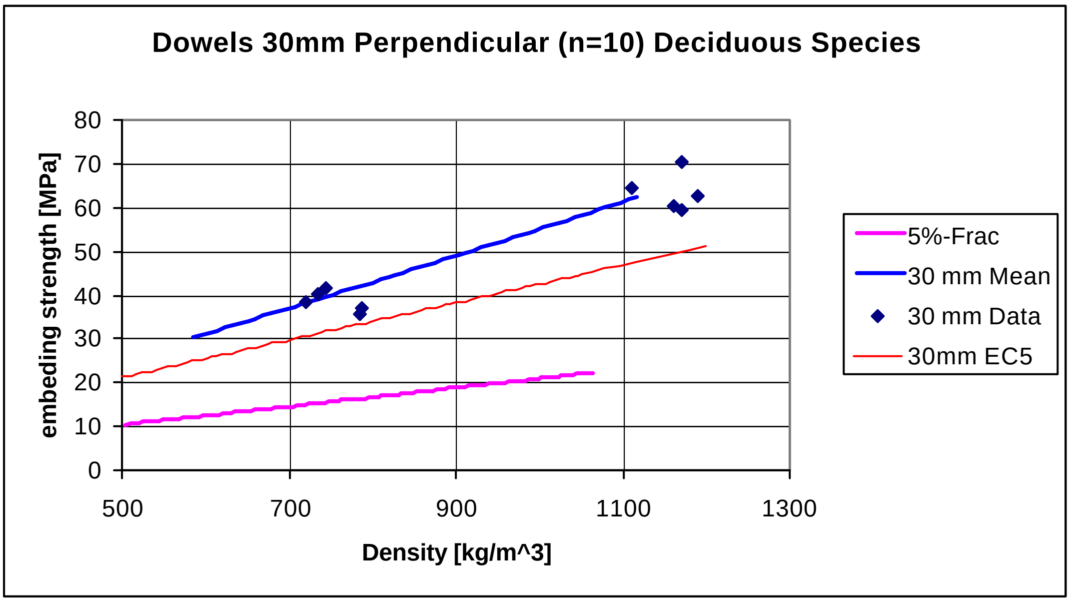
ANNEX 2


Dowels 30mm Parallel (n=39) Deciduous Species
embeding strength [MPa]
0
10
20
30
40
50
60
70
80
90
500
600
700
800
900
1000
1100
1200
Density [kg/m^3]
5%-Frac
30 mm Mean
30 mm Data
30 mm EC5

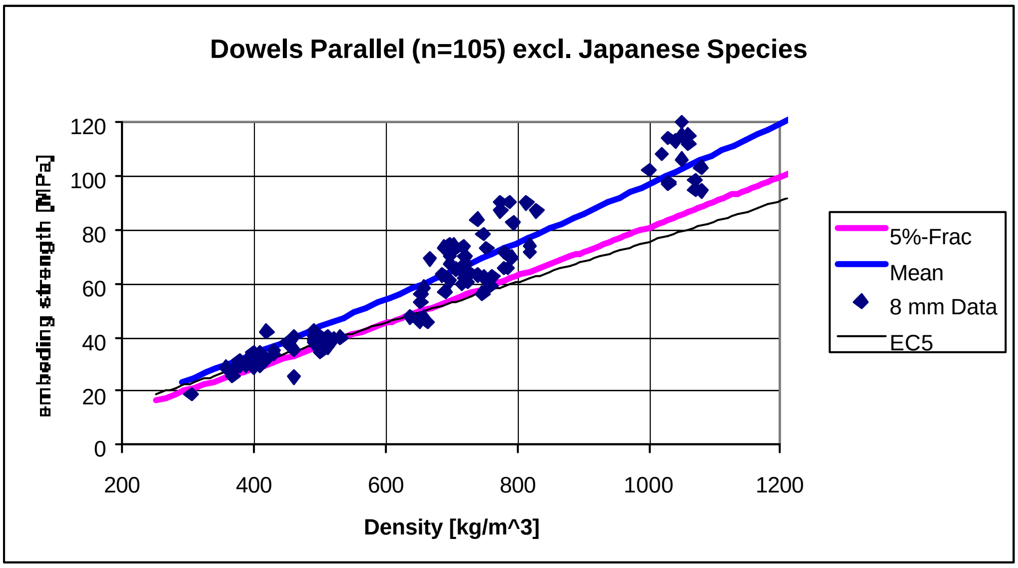

Dowels 8mm Perpendicular (n=10) Deciduous Species
embeding strength [MPa]
0
20
40
60
80
100
120
500
700
900
1100
1300
Density [kg/m^3]
5%-Frac
8 mm Mean
8 mm Data
EC5

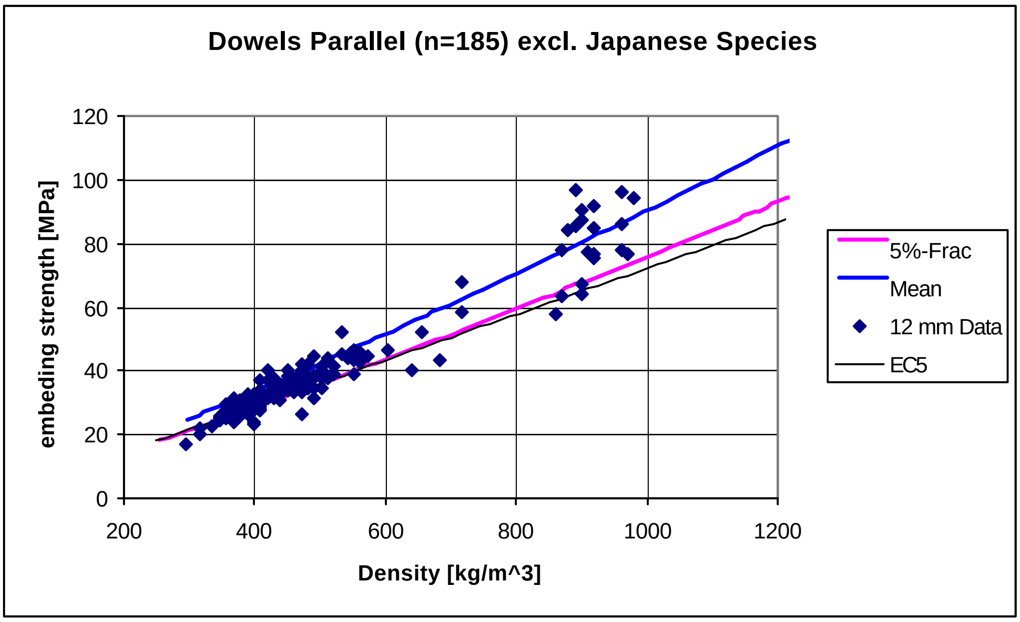

Dowels 16mm Perpendicular (n=10) Deciduous Species
embeding strength [MPa]
0
20
40
60
80
100
120
500
700
900
1100
1300
Density [kg/m^3]
5%-Frac
16 mm Mean
16 mm Data
16mm EC5

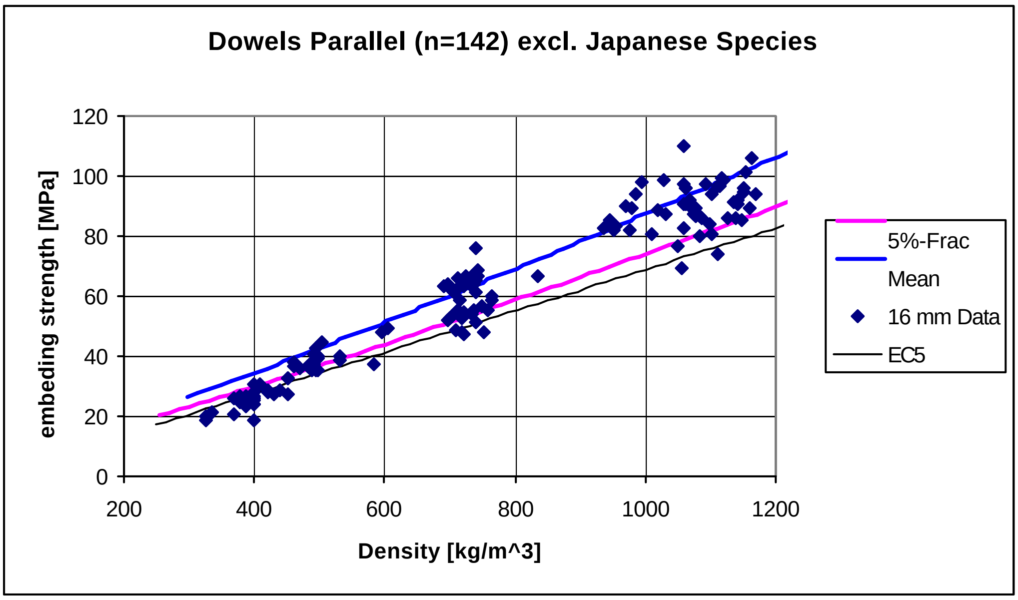
ANNEX 2


Dowels 30mm Perpendicular (n=10) Deciduous Species
embeding strength [MPa]
80
70
60
50
40
30
20
10
0
500
700
900
1100
1300
Density [kg/m^3]
5%-Frac
30 mm Mean
30 mm Data
30mm EC5

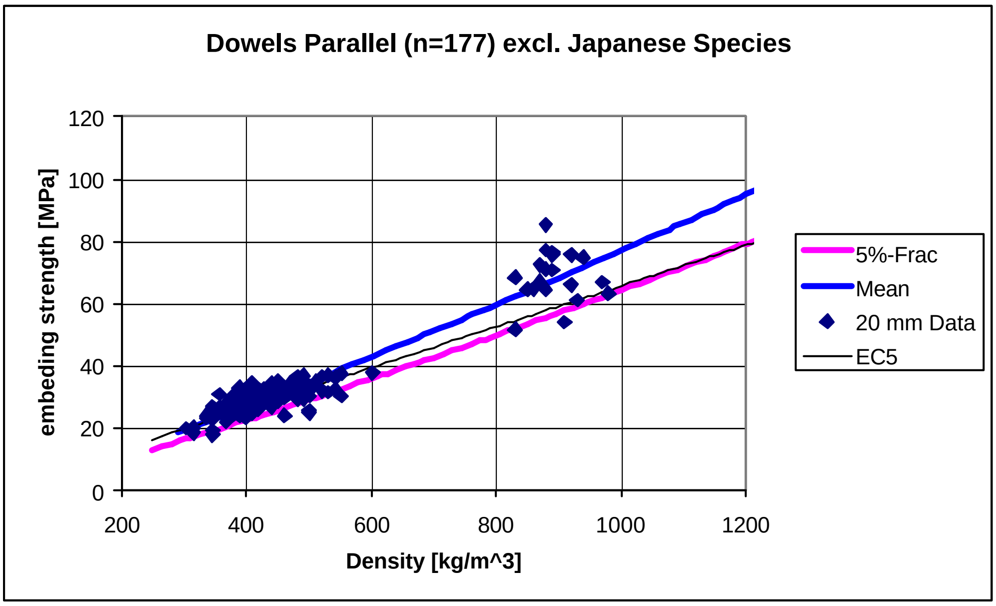
ANNEX 3

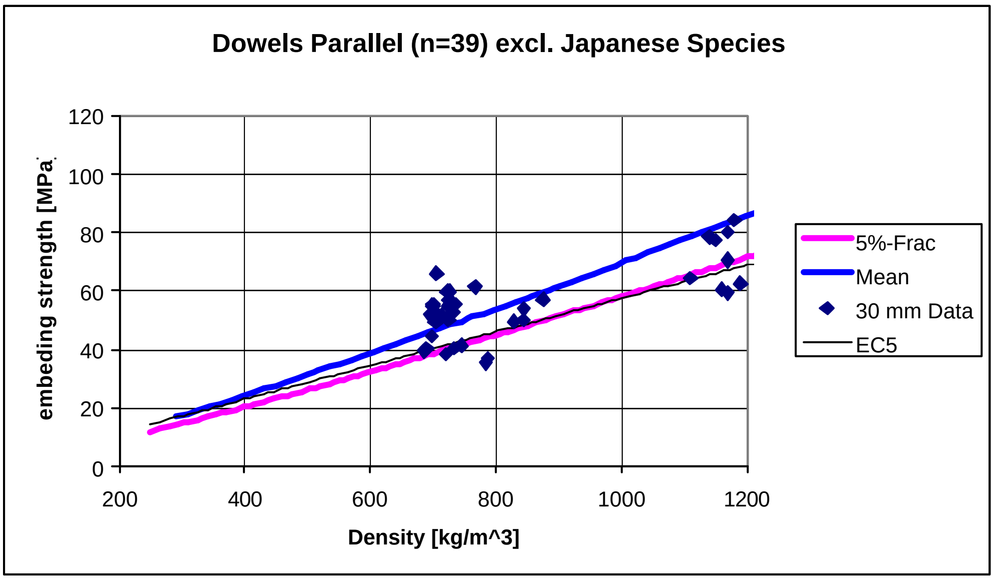

Dowels Parallel (n=105) excl. Japanese Species
embeding strength [MPa]
Density [kg/m^3]
0
20
40
60
80
100
120
200
400
600
800
1000
1200
5%-Frac
Mean
8 mm Data
EC5

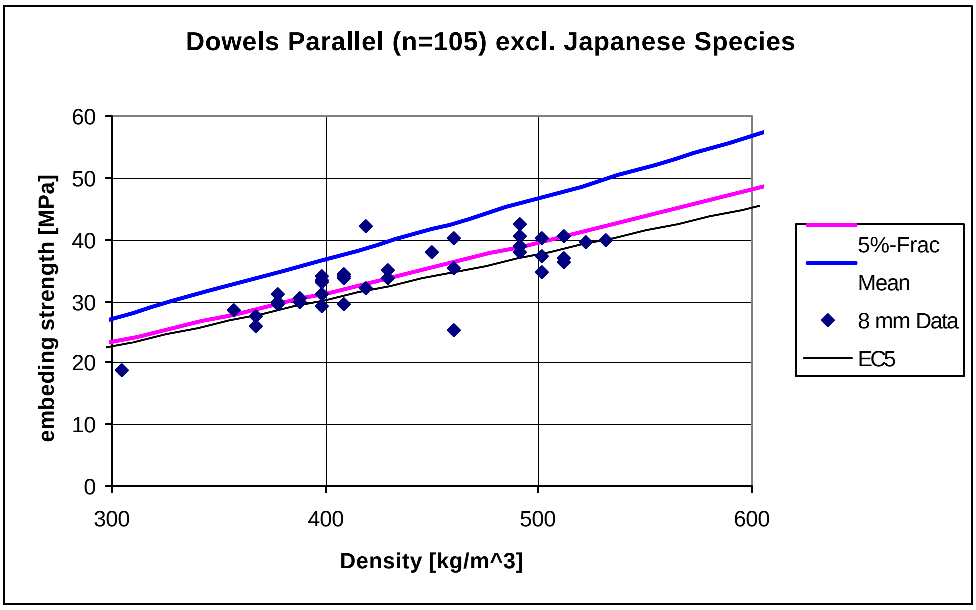

Dowels Parallel (n=185) excl. Japanese Species
embeding strength [MPa]
Density [kg/m^3]
0
20
40
60
80
100
120
200
400
600
800
1000
1200
5%-Frac
Mean
12 mm Data
EC5


Dowels Parallel (n=142) excl. Japanese Species
embeding strength [MPa]
Density [kg/m^3]
0
20
40
60
80
100
120
200
400
600
800
1000
1200
5%-Frac
Mean
16 mm Data
EC5

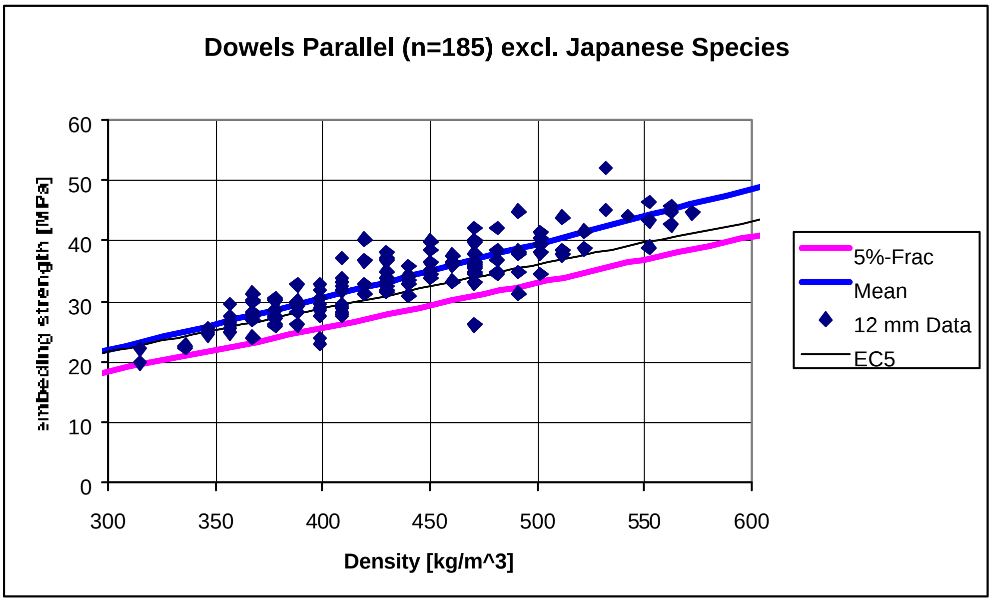
ANNEX 3

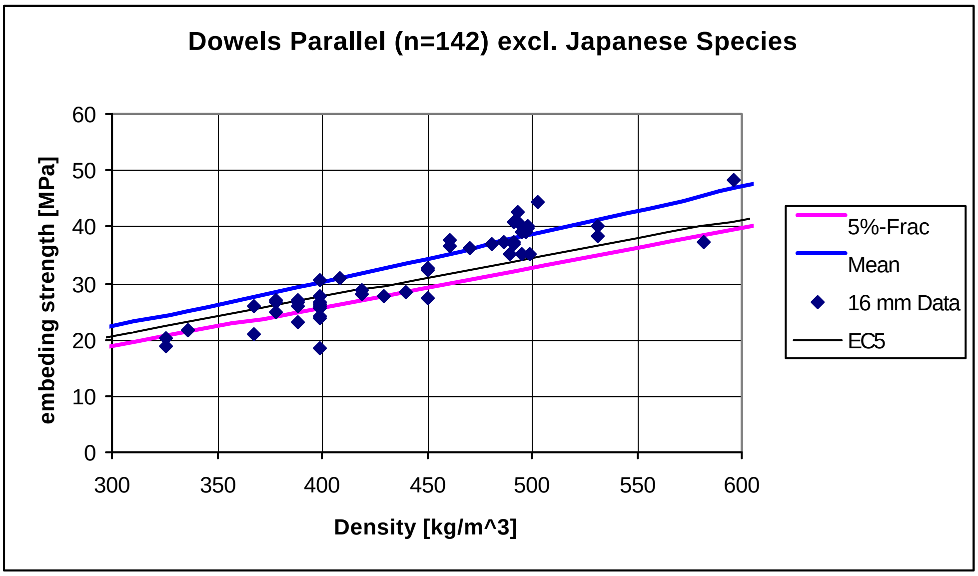

Dowels Parallel (n=177) excl. Japanese Species
embeding strength [MPa]
0
20
40
60
80
100
120
200
400
600
800
1000
1200
Density [kg/m^3]
5%-Frac
Mean
20 mm Data
EC5

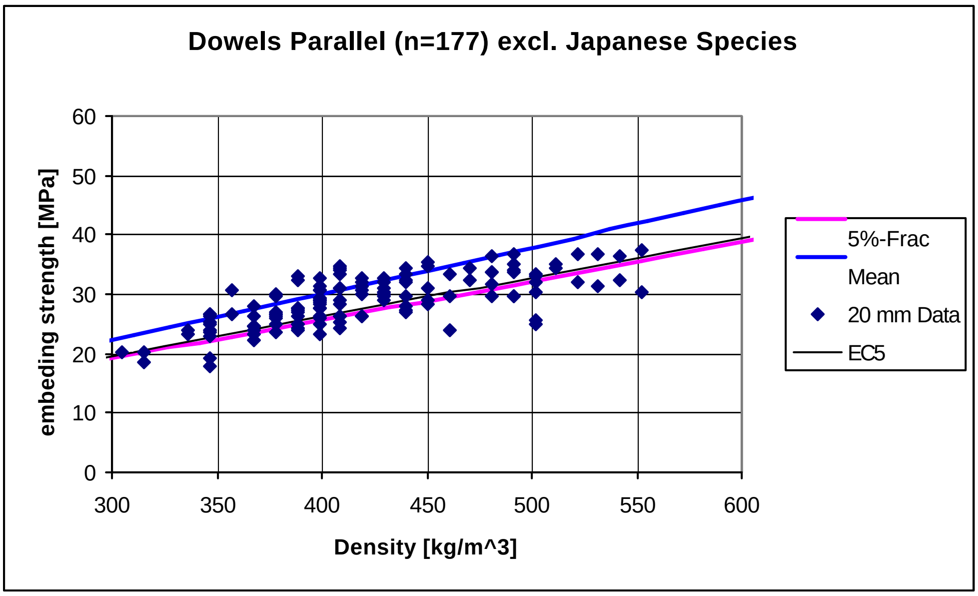

Dowels Parallel (n=39) excl. Japanese Species
embeding strength [MPa]
0
20
40
60
80
100
120
200
400
600
800
1000
1200
Density [kg/m^3]
5%-Frac
Mean
30 mm Data
EC5


Dowels Parallel (n=105) excl. Japanese Species
embeding strength [MPa]
0
10
20
30
40
50
60
300
400
500
600
Density [kg/m^3]
5%-Frac
Mean
8 mm Data
EC5

ANNEX 3


Dowels Parallel (n=185) excl. Japanese Species
embedding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
12 mm Data
EC5


Dowels Parallel (n=142) excl. Japanese Species
embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
16 mm Data
EC5


Dowels Parallel (n=177) excl. Japanese Species
embeding strength [MPa]
60
50
40
30
20
10
0
300
350
400
450
500
550
600
Density [kg/m^3]
5%-Frac
Mean
20 mm Data
EC5