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Background data for determining partial factors for concrete structures in Eurocode 2, DS/EN 1992-1-1:2023 DK NA

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Content

1. Introduction

The purpose of this document is to create the basis for determining the partial factors in the Danish national annex to EC2 part 1-1, i.e. the document DS/EN 1992-1-1:2023 DK NA.

The basis for the analysis is DS/EN 1990:2023 annex D and DS/EN 1990:2023 DK NA annex FF.

This document also deals with matters related to the tensile strength of concrete specified in DS/EN 1992-1-1:2023.

Many factors influence the testing of concrete strength. For example, a strength test with the same concrete under uniform conditions in the same laboratory at different times could give different results for, as an example, the average value of the compressive strength. Therefore, analyses of coefficients of variation associated with concrete strengths cannot yield a clear result, but results that can be indicative of usable values.

2. Partial factors i DS/EN 1992-1-1:2023 DK NA

DS/EN 1992-1-1:2023 includes several partial factors. Since Denmark has its own safety system, the partial factors specified in DS/EN 1992-1-1:2023 are not used in Denmark, i.e. Denmark has its own partial factors. The purpose of this document is to provide the basis for determining the partial factors in the Danish national annex to DS/EN 1992-1-1-:2023 i.e. DS/EN 1992-1-1:2023 DK NA.

The basis for determining partial factors is given in DS/EN 1990:2023 DK NA, annex FF.

The results of the analysis and the calculated partial factors is included in chapter 14.

3. Concrete, compressive strength of in-situ cast specimens (V_{3,R,f_c})

The compressive strength of concrete according to DS/EN 1992-1-1 is determined by testing in-situ cast, cylindrical test specimens with dimensions d = 150 mm and h = 300 mm. The compressive strength is determined after 28 days. The requirements for storage/curing of test specimens and the performance of testing are set out in the standards DS/EN 12390-1 – DS/EN 12390-3, which thus forms the basis for determining the strength of concrete according to DS/EN 1992-1-1.

Test specimens are cast at the site where the concrete is mixed, i.e. concrete plants, precast concrete element factories and universities, see Figure 3.1.

Figure 3.1: In-situ cast concrete specimens for compression testing

Table 3.1 gives statistical values for compressive strength tests carried out at precast element factories. These tests are a part of the control system documenting the compression strength of the used concrete.

Table 3.2 gives statistical values for compressive strength tests carried out at a university in connection with experiments with structural members. These test specimens have been stored in the same way as the structural test members connected to the cores, meaning that they have not been water cured.

Coefficients of variation have been calculated according to DS/EN 1990:2023 corresponding to logarithmic normal distribution.

All test values have been determined on cylinders 100x200 mm. DS 11990 states that to determine the value for cylinders 150x300 mm, stated strength values must be multiplied by a factor of 0.95.

In Appendix A, Figures A.1-A.7, the test values used for the series in table 3.1 are shown.

Series	Number of test values	f_{cm} MPa	COV %	Notes
1	35	42,3	4,0	See test values in Figure A.1.
2	10 (9)	66,7 (68,7)	11,6 (3,9)	A single test value of 48.5 MPa falls significantly outside the other test values but does not meet the requirements for Lower outliner according to DS/EN 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure A.2.
3	12 (11)	70,9 (72,5)	9,7 (4,6)	A single test value of 53,6 MPa falls significantly outside the other test values but does not meet the requirements for Lower outliner according to DS/EN 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure A.3.
4	14	62,4	6,9	See test values in Figure A.4.
5	74 (73)	47,1 (47,3)	9,7 (8,9)	A single test value of 33,1 MPa falls significantly outside the other test values but does not meet the requirements for Lower outliner according to DS/EN 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure A.5.
6	14 (12)	65,2 (67,6)	13,5 (9.5)	The air content is in the interval 4.5 – 6.8 %. Taking two of the test values away, where the air content is 6.8 % and test values are 50.8 and 50.6 MPa, the air content for the remaining test specimens is in the interval 4.5 - 5.9, values given in brackets is obtained. See test values in Figure A.6.
7	560	60,2	6,9	See test values in Figure A.7.

Table 3.1: Testing of concrete compressive strength, in-situ cast specimens at factories

All test values are in the range 40 MPa to 75 MPa.

In Appendix A, Figures A.8-A.15, the test values used for the series in table 3.2 are shown.

Series	Number of test values	f_{cm} MPa	COV %	Notes
8	5 (3)	29,4 (30,6)	7,5 (4,7)	2 test specimens have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.8.
9	6 (3)	34,9 (36,5)	14,6 (1,9)	3 test specimens have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained.See test values in Figure A.9.
10	6 (5)	39,5 (39,3)	6,2 (6,8)	1 test specimen have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.10.
11	6 (5)	38,4 (38,6)	2,9 (2,6)	1 test specimen have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.11.
12	6 (4)	39,5 (40,1)	3,5 (2,7)	2 test specimens have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.12.
13	6	37,0	6,7	See test values in Figure A.13.
14	36 (34)	49,1 (49,7)	10,7 (8,9)	2 test specimens have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.14.
15	30 (29)	40,2 (40,7)	10,3 (5,9)	1 test specimen have been eliminated because the failure mode was not correct. If these test values are removed, values given in brackets is obtained. See test values in Figure A.15.

Table 3.2: Testing of concrete compressive strength, in-situ cast specimens at university

In the following analysis the corrected coefficients of variation given in brackets in table 3.1 and 3.2 are used.

In Figure 3.2 -3.4 the coefficient of variations is shown.

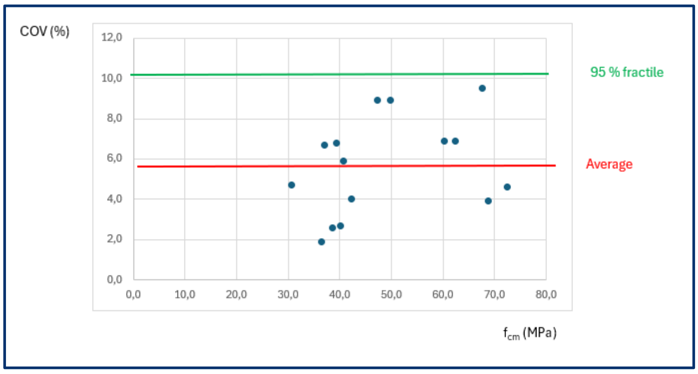


Figure 3.2: Coefficient of variations from table 3.1 and table 3.2

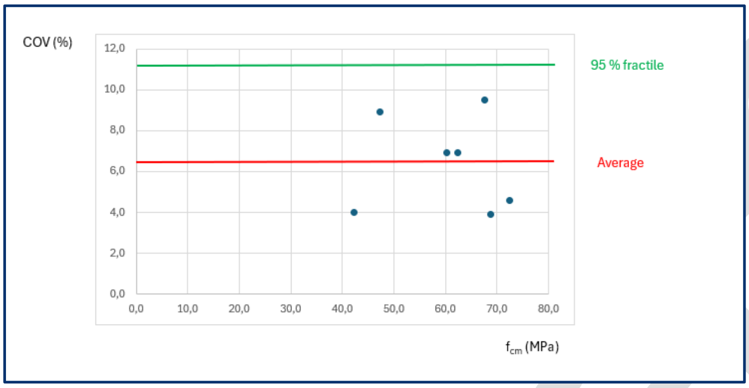


Figure 3.3: Coefficient of variations from table 3.1

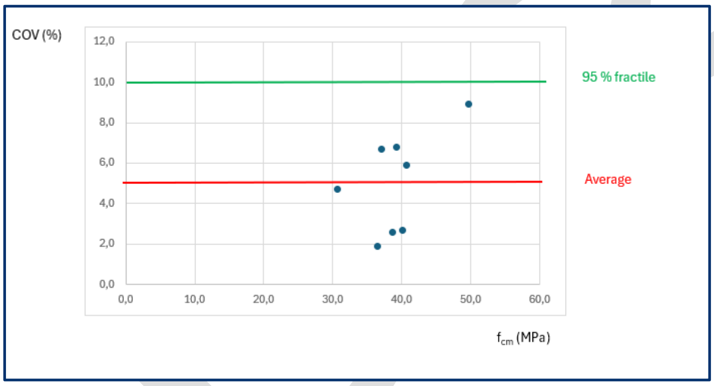


Figure 3.4: Coefficient of variations from table 3.2

The average values in Figure 3.2 – 3.4 are 5.7 %, 6,4 % and 5,0 %

Taking the 5 series with largest number of tests, i.e. series 1, 5, 7, 14 and 15, the average is 6.9 %.

The test results shows that the coefficient of variation is nearly the same for test done at factories and at the universities, meaning that there are no arguments for differing.

The background document to DS/EN 1992-1-1:2023 states that there is a difference in coefficient of variation between strengths measured at factories and at universities expressed by the values $V_{3,R,f_{c,factory}} = 6{,}0\ \%$ and $V_{3,R,f_{c,lab}} = 10{,}0\ \%$.

Based on the above, it seems reasonable to set the coefficient of variation for in-situ cast concrete specimens in accordance with DS/EN 1992-1-1:2023 to $V_{3,R,f_c} = 6{,}5\,\%$.

4. Reinforcement, tensile yield strength (V_{3,Rf_y}, V_{3,RTf_y} and V_{3,f_y})

The strength parameters of the reinforcement are determined by testing according to DS/EN 10080.

Table 4.1 gives test values for the tensile yield strength of hot-rolled steel. These tests is done at factories as a part of the control system documenting the strength of the reinforcement used.

Coefficients of variation have been calculated according to DS/EN 1990:2023 corresponding to logarithmic normal distribution.

Appendix B, Figures B.1-B.5, shows test values used for the series.

Series	Number of test values	f_{cm} MPa	COV %	Notes
S1	93 (92)	648 (646)	5,6 (5,3)	Ø = 6 mm. A single test value of 785 MPa meet the requirements for Upper outliner according to DS/EN 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure B.1.
S2	139	608	5,2	Ø = 8 mm. See test values in Figure B.2.
S3	200	620	4,2	Ø = 10 mm. See test values in Figure B.3.
S4	200 (199)	608 (608)	4,2 (4,0)	Ø = 12 mm. A single test value of 506 MPa meet the requirements for Lower outliner according to DS/EN 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure B.4.
S5	200	614	4,3	Ø = 16 mm. See test values in Figure B.5.

Table 4.1: Test values for tensile yield strength of reinforcement

In the following analysis the corrected coefficients of variation given in brackets in table 4.1 are used.

Taking the average of the calculated coefficients of variation of 4.6 % is obtained. The 95 % fractile value is 5,6 %.

The coefficient of variation seems higher for the small diameters. It is not known whether this is a general phenomenon.

Where there are many test values, i.e. series S3-S5, the coefficient of variation is seen to be fairly stable at around 4.2 %.

The background document to DS/EN 1992-1-1:2023 indicates $V_{3,R,f_y} = 4{,}5\,\%$.

Based on the above, it seems reasonable to set the coefficient of variation for reinforcement at $V_{3,R,f_y} = 4{,}5\,\%$.

The coefficient of variation is the same for laboratories and the real structure meaning that that that $V_{3,RTf_y} = 0\,\%$ and $V_{3,f_y} = 4{,}5\,\%$.

5. Concrete, compressive strength in real structures performed as in-situ cast concrete (V_{3,RTf_c} and V_{3,f_c})

5.1 Generally

This chapter deals with the drilling of test specimens from in-situ cast concrete structures to determine the compressive strength of the concrete in the real structure.

Figure 5.1: Drilling of concrete cores for testing

Samples are taken as drilled cores and taken from different types of structural members. DS/EN 13791 has been followed by the drilling and testing of the test specimens.

Coefficients of variation have been calculated according to DS/EN 1990:2023 corresponding to logarithmic normal distribution.

5.2 Columns

Table 5.1 shows test results for cores drilled at mid-height of columns that are part of a building.

A concrete with D_{max} = 8 mm was used. Drilled cores are approx. 55 mm in diameter and approx. 55 mm in height. The dimensions were chosen due to dense reinforcement in the columns. For conversion to in-situ strength corresponding to the standard cylinder size (150 x 300) according to DS/EN 1992-1-1, the factor 0.82 has been used, as specified in DS/EN 13791 and DS 11990. The statistical data provided are based on the converted values. The special rules for using cores with diameters less than 75 mm has been followed.

All series have been reviewed for the purpose of assessing the homogeneity of the population of test values e.g. in relation to the concrete type being the same within a series.

Series	Number of test values	f_{cm} MPa	COV %	Notes
CS1	7	45,5	7,6	One test value has been removed because of high air content. 5 test values have been removed because the columns was a part of a wall structure. See test values in Figure C.1.
CS2	12	47,2	10,1	4 test values have been removed because the columns was a part of a wall structure. See test values in Figure C.2.
CS3	15 (14)	54,1 (52,3)	13,7 (8,9)	A single test value of 79,0 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.3.
CS4	14 (13)	51,7 (50,7)	9,1 (6,5)	A single test value of 64,9 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.4.
CS5	13	51,7	11,2	See test values in Figure C.5.
CS6	10	56,4	13,2	See test values in Figure C.6.
CS7	12	60,5	8,7	See test values in Figure C.7.
CS8	12	58,1	8,5	See test values in Figure C.8.
CS9	15 (14)	34,5 (33,4)	13,4 (8,8)	A single test value of 49.8 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.9.
CS10	14	36,8	14,6	See test values in Figure C.10.
CS11	10	48,4	16,4	Not the same concrete type used for all specimens. One type is a mix having a lower strength. The test series is not included in the analysis. See test values in Figure C.11.
CS12	9	47,7	10,7	See test values in Figure C.12.
CS13	12	43,6	9,4	See test values in Figure C.13.
CS14	12	41,3	10,3	See test values in Figure C.14.
CS15	12	40,3	15,3	Some of the specimens shows bleeding and many air accumulations. The test series is not included in the analysis. See test values in Figure C.15.
CS16	12	44,1	11,5	See test values in Figure C.16.
CS17	12	50,1	18,8	Four test specimens have a significant higher strength than the other. At the same time, they also have a higher density. A new recipe was introduced. The test series is not included in the analysis. See test values in Figure C.17.
CS18	12	44,1	9,2	See test values in Figure C.18.

CS19	11	39,3	10,1	One test specimen excluded because it contained reinforcement. See test values in Figure C.19.
CS20	12	42,3	8,5	See test values in Figure C.20.
CS21	12	39,5	8,8	See test values in Figure C.21.
CS22	11	40,6	5,6	See test values in Figure C.22.
CS23	12	55,2	11,5	See test values in Figure C.23.
CS24	12	49,2	14,7	One test specimen excluded because it contained reinforcement. It has not been possible to identify the concrete recipes used. The test series is not included in the analysis. See test values in Figure C.24.
CS25	13	41,8	24,1	Different air admixture used for the specimens. Strengths range from 29 to 66 MPa, which identifies that something is wrong. The test series is not included in the analysis. The See test values in Figure C.25.

Table 5.1: Compressive test results for concrete in structure taken at the mid-height of columns

The test results is shown in appendix C, Figure C1-C25.

In the following analysis the red marked values in table 5.1 are not included, and the values in the brackets are used. This gives 20 series.

The coefficient of variation is in Figure 5.2 for each series shown as a function of the average compression concrete strength.

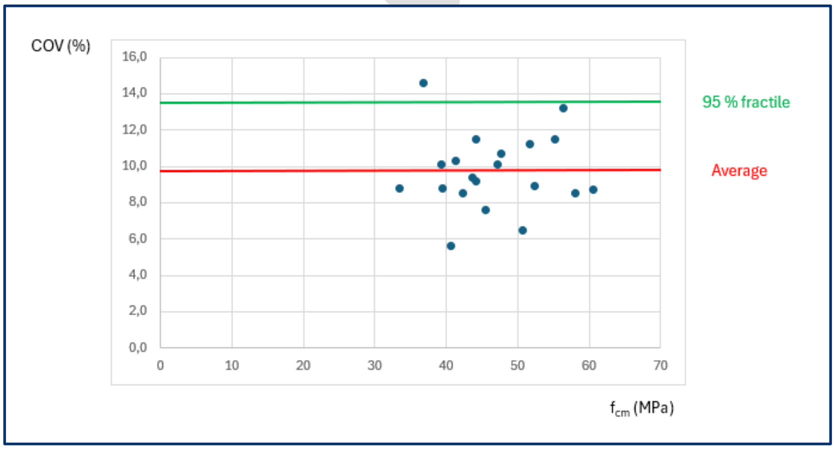


Figure 5.2: Coefficient of variation as a function of the compressive strength for each series for columns

The average value for the coefficient of variations is 9,7 %. The range of the average concrete strengths is 33 MPa to 61 MPa. Regarding the individual test values the range is a little larger.

If the 95 % probability of the 20 coefficients of variation is calculated, a coefficient of variation of 13,4 % is obtained for all the series.

5.3 Walls

Table 5.2 shows test results for cores drilled at mid-height of walls that are part of a building.

A concrete with D_{max} = 16 mm was used. The drilled cores all have a height-diameter ratio of 1. The height/diameter are in the range of 80 mm – 105 mm. For conversion to in-situ strength corresponding to the standard cylinder size (150 x 300) according to DS/EN 1992-1-1, the factor 0.82 has been used, as specified in DS/EN 13791 and DS 11990. The statistical data provided are based on the converted values.

Series	Number of test values	f_{cm} MPa	COV %	Notes
CW1	30	47,1	10,0	See test values in Figure C.30.
CW2	12	48,1	6,6	See test values in Figure C.31.
CW3	12 (11)	51,8 (50,1)	12,7 (8,4)	A single test value of 70,3 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.32.
CW4	8	49,5	8,8	See test values in Figure C.33.
CW5	8	50,1	11,8	See test values in Figure C.34.
CW6	8	51,3	5,4	See test values in Figure C.35.
CW7	8	49,8	11,7	Concrete delivered from two different plants. The test series is not included in the analysis. See test values in Figure C.36.
CW8	7	55,5	13,8	The difference in strengths seems to be connected to big differences in air admixture. The test series is not included in the analysis. See test values in Figure C.37.
CW9	8	50,9	5,4	See test values in Figure C.38.
CW10	8	55,8	7,2	See test values in Figure C.39.
CW11	8 (7)	51,6 (50,6)	5,8 (2,8)	A single test value of 58,5 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.40.
CW12	8	44,6	7,5	See test values in Figure C.41.
CW13	8	58,2	10,0	See test values in Figure C.42.
CW14	8	48,3	6,0	See test values in Figure C.43.
CW15	8	46,5	8,5	See test values in Figure C.44.
CW16	6	53,7	5,1	See test values in Figure C.45.
CW17	8	55,8	3,9	See test values in Figure C.46.
CW18	8	46,5	7,3	See test values in Figure C.47.
CW19	8	49,2	7,3	See test values in Figure C.48.
CW20	8	44,4	3,8	See test values in Figure C.49.
CW21	8	48,7	8,8	See test values in Figure C.50.
CW22	7	45,6	6,1	See test values in Figure C.51.
CW23	7	56,6	10,1	See test values in Figure C.52.
CW24	9	48,4	11,2	See test values in Figure C.53.
CW25	8	59,8	6,9	See test values in Figure C.54.

Table 5.2: Compressive test results for concrete in structure taken at the mid-height of the walls

The test results is shown in appendix C, Figure C30-C54.

In the following analysis the red marked values in table 5.2 are not included, and the values in the brackets are used. This gives 23 series.

The coefficient of variation is in Figure 5.3 for each series shown as a function of the average compression concrete strength.

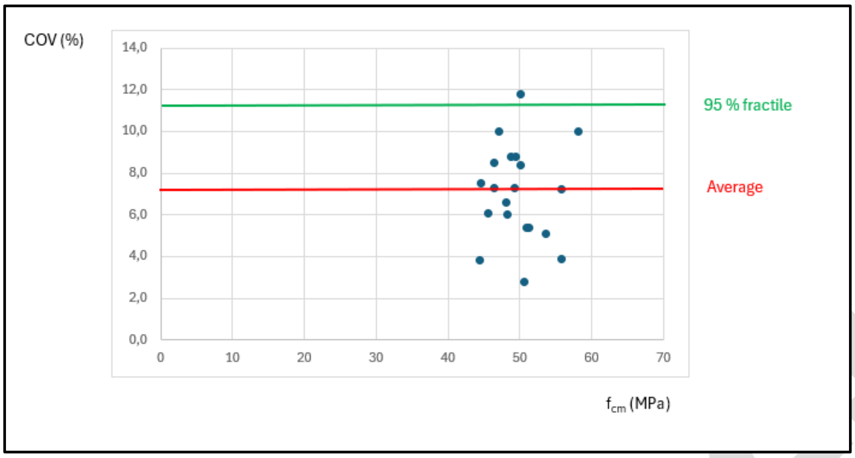


Figure 5.3: Coefficient of variation as a function of the compressive strength for each series for walls

The average value for the coefficient of variations is 7,3 %. The range of the average concrete strengths is 44 MPa to 60 MPa. Regarding the individual test values the range is a little larger.

If the 95% probability of the 23 coefficients of variation is calculated, a coefficient of variation of 11,5 % is obtained for all the series.

5.4 Decks

Table 5.3 shows test results for cores drilled in decks that are part of a building.

A concrete with D_{max} = 16 mm was used. The drilled cores all have a height-diameter ratio of 1. The height/diameter are in the range of 70 mm – 85 mm. The cores is taken from up-side slab. For conversion to in-situ strength corresponding to the standard cylinder size (150 x 300) according to DS/EN 1992-1-1, the factor 0.82 has been used, as specified in DS/EN 13791 and DS 11990. The statistical data provided are based on the converted values.

Series	Number of test values	f_{cm} MPa	COV %	Notes
CD1	3	40,7	3,1	See test values in Figure C.60.
CD2	13 (12)	41,1 (39,5)	13,8 (7,6)	A single test value of 60,2 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.61.
CD3	9 (8)	41,1 (38,5)	17,5 (7,9)	A single test value of 61,8 MPa meet the requirements for Upper outliner according to DS 13791. If this test value is removed, values given in brackets is obtained. See test values in Figure C.62.
CD4	12	44,6	11,1	See test values in Figure C.63.
CD5	3	49,3	1,2	See test values in Figure C.64.
CD6	8	57,9	11,4	See test values in Figure C.65.
CD7	3	50,7	5,3	See test values in Figure C.66.
CD8	3	52,2	3,4	See test values in Figure C.67.
CD9	3	47,7	6,6	See test values in Figure C.68.
CD10	3	48,5	6,5	See test values in Figure C.69.
CD11	3	49,1	2,8	See test values in Figure C.70.
CD12	3	46,1	4,0	See test values in Figure C.71.
CD13	8	44,8	9,0	See test values in Figure C.72.
CD14	3	42,2	4,8	See test values in Figure C.73.
CD15	3	55,3	4,0	See test values in Figure C.74.
CD16	3	48,3	8,3	See test values in Figure C.75.
CD17	3	54,6	8,5	See test values in Figure C.76.
CD18	3	47,5	3,9	See test values in Figure C.77.
CD19	3	49,1	6,8	See test values in Figure C.78.
CD20	3	48,5	7,8	See test values in Figure C.79.
CD21	3	48,7	3,2	See test values in Figure C.80.
CD22	8	51,1	9,2	See test values in Figure C.81.
CD23	8	53,4	10,8	See test values in Figure C.82.
CD24	8	47,2	9,6	See test values in Figure C.83.
CD25	3	42,8	3,3	See test values in Figure C.84.

Table 5.3: Compressive test results for concrete in structure taken at upside decks

The test results is shown in appendix C, Figure C60-C84.

In the following analysis the values in the brackets are used. This gives 25 series.

The coefficient of variation is in Figure 5.4 for each series shown as a function of the average compression concrete strength.

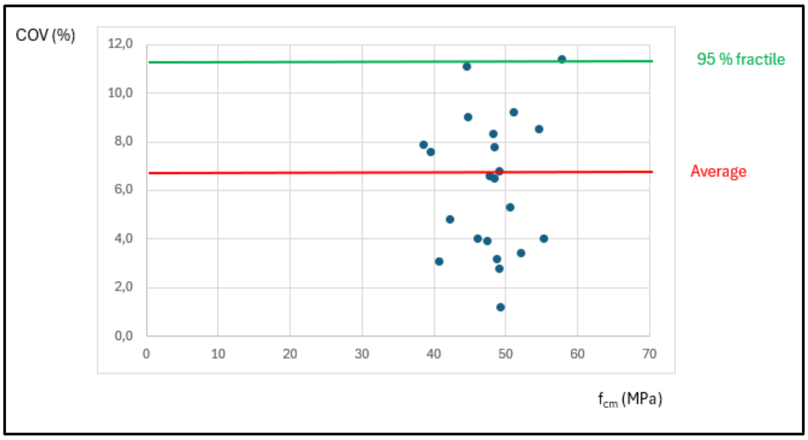


Figure 5.4: Coefficient of variation as a function of the compressive strength for each series for decks

The average value for the coefficient of variations is 6,4 %. The range of the average concrete strengths is 38 MPa to 58 MPa. Regarding the individual test values the range is a little larger.

If the 95% probability of the 25 coefficients of variation is calculated, a coefficient of variation of 11,5 % is obtained for all the series.

5.5 Summary, coefficient of variation for compression strength in real structure

The results from chapters 5.2 - 5.5 are collected in table 5.4.

Structural type	***Number of series***	***Average COV***	***95 % fractile COV***
Columns	20	9,7 %	13,4 %
Walls	23	7,3 %	11,5 %
Decks	25	6,4 %	11,5 %

Table 5.4: Overview test results for compression strength in structure

A number of factors play a role for the measured compression concrete strength and the connected coefficient of variation for the concrete in the real structures.

The strength is very dependent on where the drilled cores has been taken. Meaning that for the same concrete recipe the strength will be different for drilled cores in beams, columns, walls, slabs etc. because of the different ways the concrete is handled by casting, vibration and curing and the effect of bleeding. Furthermore, strength will depend on where the drilled core is taken in the structural member, i.e. it is taken from the upside or downside of a beam or slab or maybe at the side face of a beam. From tests it is well known that the strength is varying through the heights of a walls and columns, meaning that the strength is smaller at the top compared to the bottom.

Especially for the values in table 5.1, it should be noted that small diameters were used when taking samples, which in itself may lead to a higher coefficient of variation. The effect is not known.

The main interest in this investigation is the coefficient of variation for the determination of the partial factors for concrete. In this context, different coefficients of variation could be calculated for different situations, as described above, and thereby lead to different partial factors. However, this would complicate calculations of concrete structures with the risk of introducing errors, which is why the aim is to find a coefficient of variation that considers all types of structural members.

In the present DK NA, the used coefficient of variation is 14 %.

The background document for DS/EN 1992-1-1:2023 is using the coefficient of variation $V_{3,f_c} = 12{,}0\,\%$.

From table 5.4 it can be concluded that the coefficient of variation will be somewhere in the range of 9,7 % – 13,5 %.

It is estimated that a reasonable value for the coefficient of variation for the concrete compression strength in the structure would be $V_{3,f_c} = 11{,}0\,\%$. With $V_{3,R,f_c} = 6{,}5\,\%$ V_{3,RT,f_c} can be estimated to $V_{3,RT,f_c} = 8{,}87\,\%$

6. Concrete, tensile strength of in-situ cast specimens ($V_{3,R,f_{ct}}$)

6.1 Model for tensile concrete strength in EC2

The formula for determining the mean uniaxial tensile strength of concrete based on the characteristic compression strength of concrete according to DS/EN 1992-1-1:2023, table 5.1, is:

$$f_{ctm,EC2} = \begin{cases} 0{,}3\, f_{ck}^{2/3} & f_{ck} \leq 50\, MPa \\ 1{,}1\, f_{ck}^{1/3} & f_{ck} > 50\, MPa \end{cases}$$

A characteristic value for the compression strength is used for determination of the mean tensile strength, which is problematic.

6.2 Probabilistic analysis

In the following the model used for determining the tensile strength f_{ct} is:

$$f_{ct} = 0{,}3\, f_c^{2/3}$$

where
f_c compression strength of concrete

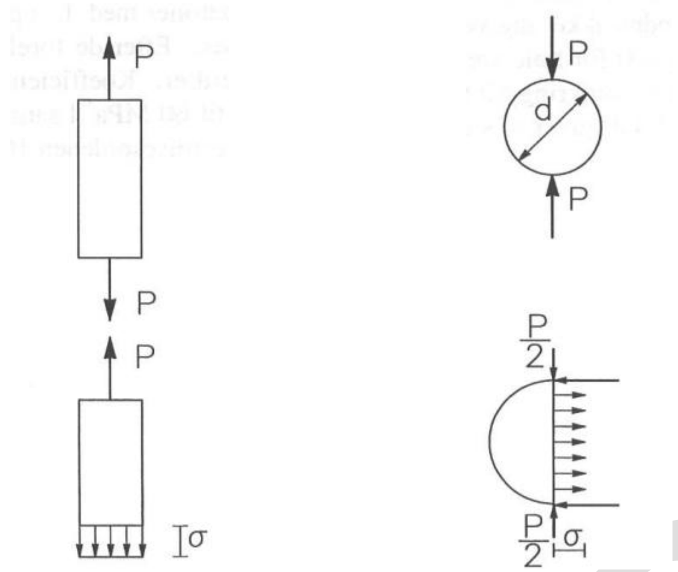
The probabilistic model is:

$$f_{ct} = b\, \delta\, 0{,}3\, f_c^{2/3}$$

where
b bias, deviation from best fit
δ model uncertainty: lognormal distributed with mean value = 1 and coefficient of variation V_δ

6.3 Tensile strength of concrete

Figure 6.1 shows how to measure the tensile strength. It is important to differ between the uniaxial tensile strength and the splitting tensile strength. Measuring the uniaxial tensile strength is complicated, while tests for determination the tensile strength normally are splitting tests.



Uniaxial tension test Splitting test

Figure 6.1: Uniaxial test and splitting test

The uniaxial tensile strength is denoted f_{ct} while the splitting tensile strength is denoted f_{csp}.

Unfortunately, it has not been possible to find tests with the tensile strength of concrete. There are tests where the compressive strength of concrete has been tested in connection with test of the tensile strength of concrete. These results are subsequently used to determine the coefficients of variation associated with the tensile strength of concrete. This means that a part of the calculation involves the transmission from compression strength to tensile strength and the uncertainty connected to this transmission.

6.4 Experimental data from Neville

The test data shown in Figure 6.2 is taken from *A. M. Neville, Properties of Concrete*, Figure 6.37.

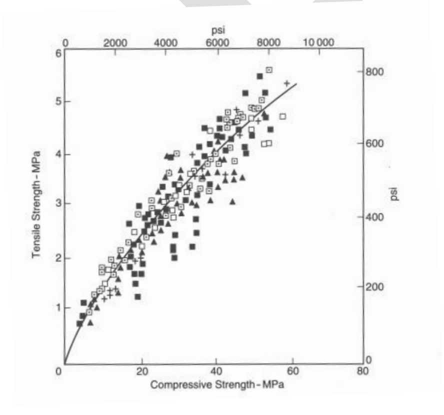


Figure 6.2: Test data from Neville

The reference states that the test results are based on splitting tests.

The test data used in Figure 6.2 is tests made by various investigators, see the reference for more information. The subsequent analysis does not assess this further or take this into account, meaning that all experimental data is included in the analysis.

Based on figure 6.2 Neville propose the formula:

$$f_{csp} = 0{,}30\, f_c^{2/3}$$

The test data in Figure 6.2 is transformed by software to values and then used for the analysis shown in Figure 6.3.

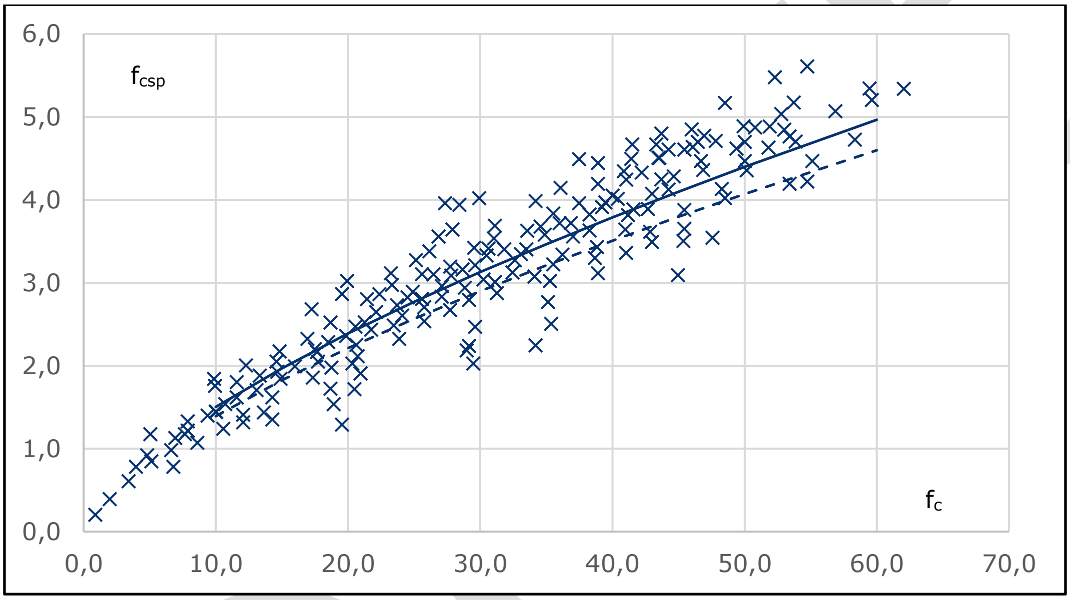


Figure 6.3: Analysing tests from Neville

In Figure 6.3:
Full line: $f_{csp} = b\, 0{,}3\, f_c^{2/3}$ i.e. best fit
Dashed line: DS/EN 1992-1-1:2023 formular, $f_{ct} = 0{,}3\, f_c^{2/3}$

Application of DS/EN1990 Annex D.8 results for the model in:
b = 1,08 and V_δ = 0,14

This means that the EC2-model (using f_{cm} instead of f_{ck}) underestimates the splitting strength by factor 1/1,08 = 0,93, and the coefficient of variation for the best-fit model is 14 %.

The coefficient of variation V_{f_{csp},f_c}(V_{rt}) connected to the splitting strength taking account of the coefficient of variation connected to the compression strength, obtained from formula (D.20) in DS/EN 1990, assuming the coefficient of variation V_{3,R,f_c} = 0,065, see chapter 3, is V_{f_{csp},f_c}= 0,04.

The coefficient of variation for the splitting strength according to DS/EN 1990, Annex D, is:

$$V_{f_{csp}} = \sqrt{V_\delta^2 + V_{f_{csp},f_c}^2} = 0{,}16$$

6.5 Experimental data from MPN

6.5.1 Test data

The test data in Figure 6.4 and 6.5 is taken from *M. P. Nielsen, Beton 1, del 1,* Figure 2.1.4.6 and 2.1.4.7.

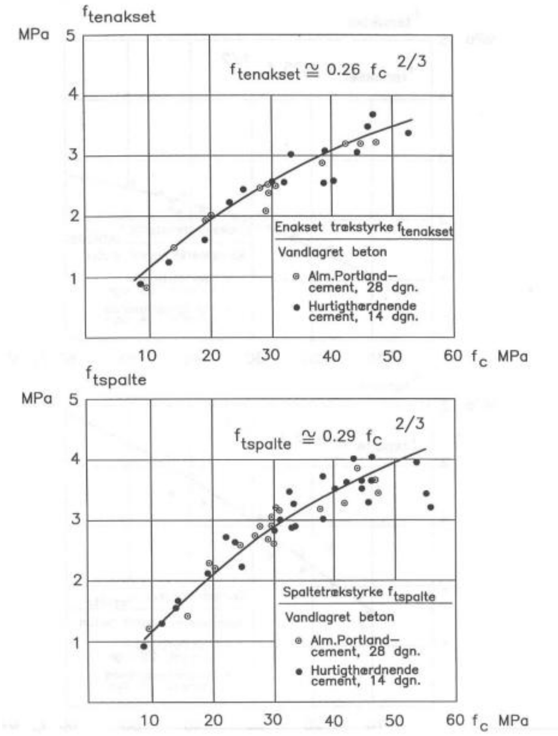


Figure 6.4: Experimental data from M. P. Nielsen; water stored test specimens

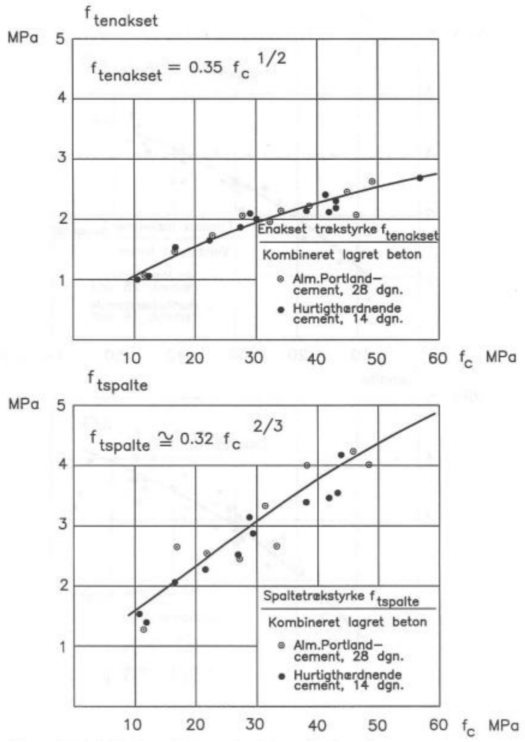


Figure 6.5: Experimental data from M. P. Nielsen, combined stored test specimens

The first Figure in both Figures 6.4 and 6.5 is the uniaxial tension strength f_{ct}, while the second Figure in both Figures is the splitting strength f_{csp}.

The experiments were carried out at the Department of Structural Engineering at DTU in the early 1970s and have never been published. The test data used in Figures 6.4 and 6.5 are both tests for the use of ordinary Portland cement and rapid-setting cement, see the reference for more information. The subsequent analysis does not assess this further or take this into account, meaning that all experimental data is included in the analysis.

The test data in Figures 6.4 and 6.5 are transformed by software into values and then used for the analysis included in the following chapters.

6.5.2 Uniaxial tensile strength, water cured test specimens

Figure 6.6 shows tests with water cured test specimens loaded to uniaxial tension.

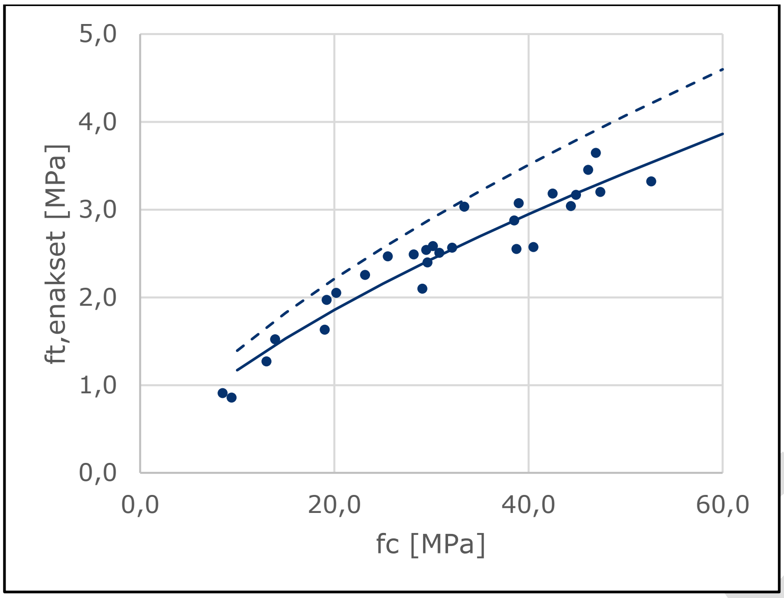


Figure 6.6: Analysing tests for uniaxial tensile strength from MPN, water cured

In Figure 6.6:
Full line: $f_{ct} = b\ 0{,}3\ f_c^{2/3}$ i.e. best fit
Dashed line: DS/EN 1992-1-1:2023 formular, $f_{ct} = 0{,}3\ f_c^{2/3}$

Application of DS/EN1990 Annex D.8 results for the model in:
b = 0,84 and V_δ = 0,10

This means that the EC2-model (using f_{cm} instead of f_{ck}) overestimates the uniaxial tensile strength by factor 1/0,84 = 1,19, and the coefficient of variation for the best-fit model is 10 %.

The coefficient of variation V_{f_{ct},f_c}(V_{rt}) connected to the uniaxial tensile strength taking account of the coefficient of variation connected to the compression strength, obtained from formula (D.20) in DS/EN 1990, assuming the coefficient of variation V_{3,R,f_c} = 0,065 for test in laboratory, is V_{f_{ct},f_c} = 0,04.

The coefficient of variation for the uniaxial tensile strength according to DS/EN 1990, Annex D, is:

$$V_{f_{ct}} = \sqrt{V_\delta^2 + V_{f_{ct},f_c}^2} = 0{,}11$$

6.5.3 Splitting strength, water cured test specimens

Figure 6.7 shows tests with water cured test specimens loaded to splitting.

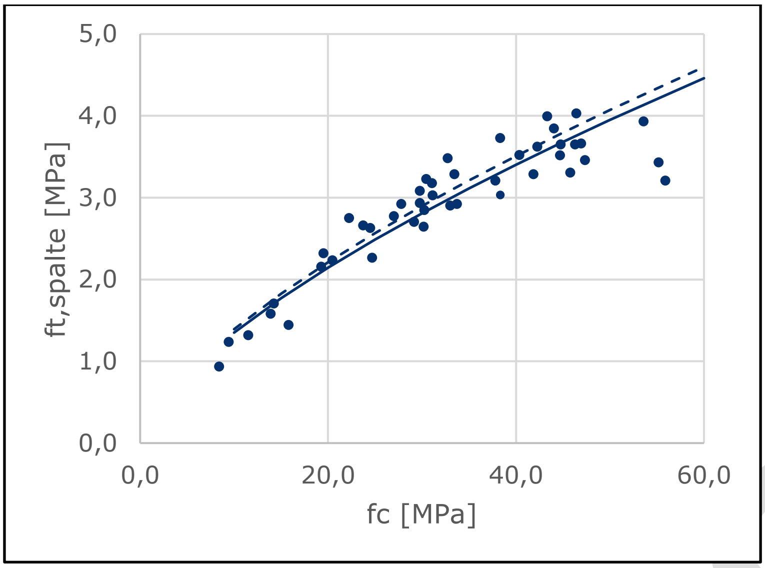


Figure 6.7: Analysing tests for splitting strength from MPN, water cured

In Figure 6.7:
Full line: $f_{csp} = b\ 0{,}3\ f_c^{2/3}$ i.e. best fit
Dashed line: DS/EN 1992-1-1:2023 formular, $f_{ct} = 0{,}3\ f_c^{2/3}$

Application of DS/EN1990 Annex D.8 results for the model in:
b = 0,97 and V_δ = 0,11

This means that the EC2-model (using f_{cm} instead of f_{ck}) overestimates the splitting strength by factor 1/0,97 = 1,03, and the coefficient of variation for the best-fit model is 11 %.

The coefficient of variation V_{f_{csp},f_c}(V_{rt}) connected to the splitting strength taking account of the coefficient of variation connected to the compression strength, obtained from formula (D.20) in DS/EN 1990, assuming the coefficient of variation V_{3,R,f_c} = 0,065 for test in laboratory, is V_{f_{csp},f_c}= 0,04.

The coefficient of variation for the splitting strength, water cured, according to DS/EN 1990, Annex D, is:

$$V_{f_{csp}} = \sqrt{V_\delta^2 + V_{f_{csp},f_c}^2} = 0{,}11$$

6.5.4 Uniaxial tensile strength, combined cured test specimens

Figure 6.8 shows tests with combined cured test specimens loaded to uniaxial tension.

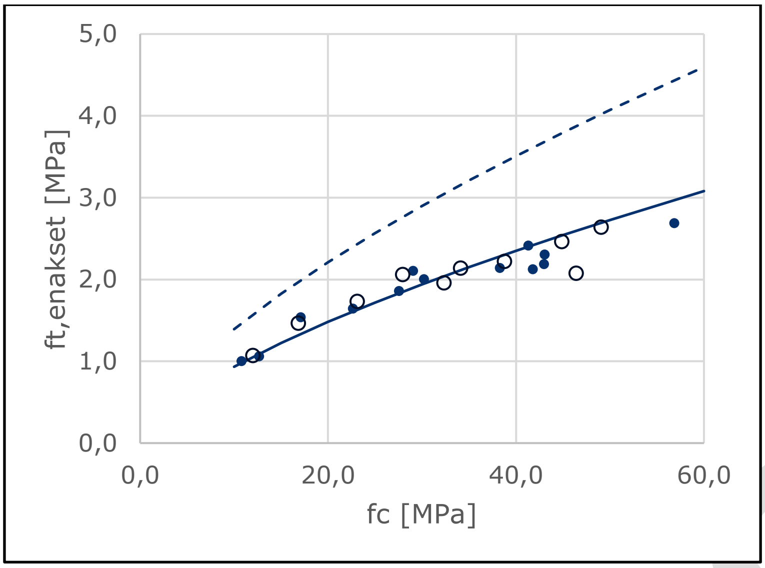


Figure 6.8: Analysing tests for uniaxial tensile strength from MPN, combined cured

In Figure 6.8:
Full line: $f_{ct} = b\ 0{,}3\ f_c^{2/3}$ i.e. best fit
Dashed line: DS/EN 1992-1-1:2023 formular, $f_{ct} = 0{,}3\ f_c^{2/3}$

Application of DS/EN1990 Annex D.8 results for the model in:
b = 0,67 and V_δ = 0,08

This means that the EC2-model (using f_{cm} instead of f_{ck}) overestimates the uniaxial tensile strength by factor 1/0,67 = 1,49, and the coefficient of variation for the best-fit model is 8 %.

The coefficient of variation V_{f_{ct},f_c}(V_{rt}) connected to the uniaxial tensile strength taking account of the coefficient of variation connected to the compression strength, obtained from formula (D.20) in DS/EN 1990, assuming the coefficient of variation V_{3,R,f_c} = 0,065 for test in laboratory, is V_{f_{ct},f_c} = 0,04.

The coefficient of variation for the uniaxial tensile strength, combined curing, according to DS/EN 1990, Annex D, is:

$$V_{f_{ct}} = \sqrt{V_\delta^2 + V_{f_{ct},f_c}^2} = 0{,}09$$

6.5.5 Splitting strength, combined cured test specimens

Figure 6.9 shows tests with combined cured test specimens loaded to splitting.

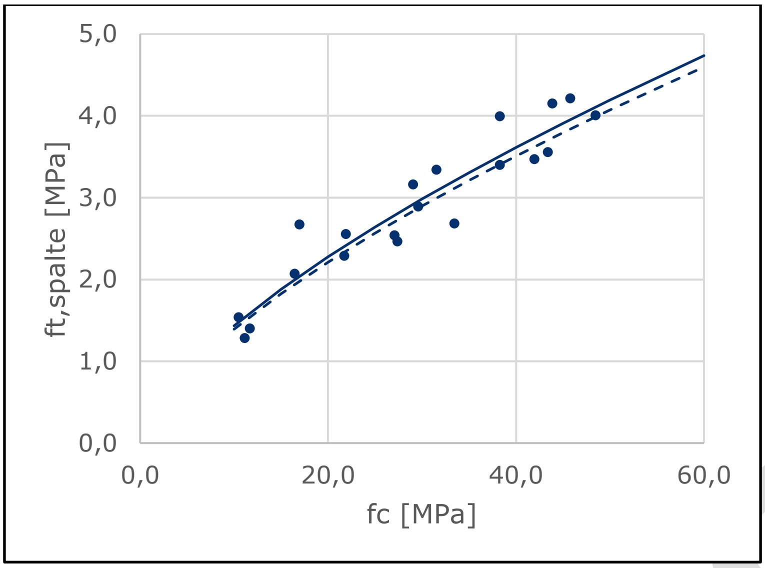


Figure 6.9: Analysing tests for splitting strength from MPN, combined cured

In Figure 6.9:
Full line: $f_{csp} = b\ 0{,}3\ f_c^{2/3}$ i.e. best fit
Dashed line: DS/EN 1992-1-1:2023 formular, $f_{ct} = 0{,}3\ f_c^{2/3}$

Application of DS/EN1990 Annex D.8 results for the model in:
b = 1,03 and V_δ = 0,11

This means that the EC2-model (using f_{cm} instead of f_{ck}) underestimates the splitting strength by factor 1/1,03 = 0,97, and the coefficient of variation for the best-fit model is 11 %.

The coefficient of variation V_{f_{csp},f_c}(V_{rt}) connected to the splitting strength taking account of the coefficient of variation connected to the compression strength, obtained from formula (D.20) in DS/EN 1990, assuming the coefficient of variation V_{3,R,f_c} = 0,065 for test in laboratory, is V_{f_{csp},f_c}= 0,04.

The coefficient of variation for the tensile splitting strength, combined curing, according to DS/EN 1990, Annex D, is:

$V_{f_{csp}} = \sqrt{V_\delta^2 + V_{f_{csp},f_c}^2}$ = 0,12.

6.6 Summary coefficient of variation for tensile strength

Table 6.1 contains the best fit curves for the test series.

Subject	***Strength type***	***Curing type***	***Best fit formulae***	***Coefficient of variation***
Neville (6.4)	splitting	combined	$f_{csp} = 0{,}324\, f_c^{2/3}$	16 %
MPN (6.5.2)	uniaxial	water	$f_{ct} = 0{,}252\, f_c^{2/3}$	11 %
MPN (6.5.3)	splitting	water	$f_{csp} = 0{,}291\, f_c^{2/3}$	11 %
MPN (6.5.4)	uniaxial	combined	$f_{ct} = 0{,}201\, f_c^{2/3}$	9 %
MPN (6.5.5)	splitting	combined	$f_{csp} = 0{,}309\, f_c^{2/3}$	12 %

Table 6.1: Overview test results

Comparing MPN test for water cured uniaxial test, chapter 6.5.2, with MPN test for combined cured uniaxial test, chapter 6.5.4, the water cured specimens have an approximately 25 % higher strength compared to the test specimens that are combined cured. This is not in agreement with the normal perception. There seems to be something wrong with the test values stated in chapter 6.5.4, which is why this test series is omitted from the present analysis.

Comparing Neville (chapter 6.4) and MPN (chapter 6.5.5) splitting test for combined cured the difference is less than 5 % confirming that the experiments reported in Neville probably are based on combined cured test specimens.

The coefficient of variation is varying between 9 % and 16 %.

While the series from MPN is made by the same laboratory, the test from Neville is based on tests from various laboratories, which leads to greater uncertainties and thereby higher coefficient of variation.

Taking the above into account and based on table 6.1 the coefficient of variation for the tensile strength for in-situ cast specimens is reasonably to be put to $V_{3,R,f_{ct}} = 11{,}0\ \%$.

6.7 Relationship between tensile strength and splitting strength

Rules for storing test specimens are contained in DS/EN 12390-2. The rules are shown in Figure 6.10, which correspond to water curing.

5.5 Curing of test specimens

5.5.1 Leave the test specimens in the mould for at least 16 hours, but not longer than 3 days, protected against shock, vibration and dehydration at a temperature of (20 ± 5) °C (or (25 ± 5) °C in hot climates).

5.5.2 After removal from the mould, cure the test specimens till immediately before testing, in water at a temperature of (20 ± 2) °C, or in chamber at (20 ± 2) °C and relative humidity ≥ 95 %.

5.5.3 Forms of curing differing from those in 5.5.2 may be factorized to the methods described in 5.5.2.

NOTE 1 In case of dispute, curing in water shall be the reference method.

NOTE 2 Maintenance and measurement of high humidity ≥ 95 % at (20 ± 2) °C is not simple. Regular checks should be made that surfaces of specimens in the chamber are continuously wet.

Figure 6.10: Rules in DS/EN 12390-2 for storing test specimens

According to table 6.1 the best formula for the uniaxial tensile strength, water cured, chapter 6.5.2, is:

$$f_{ct} = 0{,}25\, f_c^{2/3}$$

Comparing MPN test for water cured splitting test, chapter 6.5.3, with MPN test for combined cured splitting test, chapter 6.5.5, the water cured specimens have an approximately (0,309/0,291) 6,2 % lower strength compared to test specimens that are combined cured.

Going from water cured conditions test for splitting strength (6.5.3) to water storage conditions test for uniaxial strength (6.5.2) the strength is reduced by (0,291/0,252) 15,5 %. This means that the uniaxial tensile strength based on the storage conditions specified in DS/EN 12390-2 is, using the factor 0,3 that is connected to EC2 :

$$f_{ct} = \frac{f_{csp}}{1{,}062 \cdot 1{,}155} = 0{,}815\, f_{csp} = 0{,}815 \cdot 0{,}30\, f_c^{2/3} = 0{,}245\, f_c^{2/3}$$

This confirm that the Eurocode formulae is a splitting strength and based on combined cured conditions because the transmission gives the same result as stated earlier for the uniaxial tensile strength for water cured specimens.

As mentioned in chapter 6.1 the uniaxial tensile strength according to DS/EN 1992-1-1:2023 is:

$$f_{ctm,EC2} = 0{,}3\, f_{ck}^{2/3}$$

Using the coefficient of variation $V_{3,f_c} = 11{,}0\,\%$ for the compression strength of the concrete in the real structure, se chapter 4, the relationship $f_{ck} = (1 - 1{,}64 \cdot 0{,}11)\, f_{cm} = 0{,}82\, f_{cm}$ can be estimated, and the formulae for the uniaxial tensile strength in DS/EN 1992-1-1:2023 can be changed to:

$$f_{ctm,EC2} = 0{,}3\, f_{ck}^{2/3} = 0{,}3\, \left(\frac{f_{cm}}{0{,}82}\right)^{2/3} = 0{,}34\, f_{cm}^{2/3}$$

using f_{cm} instead of f_{ck}.

This means that using the formulae for the tensile strength in DS/EN 1992-1-1:2023, the correct tensile strength can be expressed by:

$$f_{ctm} = 0{,}815 \cdot 0{,}34 f_{cm}^{2/3} = 0{,}28\, f_{cm}^{2/3}$$

corresponding to the factor 0,28/0,30 = 0,93 to be applied on the EC2 formula, meaning that the correct uniaxial tensile strength is when using the formulae in DS/EN 1992-1-1:

$$f_{ctm} = 0{,}93\ f_{ctm,EC2} = 0{,}93\ \cdot 0{,}3\ f_{ck}^{2/3} = 0{,}28\ f_{ck}^{2/3}$$

Using the strength f_{ck} = 40 MPa as an example, DS/EN 1992-1-1:2023 gives:

$$f_{ctm,EC2} = \ 0{,}3\ f_{ck}^{2/3} = 3{,}5\ MPa$$
$$f_{ctk,EC2} = 0{,}7\ f_{ctm,EC2} = 2{,}5\ MPa$$

Using the correct formula for the uniaxial tensile strength with f_{cm} = 40/0,82 = 48,8 MPa and the coefficient of variation for $V_{3,f_{ct}} = 16{,}0\ \%$, see chapter 7, the result is:

$$f_{ctm} = \ 0{,}25\ f_{cm}^{2/3} = 3{,}3\ MPa$$
$$f_{ctk} = (1 - 1{,}64\ \cdot 0{,}16)\ f_{ctm} = 0{,}74\ f_{ctm} = 2{,}5\ MPa$$

The EC2-formula and the above formulae for the "correct" uniaxial tensile strength are compared in figure 6.11.

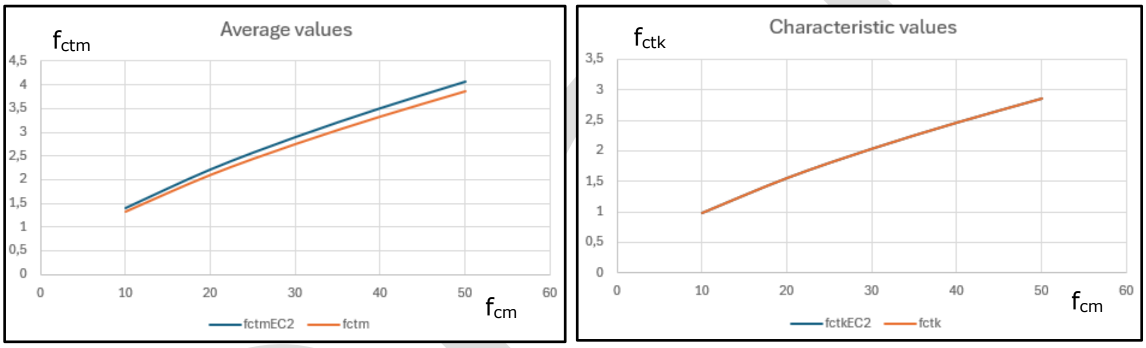


Figure 6.11: EC2 formulae and developed formulae for tensile strength

As seen from figure 6.11 there is only minor difference for the determination of the mean uniaxial tensile strength, while there is full agreement for the characteristic value.

7. Concrete, tensile strength in real structures ($V_{3,f_{ct}}$)

No tests have been found where the tensile strength of concrete in real structures has been determined.

In the following the coefficient of variation for the tensile strength in the structure is found by use of the values determined in chapter 3, 5 and 7. This means that a part of the calculation involves the transmission from compression strength to tensile strength, and the uncertainty connected to this transmission.

For in-situ cast specimens and real structures the following coefficient of variation have been determined for the compression strength and the tensile strength, se chapter 3, 5 and 7:

$V_{3,R,f_c} = 6{,}5\ \%$.

$V_{3,f_c} = 11{,}0\ \%$.

$V_{3,R,f_{ct}} = 11{,}0\ \%$.

$V_{3,R,fct}$ is the model uncertainty ($= V_{\delta_{lab}}$) for the model for the tensile strength as a function of the compressive strength, see Table 6.1, MPN (6.5.2; uniaxial; water).

The coefficient of variation $V_{f_{ct},f_c} (= V_{rt})$ of the tensile strength taking account the uncertainty of the compression strength is obtained from formula (D.20) in DS/EN 1990. Assuming the coefficient of variation $V_{3,f_c} = 11{,}0\ \%$ for the real structure, it is obtained that $V_{fctfc} = 7{,}0\ \%$ (approximately = 2/3 · 11 %).

Combining the two contributions from $V_{\delta_{lab}}$ and $V_{3,R,fct}$:

$$V_{3,R,f_{ct}} = \sqrt{V_{\delta_{lab}}^2 + V_{f_{ct},f_c}^2} = 0{,}13$$

Adding the uncertainty connected transformation of the model for the tensile strength from laboratory conditions to real structure modelled approximately to $V_{3,RT,f_{ct}}$=0,10 the resulting uncertainty of the tensile strength in structures becomes:

$$V_{3,f_{ct}} = \sqrt{V_{3,R,f_{ct}}^2 + V_{3,RT,f_{ct}}^2} = 0{,}16$$

This means that coefficient of variation for the tensile strength in the real structure is put to $V_{3,f_{ct}} = 16{,}0\ \%$.

It is important to emphasize that the used $V_{3,RT,f_{ct}}$= 10 % is an estimated value and therefore not a correct value. Therefore $V_{3,RT,f_{ct}}$ is not known.

8. Reinforcement, ultimate strain limit

Will be prepared later.

9. Shear, strength non-shear reinforced structures

In DS/EN 1992-1-1:2023 the shear capacity for non-shear reinforced concrete structures is given by the expression shown in Figure 9.1

(2) The design value of the shear stress resistance should be taken as:

$$\tau_{Rd,c} = \frac{0{,}66}{\gamma_V} \cdot \left(100\rho_l \cdot f_{ck} \cdot \frac{d_{dg}}{d}\right)^{\frac{1}{3}} \geq \tau_{Rdc,min} \qquad (8.27)$$

where

$$\rho_l = \frac{A_{sl}}{b_w d} \qquad (8.28)$$

A_{sl} is the effective area of tensile reinforcement at the distance d beyond the section considered (see Figure 8.7);

b_w is the width of the cross-section of linear members. The width b_w for cross-sections with variable width and for circular cross-sections is defined in 8.2.3(9);

d_{dg} is defined in 8.2.1(4);

d is the effective depth d_{nom}. The value d may be refined according to (3) and (4) for non-slender members and members with axial force.

Figure 9.1: Non-shear reinforced shear capacity according to DS/EN 1992-1-1:2023

DS/EN 1992-1-1:2023, annex A, indicates the values shown in Figure 9.2.

Partial factor for shear and punching γ_V (see 8.2.1, 8.2.2, 8.4, I.8.3.1, I.8.5)		
Compressive strength f_c (control specimen)	$V_{fc} = 0{,}100$	$f_{cm}/f_{ck} = \exp(1{,}645 V_{fc})$ [d]
Insitu factor $\eta_{is} = f_{c,ais}/f_c$ [e]	$V_{\eta is} = 0{,}120$	$\mu_{\eta is} = 0{,}95$
Effective depth d	$V_d = 0{,}050$ [b]	$\mu_d = 0{,}95$ [b]
Model uncertainty	$V_{\theta v} = 0{,}107$ [g]	$\mu_{\theta v} = 1{,}10$ [g]
Residual uncertainties	$V_{res,v} = 0{,}046$ [h]	–
Coefficient of variation and bias factor of resistance for shear and punching (members without shear reinforcement)	$V_{RV} = 0{,}137$ [i]	$\mu_{RV} = 1{,}085$ [i]

Figure 9.2: Data from the background document for DS/EN 1992-1-1:2023

In the background document for DS/EN 1992-1-1:2023 a partial factor for shear resistance of beams and slabs without shear reinforcement is estimated using the Design Value Format method.

In figure 9.3 the failure mechanism connected to shear in non-shear reinforced members is shown. Because the movement in the yield line is not perpendicular to the yield line the failure mechanism is a sliding failure, meaning that the compression strength of the concrete and not the tensile strength of the concrete governing the strength of the yield line.

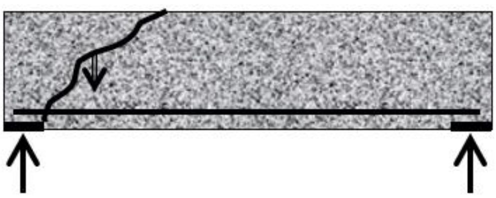


Figure 9.3: Failure mechanism in non-shear reinforced members

According to chapters 3 and 5:

$V_{3,R,f_c} = 6{,}5\%$

$V_{3,f_c} = 11{,}0\ \%$

In the calculation model the compression strength is raised to the power 1/3. Therefore, the contribution to the uncertainty of shear stress resistance is approximately a coefficient of variation $V_3 = V_{3,\tau_{R,c}}$ = 1/3 x 0,11 = 0,04.

From figure 9.2 the following coefficient of variation of the calculation model including transformation from laboratory to structure is available:

$V_{2,X,\tau_{R,c}} = 0{,}05$

$V_{2,XT,\tau_{R,c}} = \sqrt{0{,}107^2 + 0{,}046^2} = 0{,}116$

$V_{2,\tau_{R,c}} = \sqrt{0{,}050^2 + 0{,}116^2} = 0{,}13$

Conversion from laboratory to real structure, as an approximation following values are used:

- $V_{2,XRT,f_{ct}} = 10{,}0\ \%$
- Bias = 0.95 x 0.95 x 1.1 = 0.99
- Failure type : No Warning

Using the values stated above the values in table 9.1 is available.

γ_1		γ_2					γ_3					γ_v
Failure type	γ_1	**Bias**	$V_{2,XR}$ %	$V_{2,XRT}$ %	V_2 %	γ_2	**Bias**	$V_{3,R}$ %	$V_{3,RT}$ %	V_3*1) %	γ_3	
NW	1,1		-	-	13,0	1,08		-	-	4,0	1,17	1,38

Note

*1) The value is power 1/3 of 11 %

Table 9.1: Values used for determination of γ_v

10. Anchorage and laps, strength concrete

In DS/EN 1992-1-1:2023 the design anchorage length is calculated by the formulae in Figure 10.1.

(3) In cases not complying with the limitations of (2), or for a more detailed calculation, the design anchorage length l_{bd} should be calculated as:

$$l_{\text{bd}} = k_{\text{lb}} \cdot k_{\text{cp}} \cdot \phi \cdot \left(\frac{\sigma_{\text{sd}}}{435}\right)^{n_\sigma} \cdot \left(\frac{25}{f_{\text{ck}}}\right)^{\frac{1}{2}} \cdot \left(\frac{\phi}{20}\right)^{\frac{1}{3}} \cdot \left(\frac{1{,}5\phi}{c_{\text{d}}}\right)^{\frac{1}{2}} \geq 10\phi \qquad (11.3)$$

where

Ratios in Formula (11.3) shall be limited to $(\phi/20\text{ mm}) \geq 0{,}6$ and $(25/f_{ck}) \geq 0{,}3$:

c_d $c_{\text{d}} = \min\{0{,}5c_{\text{s}}; c_{\text{x}}; c_{\text{y}}; 3{,}75\phi\}$, see Figure 11.3.

k_{cp} coefficient accounting for casting effects on bond conditions:

— $k_{cp} = 1{,}0$ for bars with good bond conditions according to (4);

— $k_{cp} = 1{,}2$ for poor bond conditions and for all bars used in slipform construction unless it is shown that the vertical bars cannot move during casting;

— $k_{cp} = 1{,}4$ for all bars executed under bentonite or similar slurries unless data is available for the specific slurry to be used;

NOTE For anchorages, the following values for k_{lb} and n_σ apply unless the National Annex gives different values:

$k_{lb} = 50$ for persistent and transient design situations with $n_\sigma = 3/2$; and

$k_{lb} = 35$ for accidental design situations with $n_\sigma = 3/2$.

Figure 10.1: Formulae for calculating anchorage length in DS/EN 1992-1-1:2023

The formula includes $\sqrt{f_{ck}}$. In the former Danish codes, the tensile strength was determined by the expression $f_{ct} = \sqrt{0{,}1\, f_{cm}}$. It is well known that anchorage failures are depending on the compression strength as well as the tensile strength, see figure 10.2.

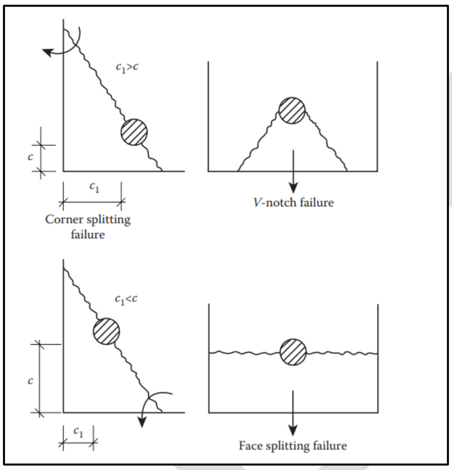


Figure 10.2: Failure mechanisms connected anchorage failure. From Limit Analysis and Concrete Plasticity, M.P. Nielsen and L. C. Hoang

The magnitude of the tensile and the compression strength is depending on the type of failures, as an example some failures are depending only on the tensile strength.

As seen from Figure 10.1 the partial factor is not included in the formulae, meaning that the safety is indirectly included in the formulae. The safety is connected to the factor k_{lb}. In Figure 10.3 some data from internal documents for the work with the new Eurocode is shown for the factor k_{lb}.

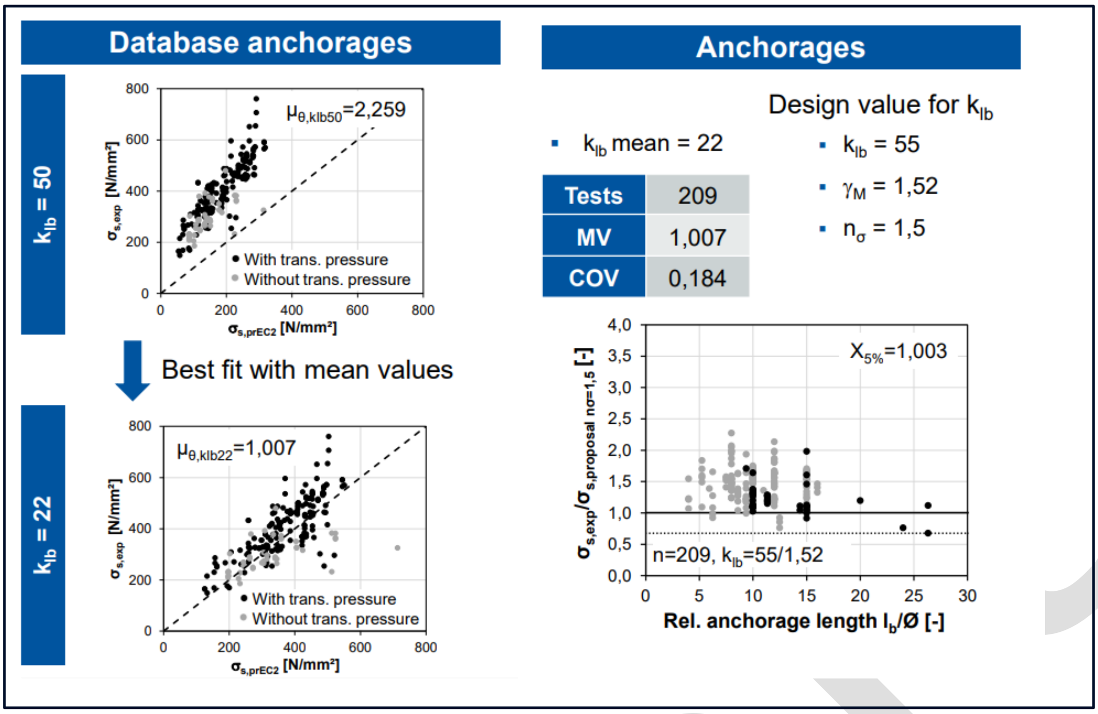


Figure 10.3: Data connected to k_{lb} for anchorage

The following probabilistic model is used:

$$l_b = b\ \delta\ k\ k_{lb}\ \frac{1}{\sqrt{f_c}}$$

where

f_c	compression strength of concrete
k_{lb}	is put to 22 giving the mean value, see Figure 10.3
k	a constant
b	bias
δ	model uncertainty: lognormal distributed with mean value = 1 and coefficient of variation V_δ

The probabilistic model has primary focus on the importance of the compression concrete strength in the formulae.

The calculation results are:

b ~ 1,0, V_δ = 0,18 and k_{lb} mean = 22

The coefficient of variation of the model in laboratory conditions is equal to V_δ and therefore becomes $V_{2,RT} = V_\delta = 0{,}18$.

The uncertainty connected to transformation of the model from laboratory conditions to real structure is chosen approximately 10 %, i.e. $V_{2,XRT} = 0{,}10$.

The coefficient of variation V_3 modelling the uncertainty of the anchorage length due to uncertainty of the compression strength f_c in the structure is obtained using the coefficient of variation $V_{3,f_c} = 0{,}11$, se chapter 5.

$V_3 \approx \frac{1}{2} V_{3,f_{c,in-situ}} \;\; = 0{,}06$

Calculation of characteristic values following DS/EN 1990:2023, Annex D formula (D.21). With f_{ck} = 40 MPa is obtained the mean value is f_{cm} = 47,9 MPa and the characteristic value l_{bk} = 3,85 k.

Using the values stated above the values in table 9.1 is available.

γ_1		γ_2					γ_3					γ_c
Failure type	γ_1	***Bias***	$V_{2,XR}$ %	$V_{2,XRT}$ %	V_2 %	γ_2	***Bias***	$V_{3,R}$ %	$V_{3,RT}$ %	V_3*1 %	γ_3	
NW	1,1		18,0	10,0	21,0	1,16		-	-	6,0	1,19	1,50

Note

*1) The value is power 1/2 of 11 %

Table 10.1: Values used for determination of γ_c for anchorage capacity based on the coefficient af variation connected to the compression strength of concrete

The design value of k_{lb} is then:

$$k_{lbd} = \frac{\gamma \, l_{bk}}{k \frac{1}{\sqrt{f_{ck}}}} = \frac{1{,}50 \; 22 \; x \; 3{,}85}{22 \frac{1}{\sqrt{40}}} \; = 37$$

It is noted that l_{bk} = 3.85 k has been used in the formula, which corresponds to f_{ck} = 40 MPa, but when inserted into the formula for k_{lbd}, the use of the 40 MPa is eliminated, which is why the result is independent of the concrete strength.

The result γ_c = 1,50 is equal to the result found for the partial safety factor for the tensile strength for concrete in chapter 14, which means that k_{lb} in figure 10.1 can be replaced by $k_{lb} = 25\gamma_c$.

In figure 10.4 some data for laps from internal documents for the work with the new Eurocode is shown for the factor k_{lb}.

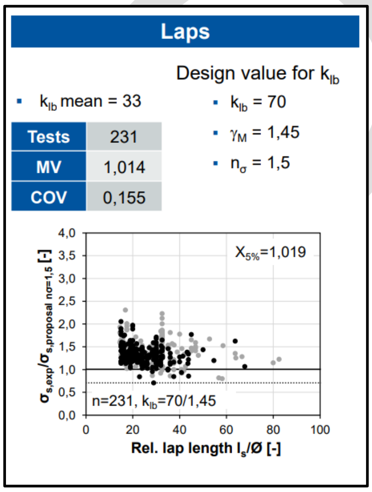


Figure 10.4: Data connected to k_{lb} for laps

The same probabilistic model as for anchorage is used which has primary focus on the importance of the compression concrete strength in the formulae.

The calculation results are:

b ~ 1,0, V_δ = 0,155 and k_{lb} mean = 33

The coefficient of variation of the model in laboratory conditions is equal to V_δ and therefore becomes $V_{2,RT}$ = V_δ = 0,155.

The uncertainty connected to transformation of the model from laboratory conditions to real structure is chosen approximately to 10 %, i.e. $V_{2,XRT}$ = 0,10.

The coefficient of variation V_3 modelling the uncertainty of the anchorage length due to uncertainty of the compression strength f_c in the structure is obtained using the coefficient of variation V_{3,f_c} = 0,11, se chapter 5.

$$V_3 \approx \frac{1}{2} V_{3,f_{c,in-situ}} = 0{,}06$$

Calculation of characteristic values following DS/EN1990:2023, Annex D, formula (D.21). With f_{ck} = 40 MPa is obtained the mean value is f_{cm} = 47,9 MPa and the characteristic value l_{bk} = 6,19 k.

Using the values stated above the values in table 9.1 is available.

γ_1		γ_2					γ_3					γ_c
Failure type	γ_1	**Bias**	$V_{2,XR}$ %	$V_{2,XRT}$ %	V_2 %	γ_2	**Bias**	$V_{3,R}$ %	$V_{3,RT}$ %	V_3 *1 %	γ_3	
NW	1,1		15,5	10,0	21,0	1,13		-	-	6,0	1,19	1,48

Note

*1) The value is power 1/2 of 11 %

Table 10.2: Values used for determination of γ_c for lap capacity based on the coefficient af variation connected to the compression strength of concrete

The design value of k_{lb} is then:

$$k_{lbd} = \frac{\gamma\ l_{bk}}{k \frac{1}{\sqrt{f_{ck}}}} = \frac{1{,}48\ 33\ x\ 6{,}19}{33\ \frac{1}{\sqrt{40}}} = 58$$

It is noted that l_{bk} = 6,19 k has been used in the formula, which corresponds to f_{ck} = 40 MPa, but when inserted into the formula for k_{lbd}, the use of the 40 MPa is eliminated, which is why the result is independent of the concrete strength.

This results in the factor 1,57 compared to the values for anchorage.

11. Calculation methods, reinforced concrete beams in bending

The document "Effektivitetsfaktoren ved bøjning af jernbetonbjælker, M.P. Nielsen & Bent Feddersen, ABK, DTU, Serie R, No. 173, 1983" contains a number of tests with beams in bending taken from several different articles.

Only beams in pure bending and without compression reinforcement is regarded.

The calculation model used is the one described in the above-mentioned reference. The calculation model is also included in "Limit Analysis and Concrete Plasticity, M.P. Nielsen & L. C. Hoang, CRC Press, 2011", chapter 5.1, se figure 11.1 and 11.2. The calculation model is not fully in agreement with the model in DS/EN 1992-1-1:2023, but the difference is negligible in relation to the purpose of this investigation.

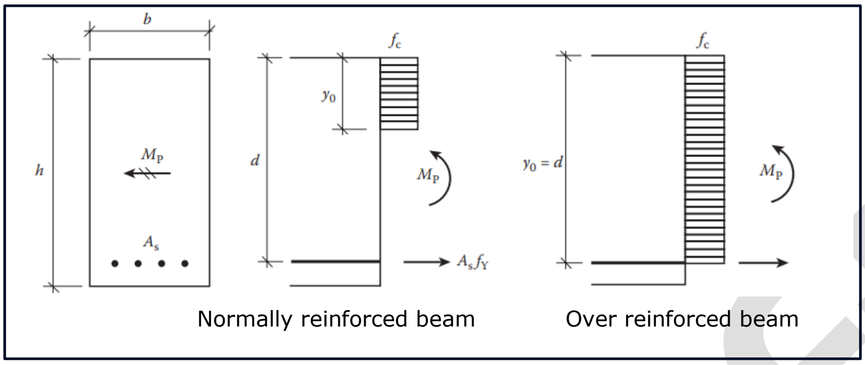


Figure 11.1: Calculation model pure bending. From Limit Analysis and Concrete Plasticity, M.P. Nielsen and L. C. Hoang

In figure 11.1 the stress distribution is shown for normally reinforced beams and over reinforced beams. The bending capacity based on this solution is shown in figure 11.2.

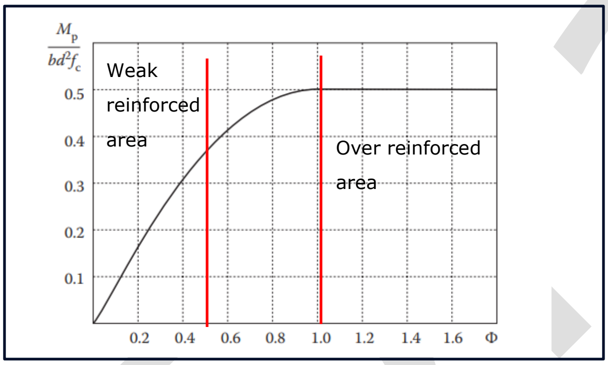


Figure 11.2: The capacity curve for pure bending. From Limit Analysis and Concrete Plasticity, M.P. Nielsen and L. C. Hoang

The calculations for each beam are based on the connected measured compression strength of the concrete and measured yield strength (f_y) of the reinforcement. This means that the tensile strength (f_t) of the reinforcement is not taken into consideration.

Over reinforced beams are defined as beams where the mechanical reinforcement ratio is bigger than the effectiveness factor, meaning that the bending capacity is fully depended on the strength of the concrete, cf. figure 11.2.

Weak reinforced beams are defined as beams where the mechanical reinforcement ratio is less than half the effectiveness factor, meaning that the bending capacity is fully depended on the strength of the reinforcement, cf. figure 11.2.

In table 11.1 some of the test series are reported.

Series number[1)]	All test			Test over reinforced beams			Test weak reinforced beams		
	Number of tests	Average test/calculation	COV (%)	Number of tests	Average test/calculation	COV (%)	Number of tests	Average test/calculation	COV (%)
A1	12	0,92	9,7	2	1,09	9,7	-	-	-
A5	57	1,06	11,5	6	1,01	6,8	33	1,11	9,8
A7	20	1,03	8,2	10	1,03	10,7	-	-	-
A8	37	0,99	9,6	13	0,92	6,9	8	1,08	8,7
A14	18	0,99	6,8	-	-	-	18	0,99	6,8
A15	22	1,21	7,0	-	-	-	22	1,21	7,0
A17	8	0,97	10,3	8	0,97	10,3	-	-	-
Average		1,00	9,0		1,00	8,9		1,10	8,1
95%-fractile			12,7			13,3			11,8

Note, For series number see the reference "Effektivitetsfaktoren ved bøjning af jernbetonbjælker, M.P. Nielsen & Bent Feddersen, ABK, DTU, Serie R, No. 173, 1983"

Table 11.1, Tests with beams in bending

The test results is shown in appendix D, Figure D1-C7.

The coefficient of variation is in Figure 11.1 – 11.3 for the types in table 11.1 shown as a function of the average of the relation between test and calculated values.

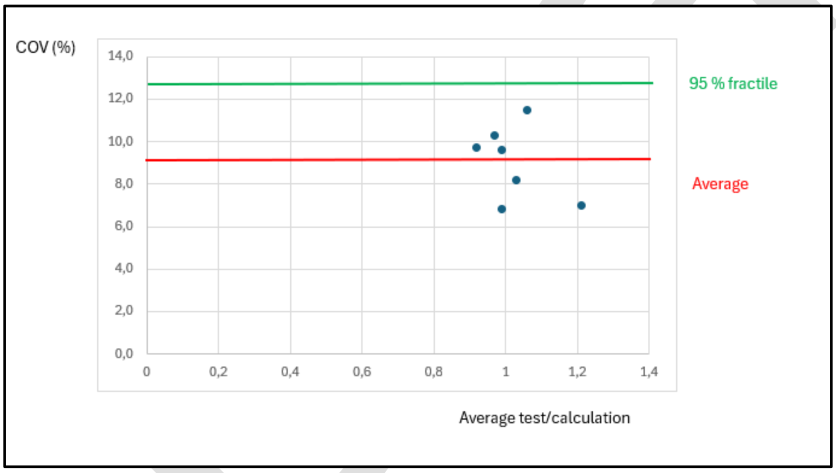


Figure 11.1, All test results for beams

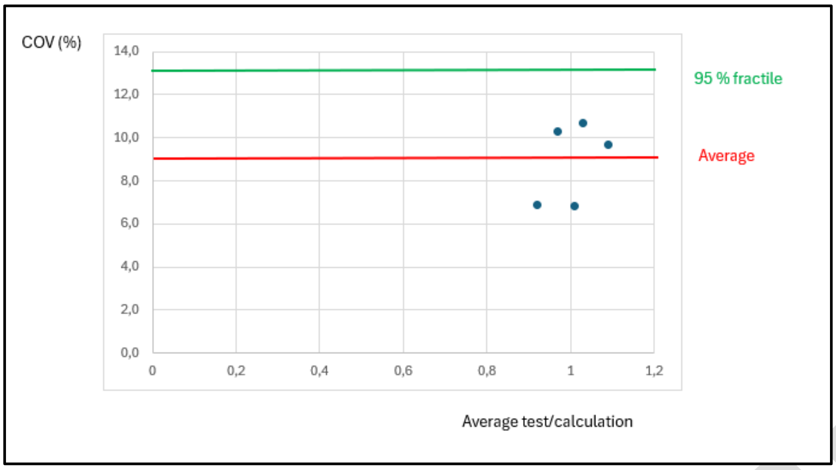


Figure 11.2, Tests with over reinforced beams

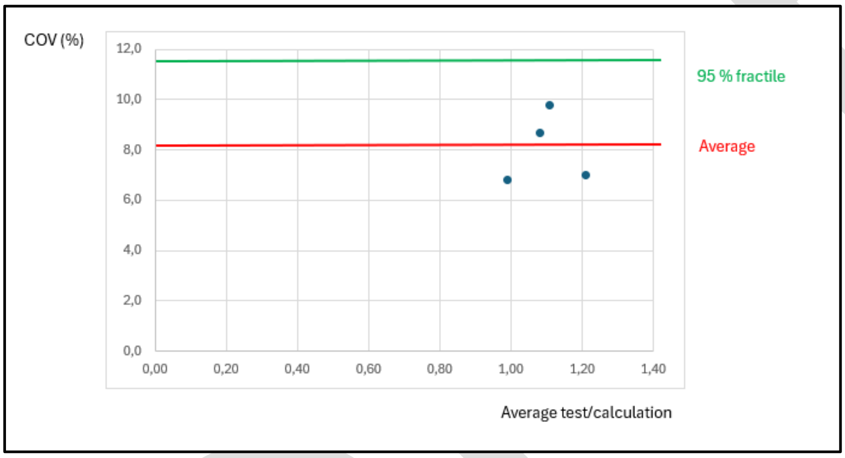


Figure 11.3, Tests with weak reinforced beams

There is no information about the f_t/f_y-ratio for the reinforcement used in the test beams. This ratio will typically be in the range of 1,05 – 1,10. This of course results in higher test values compared to the calculated values where the yield strength is used. The uncertainty connected to the f_t/f_y-ratio can also give a raise in the coefficient of variation.

Based on the above it seems reasonable to put the coefficient of variation for the calculation model to $V_{2,XR,f_c} = 10{,}0\ \%$ when the concrete is governing the failure and $V_{2,XR,f_y} = 8{,}0\ \%$ when the reinforcement is governing the failure.

12. Calculation methods, Generally

Will be prepared later.

12.1 Calculation methods, Beam shear (shear reinforced)

12.2 Calculation methods, Beam shear (non-shear reinforced)

12.3 Calculation methods, Beam torsion

12.4 Calculation methods, Construction joints

12.5 Calculation methods, Columns

12.6 Calculation methods, Unreinforced structures

13. Calculation model, real structure

The difference between the structural member being tested in laboratory and the real structure is connected to geometry, as geometry is both the dimensions of the structural members and the placement of reinforcement in the structural members.

The background document for DS/EN 1992-1-1:2023 indicates for the coefficient of variation the value $V_{2,XRT} = 5{,}0\ \%$. This value will be used without further investigations.

14. Partial factors

Table 14.1 contains the results for the coefficient of variations given in chapter 3-13.

The sub-partial factors γ_1, γ_2 and γ_3 are calculated using the tables given in DS/EN 1990:2023 DK NA, annex FF.

Subject		γ_1		γ_2					γ_3					γ_M
Topic	*Symbol*	*Failure type*	γ_1	*Bias*	$V_{2,XR}$ %	$V_{2,XRT}$ %	V_2 %	γ_2	*Bias*	$V_{3,R}$ %	$V_{3,RT}$ %	V_3 %	γ_3	
Reinforced concrete *Compressive strengt concrete* *Modulus of elasticity concrete*	γ_c	WWRR	1,00	1,00	10,00	5,00	11,18	1,06	1,00	6,50	8,87	11,00	1,23	1,31
Plain concrete *Compressive strengt concrete* *Modulus of elasticity concrete*	γ_c	NW	1,10	1,00	10,00	5,00	11,18	1,06	1,00	6,50	8,87	11,00	1,23	1,44
Tensile strength concrete	γ_c	NW	1,10	-	10,00	5,00	11,18	1,06	-	11,00	-	16,00	1,29	1,50
Shear, members without shear reinforcement *1)	γ_v	NW	1,10	1,00	-	-	13,00	1,08	1,00	-	-	4,00	1,17	1,38
Reinforcement *- Non prestressed and prestressed* *Yield strength* *Modulus of elasticity concrete*	γ_s	NW	1,00	1,00	8,00	5,00	9,43	1,04		4,50	0,00	4,50	1,17	1,22
Reinforcement *- Non prestressed and prestressed* *Ultimate strain limit*	γ_{sc}													1,22
Structures testing *Ductile failure* *Brittle failure*	γ_M													 1,20 1,40

Note
NW No Warning
WWRR Warning Without Residual Resistance
WWR Warning With Residual
Reinforced concrete: Concrete structure that contains minimum reinforcement for the relevant impacts in agreement with DS/EN 1991-1-1:2023 and DS/EN 1992-1-1:2023 DK NA
Tensile strength concrete: The partial factor is used where the capacity is depending on the tensile strength of concrete, i.e. anchorage, laps and chapter 14.
*1) The value for V_3 is power 1/3 of 11 %

Table 14.1, Calculated partial factors for concrete.

The values marked with red in table 14.1 are values that need further investigation or the background data is still not created.

Appendix A

Test results, compression concrete strength for in-situ cast specimens

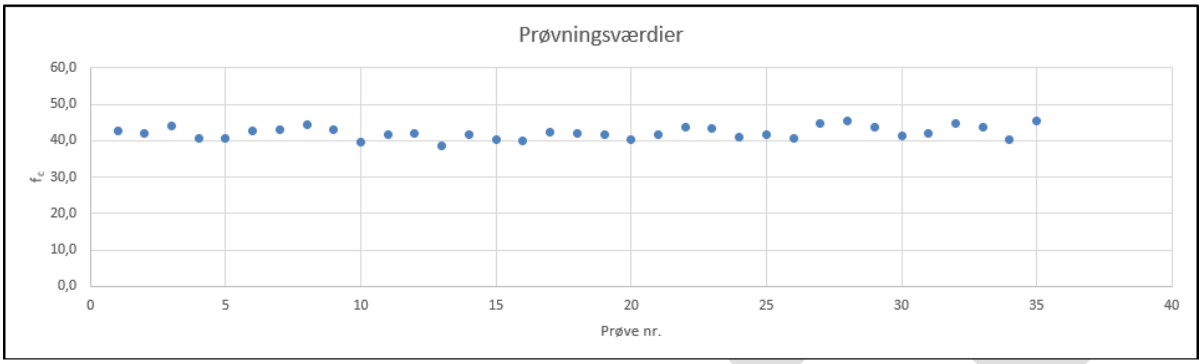


Figure A.1 Test values series 1

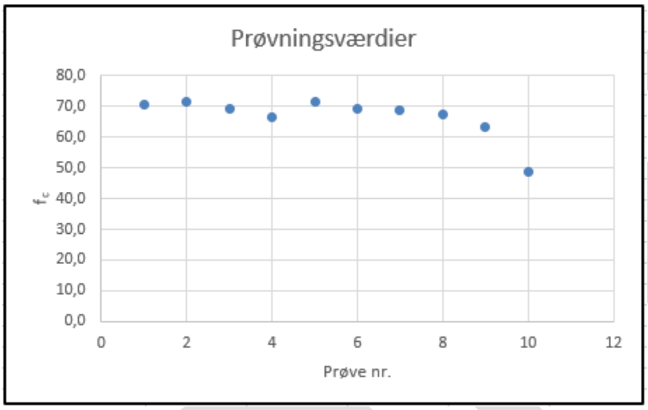


Figure A.2 Test values series 2

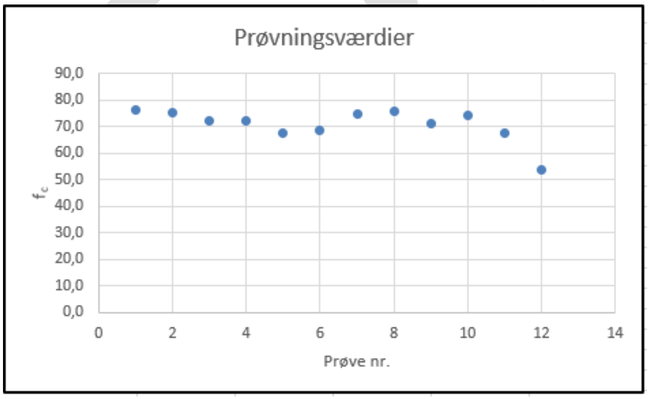


Figure A.3 Test values series 3

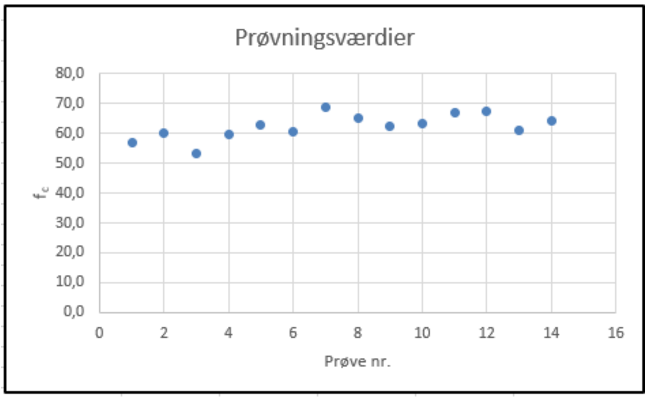


Figure A.4 Test values series 4

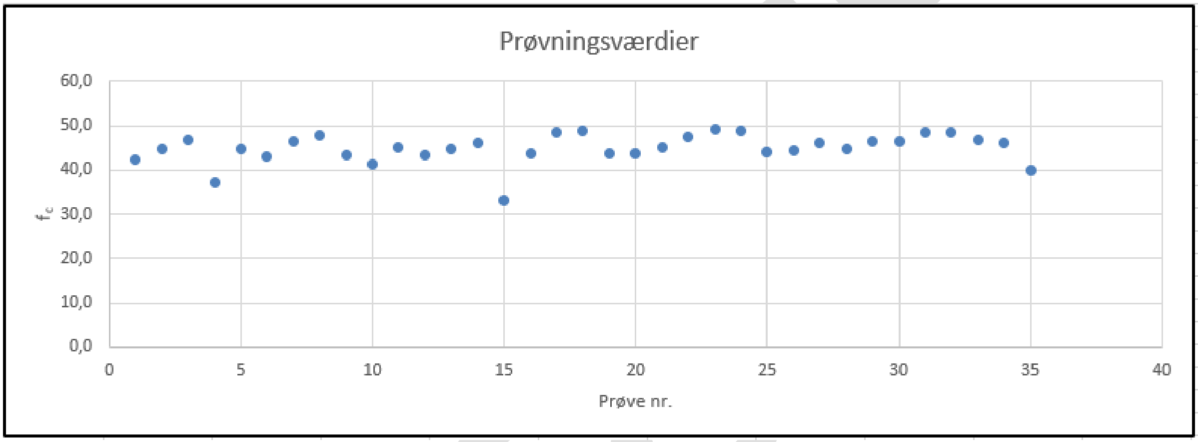


Figure A.5 Test values series 5

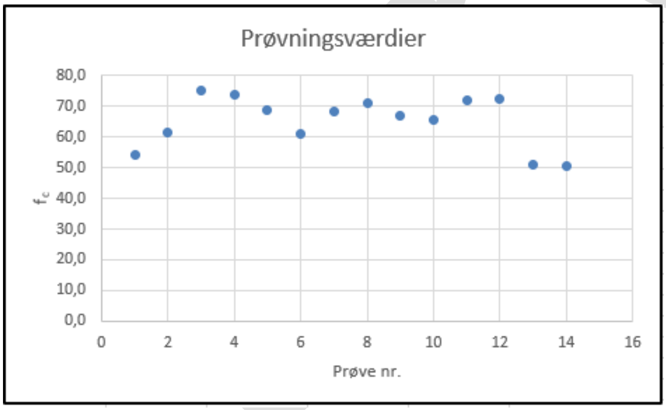


Figure A.6 Test values series 6

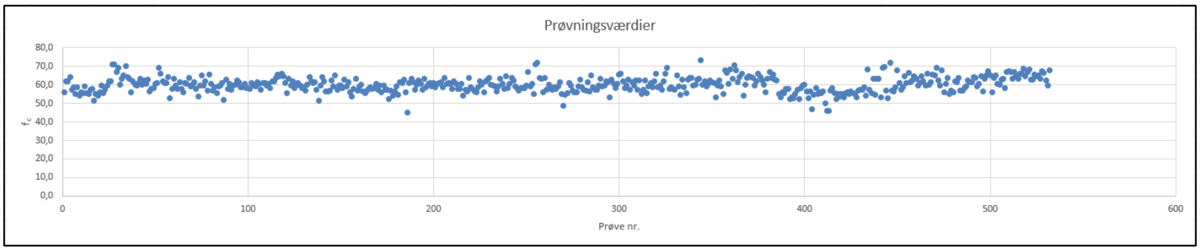


Figure A.7 Test values series 7

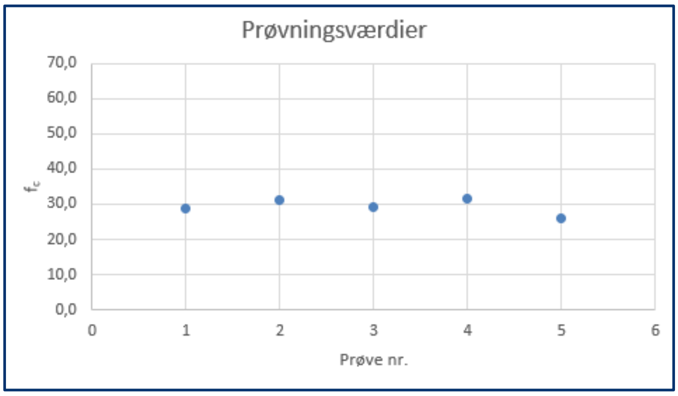


Figure A.8 Test values series 8

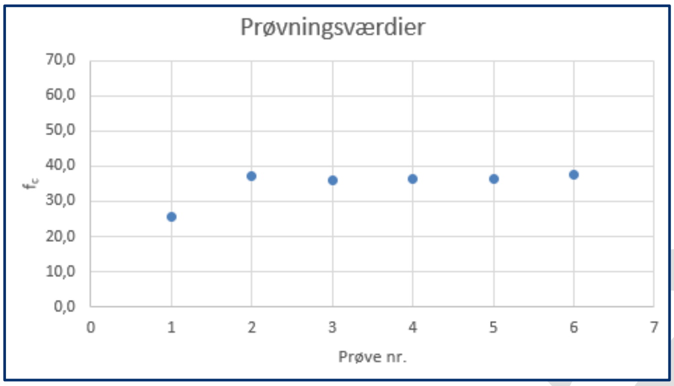


Figure A.9 Test values series 9

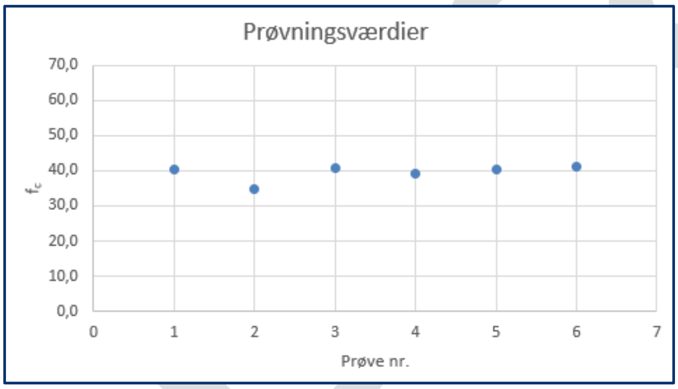


Figure A.10 Test values series 10

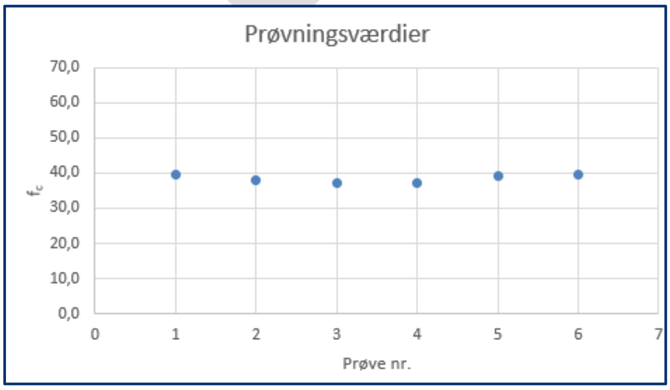


Figure A.11 Test values series 11

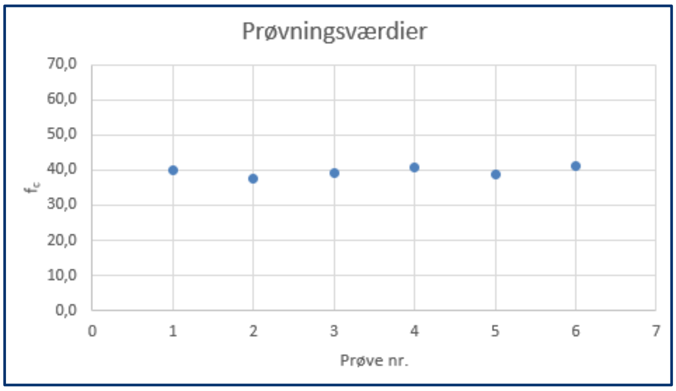


Figure A.12 Test values series 12

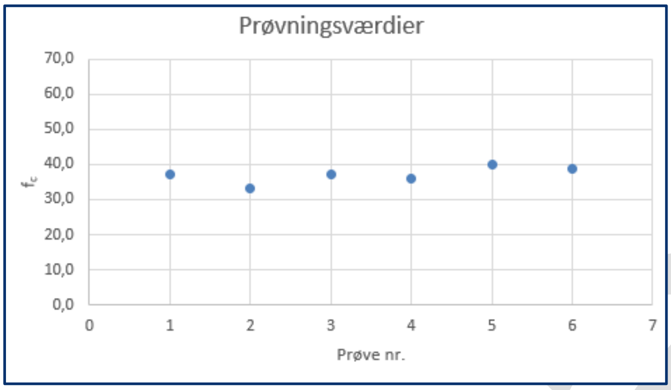


Figure A.13 Test values series 13

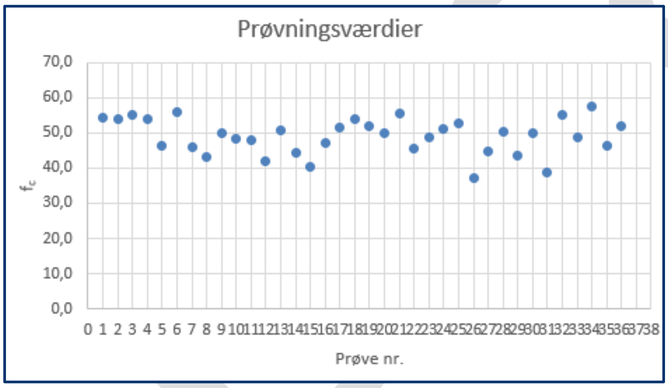


Figure A.14 Test values series 14

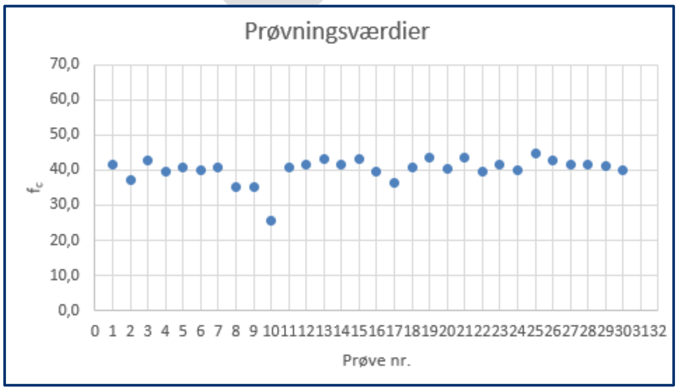


Figure A.15 Test values series 15

Appendix B

Test results, yield strength reinforcement

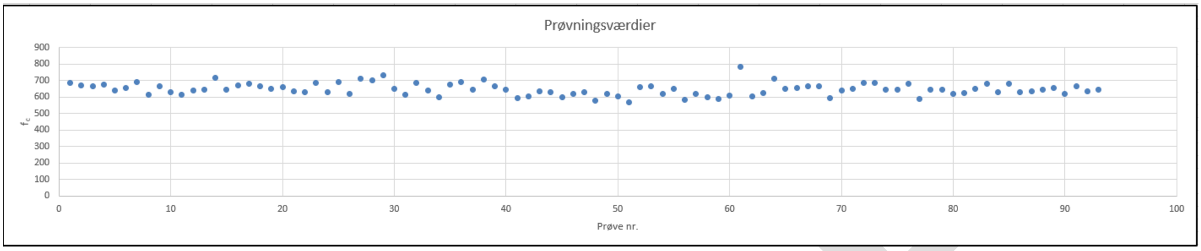


Figure B.1 Test values series S1

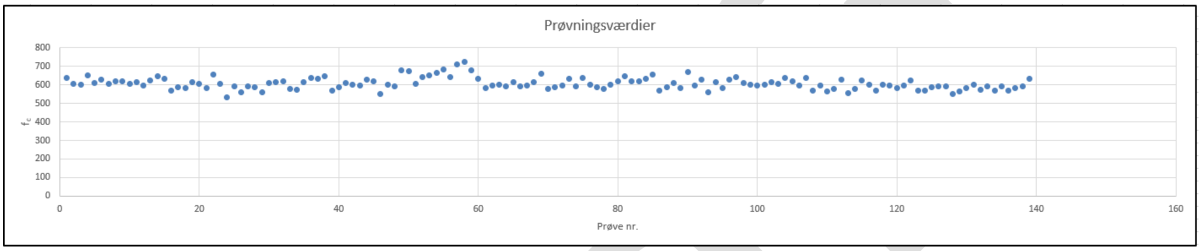


Figure B.2 Test values series S2

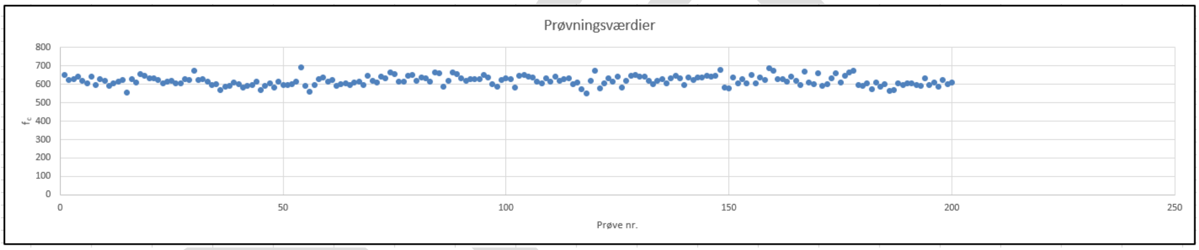


Figure B.3 Test values series S3

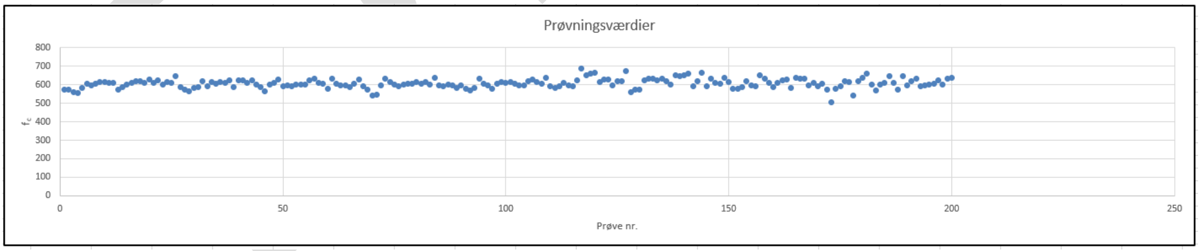


Figure B.4 Test values series S4

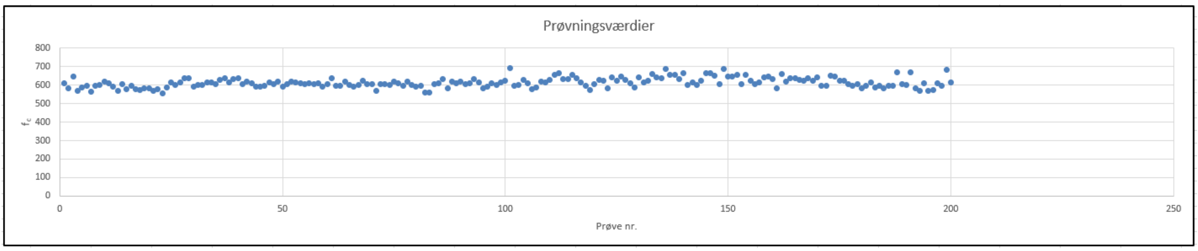


Figure B.5 Test values series S5

Appendix C

Test results, compression concrete strength in real structure

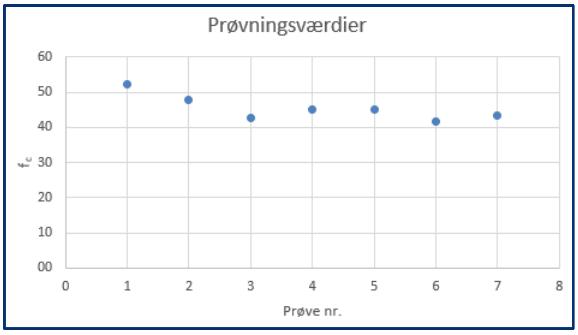


Figure C.1 Test values series CS1

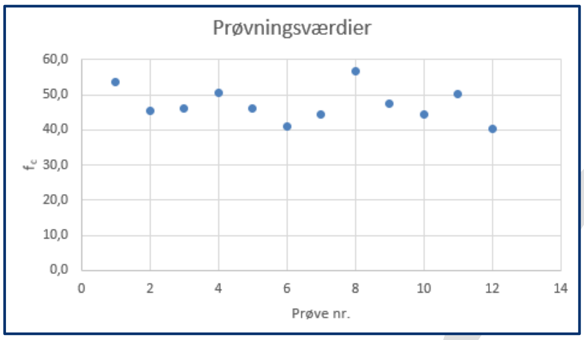


Figure C.2 Test values series CS2

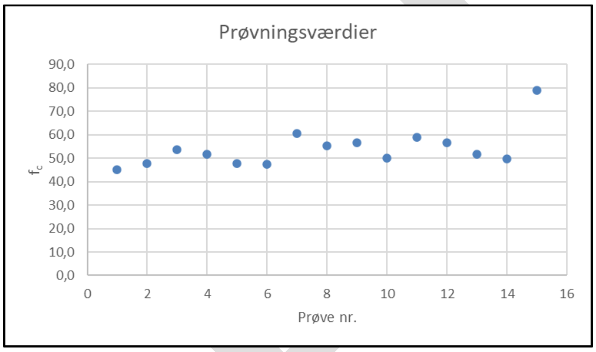


Figure C.3 Test values series CS3

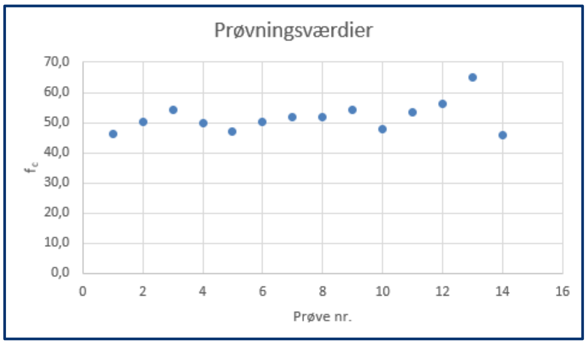


Figure C.4 Test values series CS4

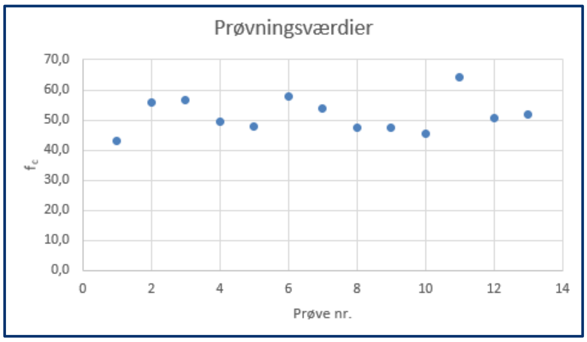


Figure C.5 Test values series CS5

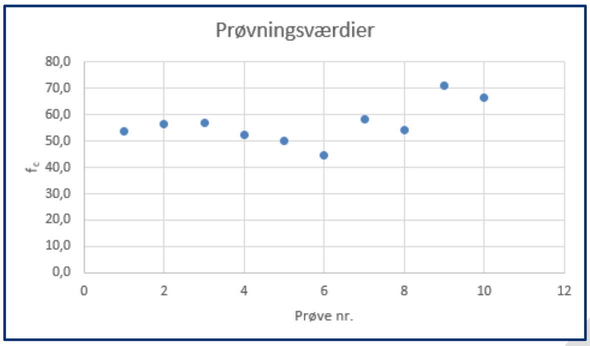


Figure C.6 Test values series CS6

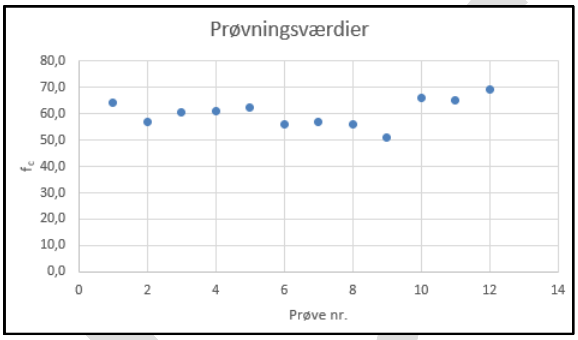


Figure C.7 Test values series CS7

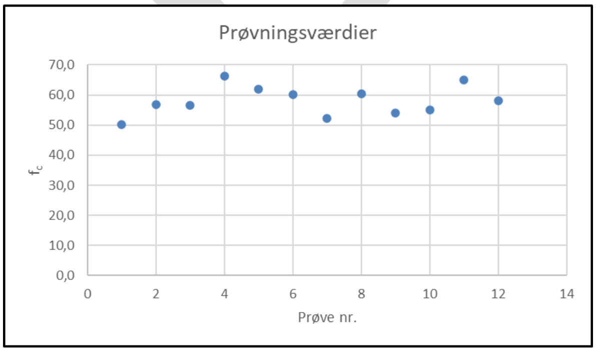


Figure C.8 Test values series CS8

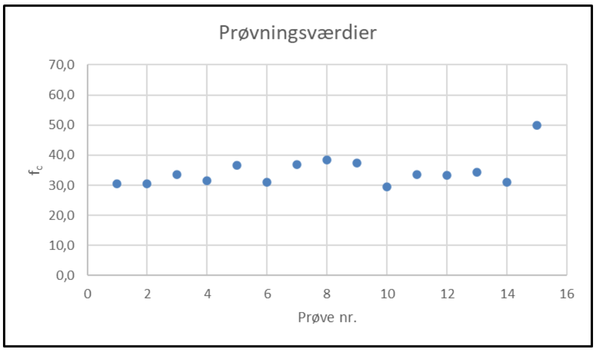


Figure C.9 Test values series CS9

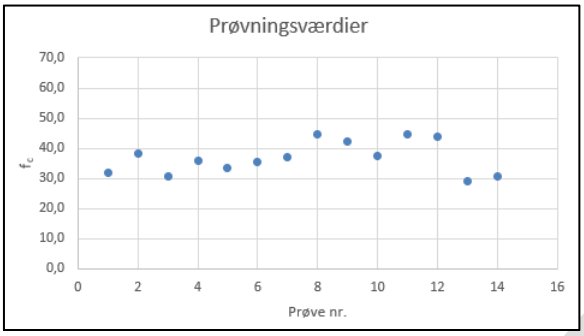


Figure C.10 Test values series CS10

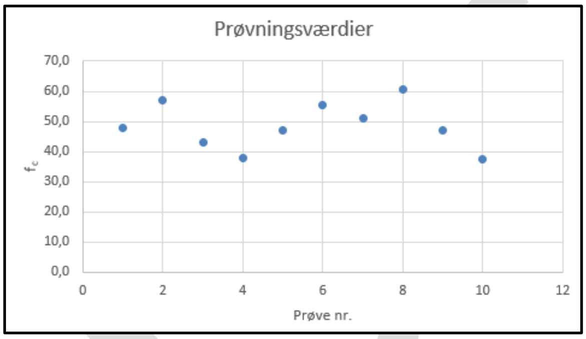


Figure C.11 Test values series CS11

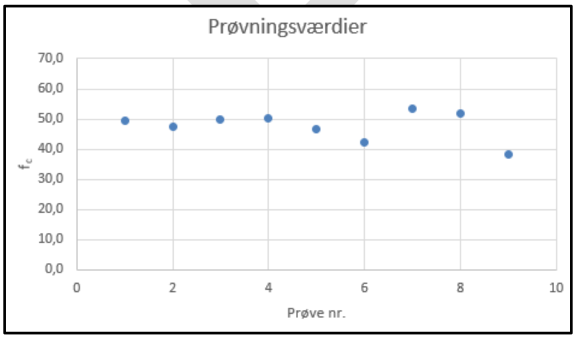


Figure C.12 Test values series CS12

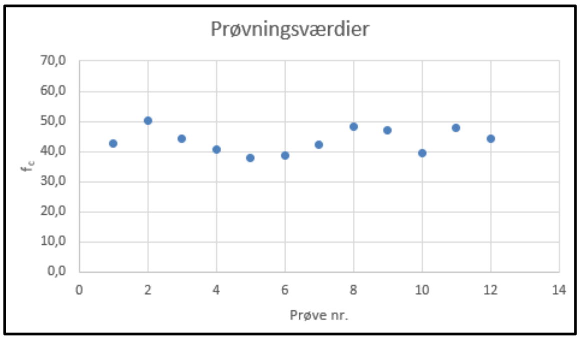


Figure C.13 Test values series CS13

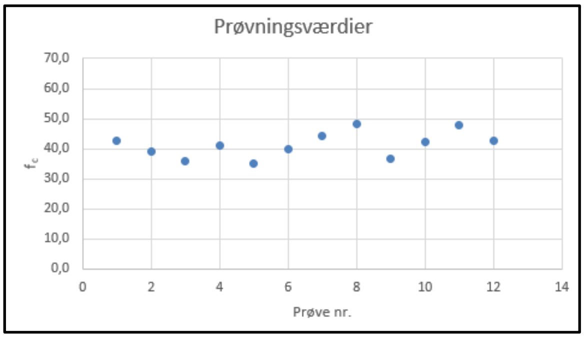


Figure C.14 Test values series CS14

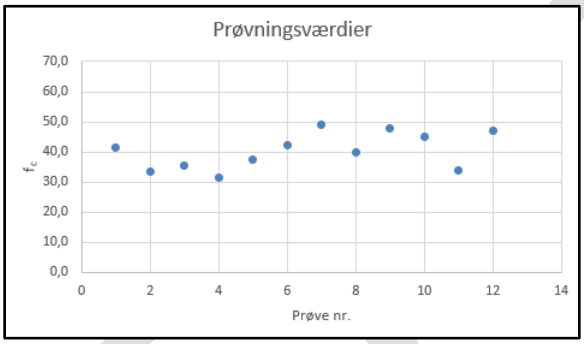
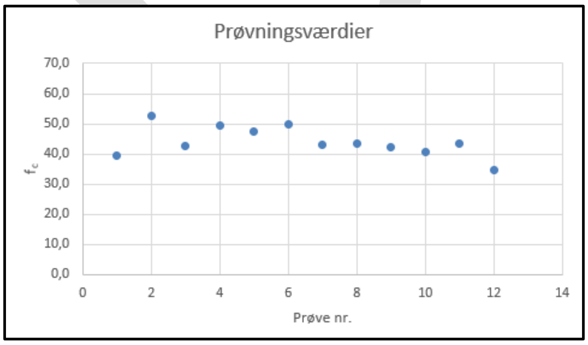


Figure C.15 Test values series CS15



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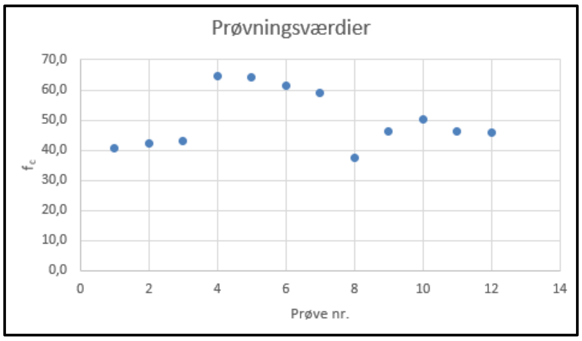

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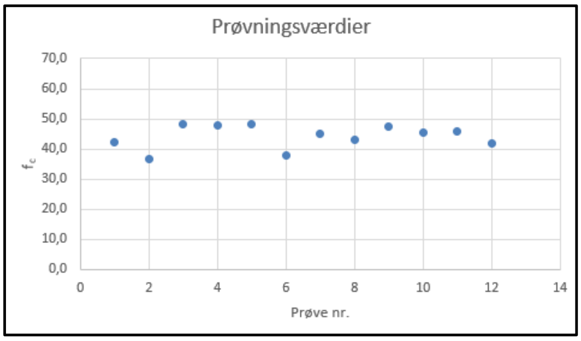

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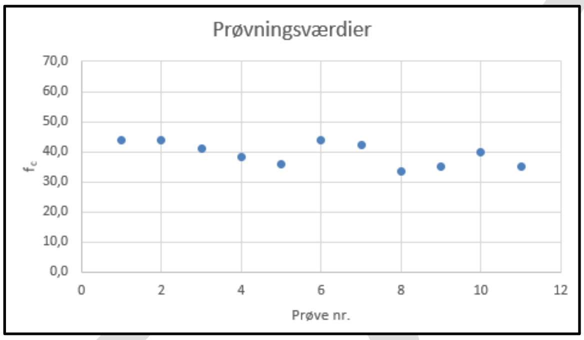


Figure C.19 Test values series CS19

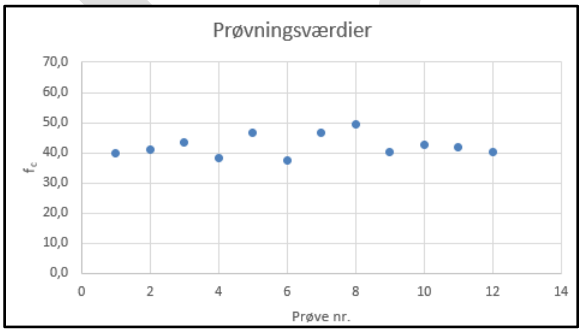
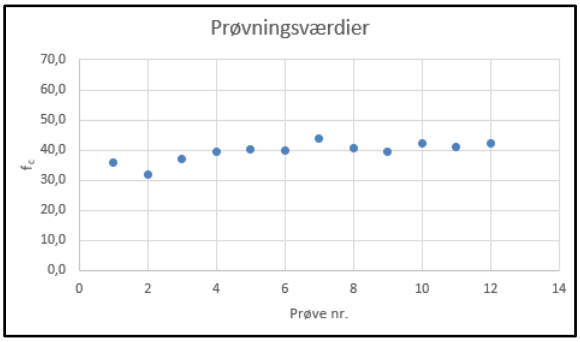


Figure C.20 Test values series CS20



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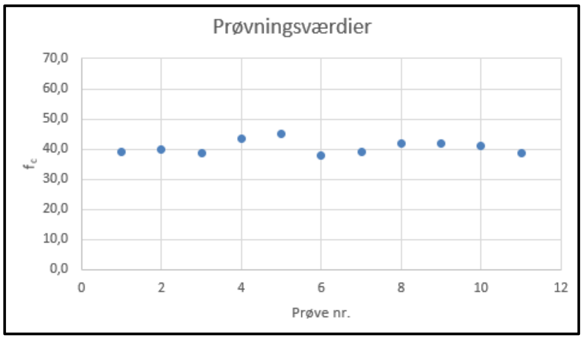
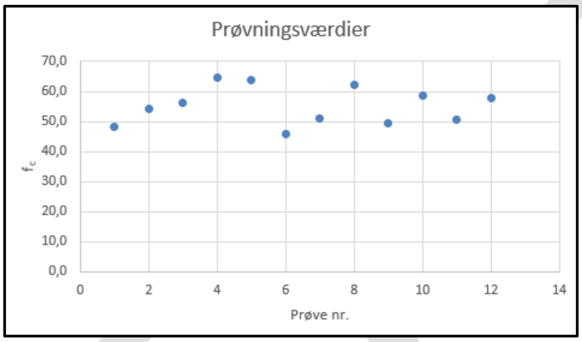


Figure C.22 Test values series CS22



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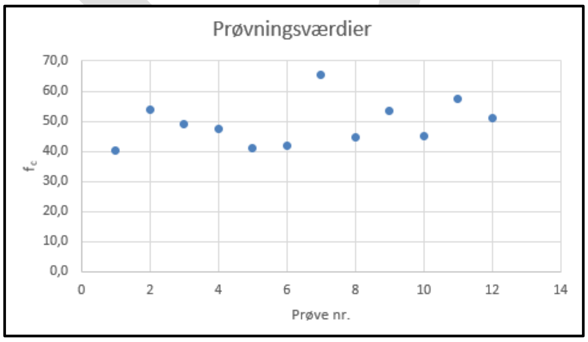

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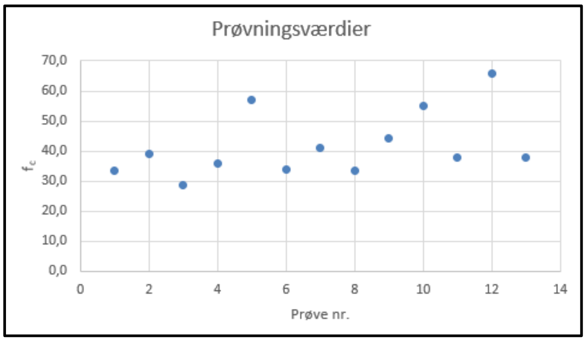


Figure C.25 Test values series CS25

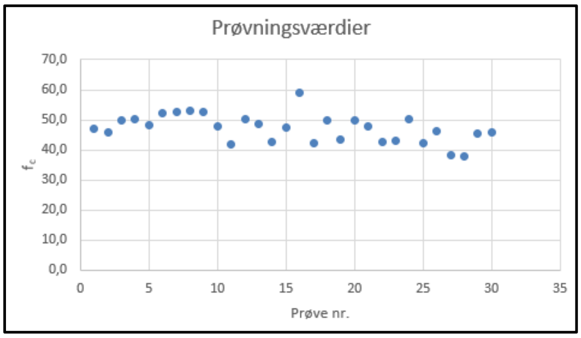


Figure C.30 Test values series CW1

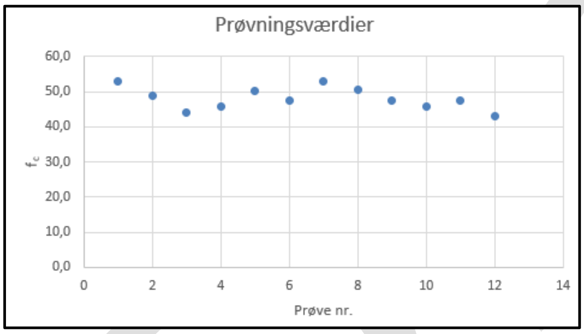


Figure C.31 Test values series CW2

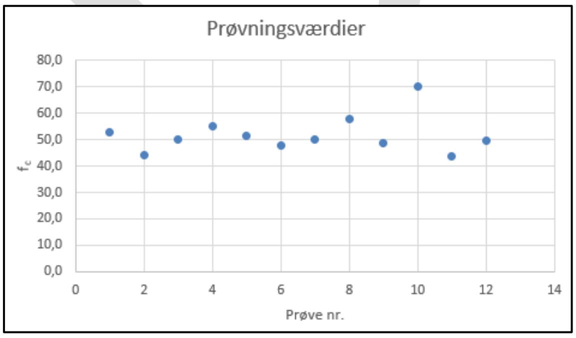


Figure C.32 Test values series CW3

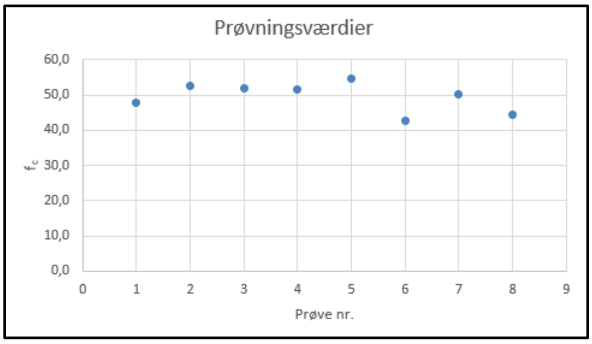


Figure C.33 Test values series CW4

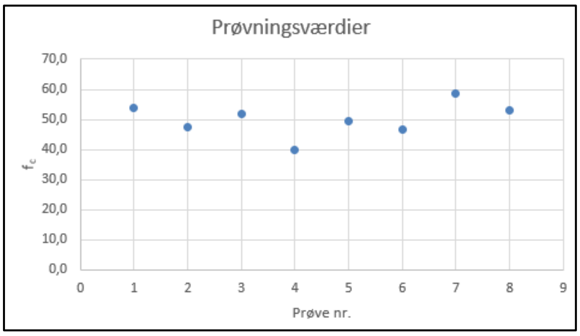
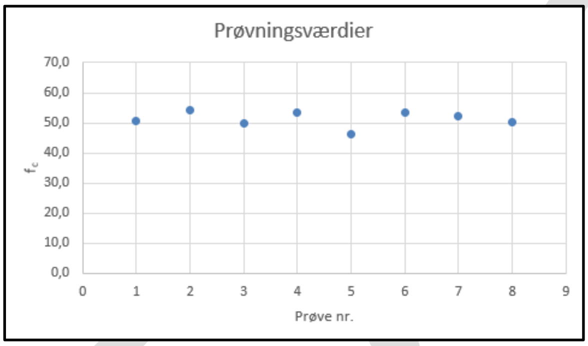


Figure C.34 Test values series CW6



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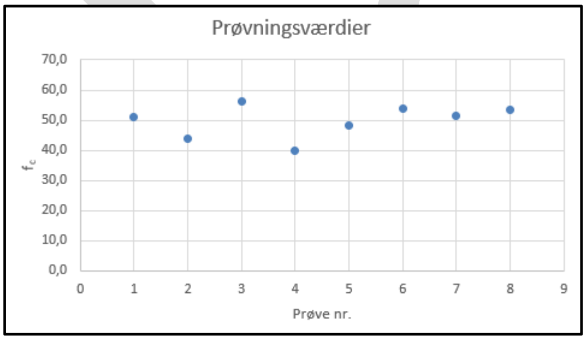


Figure C.36 Test values series CW7

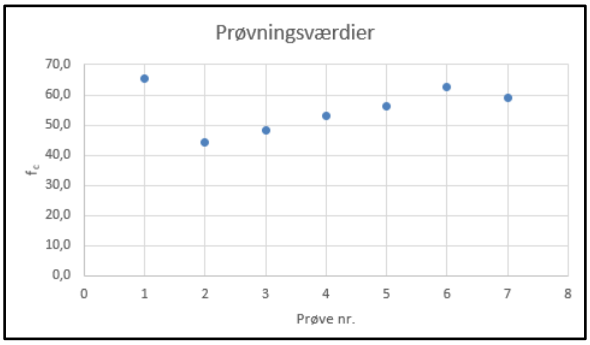


Figure C.37 Test values series CW8

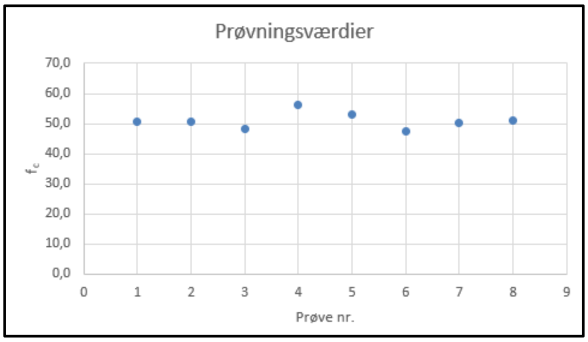


Figure C.38 Test values series CW9

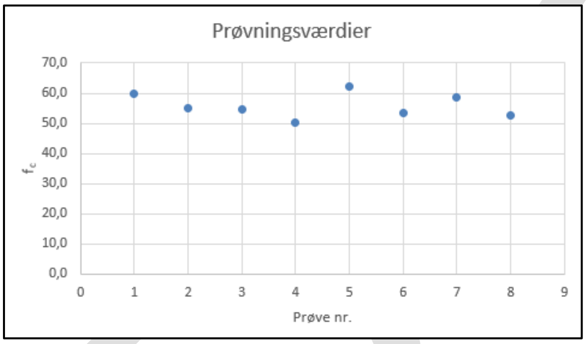


Figure C.39 Test values series CW10

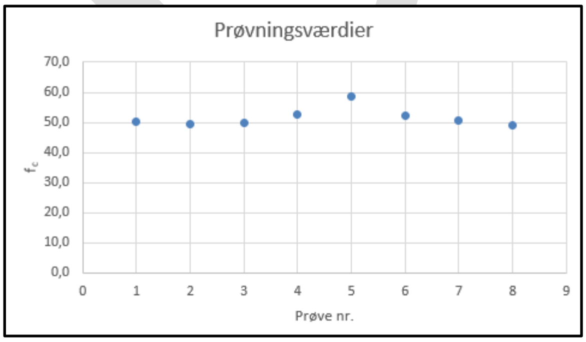


Figure C.40 Test values series CW11

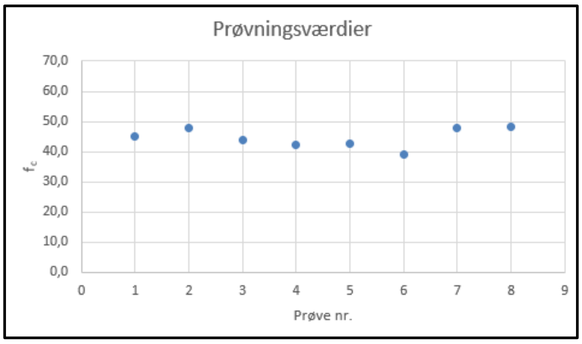


Figure C.41 Test values series CW12

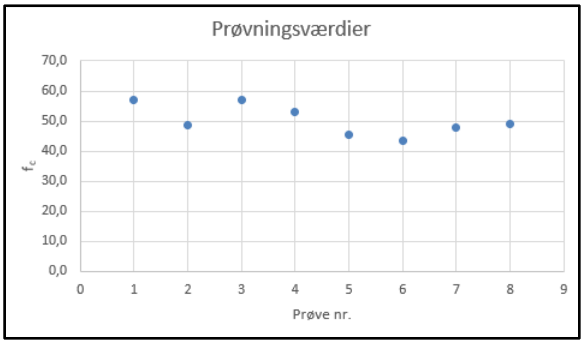


Figure C.42 Test values series CW13

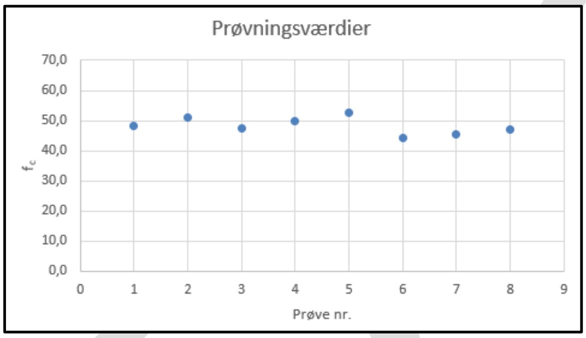


Figure C.43 Test values series CW14

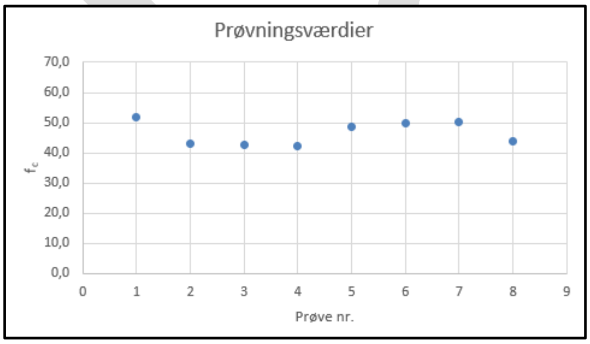


Figure C.44 Test values series CW15

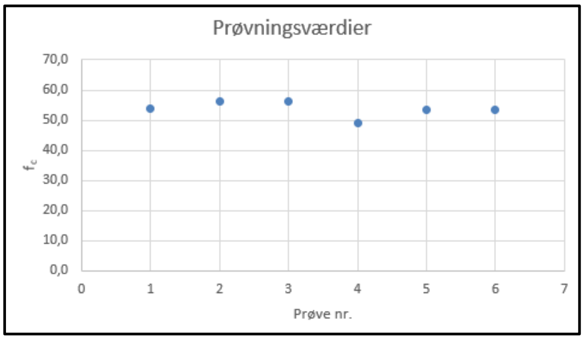


Figure C.45 Test values series CW16

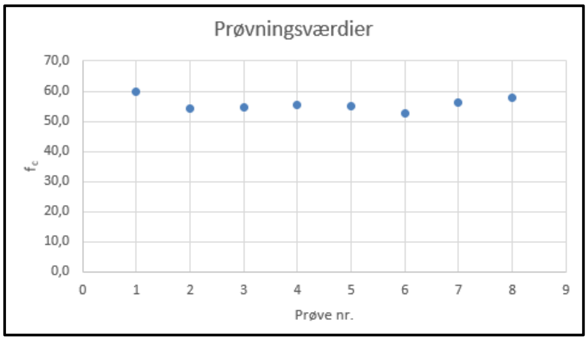


Figure C.46 Test values series CW17

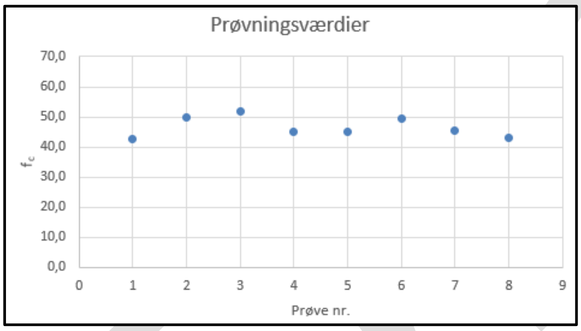


Figure C.47 Test values series CW18

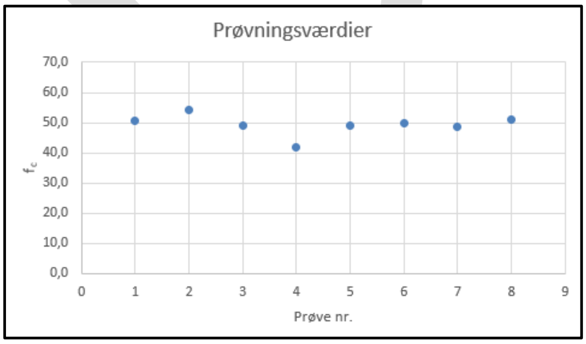


Figure C.48 Test values series CW19

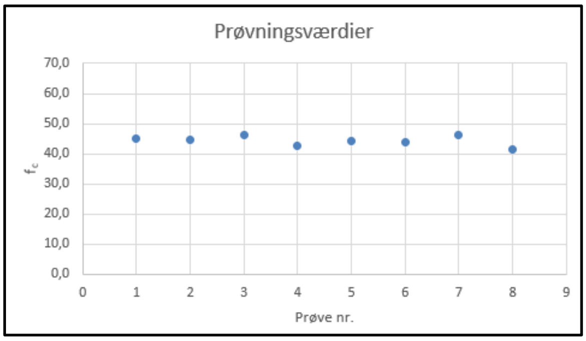


Figure C.49 Test values series CW20

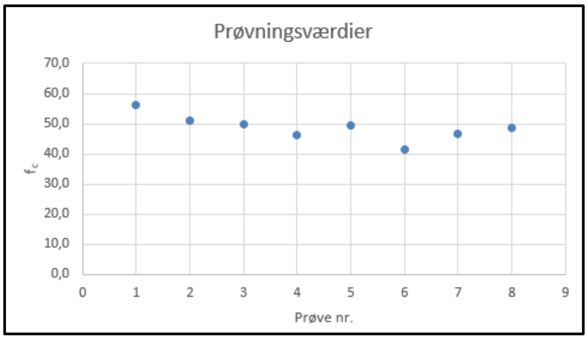


Figure C.50 Test values series CW21

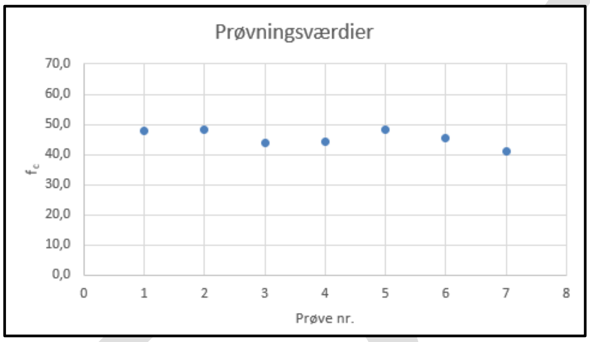


Figure C.51 Test values series CW22

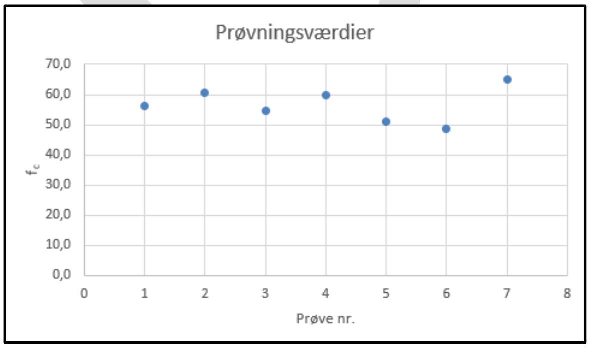


Figure C.52 Test values series CW23

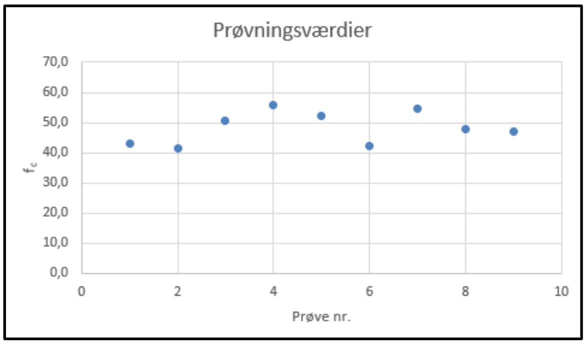


Figure C.53 Test values series CW24

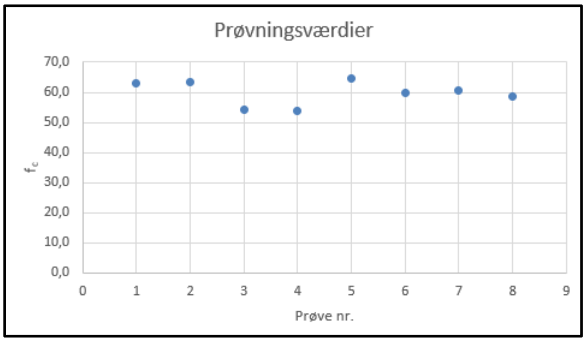


Figure C.54 Test values series CW25

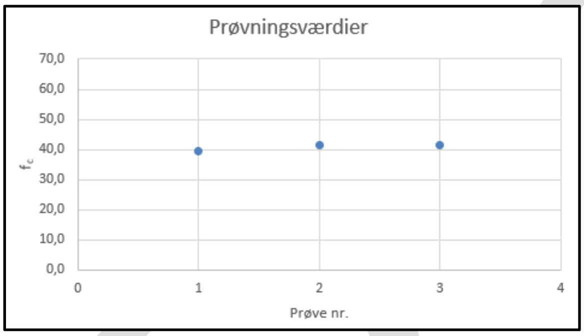
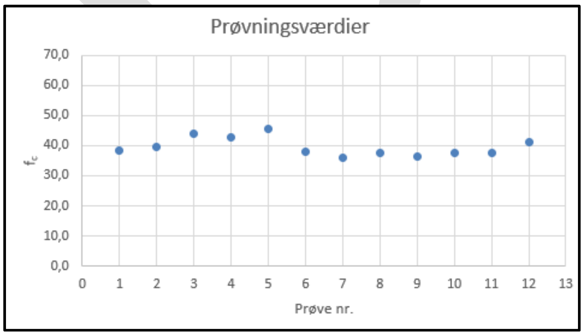


Figure C.60 Test values series CD1



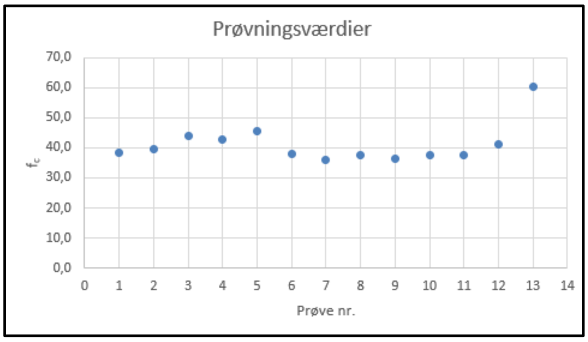


Figure C.61 Test values series CD2

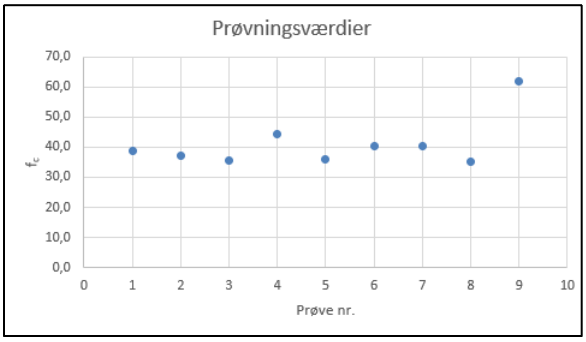


Figure C.62 Test values series CD3

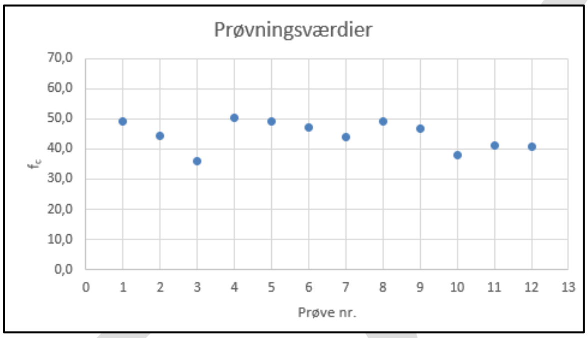


Figure C.63 Test values series CD4

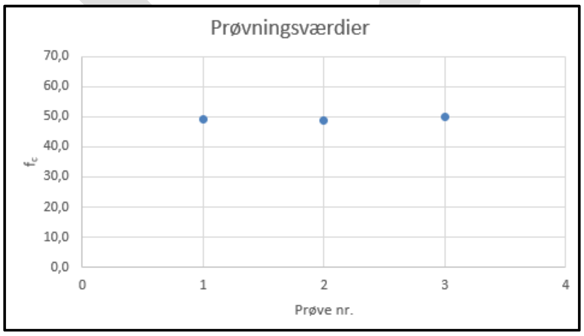


Figure C.64 Test values series CD5

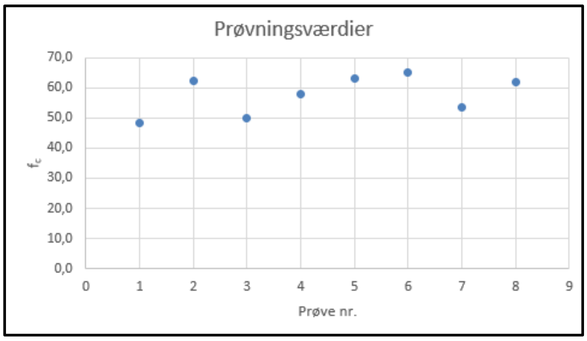


Figure C.65 Test values series CD6

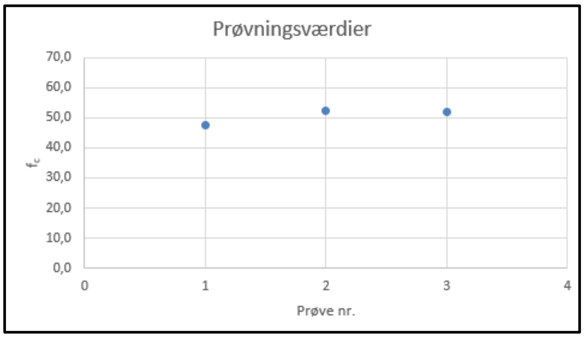


Figure C.66 Test values series CD7

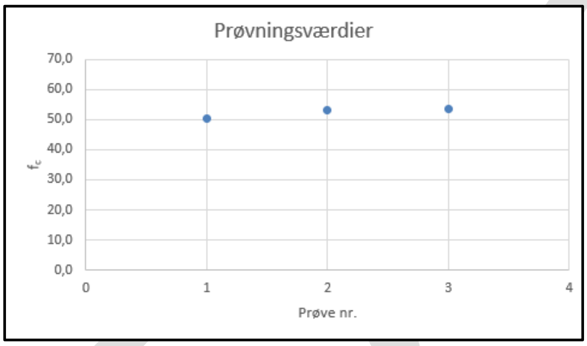


Figure C.67 Test values series CD8

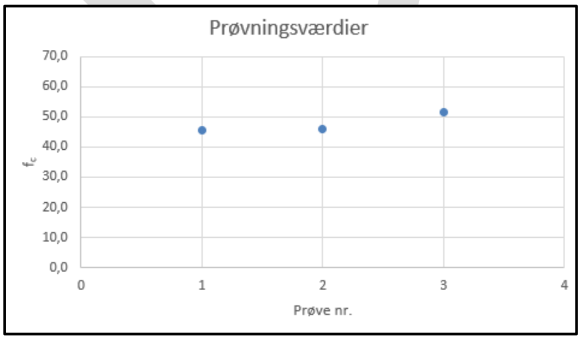


Figure C.68 Test values series CD9

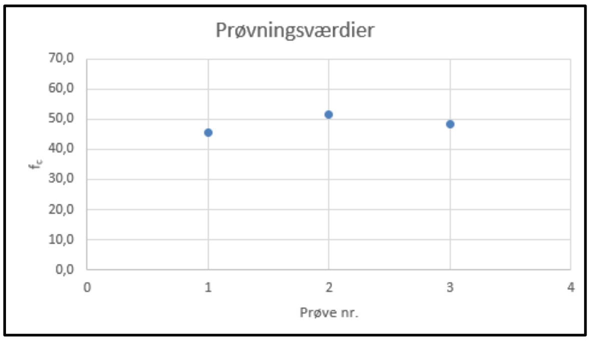


Figure C.69 Test values series CD10

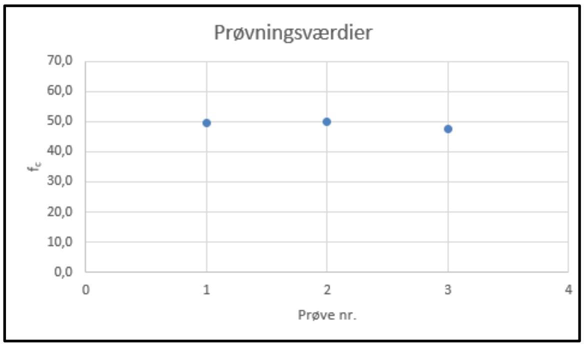


Figure C.70 Test values series CD11

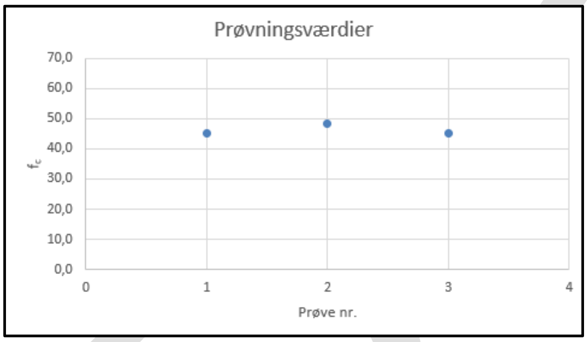


Figure C.71 Test values series CD12

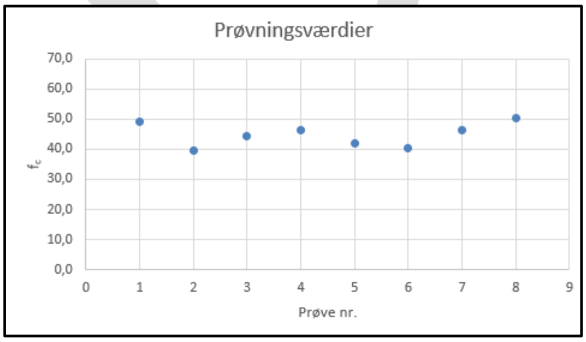


Figure C.72 Test values series CD13

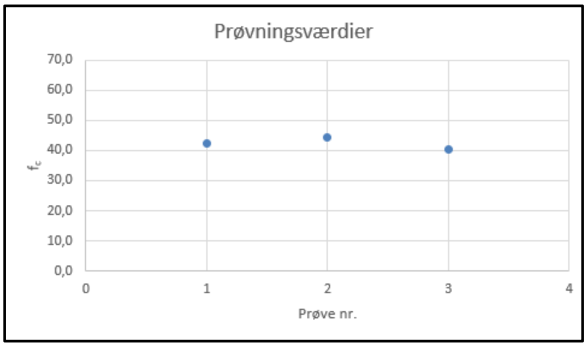
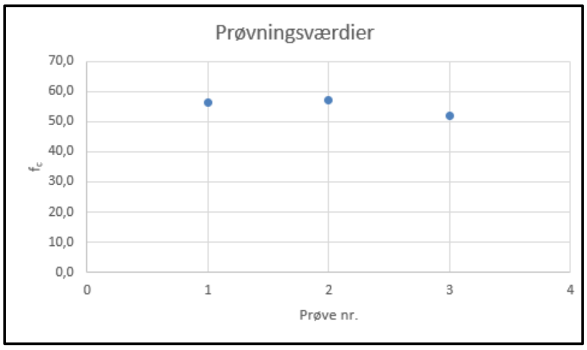


Figure C.73 Test values series CD14



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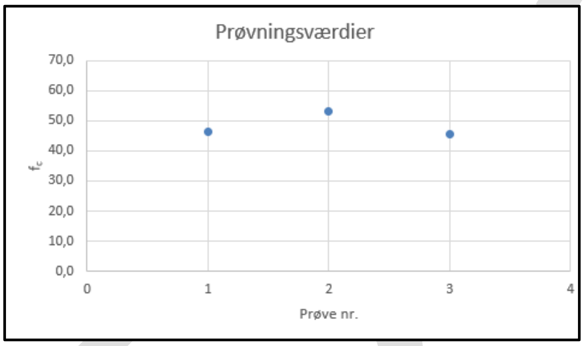


Figure C.75 Test values series CD16

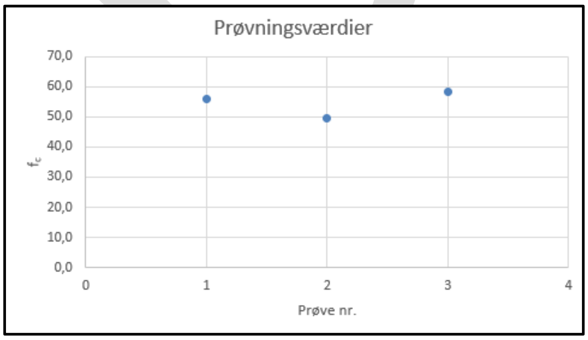


Figure C.76 Test values series CD17

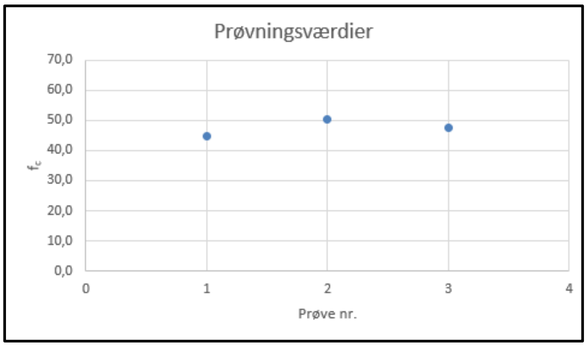


Figure C.77 Test values series CD18

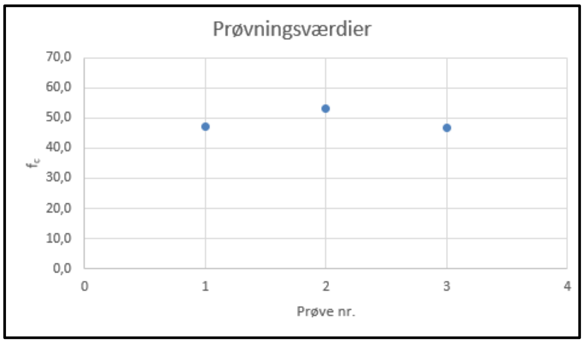


Figure C.78 Test values series CD19

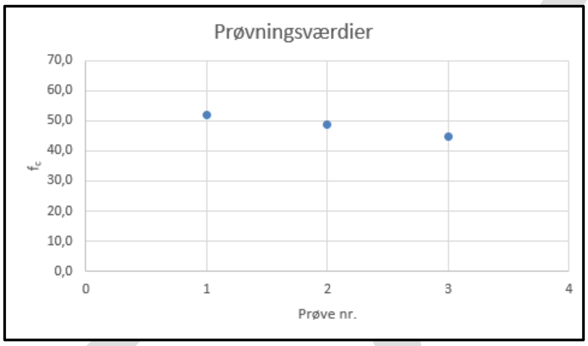


Figure C.79 Test values series CD20

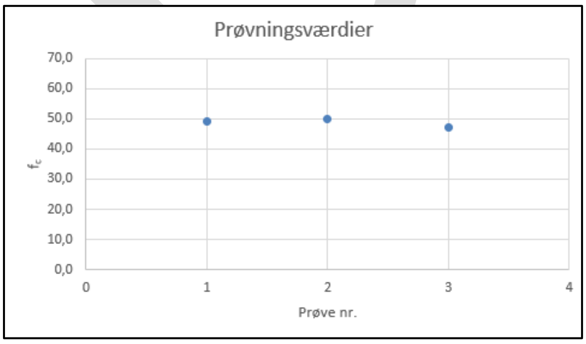


Figure C.80 Test values series CD21

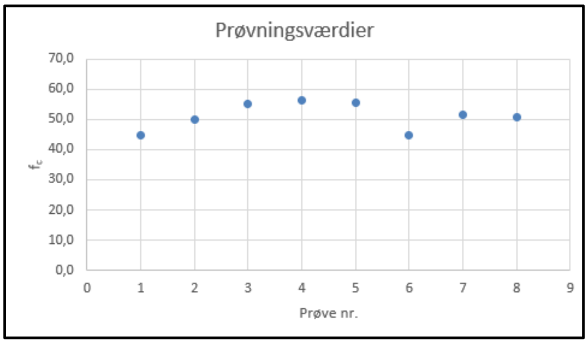
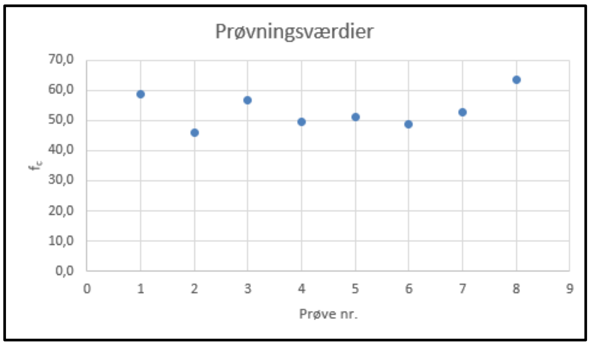


Figure C.81 Test values series CD22



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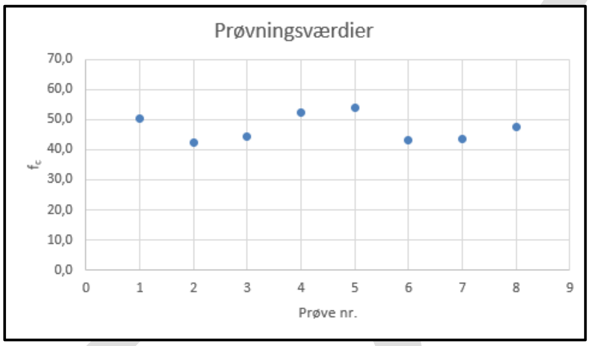

Figure C.83 Test values series CD24

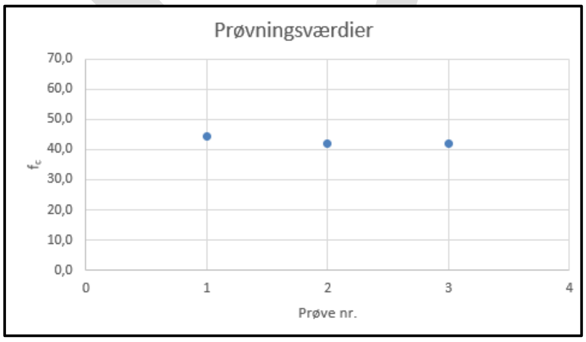

Figure C.84 Test values series CD25

Appendix D

Test results, beams in bending

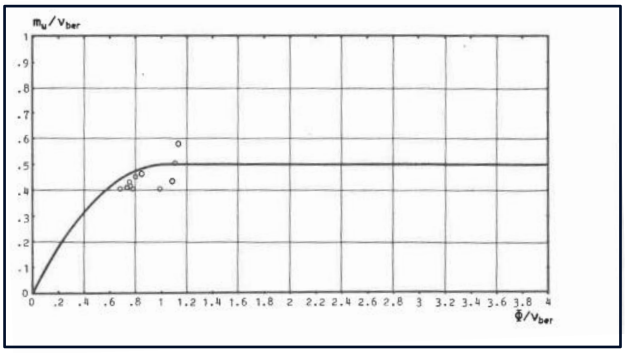

Figure D.1, Test results beams in bending, Series A1

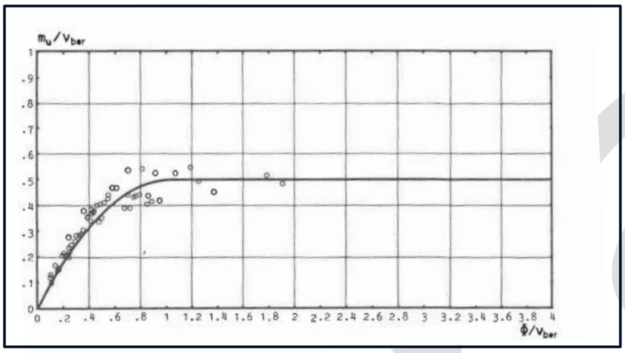

Figure D.2, Test results beams in bending, Series A5

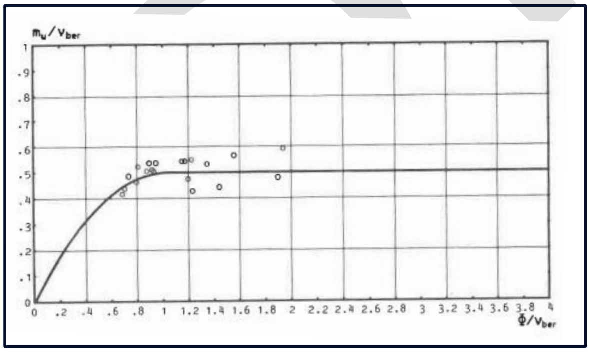

Figure D.3, Test results beams in bending, Series A7

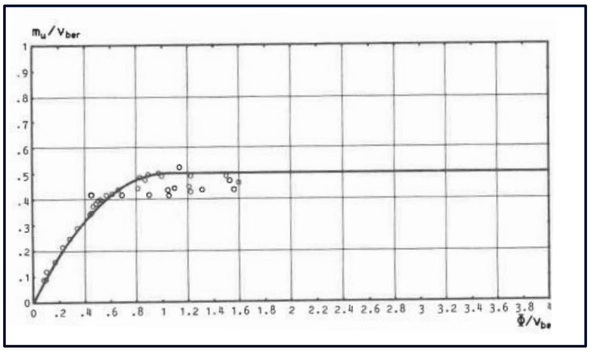

Figure D.4, Test results beams in bending, Series A8

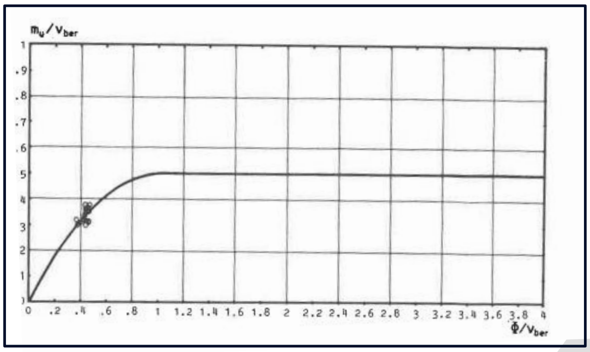

Figure D.5, Test results beams in bending, Series A14

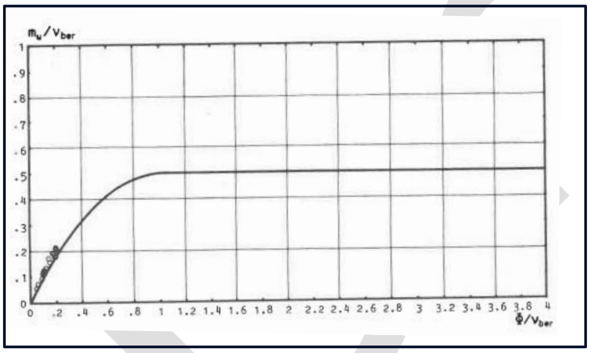

Figure D.6, Test results beams in bending, Series A15

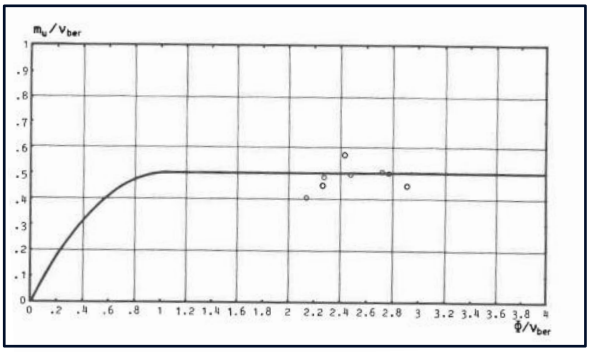

Figure D.7, Test results beams in bending, Series A17