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Determining Characteristic Values for Fiber Reinforced Concrete

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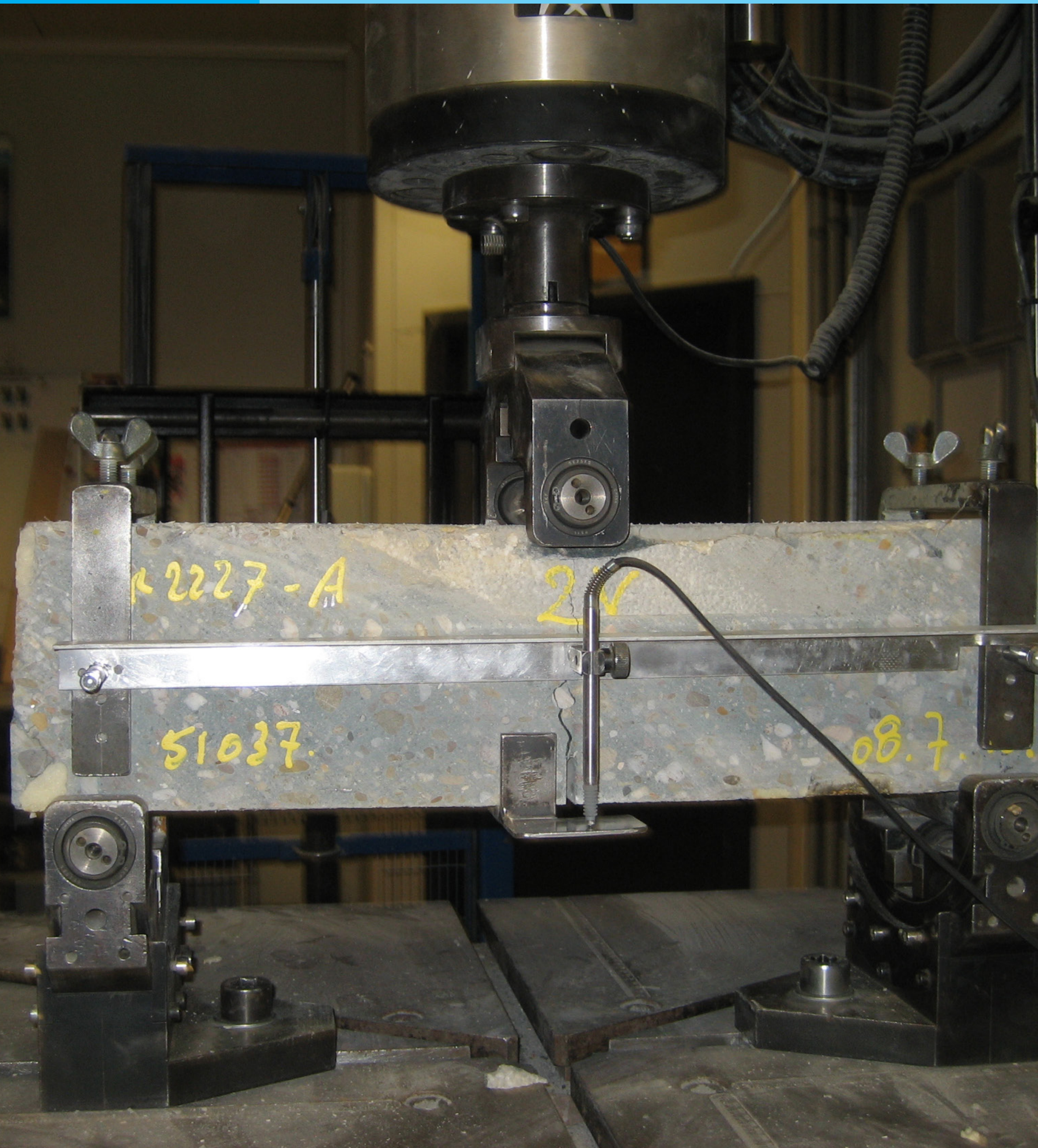

CONTENT

WHITE PAPER

Determining Characteristic Values for Fiber Reinforced Concrete

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The correct determination and use of characteristic values helps to achieve optimum material properties for structural designs incorporating Fiber Reinforced Concrete (FRC). This white paper defines characteristic values for FRC and specifies and compares various methods to determine them. In doing so it aims to support FRC designers and contractors.

INTRODUCTION

Fiber Reinforced Concrete (FRC) is a composite material characterized by a cement matrix and discontinuous, discrete fibers. The matrix consists of either concrete or mortar. The fibers can be made of steel, polymers, carbon, glass, or a variety of natural materials.

The properties of FRC depend on both the characteristics and the dosage of the constituting materials as well as on the geometry, volume fraction and mechanical properties of the fibers, the bond between the fibers and the concrete matrix, and the mechanical properties of the matrix.

The correct determination and use of characteristic values helps to achieve optimum material properties for structural designs incorporating Fiber Reinforced Concrete (FRC).

DEFINITIONS

Mean value: The sum of a collection of numbers divided by the count of numbers in the collection. This collection is often a set of results of an experiment. It is often referred to as the "average".

Minimum value: The lowest value in a collection of data.

Nominal value: A fixed value of, for example, a non-statistical or physical condition. This is a target value of a measurable quantity. As in the "nominal diameter" vs the "actual diameter" of a wire.

Characteristic value: Calculated as $f_k = f_m - f_n s$ where f_m is the average of the measurements, s the sample standard deviation (use STDEV.S function in Excel) and k_n is a factor that depends on the assumed probability distribution leading to a 95% probability that the strength is higher than f_k.

Design values: The characteristic values divided by a partial safety factor.

Standard deviation: A measure of the amount of variation in a collection of data.

Coefficient of variation (COV): The standard deviation divided by the mean result of a test series. To obtain reliable results, a test series of 12 beams according to EN 14651 is recommended, as specified in fib bulletin 83.

MATERIAL PROPERTIES

With regard to the behavior of FRC in tension, which is the most important aspect of FRC, various test methods are possible. Typically, bending tests can be carried out to determine the load-deflection relationship of a beam under either three-point or four-point loading. From this, the flexural tensile strength can be determined. Three-point bending tests are usually performed in accordance with EN 14651.

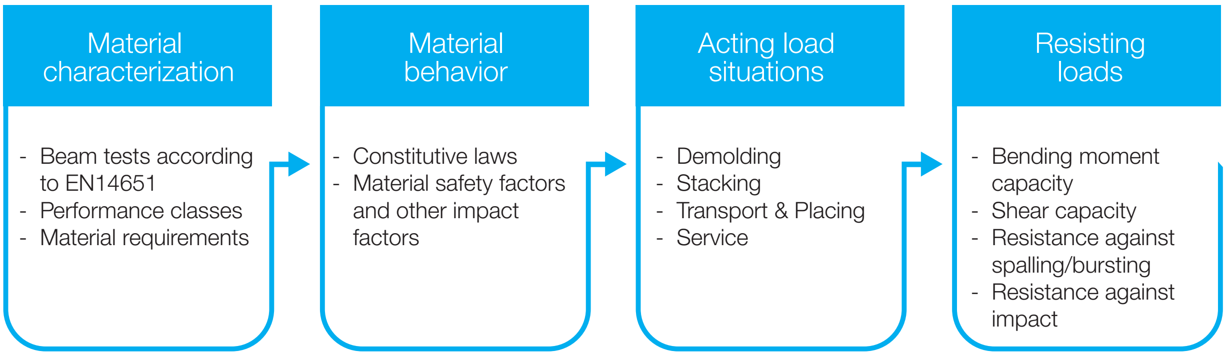

Fig. 1. Summary of a typical design process of FRC for precast segments.

In the design process, the definition of the performance expected from the material is a key factor, and the mix design of the material has to be optimized for the required structural design.

This first step is key to ensure the quality and sustainability of the full process. This step is essential to validate the material properties and in particular to determine the characteristic value to use when making a design.

The contribution of the strength in relation to potential cracks due to the presence of fibers is significant. Nominal values of the material properties are determined according to EN 14651. The diagram of the applied force (F) versus the deformation should be produced; a typical diagram is shown in Fig. 3.

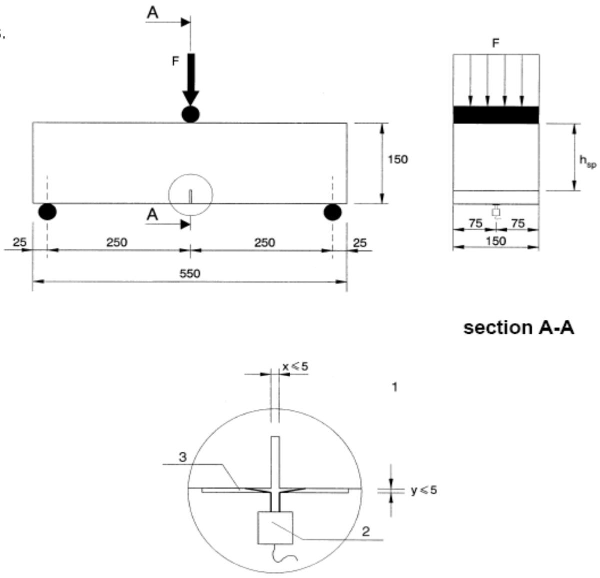

Fig. 2. EN 14 651 test set up and geometry

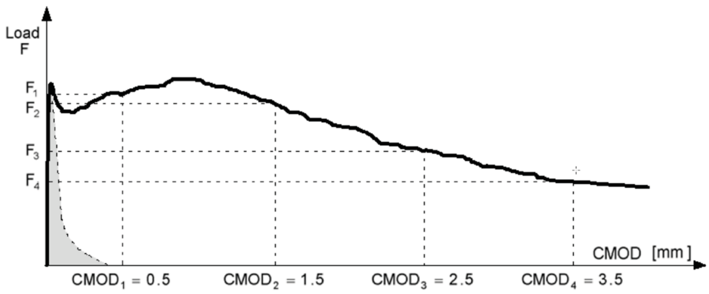

Fig. 3. Typical “force/crack width” trend.

The deformation is generally expressed in terms of Crack Mouth Opening Displacement (CMOD). Parameters fR,j representing the residual flexural tensile strength are evaluated from the F-CMOD relationship as follows:

$$f_{R,j} = \frac{3F_j I}{2bh_{sp}^2}$$

where:

$f_{R,j}$ [MPa] is the residual flexural tensile strength corresponding to CMOD = CMODj

Fj [N] is the load corresponding to CMOD = CMODj

I [mm] is the span length (500mm)

b [mm] is the specimen width (150mm)

hsp [mm] is the distance between the notch tip and the top of the specimen (125 mm).

For the definition of the tensile properties of the FRC, tests according to EN 14651 should be performed. The material should be classified according to the Model Code 2010: characteristic values of the FRC residual strengths (fLk, fR1k and fR3k) have to be determined.

In this phase, it is suggested to perform at least 12 beam tests according to EN 14651 at 28 days of curing for each fiber dosage/fiber type and concrete mix that is to be considered. The test results can be considered positive if:

- *fLk* fulfils specific requirements provided by the designer;
- the characteristic value of *fR1k* is higher than the design one;
- the ratio between *fR3k* and *fR1k* fulfils the design requirement; if a higher strength ratio is obtained, the material can be accepted (if no specific requirements are present in the design);
- the fulfilment of the Model Code 2010 requirement for substituting the traditional reinforcement with fiber is verified *(fR1k / fLk > 0.4* and *fR3k / fR1k > 0.5).*

Further information regarding the FRC design process may be found in the fib Model Code 2010 and fib bulletin 83 (fib = Fédération Internationale du Béton).

Filling the mould of an EN14651 beam

Vibrating an EN14651 beam

CHARACTERISTIC VALUES

What are characteristic values?

In their design calculations, structural engineers choose a single value for material strength. In most design codes, this material strength is based around a characteristic value. The characteristic value of a material property is normally defined as the value below which no more than 5% of test results may be expected to fail. For example, in a sample of 100 FRC bars, this would mean approximately 95 of the samples would be stronger than the characteristic value of the material strength.

The basis of using the characteristic value lies in the fact that tests performed on FRC show a significant amount of scatter. Repeating the same test will give different results. Even the mean value of a set of identical samples can vary. If one were to use the mean value instead of a characteristic value, 50% of the time the material would be less strong. The idea behind characteristic values is further explained in the following figures.

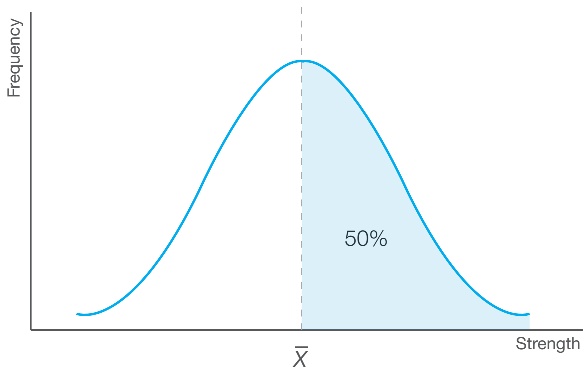

Fig. 4. Strength vs frequency graph.

Fig. 4 illustrates a typical strength vs frequency graph, with the y-axis representing the frequency at which test results end up in each strength range. When assuming a normal (Gaussian) distribution for the results, the mean of the measurements $\bar{X}$ marks the center line of the bell curve. However, this means that in one out of every two cases, the mean value overestimates the strength of the tested material.

The standard deviation s is a measure for the width of the bell curve, i.e. the amount of scatter in the measurements.

The characteristic value is calculated as $f_k = f_m - k_n\, s$ with f_m the average of the measurements, s the sample standard deviation (use STDEV.S function in Excel) and k_n a factor that depends on the assumed probability distribution leading to a 95% probability that the strength is higher than f_k.

This is shown in Fig. 5.

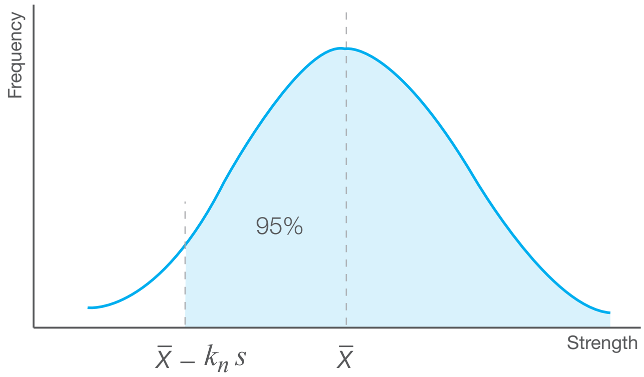

Fig. 5. Varying results possible from a set of identical samples.

Fig. 6 summarizes the mean, standard deviation, and characteristic values as discussed above.

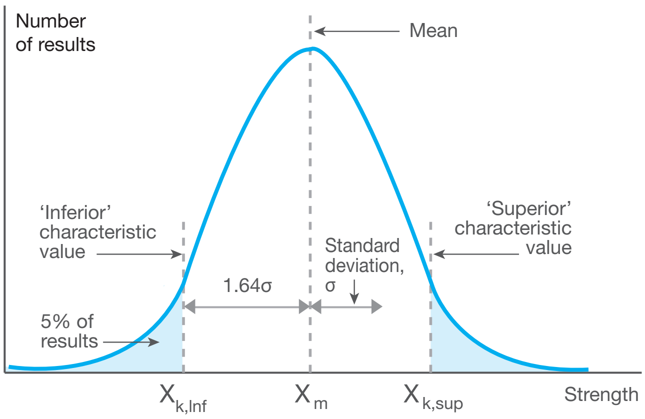

Fig. 6. Varying results possible from a set of identical samples.

4.2 How to determine the characteristic value

The procedure for the control of FRC performance should be defined in the design process.
Before starting production, compression and bending tests should be performed in accordance with EN 14651[1] or rev EN 14 488-3[2] (for spray concrete), in order to control the fulfillment of the characteristic values defined in the design. Tests according to EN 14651 or rev EN 14 488-3 should also be performed to define the tensile properties of the FRC.

The fib bulletin 83[3] based on the Model Code 2010 should be used to determine and classify characteristic values of the residual strengths (f_{Lk}, f_{R1k} and f_{R3k}) of FRC.

To define the characteristic value from the test results, the procedure suggested in Eurocode 0[4] can be used. The average value (mx) and the coefficient of variation (Vx) are defined as follows:

$$s_x = \sqrt{\frac{\sum(x_i - m_x)^2}{(n - l)}}$$

and

$$V_x = \frac{s_x}{m_x}$$

1 EN14651: Test method for metallic fiber concrete. Measuring the flexural tensile strength (2005)

2 https://standards.globalspec.com/std/274983/BS%20EN%2014488-3

3 Fib bulletin 83 "Precast Tunnel Segments in Fiber Reinforced Concrete" WP 1.4.1 October 2017

4 https://www.concretecentre.com/Codes/Eurocode-0.aspx

The characteristic value is defined as:

$$X_k = m_x\{l - k_n V_x\}$$

The value of *kn* is defined according to ISO 12491, with the use of a student's distribution:
with u0.05 fractile of the t-distribution for the probability 0.05.

$$k_n = t_{0.05}\left(l + l/n\right)^{0.5}$$

This is also a bell-shaped distribution (just like the normal distribution) but with heavier tails, as shown in Fig. 7. The more samples are available, the closer the t-distribution gets to the normal distribution.

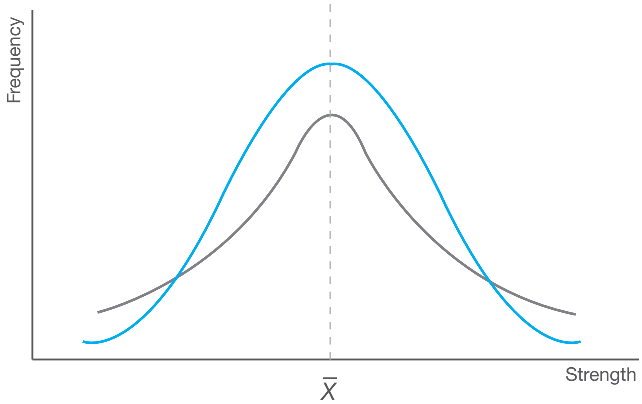

Fig. 7. Values of kn when Vx is known are calculated based on the normal distribution (blue line). Values of kn when Vx is unknown are calculated based on the student's distribution (yellow line).

There are different methods to determine the k-factor. Most standards are based on Eurocode 0. Two basic assumptions about the probability distribution are commonly used to determine kn: either the Coefficient of Variation (Vx) is known, or it is unknown. In most cases it is appropriate to choose values for Vx that are known. The values of kn are shown in Table 1 (unknown) and Table 2 (known), with n being the number of available measurements (for interpreting EN 14651 results, n should be at least 12).

n	k_n
3	3.37
4	2.63
5	2.34
6	2.18
8	2.01
9	1.96
10	1.92
12	1.87
15	1.82

Table 1. Values of k_n for unknown V_x

n	k_n
3	1.89
4	1.83
5	1.80
6	1.77
8	1.74
9	1.73
10	1.72
12	1.71
15	1.70

Table 2. Values of k_n for known V_x

In the Model Code 2010, a relationship between average and characteristic value is given only for f_{R1}.

$$f_{Ftsm} = f_{Ftsk} / 0.7 \quad \text{with} \quad f_{Fts} = 0.45\, f_{RI}$$

and as a consequence:

$$f_{Rlm} = f_{Rlk} / 0.7$$

The relationship proposed in the Model Code is based on a COV equal to 0.20. However, in the literature, very little data is available from large production runs to confirm this COV. It should be noted that the dispersion of the results depends on different factors (fiber content, fiber geometry, concrete rheology…). If data are available from large production runs of a similar material (e.g. using the same fiber and same fiber content), the COV can be considered as known. In this case, the coefficient kn is equal to:

$$k_n = u_{0.05} \left(l + l/n \right)^{0.5}$$

with *u0.05* fractile of the standardized normal distribution for the probability 0.05. If some major changes are made in the mix that can modify the properties of the material it is made of, the procedure for the initial qualification of the FRC should be repeated.

The Coefficient of Variation (COV)

As mentioned in Swedish Standard SS 812310:2014, the recommended COV is approximately 20%, although up to 30% is not uncommon. The variation will be influenced by the test execution and equipment as well as by other factors such as the concrete composition, fiber length and dosage. Comprehensive knowledge about all factors and their role on the variation is not currently available. In general, fiber orientation and fiber concentration (the number of fibers and the network effect) are the most important influences on the variation. In the examples shown in Fig. 8, the average varies between 15% and 30%.

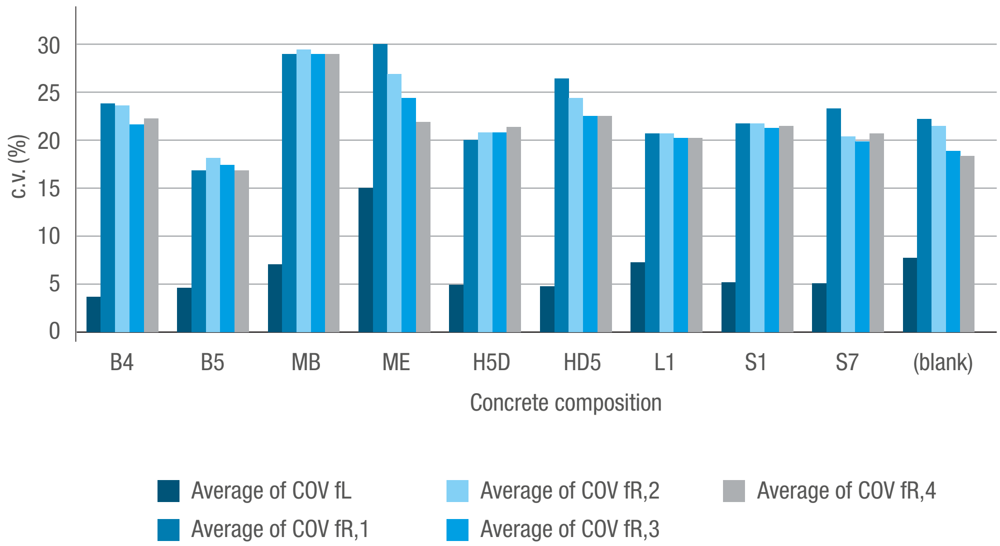

Fig. 8. Variance in COV of between 15% and 30% .

The COV will be influenced by different parameters. Fig. 9 shows the key influence of the network effect by comparing the influence of the same fiber type at different dosages from 20 kg/m³ to 80 kg/m³ on the COV.

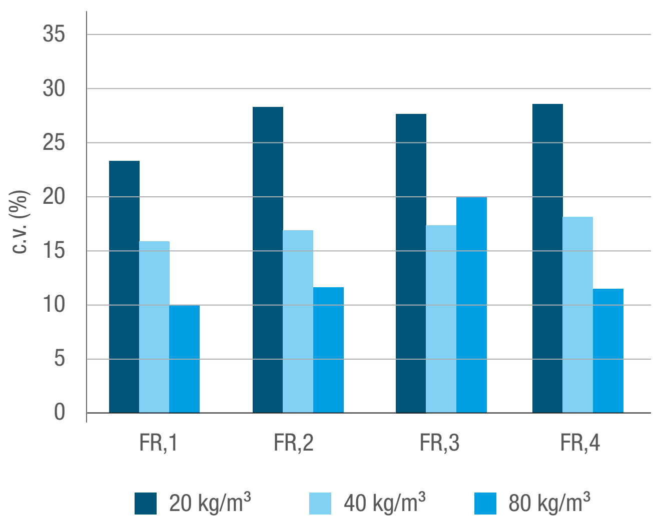

Fig. 9. The influence of fiber dosage on COV.

Determination of the outlier values

Since all the results are treated statistically, to obtain characteristic values it is necessary to take into account outlier results because they differ significantly from the observations. Since the expected results should have a normal or log-normal distribution, the outlier results are not correct. This could be due to a number of problems in the process, although they are mainly associated with incorrect preparation of the specimen.

The two key procedures to determine the outlier values are:

- ISO 16269-4: Statistical Intrepretation of Data, Part 4, Detection and Treatment of Outliers
- ASTM E178-16a: Standard Practice for Dealing with Outlying Observations.

Fig. 10 presents an example relating to EN 14651 beam tests.

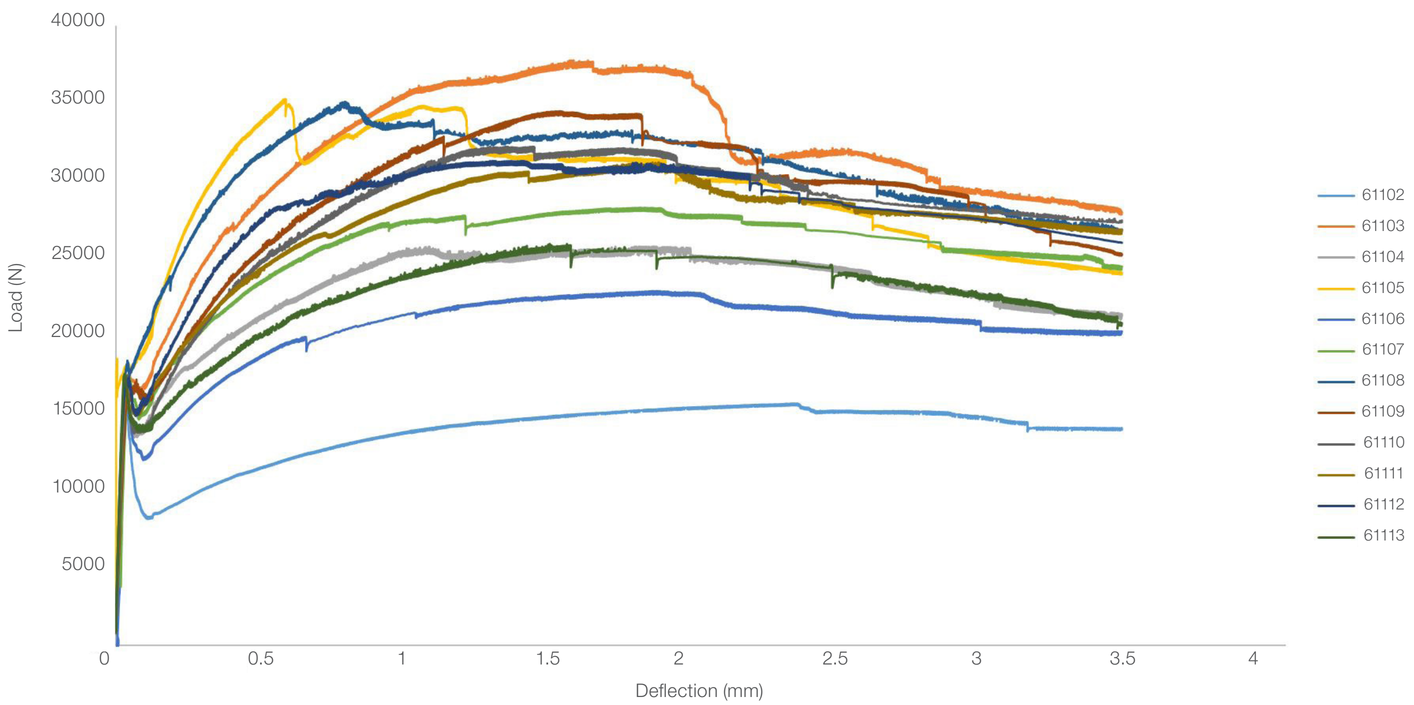

Fig. 10. Example of outlier results that need to be discarded

Tables 3 and 4 show the influence of the outlier values in the analysis. From Fig. 9 we can determine the characteristic values according to fib bulletin 83 and propose a classification according to Model Code 2010.

Characteristic values according to Fib Bulletin 83 and classification according to Model Code 2010

kn	(Fib 83)	1.71
fLk	[N/mm²]	4.9
fRk,1	[N/mm²]	4.3
fRk,2	[N/mm²]	5.7
fRk,3	[N/mm²]	6.0
fRk,4	[N/mm²]	5.5
fRk,1/fLk		0.9
fRk,3/fLk		1.4
Class MC2010		4e
Comment		Vx Known

Table 3. Keeping the outlier values.

kn	(Fib 83)	1.71
fLk	[N/mm²]	5.0
fRk,1	[N/mm²]	5.4
fRk,2	[N/mm²]	7.1
fRk,3	[N/mm²]	7.2
fRk,4	[N/mm²]	6.6
fRk,1/fLk		1.1
fRk,3/fLk		1.3
Class MC2010		5e
Comment		Vx Known

Table 4. Removing the outlier values when beam 61102 is removed from the analysis.

Examples of different methods

Model Code 2010 uses characteristic values to determine the performance class of a FRC.

Strength interval f_R1k as defined by two subsequent numbers in the series:
1.0 – 1.5 – 2.0 – 2.5 – 3.0 – 4.0 – 5.0 – 7.0 - … [MPa]

With residual strength ratios:
a if $0.5 < f_{R3k}/f_{R1k} < 0.7$
b if $0.7 \leq f_{R3k}/f_{R1k} < 0.9$
c if $0.9 \leq f_{R3k}/f_{R1k} < 1.1$
d if $1.1 \leq f_{R3k}/f_{R1k} < 1.3$
e if $1.3 \leq f_{R3k}/f_{R1k}$

Be aware that different methods to determine the characteristic value can lead to a different classification. In the example summarized below, all three highlighted methods are conducted at different classifications according to Model Code 2010:

EC0 – Vx known:	Class 5e
EC0 – Vx unknown:	Class 4e
EC0 – Vx known, log-normal:	Class 5d

This example is summarized in Fig. 11 and Table 5, which show a comparison of three different methods of calculating residual characteristic strength.

Comparison EN14651 results: Average vs Characteristic (n=10)

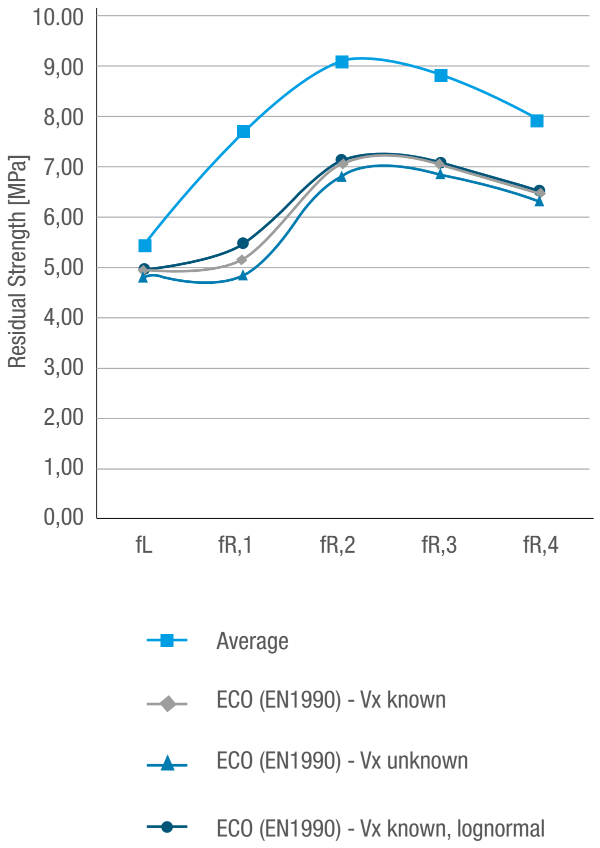

Fig 11. Curve comparison of average vs characteristic value

Statistical data

Average	5.45	7.71	9.12	8.85	7.96
Standard Deviation	0.30	1.47	1.18	1.02	0.83
Coefficient of variance	5%	19%	13%	12%	10%
Minimum	4.98	5.79	7	6.91	6.44
Maximum	5.94	10.41	10.54	10.03	8.76
Sample size	10	10	10	10	10

Characteristic values

Method	k_n	fLk	fRk,1	fRk,2	fRk,3	fRk,4
EC0 (EN 1990) - Vx known	1.72	4.94	5.18	7.10	7.09	6.52
EC0 (EN 1990) - Vx unknown	1.92	4.88	4.88	6.86	6.88	6.35
EC0 (EN 1990) - Vx known, log-normal	1.72	4.96	5.51	7.18	7.14	6.56

Table 5. Characteristic value determination according to three different methods.

CONCLUSION

To optimize mix designs incorporating Fiber Reinforced Concrete (FRC), prequalification work needs to be conducted at an early stage of the project, while keeping in mind that a composite material is being developed.

The procedure for the initial qualification of FRC performance (trial testing) should be defined in the design process.

In their design calculations, structural engineers choose a single value for material strength. In most design codes, this material strength is based around a characteristic value. Model Code 2010 uses characteristic values to determine the performance class of a FRC. Consequently, the way the characteristic value is calculated should be clearly defined. In terms of the number of specimens, 12 beams are recommended, according to EN 14651. Outlier values should be removed from the analysis. Eurocode O should be used, taking into account kn from Vx known values.

A Coefficient of Variation (COV) lower than 20% is considered as a reasonable target. In general, fiber orientation and fiber concentration (the number of fibers and the network effect) are the most important influences on this variation.

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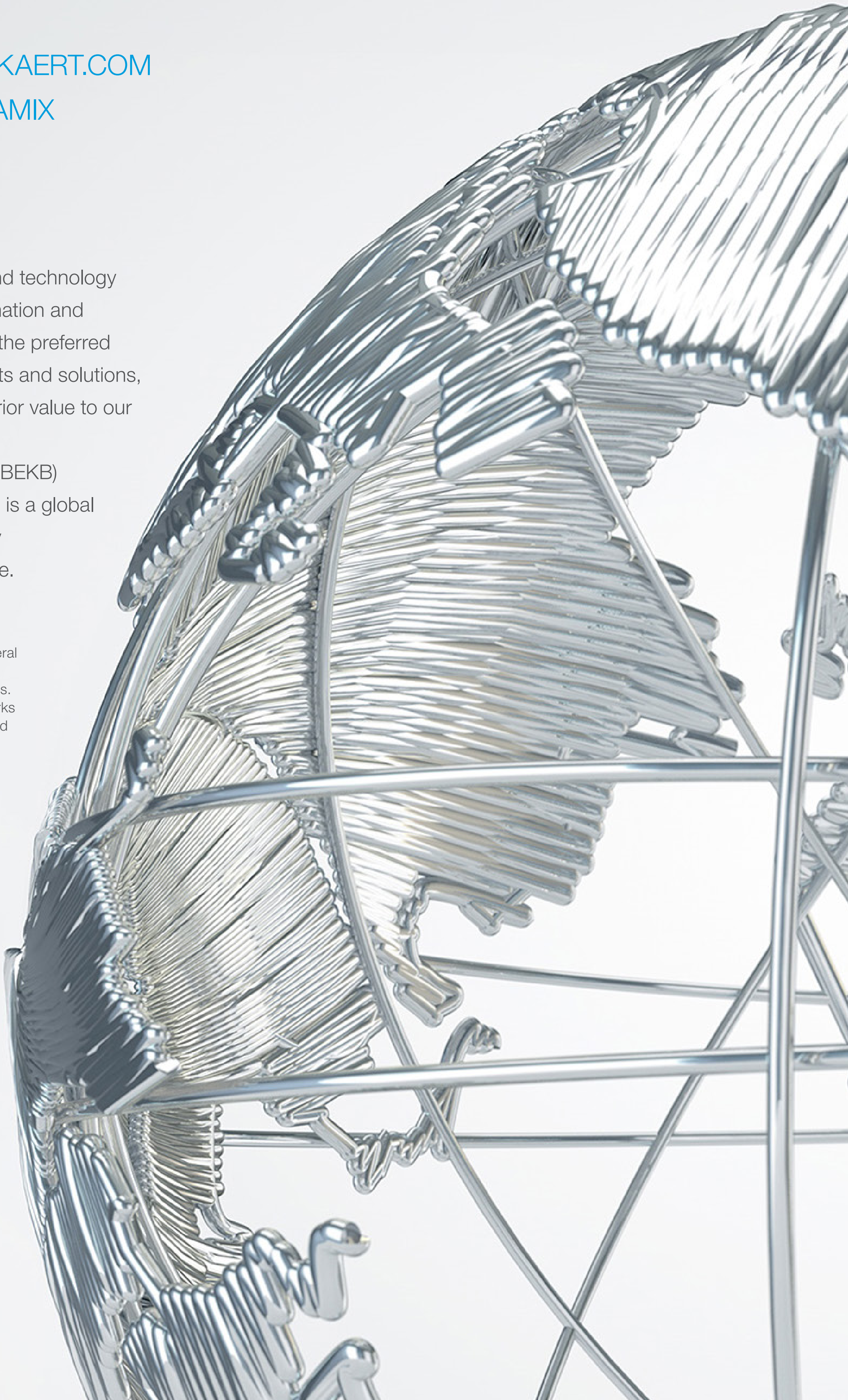

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