EVALUATION OF THE SCATTER OF THE POSTPEAK BEHAVIOUR OF FIBRE REINFORCED CONCRETE IN BENDING: A STEP TOWARDS RELIABILITY

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Abstract

Fibres enhance the energy absorption capacity (toughness) of concrete by providing it with postcracking energy. However, one of the most significant restraints for using fibre reinforced concrete (FRC) in structural applications now is the variation of the toughness parameters measured in laboratory. This shortcoming is not only caused by the heterogeneity of the material itself but is also emphasized by the test method used to determine the FRC properties.

This paper deals with the results of an extended research programme on FRC in bending. Four testing methods are compared. Special attention is paid to the analysis of the variation in the results since this indicates the power of discernment of a test method. A strong correlation (R^2 up to 0.99) has been found between the results of the round panel test and the RILEM beam test for the same deflection/cracking level.

1. INTRODUCTION

1.1 Determination of the postcracking behaviour of FRC

Fibres are well known to provide postcracking energy to concrete, enhancing the energy absorption capacity (toughness) of the material. Besides the fact that new fibres intended for structural use (e.g. macro synthetic) keep appearing on the market, there is still no general agreement about the test methods that have to be used in conjunction with the design methods. Moreover, the scatter of the test results reduces the use of (steel) fibre reinforced concrete (FRC), preventing a wider use of FRC and forcing the application of higher safety factors.

Different methods can be used to investigate the toughness properties of FRC. The most common are the bending test (with or without a notch), the uni-axial tensile test or the wedge-splitting test. More specific testing methods are often used for investigating shear, torsion, impact, or pullout properties.

1.2 Scatter in FRC performance

Due to the heterogeneity of the material, the mechanical performance of FRC is subjected to variations. The variations depend on different factors; the most important of which are [1]:

1 fibre dosage;

2 aggregate and fibre dimensions ;

3 parameter observed ;

4 geometry of the tested specimens / test method.

Fibre dosage is known as the leading factor when variations within a mix are analysed. The higher the dosage used, the less is the variation observed. This can easily be explained by the fact that high dosages allow for a statistically more uniform mix with a reduced fibre distribution variation (more fibres cross the section if the dosage is higher).

Geometry, and in particular the depth of the specimens, is another important parameter. On one hand, the reduction of the depth of tested beams increases the scatter of the results, especially at low dosages because of the small number of fibres crossing the crack. On the other hand, the better orientation of the fibres (the so-called "wall effect", perpendicular to the depth) increases the general performances of the FRC element.

According to different studies on (steel) fibre reinforced concrete (SFRC), variation coefficients between 10 and 30% have been observed for bending tests within a mix for a notched specimen (EN 14651/RILEM). A variation coefficient above 20% is common for this type of test. Inter-lab variations can reach up to 50% for uni-axial tests on cylinders. This is essentially because the testing machine (e.g., rotational stiffness, etc.) can produce high variations from lab to lab. The parameter which is used as a toughness indicator is also subjected to variations. Depending on the deflection/cracking level (DCL), variation of the results could be more or less important. This could be very important when comparing different types of fibres: some fibres show good performance for low deflection levels but poorer properties for high deflections while this is the opposite for other fibres.

Plate tests were defined to correspond better to the performances of the material in the real situations. These tests were initially developed to evaluate the performance of fibres in shotcrete for tunnel linings and mining applications. There exist two types of test methods on plates: a first one based on a round panel and a second one based on a square plate. Both methods reveal a very interesting characteristic: a scatter varying between 6% and 9% only [2] by opposition to the classical bending tests on prisms discussed above.

Do these relatively high variation coefficients mean that FRC is an unreliable material? Up to now, industrial applications have shown that FRC has proven to be a very good construction material …when correctly used. A correct application is based on a correct execution (quality control/assurance), with a safe design, and in a suitable application. As always, the relationship between material properties and design methods is crucial. Hence, is it logical to use parameters derived from static tests in the laboratory for highly hyperstatic structures where redistribution effects are predominant? Very few studies were found dealing with different test methods applied on the same fibre concrete in order to investigate the scatter of the results. This paper discusses the results of such a study.

Finally, although the influence of the fibre type on the variations was not of primary concern during the first studies, this parameter cannot be neglected when sensitivity of FRC results is discussed. The harmonization of the test procedures for FRC together with a good identification of the appropriate design parameters was already discussed in different papers (see e.g. [3]) but only a few studies were realised with different fibre types, mainly due to the high number of specimens needed for the complete study.

1.3 Link with the design methods

One of the most common applications of SFRC today is slabs-on-grade. SFRC offers very good performance for this type of structure. Designs are made according to specific publications [4][5] which are based on toughness parameters derived from bending test results (mainly with the beam tests). While the methods presented in these recommendations are quite simple (and very conservative like the Westergaard solution), the lack of a generally accepted method for any structural element in FRC prevents this material from its use as common alternative to reinforced concrete. The recent RILEM TC162-TDF recommendations regarding to the design methods [6][7] or other publications (see e.g. [8]) were, however, a step forward to introduce the material into a new knowledge-based system with a close link between test and design method. The ongoing work in the framework of the *fib* TG 8.3 "Fibre concrete" tries to tackle the final ambiguous points of these test/design methods with a common approach worldwide. This will be, for sure, the basis for a next chapter of Eurocode 2 (EN 1992-1-1), the reference for designers and the public administration.

2. EXPERIMENTAL INVESTIGATION

2.1 Identification of toughness properties in bending

The programme carried out by the BBRI together with the Department of Civil Engineering of the K. U. Leuven aims at a better identification of the parameters deduced from laboratory tests and used to design FRC structures.

Four testing methods in bending (2 on prisms and 2 on plates) applied on ordinary concrete with 7 different fibre types (5 steel fibres and 2 synthetic fibres) were compared. The goal was to measure the scatter of the results and the potential influence of the fibre type on it. In a second phase, the influence of the fibres dosage was investigated.

These tests were a part of a more detailed programme about FRC including ring and bone tests for the analysis of the behaviour of FRC in tension.

2.2 Concrete composition and fibres

The composition of the concrete used for the study is presented in Table 1. Two types of concrete were used in the first phase of the study: an ordinary concrete (NC) with a mean compressive resistance $f_{cm,cube}$ of 47 N/mm² and a high strength concrete (HSC) with a mean compressive resistance of 85 N/mm².

Firstly, only one fibre type (normal or high strength hooked end steel) was tested in NC and HSC according to four different test methods. In a second phase, 7 fibre types were investigated according to the two methods presenting the lowest scatter of the results.

The fibres used in this second phase are listed hereafter (reference in bracket):

- Hooked end steel (C, D)
- Ribbed steel (E)
- Undulated steel (F)
- Conical heads steel (G)
- Macro synthetic (H, I)

The dosage was 30 kg/m³ (0.38% vol.) for the steel fibres and 4.5 kg/m³ (0.49% vol.) for the macro synthetic fibres. Each (steel) fibre has approximately the same slenderness ratio ℓ/d = 50. For synthetic fibre, this parameter was not taken into account for choosing the fibre type.

Table 1: Concrete composition

		NC	HSC
		kg/m³	kg/m³
Cement CEM I 42.5R		320	400
Water		176	147
Sand 0/5		856	824
Aggregates (crushed limestone)	4/7	260	482
	7/10	210	210
	10/14	237	312
	14/20	341	-
Silica fume		-	21
Superplasticizer	(Sika Viscocrete)	-	4.2
W/C		0.55	0.35

2.3 Testing methods

Four testing methods were used to compare the scatter on the toughness properties in bending measured in the laboratory. For each test method, 6 samples were tested.

Three-point bending test according to EN 14651

The 3-point bending test was realised according to EN 14651. The dimensions of the specimens are 150x150x600 mm with a notch at midspan for performing a crack-controlled test. The results in terms of toughness are given by residual stresses for different levels of deflection between 0.46 and 3 mm or crack mouth opening displacement (CMOD) of 0.5 and 3.50 mm, respectively. This test is based on the recommendations of RILEM TC162-TDF and will be named as “RILEM beam tests” in the following.

Four-point bending test according to NBN B15-238

The samples are also prisms with dimensions 150x150x600 mm but without a notch. The test is deflection-controlled. The toughness properties of the FRC are expressed as energy values (surfaces under the curve load-deflection) at 1.5 and 3 mm deflection.

Round panels according to ASTM C1550-05

The diameter of the round panels is 800 mm and the thickness is 75 mm. The plates are supported by 3 symmetrically arranged hinged supports at 120°. The point load is applied in the centre of the specimens. The toughness is calculated as the energy absorption at deflection points between 0.5 up to 40 mm.

Square panels according to EFNARC

The plates are supported on a rigid steel frame and tested under a central point load. The dimensions of the samples are 600x600x100 mm. The energy absorption is measured at deflections between 5 and 40 mm.

3. RESULTS

3.1 Influence of the test method on the scatter

The average results of the RILEM beam tests are shown in Figure 1. The variation results of the different tests were compared at the same deflection levels: 2.15 mm for the beams which corresponds to 5 mm for the plates reflecting the same crack opening. As it can be seen from Figure 2, the variation of the results from the plate tests remain below 10% while the maximum scatter observed for the beam tests is 24%. This confirms what is found in literature. It seems that the influence of the concrete compressive strength is rather insignificant on the dispersion. Based on these results, it was decided to only use the RILEM beam test and the ASTM round panel test for the second phase of the research programme dealing with the influence of the fibre type and dosage.

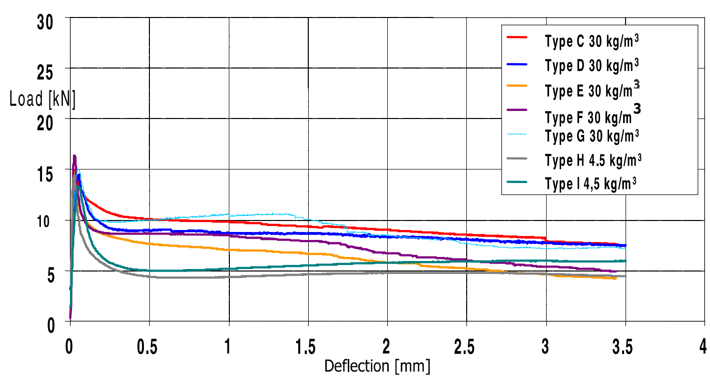

Figure 1: Average curves of the results of the RILEM beam tests for 7 different fibre types

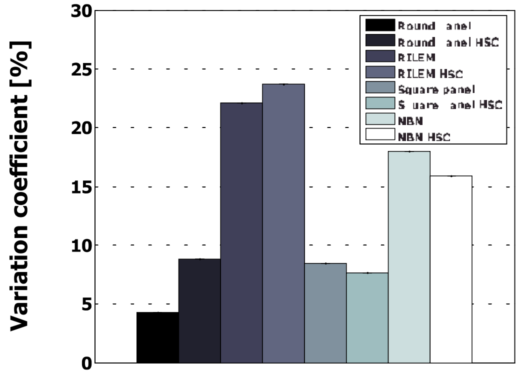

Figure 2: Variation of the results of the different test methods for hooked ended steel fibres

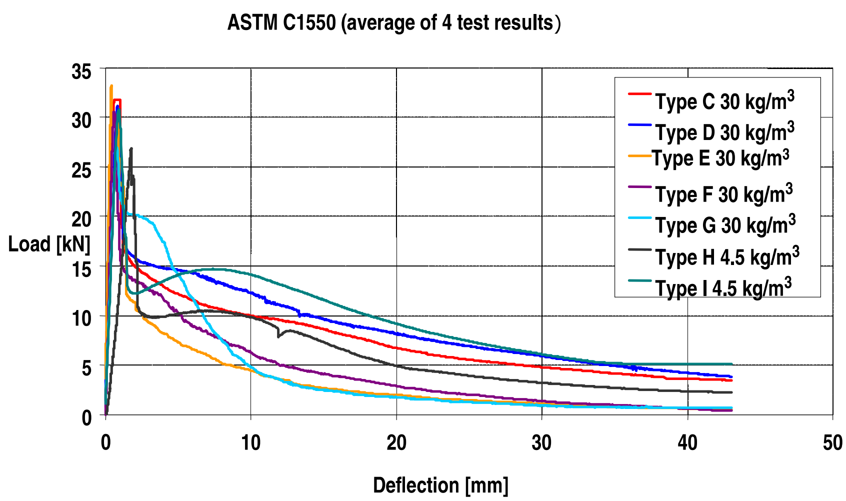

Figure 3: Average curves of the results of the round panel tests for 7 different fibre types

3.2 Influence of the fibre type

Only the normal concrete was used for the second phase of the study. The composition is the same as for the first phase (see Table 1). Dependent on the fibre type, the value of the measured slump varies between 20 mm and 80 mm but the average compressive resistance was kept between 45 and 50 N/mm². The dosage for steel fibres was 30 kg/m³ and 4.5 kg/m³ for synthetic fibres.

Importance of the deflection/cracking level (DCL) for the toughness characterization

Figure 1 shows the average beam test results for all the tested fibres. It is clear that each fibre presents a different behaviour depending on its ability to sustain stresses in the matrix and its anchorage mechanism. It is also important to keep in mind that the performance has to

be compared on the same basis. This depends on the DCL which is used. If the extreme values are compared (residual stress at 0.46 mm and 3 mm deflection, see Table 2), it should be noted that fibre classification in terms of toughness is highly DCL related. For example, fibres with conical heads (type G) show good performances for low levels of crack opening but seem to perform worse at higher deflections while it is the opposite for other fibres (e.g. type I or D).

These differences seem to be less important for equivalent stresses ($f_{eq,2}$ and $f_{eq,3}$) which rank the fibres almost identically. If the dispersion is analysed, it can be observed that the higher DCL, the larger the scatter. Hence, the value of $F_{R,0.46}$ shows the lowest variation coefficient allowing to distinguish fibre properties at a higher confidence level.

Table 2: Fibre classification in terms of toughness (residual or equivalent stress) - RILEM beam tests

Residual / Energy value	**Performance classification**
$F_{R,0.46}$	C > F > **G** > E > D > I > H
$F_{R,3.00}$	C > D > I > F > H > E > **G**
$f_{eq,2}$	C > **G** > F > D > E > I > H
$f_{eq,3}$	C > F > **G** > D > E > I > H

Influence of test method

If we analyse the results obtained from the round panels, the findings (see Figure 3) are quite similar to those obtained from the beam tests. The "G" fibre appears to be the best at 5 mm deflection while it is almost the worst at 40 mm. The influence of the DCL is confirmed.

However, by analyzing the classification of the results (see Table 3), it should also be noticed that some fibres show very good results for large deflections in the round panels (e.g. type I) while the performance of fibre type I in the beam tests at large deflections is almost the worst.

Table 3: Fibre classification in terms of toughness (energy values) - round panel tests

Energy at specific deflection	**Performance classification**
W' 5 mm	**G** > C > D > I > F > E > H
W' 40 mm	I > D > C > H > F > **G** > E

Hence, the correlation between toughness factors (known as DCL related) depends on the fibre type.

The coefficient of variation (COV) of the results depends also on the fibre type. For both test methods (round panels and beam tests), the macro synthetic fibres (types H and I) show the lowest variations i.e. around 20% for the RILEM tests and 5% for the round panels while the worst results in terms of scatter for the round panels at large deflections are observed for

fibre type F which is the undulated steel fibre. Surprisingly, this fibre type presented a variation coefficient of almost 20% in the round panel test whereas the global average for this type of test is 10% (Table 5). The rankings determined for each test method (in terms of dispersion) seem to be very similar except for fibre type E and G.

Table 4: Classification of the fibres in terms of dispersion on the residual loads **- RILEM beam tests**

Residual stress	Performance classification*
$F_{R,0.46}$	**I**(14)<H(15)<G(19)<C(21)<D(23)<E(25)<**F**(26)
$F_{R,3.00}$	H(16)<I(21)<C(24)=D(24)<G(31)=F(31)<E(32)

(*) The numbers between brackets indicate the value of the coefficient of variation (COV) [%].

Table 5: Classification of the fibres in terms of dispersion on the energy values - round panel tests

Energy at deflection	Performance classification*
W' 5 mm	**I**(3)<D(6)=H(6)<E(8)<C(10)<G(12)<**F**(20)
W' 40 mm**	E(4) < I(6) < G(7) < D(15) < F(18)

(*) The numbers between brackets indicate the value of the coefficient of variation (COV) [%].

(**) Fibre types H and C are not included because of the limited number of successful results at 40 mm. This is caused by the movements of the displacement transducers when cracking occurs at the bottom of the plates.

3.3 Influence of dosage

The influence of dosage on the scatter of the results was investigated for 3 fibre types, i.e. types F and G (steel) and 1 macro synthetic fibre, i.e. type H. The goal of this task was to make some observations regarding the dosage effects.

Once again, the study was based on the analysis of the RILEM beam tests and on the ASTM round panel tests.

Generally, the higher is the dosage, the higher is the performance. However, the effect is not proportional beyond 40 kg/m³.

If the variation on the results is investigated (Figures 4-5), it is firstly noticeable that the lower dispersion of the round panel test results is confirmed (below 10% in general, depending on the DCL) and that the general trend shows a scatter reduction for higher fibre dosages.

Looking at the RILEM beam test results, it seems that both fibre types F and H show lower variations when dosage increases. However, this was not observed for fibre type G which presents an opposite trend. The increasing variation on the bending load F_{max} for higher dosages indicates however that something particular happened for this mix. Fibres normally have no influence on this parameter (only for very high dosages and specific compositions where strain hardening is looked for). This maybe indicates that (high dosages of) fibres were

not mixed properly into the matrix, causing higher dispersion on the results. This effect is actually stressed by the increase of the fibre volume.

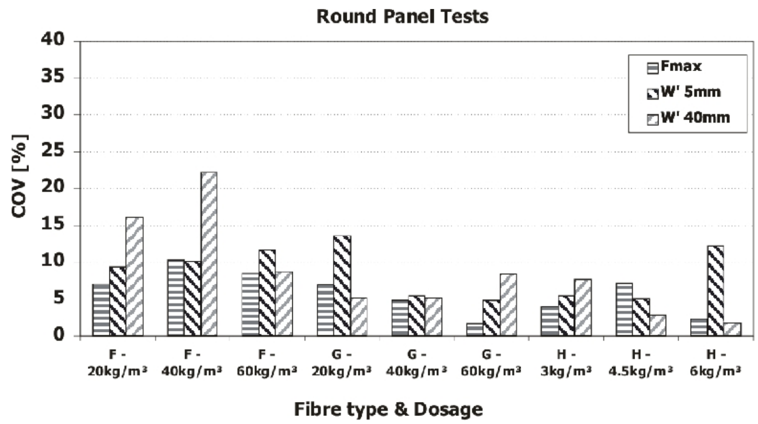

Figure 4: Variation of the results vs. dosage for the round panel tests

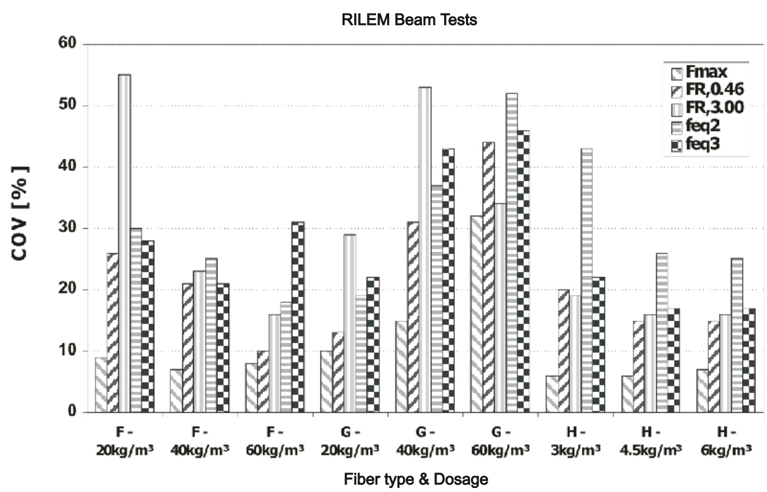

Figure 5: Variation of the results vs. dosage for the RILEM beam tests

3.4 Correlations between test methods

Correlations between test methods could significantly improve the confidence level between test results and performance classification. It also would help if the results obtained with one specific test method could be used to deduce parameters needed for another design method (for another application). This would drastically reduce the number of tests needed to explore specific applications for the material. Some results presented in the literature show that these correlations exist and depend on the DCL. In other words, results are correlated if they are associated with the same DCL.

However, two questions arise:

- Is the correlation related to the fibre type?
- Is the correlation related to the fibres dosage?

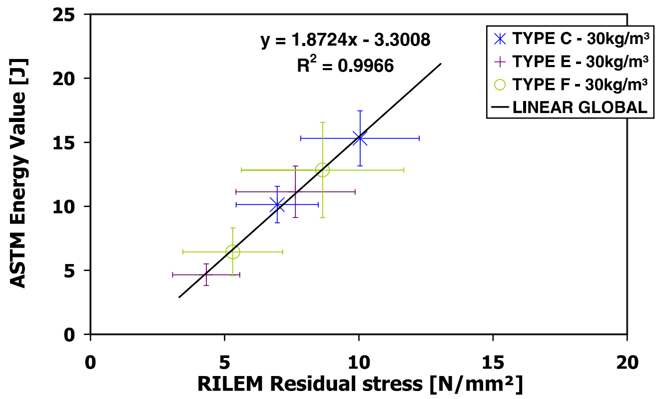

Figure 6 : Correlation between RILEM beam test and round panel test for 3 fibre types

Figure 6 gives the first insight into the possible answers to these questions. For 3 fibre types (with the same dosage), two toughness factors were compared: the value of the residual stress in the RILEM beam tests at 0.46 and 3.19 mm deflection and the values of absorbed energy at 1.80 and 9.31 mm for the round panel tests. These deflection levels correspond to a crack opening of 0.46 and 3 mm, respectively. From Figure 6, it follows that the correlation between the two test methods seems to be excellent, with a correlation coefficient of about 0.99. That means that the results of both testing methods are well correlated for these 3 fibres. The equation of the linear regression allows for the calculation of the energy value or residual stress, one from another, at the same cracking level. If the data from fibre type H are added, the correlation does not seem as good. The correlation coefficient drops to 0.83 if all fibres and dosages are taken into account.

4. CONCLUSIONS

Variation of toughness performances of FRC is a well-known limitation for its use today in structural applications. But this shortcoming is not only caused by the heterogeneity of the material itself. It is also emphasized by the test method. The results from the study presented in this paper confirm what is found in literature, i.e. that the variation of the beam test results is much higher than of the panel test results (square or round).

The study also demonstrated the importance of the deflection-cracking levels taken as references for the toughness parameters, i.e. firstly, for the classification of fibres using the same test method and secondly in order to compare the results from one test method to another. The same crack opening should serve as reference to compare toughness values and to define a strong relationship which was observed for different fibre types with an excellent correlation coefficient (0.99). More tests are needed to validate this correlation with other fibre types.

5. ACKNOWLEDGEMENTS

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