FIBRE REINFORCED SPRAYED CONCRETE PANEL TEST - TEST PROCEDURES AND INFLUENCING FACTORS

PLATTENVERSUCH AN FASERSPRITZBETON – PRÜFMETHODEN UND EINFLUSSFAKTOREN

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The paper discusses the Norwegian guidelines on sprayed concrete in relation to relevant European standards. Control of fibre content and fibre distribution throughout a concrete load are dealt with. Panel test methods are paid special attention as they measure a primary property; namely energy absorption capacity of fibre reinforced sprayed concrete. The paper provides the main findings from a variety of tests performed both before and after the last revision of our guideline in 2011, and discusses both methodology issues as well as the influence of concrete mix-design and concrete properties.

In diesem Artikel werden die norwegischen Richtlinien für Spritzbeton in Bezug auf die relevanten europäischen Normen diskutiert. Die Kontrolle des Fasergehalts und der Faserverteilung über eine Betonladung werden behandelt. Besondere Aufmerksamkeit wird auf die Platten-Prüfmethoden gelegt, da sie die primäre Eigenschaft des faserverstärkten Spritzbetons, das Energieabsorptionsvermögen, messen. Der Artikel gibt die wichtigsten Erkenntnisse aus einer Vielzahl von Tests wieder, die sowohl vor als auch nach der letzten Revision unserer Richtlinien 2011 durchgeführt wurden, und diskutiert sowohl methodische Fragen als auch den Einfluss von Betonzusammensetzung und Betoneigenschaften.

1. Introduction

Guidelines for production, execution and quality control of wet-sprayed fibre reinforced sprayed concrete (FRSC) are compiled in the “Norwegian Concrete Association’s Publication no. 7” (NB 7) [1]. In road tunnel projects the Norwegian Public Roads Administration (NPRA) refer to NB 7, hence NB 7 work as a requirement for such projects. The last revision of NB 7 was released in 2011, taking into consideration the family of new European standards on sprayed concrete that were released some years before (EN 14487-1 and -2, EN 14488-1 to -7, EN 14489-1 and -2). The EN-standards cover both wet- and dry-mix methods for a wide range of applications. The guideline NB 7, however, only covers rock support using the wet-mix sprayed concrete method, incorporating relevant information from the European standards.

The revision committee for NB 7 (the Sprayed Concrete Committee) started in 2007 and concluded in 2011. The main changes in the 2011-edition was on quality control of fibre content and fibre distribution in fresh concrete (the basic mix) before spraying, and on the test procedure and documentation of energy absorption capacity (the panel test/robustness test). For results reported from the various studies, see references from [2] through [19]. Status at the point of revision in 2011 was reported in [2] and [7]. The present paper draws a general outline and gives some selected results, including also some more recent results from laboratory research tests (section 3.6.1) and from quality control in tunnel projects (section 3.6.2).

The Norwegian round panel method and the EN 14488-5 square panel method are dealt with extensively, whereas the ASTM C1550 round panel test method is dealt with more briefly. Regarding the two former methods, a standard test result is generally the average result of a set of 3 FRSC panels, all centrally loaded with displacement control at a fixed rate. The energy absorption capacity is defined as the energy uptake (in Joule) of each panel from zero to 25 mm centre point deflection. The final deflection in these tests involves crack openings normally around 15-20 mm wide (depending on crack pattern), which are large cracks, but it is important that a FRSC lining maintain toughness/structural performance also at large cracks (ultimate state).

2. Overview of investigations/content

The following list gives an overview of the various investigations and considerations dealt with under the revision work of NB 7 (performed by the Norwegian Sprayed Concrete Committee) and in the time after the revision (mainly performed by the NPRA):

- The content and distribution of fibres through a concrete load
- Panel production
- Panel methodology: Effect of friction against the support fixture
- Panel methodology: Panel test method comparison and variability
- Panel methodology: Test and analyzing procedure
- Effect of concrete parameters (age, strength, w/c, fibre type and fibre content).

3. Selected findings and results

3.1 The content and distribution of fibres through a concrete truck

The preference was to focus the control of fibre content in sprayed concrete on the production phase (allowing opportunity for correction), rather than on the final executed rock support ("to late"). In addition, each core taken from a final sprayed concrete rock support constitutes a small volume and extracting fibres from hardened concrete is rather cumbersome. The method demands many samples and has a high variability, and the results also generated discussions in projects. Still, the method revealed that the fibre distribution over a sprayed concrete lining, in a few alarming cases, appeared to be very uneven.

In NB 7 it was therefore decided to require control of fibre content of the basic mix during loading from the concrete truck at the point of deliverance, i.e. just before pumping/spraying. At each control, 3 samples should be taken, one early, one in the middle and one at the end of a truck-load. Each sample having a minimum volume of 8 litres (which is much larger than described in EN 14488-7 "Fibre content of fibre reinforced concrete"). The lower limit for each of the 3 single results was set to 80% fibre content compared to agreed dosage, and 85% for the average of the 3 samples. The limits were based on several measurements on-site and were considered reasonable. Their intent is to increase focus on the fibre addition method (generally added directly on the truck) and mixing time. For cast fibre reinforced concrete the current standard for concrete production (EN 206) requires the same regime as described above.

When sprayed concrete panels are produced for control of energy absorption capacity, NB 7 requires that the fibre content shall be controlled simultaneously, on the same truckload delivered. During such simultaneous control, there are both lower and upper limits for the fibre content (80-120% for each of the 3 single results, and 85-115% for the average). This is to secure a representative fibre content in the panels before sending them to a laboratory.

3.2 Panel production

On the issues of panel production, it was investigated:

- accelerator dosage and spraying technique
- spraying 1000x1000x100 mm square panels (EN 14488-1), 600x600x100 mm square panels (EN 14488-5), Ø600x100 mm round panels (NB 7), and Ø800x75 mm round panels (ASTM C1550)
- effect of sprayed vs. cast panels.

In the early phases of our study we looked at all the available panel methods; the round panel method used in Norway (NB 7, continuous support, statically indeterminate), the square panel method EN 14488-5 (also continuous support and statically indeterminate) with panel production according to EN 14488-1, and the ASTM panel method ASTM C1550 (3-point support, statically determinate). Accelerator dosage, screeding/trimming, handling/weight were evaluated during execution. The EN-specification involving spraying of 1000x1000x100 mm square panels was difficult to execute, and the later saw-cutting to test panel 600x600x100 mm (to avoid the so-called "defective zone") is very laborious. Spraying directly into the final size of 600x600x100 mm is of course much easier and it is difficult to see any drawbacks as long as the panel looks visually homogeneous after demoulding. This holds also for the round panel method. We have observed no results in the literature on this issue, and, in this regard, we are open for a debate on this issue if someone has specific experiences.

Since it was found that the EN 14488-5 square panel and the "Norwegian" round panel gives equal results (provided exact the same laboratory conditions, see section 3.4) these two panel geometries were chosen and equated in NB 7. Both methods are statically indeterminate. The ASTM C1550 method is thoroughly documented, and appears to be very suitable. However, it was not chosen mainly because the panels are different, the test is statically determinate, thus giving a test outcome, which numerically does not correlate with the energy absorption classes in the EN-system (EN 14487-1).

Quality control testing for energy absorption always involves sprayed panels, but for pure methodology studies, casting panels were considered practical as a production technique. In this regard it was found [14] that cast panels gave on average 10% lower energy absorption capacity compared to sprayed panels. Reasons for this may be differences in air content, fibre orientation, compaction and w/c-ratio (due to the accelerator).

3.3 Effect of friction against the support in panel tests

One of the main findings during all the tests prior to the revision of NB 7 [1] was the existence of the great influence of friction from the support fixture during the testing of the panels. The energy associated with friction between panel and support is during a test erroneously taken to be energy uptake by the panel, unless compensated for. Using a continuous steel support, the friction effect was in several tests, on average, found to constitute around 25% of what is measured directly as the energy uptake during a test. Figure 1 shows an example for the effect of friction on the measured result in one of our studies; all tests are on round panels made of a given load of a fibre reinforced concrete. The only variable is the support/bedding condition. The right column in the figure (steel support with bedding of a "sandwich" of PVC-grease-PVC) is assumed to reduce friction to near-zero, thus representing the true energy uptake of the given FRSC. It is clear that the friction effect is substantial for supports of steel and wood. Wooden support was previously used in Norway. Today steel support (no bedding) is required, and the measured result from each panel test shall be multiplied by 0.75 to compensate/eliminate the 25% (0.25) friction effect.

EN 14488-5 do not consider friction against the support and, hence, do not require compensation for the friction effect. This is probably a longer discussion since the energy absorption classes given in 14487-1 were, in its time, likely to be designed with a built-in friction effect. However, the friction effect may vary, as we have seen, and the issue should be treated much more thoroughly in the EN-standard to avoid variable test conditions. Even the panel's moisture content during testing will influence the test result, since it influences the friction. It is notable that when the panel test (supported on wood) and energy absorption classes were introduced in Norway in the late 1990ties, the fibre content in Norwegian sprayed concrete dropped dramatically to disturbing low levels. After identifying, and now requiring correction for the friction effect, the steel fibre content in sprayed concretes around the country have generally increased to more than 10 kg/m^3, reaching more sensible levels.

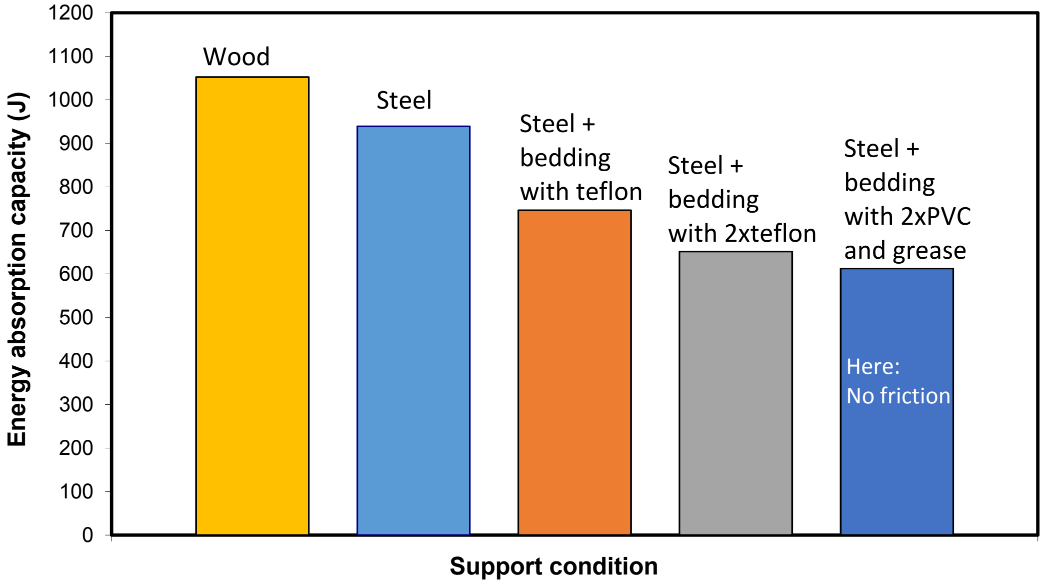

Figure 1: Energy absorption capacity (up to 25 mm central deflection) for a given FRSC as measured directly from panel tests with different friction/support conditions. [15][8]

3.4 Panel test method comparison and variability

Our conclusion was that the EN 14488-5 square panel test and the round "Norwegian" panel for any practical purposes gives the same result provided exactly the same support/friction condition. *Figure 2* shows two examples of parallel testing of round and square panels under identical support conditions. It can be seen that the energy uptake is similar, considering normal spread. NB 7 therefore do not distinguish between round and square panels and opens for both geometries, both with steel as support (no bedding). Of course, this means a square steel support frame for the square panels, and a steel support ring for the round panels. The panels shall be moist (without free water) during testing. Again, either square or round panel, the result from each test must be multiplied by 0.75 to numerically eliminate the effect of friction. EN 14488-5 describes that there should be a bedding material of either mortar or plaster between panel and support. The clear impression is that this bedding is omitted internationally, which is sensible as, first, such bedding appears to be very cumbersome and, second, any bedding must be described much more detailed considering the large effect on the result, as discussed above. This issue should be reformulated in EN 14488-5.

For the ASTM C1550 round panel test the effect of friction from its 3-point steel plate support has been found to constitute 15-20% [21] of what is measured during a test. The test procedure does not describe any correction for this effect.

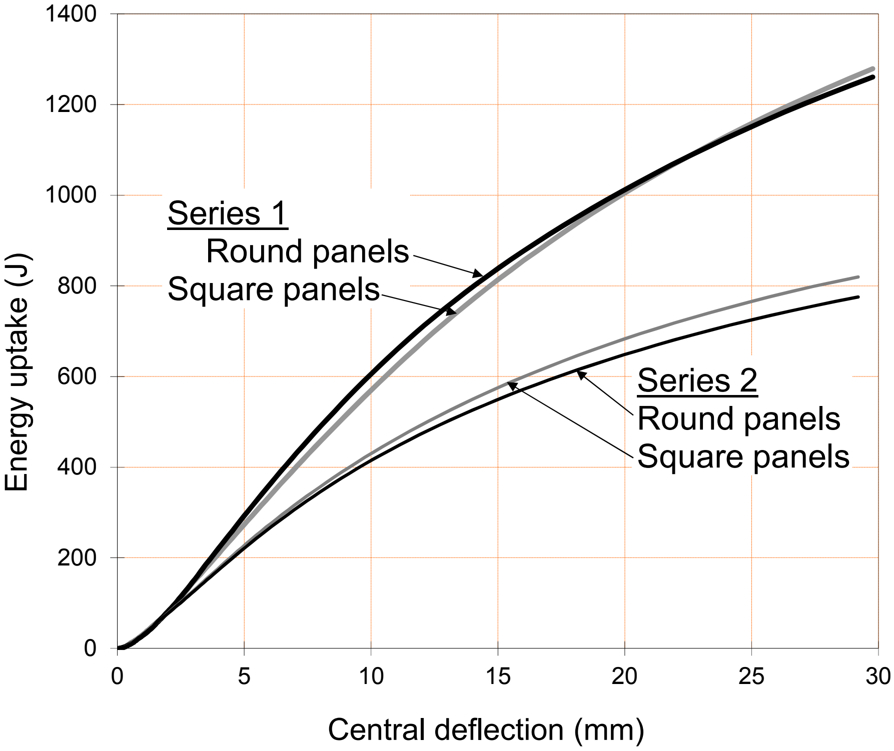

Figure 2: Energy uptake during two test series, both with parallel testing of round and square panels under identical support conditions. Each curve is the average of four panels. [16][8]

When it comes to variability, we have today knowledge of 61 sets of round panel tests. Most of these sets are from our own laboratory of the NPRA, but some are also from other laboratories in connection with Round Robin test programs or from quality control in tunnel projects. Most of these concretes had a mass ratio of 0.45 and cube strength of 50 MPa or higher. The average coefficient of variation among the 61 sets is 7.3% and the standard deviation of the coefficient of variation is 4.4%. Hence, the standard variation range for the coefficient of variation of these sets is (rounded) from 3% to 12%. 8 (13%) of the 61 sets have a higher coefficient of variation than 12%. For square panels we have much less data, but there is no reason to believe that the variation should be very different.

We have participated in two Round Robin test programs (inter-laboratory study) on the “Norwegian” round panel method, [3] and [20], both involving four laboratories testing 5 panels each. In the first one the between-laboratory coefficient of variation (according to [23]) was found to be 10.1% (average within-laboratory coefficient of variation was 9%), and in the second one the between-laboratory coefficient variation was 13.7% (average within-laboratory coefficient of variation was 8%). We have also participated in one Round Robin test program on the ASTM C1550 round panel method [13], involving four laboratories. Among the totally 20 sets of panels involved here, the average within-laboratory coefficient of variation was 12%.

3.5 Test and analyzing procedure in panel tests

The following issues were investigated:

- panel thickness (*t*): Moment capacity of concrete is generally dependent on the square of thickness (t^2), and for (post-cracked) FRSC the panel thickness and energy absorption capacity is related rather similarly. A theoretical consideration was carried out in [18], and the outcome of this is incorporated in NB 7 on how panel thickness should be corrected for, see also [7]. Target thickness is 100 mm, but NB 7 gives rather liberal limits for panel thickness variation (90 – 115 mm). EN 14488-5 gives stricter limits (100 – 105 mm) and no thickness correction procedure. It is notable that a relation t^2 on capacity means that a 105 mm thick panel gives, as an approximation, ($[105/100]^2 = 1.1$] 10% higher energy absorption capacity than a 100 mm thick panel. The question is whether EN 14488-5 should include a thickness correction procedure and, consequently, be able to open for wider tolerance limits for panel thickness. Today's range 100-105 mm is likely to be a practical challenge. The thickness dependency also holds for measured maximum load and residual load, but these parameters are generally not considered in panel tests.

- the effect of the non-linear behavior during the onset of loading: Following the requirements for the stiffness of the loading frame this effect was judged to be minor and no correction procedure is given in NB 7, similar to EN 14488-5.
- the effect of numerical integral calculus method for converting load-displacement data to energy absorption: Start-point, mid-point or end-point approximation was found to have minor influence, partly due to the fact that the load-deflection curve has an ascending branch followed by a descending branch. Nevertheless, NB 7 describes the mid-point approximation, which will be most correct irrespective of load-deflection curvature. EN 14488-5 does not specify the approximation method.
- the effect of loading rate: For NB 7 it was decided to increase the load rate from the earlier 1.5 mm/min to 3 mm/min. The load rate is reported [22] not to influence the result at these ranges (3 mm/min is still slow) and the increase in loading rate simply shortens the duration of each test, to only 10 min. EN 14488-5 require 1 mm/min, meaning 30 min duration pr. panel test.
- the effect of friction between panel and support (discussed earlier).

3.6 Effect of concrete parameters

3.6.1 Energy absorption capacity vs. concrete age, strength and w/c-ratio

Compressive strength and energy absorption capacity is normally determined at 28 days, while the ability of a sprayed concrete lining to work as rock support is dependent on these properties over the whole lifespan from very early (preliminary safety during tunneling) and over years (permanent support). The amount of data in the literature on this issue is very scarce. A study was therefore undertaken to determine the development of strength and energy absorption capacity over time. Compressive strength and panel tests were performed at 2, 4, 7, 30, 91 and 365 days of concrete age (cured at 20 °C). Four sprayed concrete basic mixes were produced at a ready-mix plant, and delivered to and sprayed at "MAPEI Shotcrete Test Centre" in Norway. The fibre type and fibre dosage varied in the four concretes. 3 different fibre types were used; two different steel fibres and one type of macro PP-fibre, the latter in two different dosages. The two steel fibres had identical geometry, but different tensile strength, see Table 1.

The framework for concrete proportioning was water-to-cement (w/c) ratio = 0.45, 28-days strength C35/45 (minimum 45 MPa cube strength) and E700 (minimum 700 Joule energy absorption capacity). The four concretes were made of a binder with 475 kg/m^3 of a CEM II/A-V cement and 5% silica fume of binder weight. The final w/c-ratio after spraying was 0.45 (before spraying/addition of alkali-free accelerator the w/c-ratio was 0.42). Local sand and stone (d_{max} 8 mm) used by the plant, and a super-plasticizer. Fresh basic mix slump around 200 mm.

Table 1: Fibre types, characteristics and dosage in the concrete mix

	Shape	Length / diameter	Tensile strength	Dosage
Steel fibre N *(normal strength)*	End-hooked	35 mm / 0,55 mm	1250 MPa	35 kg/m^3
Steel fibre H *(high strength)*	End-hooked	35 mm / 0,55 mm	2400 MPa	30 kg/m^3
Macro PP-fibre	Embossed	54 mm / -	640 MPa	5 kg/m^3 6 kg/m^3

The compressive strength results are shown in *Figure 3*. As expected, strength is not strongly influenced by the fibre type. Still, there is somewhat lower strength at high strength levels for the two concretes with the PP-fibre compared to the two steel fibre concretes. What is particular notable is that for all concretes the strength is significantly higher than the required strength of 45 MPa at 28 days, and the “overshoot” increases with further curing. In projects, such high 28-days strength appears to be a prevailing situation in Norway rather than the opposite.

The energy absorption capacity results are shown in Figure 4, vs. time (Fig. a) and vs. strength (Fig. b), which also contains a fifth curve denoted “Separate study”, see later discussion. Already in the early age, Figure 4a shows that the energy absorption capacity is significant and rather similar for all concretes (around 600-800 Joule). From around 7 days on (around from which the required 45 MPa strength is exceeded) the capacity of the concretes develops quite differently.

For the concrete with 35 kg/m^3 of “Steel fibre N” the energy absorption capacity declines significantly (17%) as the strength increases from 50 MPa (7 days) to 77 MPa (28 days). On

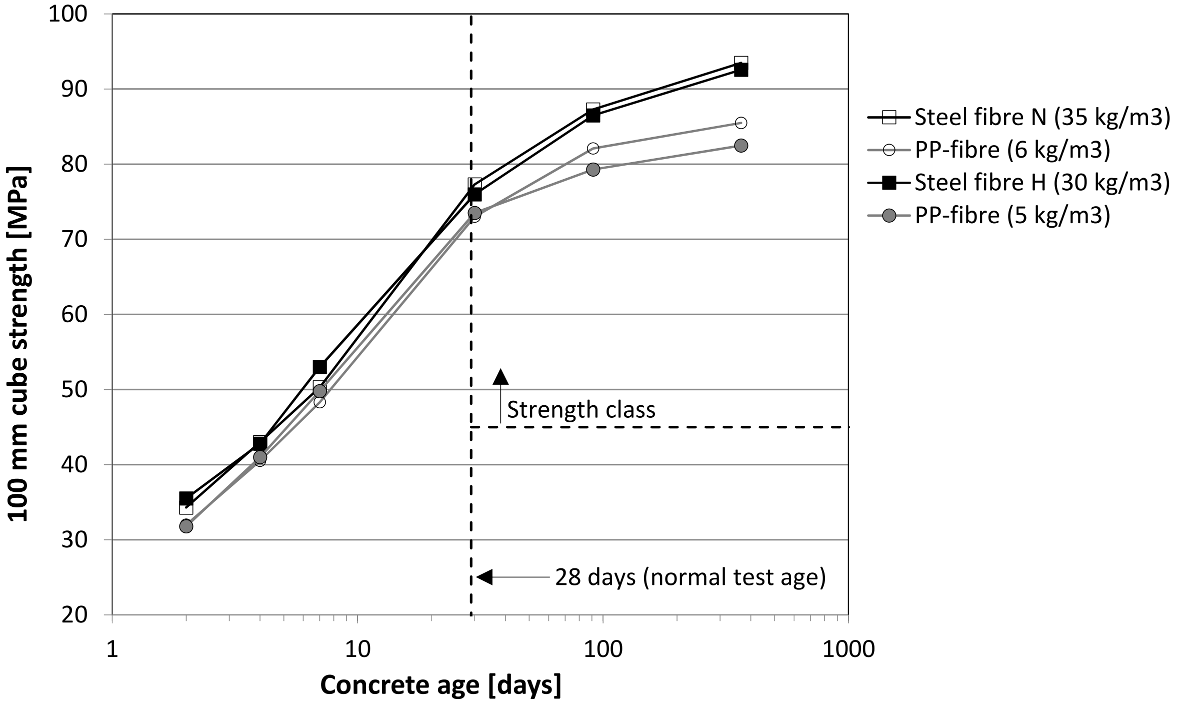

Figure 3: Cube strength over time (2 - 365 days) for the four tested concretes. Cast cubes with the sprayed concrete basic mix. Each result is the average of two cubes.

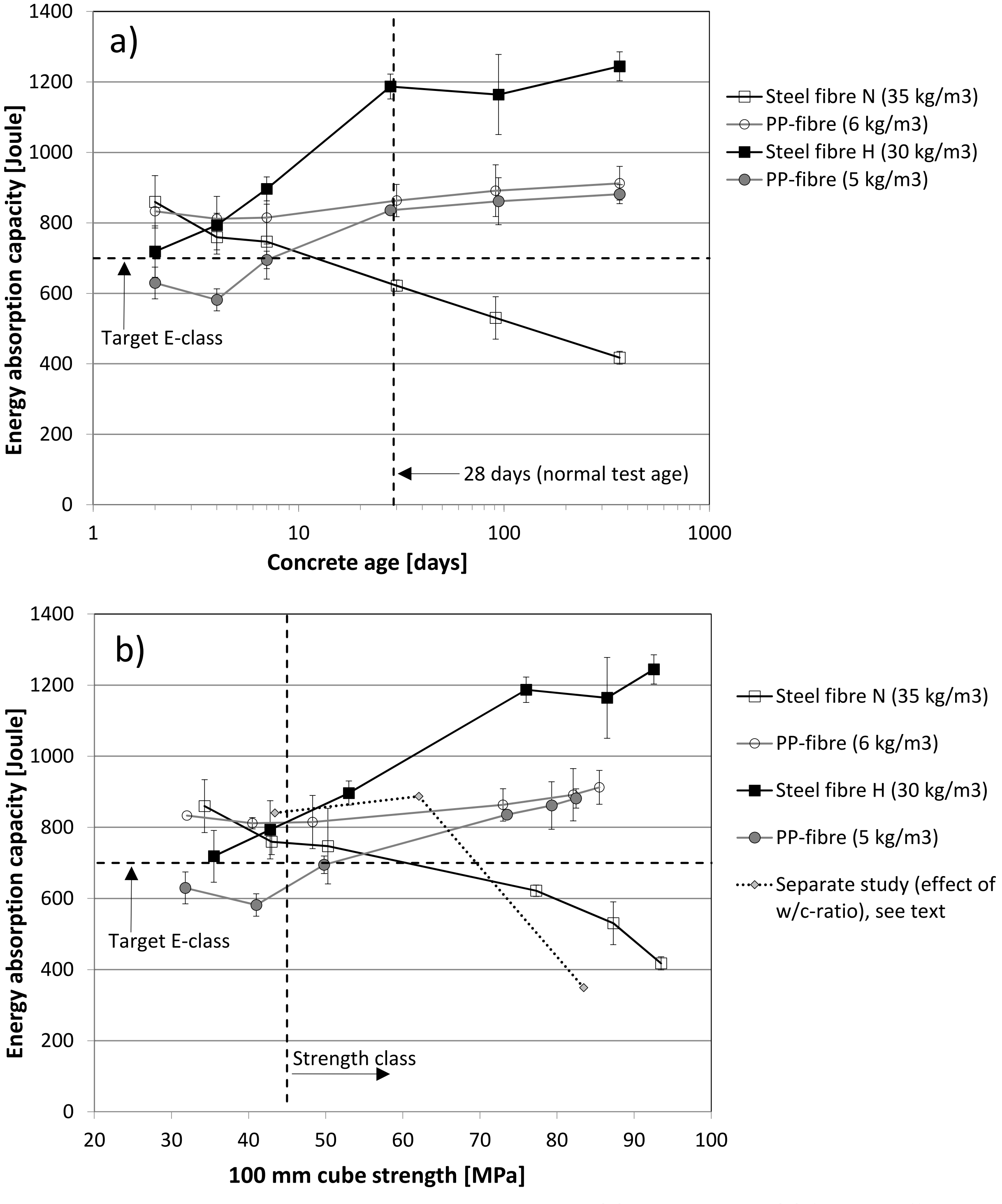

Figure 4: Energy absorption capacity vs. concrete age (a) and strength (b) for two different steel fibre types (N and H) and one PP-fibre. Each result is the average of 3 panels (the standard deviation is indicated).

further curing the decline continues with increasing strength and at 94 MPa strength (365 days) the capacity is only 55% of that at 7 days. This steel fibre (with normal tensile strength) could obviously not cope with such high strength levels, and fibres were observed to develop tensile failure in the cracks during the panel tests (perhaps a higher fibre dosage would have improved the performance). The energy absorption capacity is the energy uptake from zero to 25 mm central displacement during panel tests. It is notable that the reduced capacity over time discussed above is not present if the energy uptake was calculated only up to around 10 mm displacement, i.e. the steel fibre N performed well at smaller cracks.

The other concrete, with a lower dosage of “Steel fibre H” (30 kg/m^3), shows completely opposite behavior as the energy absorption capacity increases continuously with time and strength. At the final strength level at 365 days (93 MPa) the capacity becomes very high (1200 Joule) which is around 40% higher than at 7 days (53 MPa). The high tensile strength of the fibre has obviously promoted bond failure in the cracks during loading of the panels, in contrast to the fibre tensile failure for “Steel fibre N”.

The two concretes with the macro “PP-fibre” (5 and 6 kg/m^3, respectively) show quite similar behavior, except in the early age where the one with the lowest fibre dosage has somewhat lower energy absorption capacity. Somewhere beyond 7 days (beyond 50 MPa) the two PP-fibre concretes more or less stabilize at energy absorption capacity levels of 850-900 Joule.

Overall, the present results show that the energy absorption capacity for steel fibre reinforced concrete can change significantly with time and strength level. Hence, the 28 days standard age for panel tests may not necessary give a representative energy absorption capacity of the concrete if there is a significant strength increase on further curing.

The results in Figure 4b denoted “Separate study” are from another test series where the effect of w/c-ratio on energy absorption was studied. The series contain 3 concretes, all with 30 kg/m^3 dosage of a steel fibre very similar to the fibre “Steel fibre N” in Table 1, but this fibre has a tensile strength of 1100 MPa. The 3 concretes were all made with the same constituents (CEM II/A-V, 5% silica fume, standard laboratory sand 0-8 mm, plasticizer), but with w/c-ratios of 0.60, 0.45 and 0.37, respectively. The results were included in Figure 4b as they may illustrate the same feature as discussed above. In these tests, the concretes were mixed in the laboratory and the panels were cast, not sprayed. The test age was 49 days. The results show that decreasing w/c-ratio systematically led to increased strength, as expected. It can be seen that there is a dramatic drop in the energy absorption capacity from the middle strength level for the w/c=0.45 concrete (strength=62 MPa) to the high strength level for the w/c=0.37 concrete (strength=83 MPa). For the latter it was observed after testing of the panels that the vast majority of the fibres were broken due to tensile failure.

3.6.2 Effect of fibre content

From all the results we have available on w/c=0.45 FRSC, the relation between energy absorption capacity and fibre content is plotted in Figure 5; normal tensile strength steel fibres in figure (a) and macro PP-fibres in figure (b). The regression line with the best fit was linear, as indicated (still, the fit is not very good). The relation is not fair in many ways since many of the results are from different concretes made with different concrete constituents and fiber types. Anyhow, the figure shows (as expected) the trend that higher fibre dosage gives higher energy absorption capacity. The figure also shows, for these different concretes, that the energy absorption capacity may vary greatly for a given fibre dosage. The lesson to learn is that a relation between fibre dosage and energy absorption capacity for a given concrete in one project/site is not directly transferable to another project/site using another concrete/constituents, even if the fibre product is the same.

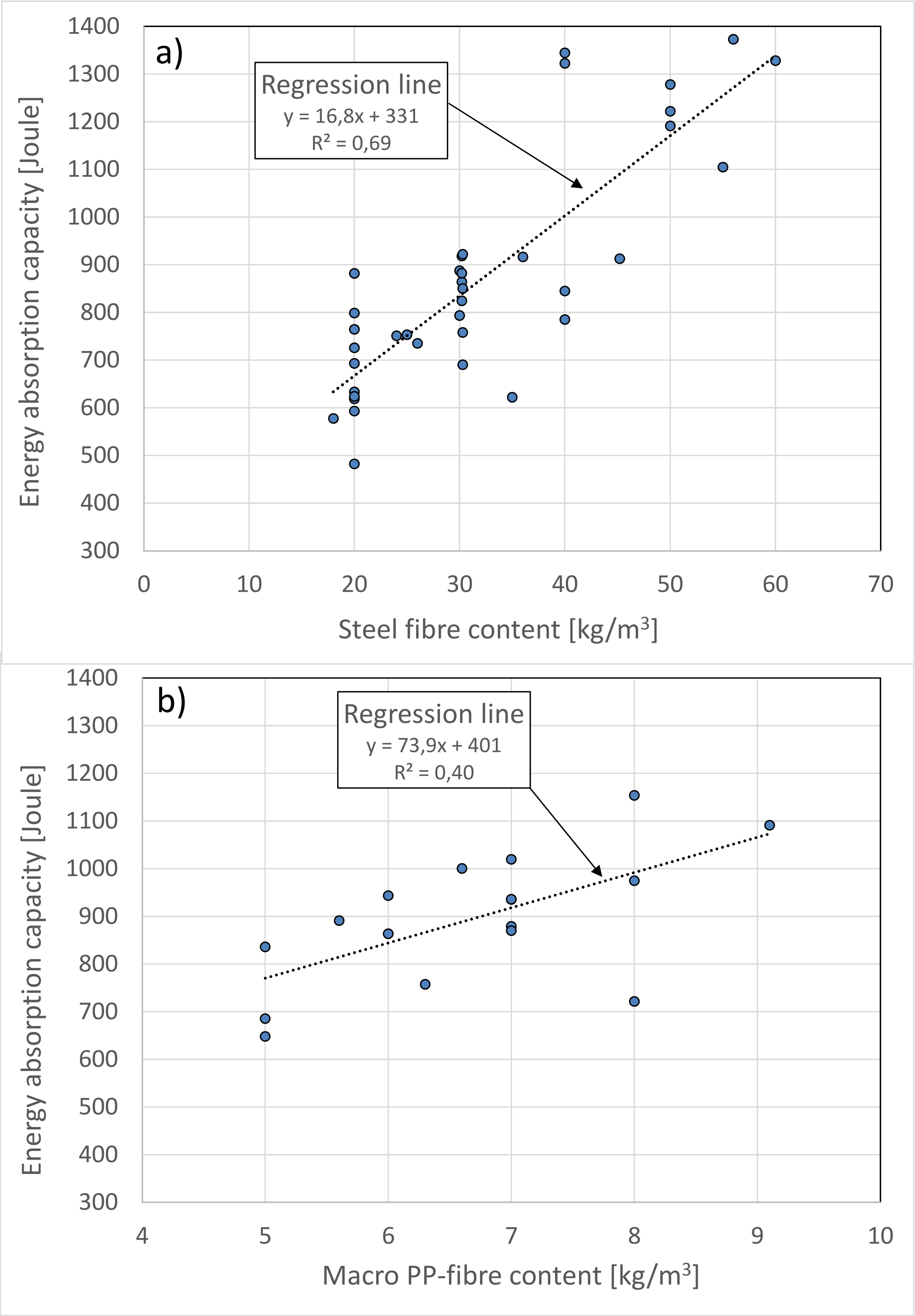

Figure 5: Energy absorption capacity vs. steel fibre content (a) and macro PP-fibre content (b). Both cast and sprayed panels. Concrete specification w/c=0.45 (and only normal tensile strength steel fibres).

4. Conclusions

Control of fibre content and fibre distribution in sprayed concrete basic mix deliverances is a prerequisite for uniform fibre action in the final FRSC lining. Measuring method and variability of fibre content through concrete loads were studied, and NB 7 now specifies quality control method, control frequency and lower tolerance limits for single measurements and average result. When producing panels for control of energy absorption capacity, fibre content/distribution must be measured simultaneously through the same concrete load. Then there is both a lower and an upper limit for single measurements and average result; this is to secure a relevant fibre dosage in the panels.

There is no reason to distinguish between the Norwegian round panel and the EN 14488-5 square panel. The laboratory tests showed that the two panel types give the same result provided identical support condition during the test. NB 7 equates the two methods.

In NB 7 the panel test and result evaluation procedure is described in detail (panel thickness correction, panel moist condition, no support bedding material, correction for friction against the support, raw data evaluation, and integral approximation method). EN 14488-5 should be evaluated in light of the presented findings.

Among 61 sets of panel tests the average coefficient of variation was 7.3% and the standard variation range for the coefficient of variation was 3 – 12%.

Both NB 7 and EN 14488-5 relate to the same energy absorption classes given in EN 14487-1. However, since only NB 7 requires the correction factor for friction (0.75), the consequence is higher fibre dosage to satisfy a given energy absorption class.

The energy absorption capacity of FRSC panels was shown to be significant already after 2 days of curing. Standard testing age is 28 days, and if strength increases markedly on further curing a significant drop in the energy absorption capacity may occur. Such drop with time was found for a FRSC with a given steel fibre, supposedly due to low tensile strength and/or to low dosage with regard to the very high strength that was developed at longer times (giving fibre failure instead of bond failure during crack propagation in the panel test). Low w/c-ratio (giving higher strength) may also cause a drop in energy absorption capacity due to the same feature. The feature can be avoided, for instance with higher tensile strength fibres.

Increased fibre dosage gives generally higher energy absorption capacity, but the absolute level is likely to change from site to site even if the fibre product is the same.

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