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Round and square panel tests—a comparative study

S.A. Myren & Ø. Bjøntegaard
Norwegian Public Roads Administration, Oslo, Norway

ABSTRACT: In order to determine the Energy Absorption Capacity (EAC) of Fibre Reinforced Sprayed Concrete (FRSC) the practice in Norway has been to test round ∅600 mm panels on a continuous simple support. Today the method is challenged by the new European standard EN 14488-5 which prescribes square 600 mm panels, also with a continuous simple support. In this regard, a comparative study of round and square panels was undertaken by the Norwegian Sprayed Concrete Committee. The main scope was to carry out a comparative study of the EAC for the two methods. It was also a goal to gain experience regarding the practicalities associated with the two methods on-site, on handling of specimens as well as on details of the measuring procedures in the laboratory.

1 INTRODUCTION

In Norway the round panel method has been used for about a decade for determination of fibre effect and for Quality Control in tunnel projects. The round panel method is described in the Norwegian Concrete Associations Publication No. 7 (NB 7): "Sprayed concrete for rock support". Today, however, this method is challenged by the square panel method, described in EN 14488-5 "Testing sprayed concrete—Part 5: Determination of energy absorption capacity of fibre reinforced slab specimens" and EN 14488-1 "Testing sprayed concrete—Part 1: Sampling fresh and hardened concrete". Now it is quite evident, for both panel methods, that little is reported on aspects that appear to be important with regard to both sampling on-site and on details of the test procedure itself.

The present program of research was undertaken in order to collect documentation on energy absorption capacity (EAC) from the two panel methods in parallel sets of nominally identical panels and perform testing in two laboratories. The intention was also to gain experience in spraying, sampling and handling the two panel types on-site according to their respective standards and gain experience with respect to the practicalities of the test procedures in the laboratory.

2 TEST PROGRAMME

2.1 *Concrete mix*

A total of three test series were undertaken. The concrete mix used in the various test series was a typical Norwegian mix for sprayed concrete. There were only minor differences in the concrete mix among the test series. The concrete mix is shown in Table 1. For Series 1, the only one that involved sprayed concrete, set accelerator was used, while for Series 2 and 3 no set accelerator was used. The fibre types included were Dramix RC 65/35, a steel fibre with hooked ends, and Enduro 600, a crimped macro-synthetic polypropylene fibre (macro pp-fibres).

2.2 *Test series*

During the period January 2007—February 2008 three test series were carried out, each series consisting of parallel sets of square and round panels. In addition to fibre effect, the effect of other factors was investigated. These included: spraying and sampling according to standards, age at testing

Table 1. Concrete mix with variations.

Material	Quantity (kg/m³)
CEM II/A-V 42.5R	460–475
Silica fume	23–24 (46 for w/(c + 2s) = 0.39)
Sand 0–8 mm	1487–1546
Fibre content	See Table 2
Superplasticizer	3.7–6.2
Retarder*	0.47–0.98
Pump aid**	2.3–2.5
Internal curing agent***	4,6
Air entraining agent	1.4–3.4
w/c + 2 s	0.39–0.42
Free water (L)	208–214

*Series 3 A and 3 B;
**Series 3 B;
**Series 1 and 2.

EAC, orientation of the panel during testing, support frame for round panels, and supplementary tests. Table 2 gives an overview of the three test series. A total of 80 panels have been tested, 40 for each geometry, and there were 12 comparative sets of round and square panels.

2.3 *Production and curing*

2.3.1 *Series* 1

The panels were sprayed with a robot on-site according to the respective standards. Hence, the round panels were sprayed in their final size, whilst the square panels were sprayed 1 × 1 m and later saw-cut to the final size of 600 × 600 mm. To be able to trim the square panels in acceptance with the tolerances in the standard ($100_{+5/-0}$ mm) it was necessary to reduce the accelerator from nearly 30 L/m³ (as used with the round panels) to about 20 L/m³.

After spraying the panels were covered with plastic and left for 5 days in the tunnel. The round panels were placed horizontally on the ground, while the square stood with the same angel to the wall as when they were sprayed, 20° off the vertical. Six of the panels, 3 round and 3 square were then transported to SINTEF Building and Infrastructures laboratory in Oslo, and kept in water until testing. The rest of the panels were transported to the Norwegian Public Roads Administration (NPRA) Central Laboratory in Oslo and kept in plastic for another 9 days, then placed in water until testing.

Table 2. Summary of the three test series.

Series	m = w/(c + 2s) Fibre dosage	No of panels of each geometry	Age at EAC testing	Orientation of sprayed/cast surface	Support	Supplementary tests
Series 1* Robot sprayed	m = 0.42–0.43 ** 20 kg steel fibre	 6 + 6	56 / 57 days	NPRA: Round: Down Square:Down SINTEF: Round: Down Square: Up	Round: Plywood of birch Square: Steel + strips of a hard and smooth type of chipboard	Fibre content Compressive strength Density ***
Series 2 Trad. casting	m = 0.41 20 kg steel fibre 35 kg steel fibre	 5 + 5 5 + 5	49 days	Round: Down Square: Down	Round: Chipboard Square: Steel + strips of a hard and smooth type of chipboard	Slump Air content Concrete temp. Fibre content Compressive strength Density
Series 3 A Trad. Casting	m = 0.40 15 kg steel fibre 30 kg steel fibre 45 kg steel fibre m = 0.39 30 kg steel fibre	 3 + 3 3 + 3 3 + 3 3 + 3	34 / 35 days	Round: Up Square: Up	Round: Plywood of birch Square: Steel + strips of a hard and smooth type of chipboard	Slump Air content Concrete temp. Air temp. Fibre content Compressive strength Density
Series 3 B Trad. casting	m = 0.41 3.0 kg macro pp-fibre 5.5 kg macro pp-fibre 8.0 kg macro pp-fibre m = 0.39 5.5 kg macro pp-fibre	 3 + 3 3 + 3 3 + 3 3 + 3	37 / 38 days	Round: Up Square: Up	Round: Plywood of birch Square: Steel + strips of a hard and smooth type of chipboard	Slump Air content Concrete temp. Air temp. Fibre content Compressive strength Density

* 3 + 3 samples tested at two different laboratories;
** m = 0.41 before adding accelerator;
*** all tests on drilled cores, NPRA did not measure fibre content.

2.3.2 *Series* 2

When the second test series was to be carried out, it was decided to cast all the panels traditionally in their final size in order to delineate the panel geometry-effect on the EAC. The casting took place in a tent at site. Since the specimens were cast no set accelerator was used. After casting the panels were covered in plastic, and left at site lying horizontally on the ground for one day. They were then transported to the NPRA Central Laboratory and stored in water until testing.

2.3.3 *Series* 3

Casting and curing for the third series was the same as for the second series.

3 TEST METHODS

3.1 *Supplementary tests*

3.1.1 *Slump*

Slump of fresh concrete was measured according to the NPRA Handbook for laboratory testing (HB 014); this method is similar to the method described in EN 12350-2.

3.1.2 *Air content*

Fresh concrete air content was measured according to HB 014; a similar method is described in EN 12350-7.

3.1.3 *Air- and concrete temperature*

Air- and fresh concrete temperature was measured with an electronic thermometer.

3.1.4 *Fibre content*

For Series 1 fibre content was measured on drilled cores of hardened concrete, simply by using a magnet on the crushed concrete and subsequent washing and drying. One sample consisted of two specimens each with diameter 74 mm, and height 74 mm (Volume = 0.64 L). This is in accordance with the method described in NB 7 and EN 14488-7.

For Series 2 and 3 fibre content was measured by washing the fresh concrete. Steel fibres were gathered with a magnet, and synthetic plastic fibres were gathered with a landing net and then dried. In Series 2 the size of the concrete samples was 2.0 litres (about 4.5 kg), and in Series 3 the size of the concrete samples was 3.0 litres. This is mainly in accordance with NB 7 and EN 14488-7, except for the size of the samples; NB 7 requires 10 kg (about 4.5 L) sample size, whilst EN 14488-7 requires samples of 1–2 kg (0.5–1.0 L).

3.1.5 *Compressive strength*

For Series 1 compressive strength was measured on drilled cores with various h/d ratio, d = 74 mm and $h = 74$–81 mm. The results were therefore converted to compressive cylinder strength for cylinders with h/d ratio of 2.0. This is according to HB 014; EN 12504-1 describes no conversion to h/d ratio 2.0. For Series 2 and 3 compressive strength was measured on cast cubes $100 \times 100 \times 100$ mm, according to HB 014 and EN 12390-3.

3.1.6 *Density*

Density was measured on the same samples as compressive strength, by weighing in air and immersed in water. This is according to HB 014 and EN 12390-7.

3.2 *Energy absorption capacity*

3.2.1 *Test rig*

The test set-ups are shown in Figures 1 and 2. For the round panels the support fixture was made of plywood of birch (Series 1 and 3) or chipboard (Series 2). The plywood/chipboard support was 40 mm high and 50 mm wide and had an inner diameter of 500 mm. For the square panels the support fixture was made of steel, 20 mm thick and 500 mm internal dimension. Strips of a hard and smooth type of chipboard were used as bedding material. According to the EN-standard the bedding

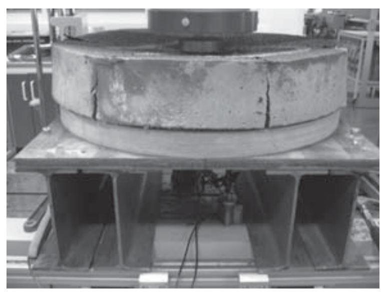

Figure 1. Set-up for round panels. The support fixture was made of plywood of birch/chipboard, no bedding material

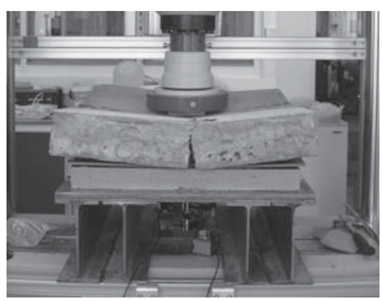

Figure 2. Set-up for square panels. Support of steel, strips of plywood as bedding material.

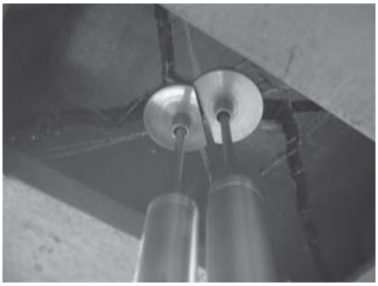

Figure 3. Placing of the two displacement transducers with metal caps.

material should be made of mortar or plaster, but this was considered too cumbersome and time-consuming to implement. The central displacement of the panels was measured by two displacement transducers as shown in Figure 3. The transducers are spring-loaded and have a measuring range of 50 mm. On top of the two transducers there were placed caps of metal to ensure that the transducers did not penetrate the cracks when they opened during testing.

A steel plate was put between the central load cell and the specimens, a ∅100 mm cylindrical plate for the round panels (and a thin sheet of cardboard) and a 100 × 100 mm square plate (and a thin sheet of cardboard) for the square panels. The test machine had a maximum load capacity of 200 kN. The deformation rate during the test was controlled by the average signal from the two displacement transducers. Prior to the test, the load-cell was stabilized at a load of 1 kN. With this initial load the test was started.

The stiffness of the test machine (frame, load cell and loading block) is 235 kN/mm. With a support fixture made of plywood/chipboard, the total stiffness is unknown. With a support fixture made of steel the stiffness of the total load system satisfies the requirements in EN 14488-5.

3.2.2 *Test procedure*

Prior to testing, each panel was taken out of the water bath and transported to the test rig where the test was started within 45 minutes. The procedure was then as follows. The mid-point was marked on the side of the panel facing down during testing and then the panel was placed in the test rig and centred. Two displacement transducers were placed under the centre of the panel. The average of the two transducers forms the signal for deflection control. On the upper side of the panel a load plate (and a thin sheet of cardboard) was placed at the centre. The load cell is prepared for testing by lowering it to the load plate until a load of 1 kN is applied to the panel. The test was started and load and deflection signals were logged continuously by a computer. According to NB 7 the load was applied deformation-controlled at a rate of 1.5 mm/min central deflection for the round panels, and according to EN 14488-5 at a rate of 1.0 mm/min central deflection for the square panels. The test was stopped automatically when the central deflection was 30 mm. The panel was lifted out of the test rig and the bottom side of the panel was photographed. The EAC was calculated as described in the standards as the area under the load-deflection curve from zero to 25 mm deflection. The results are corrected for thickness when deviating from 100 mm (see below).

3.3 *Correction for panel thickness*

The panel thickness influences the ability to absorb energy, where increased panel thickness will increase the energy absorption compared to the reference thickness. Consequently, the calculation of EAC should be corrected when the thickness deviates from the reference thickness. A theoretical evaluation of the effect of panel thickness has been reported (Thorenfeldt 2006). Target panel thickness is in this case $h_0 = 100$ mm. The following analysis procedure was proposed for panels with thickness h deviating from h_0:

1. Absorbed energy should be calculated under the load-displacement curve between 0 and a modified displacement $\Delta_m = 25\ \text{mm} \times k$, where $k = 100/h$,
2. Calculated EAC should then be multiplied by the factor k,
3. The final corrected EAC is then the result for the test.

The procedure assumes that four cracks develop and that the moment resistance at each crack is determined by the crack rotation angle. The total moment capacity is then linearly related to the thickness of the panel and the crack opening. It is likely that the correcting procedure will be valid within reasonable variations in panel thickness and that it will certainly contribute to achieving more comparable results. Note that neither NB 7 nor EN 14488-5 describes any procedures for correcting the EAC for deviations in panel thickness.

4 RESULTS

4.1 *Supplementary tests*

The results of the measurements done on fresh concrete are shown in Table 3, and Table 4 shows the results from the measurements done on hardened concrete. The high air content in some of the samples correlates with the lower compressive strength and density in the same samples.

Table 3. Measurements on wet concrete for all concrete mixes.

Series		Fibres	Slump (mm)	Air content (%)	Concrete temperature (°C)	Air temperature (°C)	Fibre content (kg/m^3)	
							Av.	Std
1 st Series	NPRA	20 kg steel fibre	–	–	–	–	–	–
	SINTEF*	20 kg steel fibre	–	–	–	–	18.5	1.94
2nd Series		20 kg steel fibre	190	7	23.6	–	21.8	1.84
		35 kg steel fibre	210	6	22.5	–	35.6	6.88
3rd Series	w/(c + 2s) = 0.40	15 kg steel fibre	220	8.8	22	6	16.1	–
		30 kg steel fibre	240	12.5	19	6	37.0	–
		45 kg steel fibre	–	11.5	18	6	49.1	–
		3 kg synthetic fibre	180	8.5	19	10	3.3	–
		5.5 kg synthetic fibre	180	8.5	19	10	7.8	–
		8 kg synthetic fibre	200	8.5	19	10	10.3	–
	w/(c + 2s) = 0.39	30 kg steel fibre	–	11	18	6	32.7	–
		5.5 kg synthetic fibre	200	7.9	20	10	9.11	–

*Fibre content measured on drilled cores.
av. = average, std. = standard deviation.

Table 4. Measurements on hardened concrete for all concrete mixes.

			Compressive cube strength (MPa)				Density (kg/m^3)			
			7 days		28 days		7 days		28 days	
			av.	std.	av.	std.	av.	std.	av.	std.
1 st Series	NPRA*	20 kg steel fibre	–	–	56.6	6.62	–	–	2293	19.15
	SINTEF**	20 kg steel fibre	–	–	60.8	3.16	–	–	2280	11.55
2nd Series		20 kg steel fibre	48.3	0.4	62.3	0.0	2250	0.0	2250	0.0
		35 kg steel fibre	42.5	0.0	60.0	2.1	2290	0.0	2295	7.1
3rd Series	w/(c + 2s) = 0.40	15 kg steel fibre	38.5	1.41	51.5	2.12	2185	7.07	2190	0.0
		30 kg steel fibre	29.5	0.0	39.8	0.35	2090	0.0	2100	0.0
		45 kg steel fibre	33.3	1.06	47.0	0.71	2130	0.0	2140	0.0
		3 kg synthetic fibre	43.3	0.35	57.8	0.35	2170	0.0	2180	0.0
		5.5 kg synthetic fibre	49.0	0.0	64.0	2.12	2200	0.0	2210	0.0
		8 kg synthetic fibre	45.3	0.35	59.3	2.47	2190	0.0	2200	0.0
	w/(c + 2s) = 0.39	30 kg steel fibre	37.0	0.0	51.8	1.06	2190	0.0	2200	14.14
		5.5 kg synthetic fibre	50.0	2.12	69.3	2.47	2225	7.07	2245	7.07

*Compressive strength measured on drilled cores, 56 days;
**Compressive strength measured on drilled cores, 28 days;
av. = average, std. = standard deviation.

4.2 *Energy absorption capacity*

The results from the EAC tests, including panel thickness and maximum load, are shown in Table 5. The correlation factors between square and round panels are also included in the table.

Average thickness for all panels was 102.0 mm, but 30% of the panels did not satisfy the requirements for panel thickness given in EN 14488-5 ($100_{+5/-0}$ mm). NB 7 does not give any tolerances for panel thickness. For the EAC the average coefficient of variation (COV) for round and square

Table 5. Panel thickness, maximum load, energy absorption capacity (EAC) for all concrete mixes (average, standard deviation and coefficient of variation in %), and the correlation factor for EAC between square and round panels. EAC are corrected for deviating panel thickness

Series		Fibres		Panel thickness (mm)			Maximum load (kN)			EAC (J)			EAC square/ round
				av.	std.	COV	av.	std.	COV	av.	std.	COV	
1 st Series	NPRA	20 kg steel fibre	R	101.9	2.37	2.33	50.6	1.09	2.15	727.1	70.31	9.67	
			S	101.8	3.82	3.75	52.8	2.01	3.80	527.0	73.66	13.98	0.72
	SINTEF	20 kg steel fibre	R	103.3	1.53	1.48	57.0	4.56	8.00	717.4	83.38	11.62	
			S	99.5	0.71	0.71	63.7	3.18	5.00	583.6	98.09	16.81	0.81
2nd Series		20 kg steel fibre	R	104.5	3.48	3.33	70.8	5.98	8.44	1143.5	37.42	3.27	
			S	104.9	1.49	1.43	79.8	8.15	10.22	1204.1	116.71	9.69	1.05
		35 kg steel fibre	R	104.4	1.84	1.77	93.1	5.13	5.51	1467.4	99.04	6.75	
			S	105.4	1.95	1.85	109.9	8.17	7.43	1645.3	103.30	6.28	1.12
3rd Series	w/(c + 2s) = 0.40	15 kg steel fibre	R	99.3	1.52	1.53	57.8	5.07	8.78	894.8	40.60	4.54	
			S	99.8	1.36	1.37	56.7	6.54	11.54	895.2	142.09	15.87	1.00
		30 kg steel fibre	R	101.1	2.39	2.36	43.5	3.54	8.15	686.9	53.87	7.84	
			S	101.2	1.55	1.53	41.6	5.06	12.16	561.3	77.93	13.88	0.82
		45 kg steel fibre	R	101.7	1.51	1.49	83.1	4.56	5.49	1487.6	39.11	2.63	
			S	101.4	1.24	1.22	75.0	5.72	7.63	1086.6	192.25	17.69	0.73
		3 kg macro pp-fibre	R	101.4	1.87	1.84	54.8	4.25	7.75	543.3	23.51	4.33	
			S	100.7	1.17	1.17	57.1	5.97	10.45	563.9	52.43	9.30	1.04
		5.5 kg macro pp-fibre	R	102.2	2.76	2.71	65.5	1.62	2.48	935.9	107.49	11.49	
			S	101.2	1.73	1.71	65.9	6.94	10.53	896.9	28.41	3.17	0.96
		8 kg macro pp-fibre	R	102.7	1.73	1.68	68.9	7.58	11.01	1200.9	128.36	10.69	
			S	102.4	1.51	1.47	74.1	9.56	12.90	1226.6	233.00	19.00	1.02
	w/(c + 2s) = 0.39	30 kg steel fibre	R	101.2	1.62	1.60	78.0	9.96	12.77	1399.3	208.39	14.89	
			S	101.3	1.38	1.36	66.2	3.08	4.65	978.0	70.39	7.20	0.70
		5.5 kg macro pp-fibre	R	103.9	3.46	3.33	66.0	2.05	3.11	998.0	38.82	3.89	
			S	101.2	1.05	1.04	59.5	8.89	14.95	912.6	144.41	15.82	0.91
Average correlation factor EAC, square/round													0.91
Average COV, round													7.63
Average COV, square													12.39
Average COV, round and square													10.01

av. = average, std. = standard deviation, COV = Coefficient of variation.

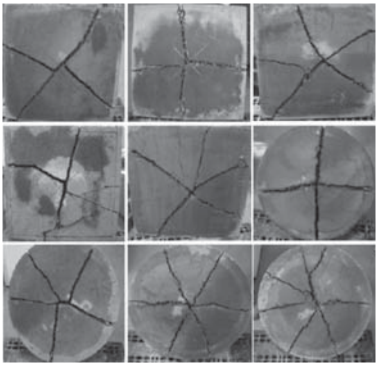

Figure 4. Different crack patterns; 4, 5 6 and 7 cracks appear, examples from different series.

panels for all sets in all series was 10%. Round panels displayed a somewhat lower COV (7.6%) than the square panels (12.4%). The average correlation factor between square and round panels for EAC for all sets was 0.91. Examples of different crack patterns are shown in Figure 4. Multiple cracking and shear crushing appeared for both round and square panels, and generally in panels with high fibre content.

5 DISCUSSION

5.1 *Experiences from spraying panels*

Prior to spraying the panels in Series 1, there were deliberations about how to spray the square panels. The surface area of the square panels is more than three times greater than the surface area of the round panels, and we were afraid that it would be too difficult to trim to the necessary thickness. These concerns were to a great extent confirmed during the trial.

The spraying of the round panels went as plan-ned. The mould was placed on a steep angle to a rocky wall and sprayed. The mould was then carried away by two persons, placed horizontally on the ground and then trimmed by one person. This was possible to do with a normal accelerator dosage of 30 L/m^3. When spraying the square panels, it soon became clear that the accelerator dosage had to be reduced; the first was damaged while trimming due to the extended time needed for the process and despite the fact that two persons were working hard. When the accelerator dosage was reduced to 20 L/m^3, it was possible for two persons to trim the square panels, but it was very hard work. However, trimming the surface to an accuracy of –0/+5 mm was impossible; there were always some pits and bumps.

The round panels, with a weight of about 65 kg, could be handled by two persons. With a weight of about 230 kg, manual handling was impossible for the square panels. When the square panels in addition have to be saw-cut to 600 × 600 mm, much larger machinery was required to be able to do the testing.

Another very important aspect of casting the square panels on-site is that the panels shall not be moved within 18 hours after being sprayed. This implies that the panels can not be produced where excavation is taking place and sprayed concrete is used. The close connection between in-situ use and testing will be lost, and the relevance of the testing will be reduced.

5.2 *Experiences from testing energy absorption capacity*

One of the observations during testing in the laboratory was that not all the panels were completely flat, especially the square panels. The round moulds were made of steel while the square moulds were made of wooden materials. The plywood used in the bottom of the square moulds was 5–6 mm thick, while EN 14488-1 requires at least 18 mm thick plywood or steel moulds. The wooden moulds were therefore probably not as stable with regard to weight and moisture, and the panels would easily be bent. Uneven panels mean that during the start of testing there will only be point contact between the panel and the support; hence the support is not continuous as required. This situation may influence the crack pattern, and the number of cracks. In particular the latter may affect the energy absorption during the test, and may have contributed to the increased scatter in results seen for square panels, see Table 5.

Another issue that might influence the crack pattern is if the sprayed surface is placed down during testing, and the surface is uneven with pits and bumps. This situation will also give rise to point contact with the support. In a tunnel lining of sprayed concrete there will be tensile stresses both at the inner side against the rock and on the outer exposed side. Hence, from this perspective the relevant orientation for panels in laboratory testing is unimportant. This may explain why the panel orientation is prescribed differently in the present standards (NB7 and EN). From a test methodology point of view, however, it appears to be sound to place the panels with the moulded/smooth surface against the support and apply the loading on the rougher trimmed/cast surface. This is related to the fact that the rougher surface will, if placed against the support, increase the chances for point contact with the support and may in this way influence the test results.

Panel thickness has been measured by different methods. Parallel measurements of thickness in a pattern over the entire surface and along the circumference gave quite similar average results. The former is a cumbersome way of doing it. In principle the thickness should be measured over the yield-lines, after the test. Length/diameter was not measured, but a visually control when placing the panels in the test rig showed that some of the panels where just slightly oval/rectangular. Any possible effect of this is not investigated, but this effect is likely to be far smaller than the effect of panel thickness.

The panel thickness varied between 98.3 and 107.5 mm. Instead of discarding the panels with deviating thickness, the energy absorption was corrected for thickness. Even within the given tolerances, the EAC was noticeably over-estimated when not correcting for thicknesses deviating from 100 mm. An example from series 2 shows that a 105 mm thick panel gives, if not corrected for, up to 9% higher EAC when compared to a 100 mm thick panel. Hence, thickness should be corrected for panels even if they are within the given tolerances.

In Series 2 we made an important observation; the round chipboard support failed, see Figure 5. Occasionally the strips of hard and smooth chipboard used as bedding material for the square panels also failed. These two occurrences had to be a result of friction between the panel and the support, and made us wonder what effect friction had on the measured EAC. This aspect was investigated further in later tests, see Bjøntegaard (2009).

When testing of Series 3 A panels was carried out, there was a deviation in the deformation rate early in the test for some of the square panels with steel fibres. This deviation occurred for all the panels with w/(c + 2s) = 0.40 and 45 kg steel fibre and with w/(c + 2s) = 0.39 and 30 kg steel fibre, and also on one of the panels with w/(c + 2s) = 0.40 and 30 kg steel fibre. For the square panels that were tested with an early deviating deformation rate the following happened, for unclear reasons. The period with deviating deformation rate was from the start of testing and until around 3 seconds. The deflection was at this point in the range of 1 mm. With a correct deformation rate (1 mm/min) the deflection should have been 0.05 mm after 3 seconds, hence the deviation was in the range of 20 times the normal load-rate. At this point (after around 3 seconds) cracking occurred; this is earlier than it should and was also at a lower deflection than normal (but at normal peak-load level). From the point of cracking onward, the deformation rate stabilized at the correct speed at 1 mm/min. The extent to which these early deviations in the test procedure have influenced the results is not clear, but it is notable that the square panels that suffered such a procedure performed poorly with regard to EAC.

Figure 5. Failure in chipboard support.

5.3 *Energy absorption capacity*

In principle, we believe the round and square methods are close to equal, hence in theory we expect the correlation factor for EAC to be 1. This would indeed be the case for the situation shown in Figure 6(a) for four cracks being perpendicular to the support. But square panels can fail by a crack pattern that approaches the case in Figure 6(b), which results in 40% less total crack rotation. The sensitivity to the crack orientation implies a higher coefficient of variation (COV) for the square panels, something which is also the case in these tests (on average). The inherent scatter in results for each panel method can actually explain the variable correlation factor, from 0.7 to 1.1, which was found in the different sets of parallel sets of round and square panels. Note that Figure 6 does not show all possible crack situations that are apparent in Figure 4.

Assuming that the two panel methods are equal, hence among a large number of parallel sets the average correlation factor is 1.0. The overall average COV for EAC was here found to be 10% (0.1),

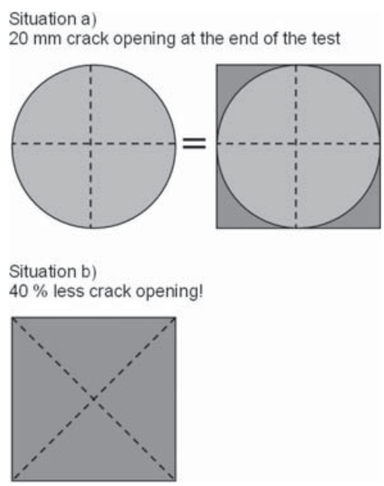

Figure 6. Possible crack patterns, four perpendicular cracks.

thus the expected "standard" interval for the correlation factor between square and round panels will then be from 0.82 to 1.22, see Equations 1 and 2.

$$\frac{EAC_{Round}}{EAC_{Square}} = \frac{1-COV}{1+COV} = \frac{1-0.1}{1+0.1} = \frac{0.9}{1.1} = 0.82 \qquad (1)$$

$$\frac{EAC_{Round}}{EAC_{Square}} = \frac{1+COV}{1-COV} = \frac{1+0.1}{1-0.1} = \frac{1.1}{0.9} = 1.22 \qquad (2)$$

All correlation factors from all parallel sets of round and square panels are shown in Figure 7; from the left to the right:

- Series 1, NPRA, 20 kg steel fibres
- Series 1, SINTEF, 20 kg steel fibres
- Series 2, 20 kg steel fibres
- Series 2, 35 kg steel fibres
- Series 3A, w/(c + 2s) = 0.40, 15 kg steel fibres
- Series 3A, w/(c + 2s) = 0.40, 30 kg steel fibres
- Series 3A, w/(c + 2s) = 0.40, 45 kg steel fibres
- Series 3B, w/(c + 2s) = 0.40, 3 kg macro pp-fibres
- Series 3B, w/(c + 2s) = 0.40, 5.5 kg macro pp-fibres
- Series 3B, w/(c + 2s) = 0.40, 8 kg macro pp-fibres
- Series 3A, w/(c + 2s) = 0.39, 30 kg steel fibres
- Series 3B, w/(c + 2s) = 0.39, 5.5 kg macro pp-fibres

The black dashed line at 1.0 indicates "expected behaviour". The "standard interval" is also indicated by grey dashed lines at 0.82 and at 1.22. It can be seen that most of the correlation factors lay within the "standard interval", but some fell outside; which also can be expected from a statistical viewpoint.

As stated earlier, the average correlation factor for all sets was 0.91. This means that the square panels gave on average 9% lower EAC than the round ones. As discussed earlier the loading rate was somewhat different for some of the square panels in Series 3 A. If these panels were removed from the data two of the square sets would be completely eliminated ("w/(c + 2s) = 0.40 and 45 kg steel fibre" and "w/(c + 2s) = 0.39 and 30 kg steel fibre") as well as one panel in the set "w/(c + 2s) = 0.40 and 30 kg steel fibre". When eliminating the deviating panel test from the latter square panel set the correlation factor increases from 0.82 (see Table 5) to 0.88. With this correlation factor for this particular set, as well as the complete elimination of the other two square panel sets, the average correlation factor for the remaining 10 parallel sets becomes 0.95.

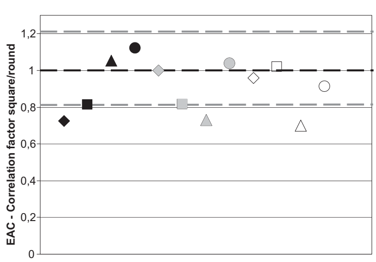

Figure 7. Energy absorption capacity, correlation factor square/round, all series.

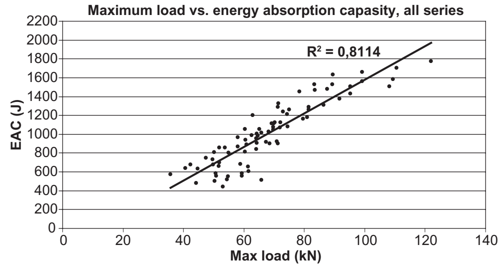

Figure 8. Maximum load versus energy absorption capacity, all series.

Another peculiarity is that in sets of nominally identical panels there is a trend that a high EAC from a given panel test is associated with a high peak-load, see Figure 8. This interaction is surprising since the former should be governed mainly by the fibre action, while the latter is governed by the matrix properties. Note that this is not the case for Series 1, but applies to Series 2 and 3 individually, and all sets put together. This might indicate that fibre performance was related to concrete strength for the present mixes.

6 CONCLUSION

Spraying, trimming, storing and handling (including saw-cutting) of 1 × 1 m square panels is difficult and time-consuming. Trimming of such sprayed concrete panels (Series 1) was only possible with a reduced accelerator dosage. We recommend that square panels should be sprayed to their final size (as done for round panels), assuming that the influence of edge-effects (rebound) is minor. Steel moulds should be used for both square and round panels in order to cope with the weight of the concrete and to be stable over time with regard to handling and moisture. A minimum of 4 mm steel sheet, as required in EN 14488, should be used for both square and round panels. This ensures that the degree of flatness of the panels is as high as possible. Any panel unevenness will lead to point contact with the support fixture and thus the support will not be continuous, something which will influence the crack propagation and crack pattern. For the same reason we recommend that panels should be oriented with the smooth moulded face against the support fixture (the orientation of round panels have traditionally been the opposite).

In the present investigation a steel frame bedded on thin strips of a hard and smooth type of chipboard was used as support fixtures for the square panels, whereas a wooden ring (no bedding material) was used as the support fixture for the round panels. The use of a bedding material of mortar or plaster, as described for square panels, is considered too impractical for routine testing.

Energy absorption capacity (EAC) test results should be corrected for panel thickness. For the present results this has been done using an analytical approach. Naturally, such corrections can also be performed using an empirical approach. The correction procedure assumes that at a given crack opening the moment intensity in a crack is lineary dependent on the panel thickness. The procedure therefore corrects for thickness and modifies the final displacement level at the end of the test in order to ensure that the crack opening interval from start till end is the same in all tests. The procedure assumes 4 cracks, and thus do not take into account that the number of cracks can sometimes be more. We have no data that documents the area of application, but assumes that it is valid for relative small variations in panel thickness; such as the variations reported in this paper.

It is expected that the square and round panel methods should give about the same EAC-result; hence in theory, the correlation factor (EAC from square panels divided by EAC from round panels) is believed to be 1. But in practice the result from the square panel may be affected by the crack orientation. The results from the sets of parallel testing of square and round panels with nominally identical fibre reinforced concrete show that the correlation factors varied from 0.70 to 1.12 and that the average correlation factor for all parallel sets (12 in total) was 0.91. The variability of the correlation factors must be expected with the given scatter of the two panel methods. The average coefficient of variation among all sets with square panels was 12.4% and for the round panels the variation was 7.6%.

Within a set of panels there is a trend evident that a higher EAC from a given panel test is associated with a high peak load, and vice versa. This is surprising since the former should be governed by fibre actions while the latter is a property of the concrete matrix, and both fibre dosage and concrete mix is the same within each set.

Visual observations during the tests showed that the panels transfer friction forces to the support fixture. Friction forces to the base will influence the measured EAC. The friction effect has been quantified in later tests.

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REFERENCES

Bjøntegaard Ø. & Myren S.A. 2008. Energy absorption capacity for fibre reinforced sprayed concrete. Effect of panel geometry and fibre content (Series 2). Technology report no. 2532, Norwegian Public Roads Administration (in Norwegian).

Bjøntegaard Ø. 2009. Energy absorption capacity for fibre reinforced sprayed concrete. Effect of friction in rounds and square panel tests with continuous support (Series 4). Technology report no. 2534, Norwegian Public Roads Administration.

EN 12350-2 Testing fresh concrete—Part 2: Slump test, 2000.

EN 12350-7 Testing fresh concrete—Part 7: Air content—Pressure methods, 2000.

EN 12390-3 Testing hardened concrete—Part 3: Compressive strength of test specimens, 2001.

EN 12390-7 Testing hardened concrete—Part 7: Density of hardened concrete, 2001.

EN 14488-1 Testing sprayed concrete—Part 1. Sampling fresh and hardened concrete, 2005.

EN 14488-5 Testing sprayed concrete—Part 5. Determination of energy absorption capacity of fibre reinforced slab specimens. 2006.

EN 14488-7 Testing sprayed concrete—Part 7: Fibre content of fibre reinforced concrete, 2006.

Handbook 014 Laboratory investigations. Guidelines. The Norwegian Public Roads Administration, 1997 (in Norwegian).

Myren S.A. & Bjøntegaard Ø. 2008. Energy absorption capacity for fibre reinforced sprayed concrete. New test rig, effect of panel geometry and testing laboratory (Series 1). Technology report no. 2531, Norwegian Public Roads Administration (in Norwegian).

Myren S.A. & Bjøntegaard Ø. 2009. Energy absorption capacity for fibre reinforced sprayed concrete. Effect of panel geometry, fibre content and fibre type (Series 3). Technology report—to be published in 2009.

Norwegian Concrete Association's publication no. 7 (NB 7): Sprayed concrete for rock support. 2003 (in Norwegian).

Thorenfeldt E. 2006. Fibre reinforced concrete panels. Energy absorption capacity for standard samples. SINTEF memo (in Norwegian).