EFFECT OF SPECIMEN SIZE AND CAPPING METHOD ON APPARENT COMPRESSIVE STRENGTH OF HIGH-STRENGTH CONCRETE

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Abstract:
Compressive testing of high-strength concrete is a critical issue on which no consensus has yet been reached. Among the many factors that are often under discussion are the effects of specimen size, shape and capping method on the compressive strength results.

The main objectives of the present investigation were to conduct a well designed and statistically analyzed experiment to investigate effects of the abovementioned factors, and possible interactions of these on compressive strength of high-strength concrete. A 3x4x3 factorial experimental design was adopted with three levels of specimen sizes, three methods of specimen capping and four levels of concrete strength grades. In order to analyze the overall repeatability of compression testing, replicates were incorporated in the experiment. To properly evaluate the test result, two and three way analyses of variance and procedures for pairwise comparison of factor main effects were used.

Keywords: capping methods, compressive strength, concrete, experimental design, grinding, high-strength, specimen size, statistical analysis

1. INTRODUCTION

High-strength concrete is still a fairly new material in Finland and, up to now, it has been utilized only in a limited number of concrete structures /1,2/. Most typically, high-strength concretes are used for critical structural applications, where failure to reach the specified strength can cause costly delays while further testing is done /2,3/. It is especially important to avoid low mean values or high variation in compressive strength results caused by incorrect testing procedures.

Despite greater sensitivity of high-strength concrete to testing errors and to geometrical imperfections on the ends of the test specimens /4,5/, no special testing standards exist. In Finland, all structural concrete is subjected to the same testing standard SFS 4474, which is based on ISO 4012. It is the author's experience that, so far, the research on high-strength concrete has been so polarized by the improvement of the mechanical properties that feasibility of the existing testing techniques has been taken for granted. However, compressive testing of high-strength concrete is a critical issue, on which no consensus has yet been reached /6-9/.

Among the many factors that are often under discussion are the effects of specimen size and capping method on the apparent compressive strength results.

The main objectives of the present investigation were to conduct a well designed and statistically analyzed experiment to investigate effects of the abovementioned factors, and possible interactions of these on compressive strength of high-strength concrete.

2. EXPERIMENTAL DESIGN

A 3x4x3 factorial experimental design was adopted with two replicates (each an average of three specimens), giving a total of 72 test values (216 specimens). Main factors, factor levels and the layout plan of the experimental design are given in Table 1.

Three levels of specimen capping methods (factor A), four levels of concrete strength grades (factor B) and three levels of specimen sizes (factor C), were selected. In order to be able to analyze the overall repeatability of compression testing, replicates (factor D) were incorporated in the experiment. The test data makes it also possible to analyze compressive strength ratios between the various specimen sizes. However, this regression analysis is not presented in this paper; it is reported elsewhere /6/.

The strictest possible precautions were taken to ensure that all other factors which would concievably influence compressive strength were held constant. Preliminary tests were carried out to ensure that no test values would be omitted and that the levels of all factors, especially the concrete strength grade, could be adequately controlled. The statistical methods utilized included multiway analyzes of variance and Tukey's tests for pairwise comparisons of factor main effects.

Table 1. Factors and layout plan of the factorial experimental design. Each element $a_ib_jc_kd_l$ is one treatment combination.

LEVELS OF A; SPECIMEN CAPPING METHOD	LEVELS OF C; SPECIMEN SIZE & TYPE	LEVELS OF B; CONCRETE STRENGTH GRADE			
		b_1= 60MPa	b_2= 80MPa	b_3= 90MPa	b_4= 110MPa
a_1= nontreated surfaces	C_1=□100				
	C_2=□150				
	C_3=ø150				
a_2= sulphur capped surfaces	C_1=□100			...	
	C_2=□150		...	$a_ib_jc_kd_l$	...
	C_3=ø150			...	
a_3= ground surfaces	C_1=□100				
	C_2=□150				
	C_3=ø150				

3. TEST PROGRAM

3.1 Concrete materials

Binders: One brand of local Finnish sulphate-resisting Portland cement meeting SFS 3165, and silica fume, with 91.5% SiO_2 content and 20 m^2/g specific surface area, were used in all the concrete mixtures. The initial setting time, the 28d compressive strength, the specific gravity and specific surface area of the cement were 4h 50min, 55.0 MPa, 3180 kg/m^3, and 0.310 m^2/g, respectively.

Aggregate: The aggregate used in the test concretes had a maximum grain size of 16 mm, and was combined from six fractions. All the fractions were granitic natural sand and gravel, having a dry specific gravity of 2680 kg/m^3.

Water and admixtures: The mixing water used was cold tap water. In all the test mixtures, modified naphthalene-formaldehyde-polycondensate-based superplasticizer and tributyle-phosphate-based air release agent were used as chemical admixtures. The dosages used were 1.5% and 0.01% of the total amount of binder, respectively.

3.2 Test mixtures

The test program consists of eight concrete mixtures (M1-M8). The composition of the mixtures is identical; the proportioned cement, silica fume, aggregate, water, superplasticizer and air release agent contents were 560, 56, 1700, 127.5, 9.24 and 0.062 kg/m^3.

However, the testing age was varied in such a way that the specimens made of mixtures M1-M2, M3-M4, M5-M6 and M7-M8 were tested at the age of 23-24h, 2d, 7d and 28d, respectively. Consequently, the strength grades of mixtures M1-M2, M3-M4, M5-M6 and M7-M8 were 60, 80, 90 and 110 MPa, respectively.

3.3 Mixing and testing of fresh concrete

The ingredients were weighed according to the proportioning and mixed with a vertical-shaft mixer in 120-litre doses. Mixing was started by mixing all the dry ingredients for one minute. While the mixer continued to operate, 75% of the water and 25% of the superplasticizer were added, whereafter mixing was continued for two minutes. Finally, 25% of the water, 75% of the superplasticizer and the air release agent were added, and mixing was continued for two more minutes.

Freshly mixed concretes were tested for temperature (23.7°C), density (2470 kg/m^3), air content (1.9%), slump (130 mm) and Vebe-time (1 sVB). The tests were made according to the appropriate Finnish standards.

3.4 Casting and storing of test specimens

Of each of the eight test mixtures, nine 100 mm cubes, nine 150 mm cubes and nine cylinders of ø150·300 mm were cast in steel moulds. Thus, a total of 216 (= 8 x 27) test specimens were cast, Table 2.

Table 2. Specimen type, shape, amount and surface treatment method for each of the test mixtures M_i, i = 1-8.

MIX-TURE	SPECIMEN TYPE	SPECIMEN SIZE (mm)	NUMBER OF SPECIMENS	SURFACE TREAT-MENT METHOD
M_i	cube	100·100·100	3	mould surface
	cube	100·100·100	3	sulphur capping
	cube	100·100·100	3	ground surface
	cube	150·150·150	3	mould surface
	cube	150·150·150	3	sulphur capping
	cube	150·150·150	3	ground surface
	cylinder	ø150· h300	3	sawn surface
	cylinder	ø150· h300	3	sulphur capping
	cylinder	ø150· h300	3	ground surface

After internal vibration and casting, all the moulds were covered with a plastic sheet to prevent moisture evaporation. The specimens were demoulded at the age of 16-24 h, numbered and transferred to water storage at the temperature of 20±2°C.

At the testing age, the specimens were taken out of water 2-3 h before the testing. Specimens to be tested on mould surfaces were therafter stored at 20±2°C, RH 45±5%. Alternatively, specimens to be tested on sawn, sulphur capped or ground surfaces were treated 1-2 h before the testing, and thereafter stored at 20±2°C, RH 45±5%

3.5 Preparation of specimen compression surfaces

The alternatives for the specimen load-bearing surfaces used in the experiment were nontreated, sulphur capped and ground surfaces for cubes, and sawn, sulphur capped and ground surfaces for cylinders, respectively, see Table 2.

Nontreated surfaces: Some of the cubical specimens were tested against nontreated mould surfaces. This "vertical" testing of specimen usually eliminates the necessity for special preparation or capping of the specimen ends prior to testing.

Sawing: Sawing of the cylindical test specimens was accomplished with a water cooled specimen cutting machine (Seidner Type By-300-72). The machine is equipped with a diamond saw blade of ø625 mm, capable of cutting concrete specimens up to 250 mm in diameter.

Sulphur mortar capping: Some of the test specimens were capped with a thin (1-2 mm) layer of high-strength capping compound according to the procedure outlined in SFS 4474. The composition (in weight-parts) of the capping compound used in the study was sulphur: quartz filler: chalk powder 1.25:0.25:0.75. The 40 mm cube compressive strength of the sulphur compound averaged 44 MPa.

Grinding: The test specimens were ground with a semi-automatic, water cooled grinding machine (Megatron). This machine has been specially designed to grind concrete specimens up to 200 mm in maximum diameter. The machine is equipped with a grinding head of 230 mm, and a special grinding wheel with diamond sectors. The test specimen is held in position by means of special clamps. During operation the grinding head is doing a pendulum motion thus grinding the specimen end. A handwheel is provided for manual operation and initial setting-up.

3.6 Compression testing

The compressive strengths were determined according to the national standard SFS 4474. However, instead of the nearest 0.5 MPa, the test results were rounded to the nearest 0.1 MPa. The stressing rate used was 6 kN/s for 100 mm cubes, 15 kN/s for 150 mm cubes and 10 kN/s for 150·300 mm cylinders, respectively.

The specimens were compressed with a 5000 kN hydraulically (servo) driven testing machine (Seidner, Type PK-D-SRG) equipped with a lower, moving platen base, and a fixed, spherically seated upper platen. For ø150·300 mm cylinders and 150 mm cubes, the diameter of the platen was 420 mm, and that of the spherical bearing block 305 mm. However, for 100 mm cubes the testing machine was equipped with a testing jig (Seidner, Type DV-1000), having a 170 mm platen and a 135 mm bearing block diameter. Both blocks comply with SFS 4474.

4. TEST RESULTS AND DISCUSSION

4.1 Compressive strengths

The compressive strength results used in the analysis are shown in Table 3. The compressive strengths ranged from 47.6 to 99.6 MPa for ø150·300 mm cylinders, from 68.1 to 118.0 MPa for 150 mm cubes, and from 64.3 to 122.6 MPa for 100 mm cubes, respectively.

The coefficients of variation, based on the test data shown in Table 3, are presented in Table 4. The coefficients of variation ranged from 0.36 to 10.07% for ø150·300 mm cylinders, from 0.21 to 2.35% for 150 mm cubes, and from 0.00 to 5.73% for 100 mm cubes, respectively.

4.2 Analysis of variance

The compressive strength results presented in Table 4 were subjected to multivariate analysis using a *Statistix 4.0* computer program /10/. The test data were not subjected to any transformation before application of the analysis of variance technique, because it has been shown /11/ that the analyses of variance performed on transformed and untransformed data of this kind are closely similar.

Table 3. Compressive strengths used in the analysis. Each result is an arithmetic mean of strength results of three specimens.

SPECIMEN CAPPING METHOD	SIZE (mm)	CONCRETE STRENGTH GRADE (MPa)			
		60	80	90	110
Nontreated specimen surfaces	□ 100	66.3 71.9	86.8 86.3	104.0 102.4	113.8 120.2
	□ 150	70.2 71.1	83.2 81.7	97.9 96.0	112.3 111.5
	ø 150	47.6 54.9	59.6 67.1	83.0 79.0	79.7 91.3
Sulphur capped surfaces	□ 100	64.3 67.3	81.8 82.0	94.1 94.1	107.3 108.5
	□ 150	68.1 70.4	78.1 77.7	92.5 90.6	101.5 104.4
	ø 150	60.7 60.2	70.8 74.2	85.2 83.3	96.8 97.3
Ground surfaces	□ 100	66.8 69.7	87.5 86.9	103.3 103.9	121.3 122.6
	□ 150	70.9 71.8	84.7 85.0	100.1 99.8	117.1 118.0
	ø 150	58.5 59.3	69.3 71.6	85.1 85.7	99.6 99.1

Table 4. Coefficient of variations (%) based on the test data shown in Table 3.

SPECIMEN CAPPING METHOD	SIZE	COEFFICIENT OF VARIATION (%)					
		60 MPa	80 MPa	90 MPa	110 MPa	Mean	Mean
Nontreated specimen surfaces	□ 100	5.73	0.41	1.10	3.87	2.78	3.89
	□ 150	0.90	1.29	1.39	0.51	1.02	
	ø 150	10.07	8.37	3.49	9.59	7.88	
Sulphur capped surfaces	□ 100	3.22	0.17	0.00	0.79	1.05	1.35
	□ 150	2.35	0.36	1.47	1.99	1.54	
	ø 150	0.58	3.32	1.59	0.36	1.47	
Ground surfaces	□ 100	3.00	0.49	0.41	0.75	1.16	0.89
	□ 150	0.89	0.25	0.21	0.54	0.47	
	ø 150	0.96	2.31	0.50	0.36	1.03	
Mean		3.08	1.88	1.13	2.08	2.04	

In Table 5, the analysis of variance is made on the whole strength data. The four factor interactions (A*B*C*D) were used as error, giving a total of 36 degrees of freedom for the error sum of squares used in determination of significance of main effects and two and three factor interactions (A*B, A*C, B*C, A*B*C).

Table 5. Analysis of variance for the whole test data.

Source	DF	Sum of squares	Mean sum of squares	Variance ratio F	Probability P	Significance level
A	2	370.06	185.03	32.87	0.0000	highly significant
B	3	17682.00	5894.01	1047.00	0.0000	highly significant
C	2	3770.97	1885.48	334.93	0.0000	highly significant
A*B	6	172.34	28.72	5.10	0.0007	highly significant
A*C	4	539.16	134.79	23.94	0.0000	highly significant
B*C	6	211.65	35.28	6.27	0.0001	highly significant
A*B*C	2	56.35	4.70	0.83	0.6160	insignificant
Error	36	202.66	5.63			
Total	71	23005.20				

In Table 6, the analysis of variance is made on 100 mm and 150 mm cube data. The four factor interactions were used as error, giving a total of 24 degrees of freedom for the error sum of squares used in determination of significance of main effects, two factor interactions (A*B, A*C, B*C), and three factor interaction (A*B*C).

Table 6. Analysis of variance for strength data; cubes only.

Source	DF	Sum of squares	Mean sum of squares	Variance ratio F	Probability P	Significance level
A	2	538.04	269.02	104.97	0.0000	highly significant
B	3	12997.20	4332.42	1690.57	0.0000	highly significant
C	1	71.30	71.30	27.82	0.0000	highly significant
A*B	6	157.97	26.33	10.27	0.0000	highly significant
A*C	2	6.53	3.26	1.27	0.2980	insignificant
B*C	3	108.24	36.08	14.08	0.0000	highly significant
A*B*C	6	4.94	0.82	0.32	0.9194	insignificant
Error	24	61.51	2.56			
Total	47	13945.80				

In Table 7, the analysis of variance is made on cylinder strength data. The three factor interactions (A*B*D) were used as error, giving a total of 12 degrees of freedom for the error sum of squares used in determination of significance of main effects (A, B) and two factor interaction (A*B).

Table 7. Analysis of variance for strength data; cylinders only.

Source	DF	Sum of squares	Mean sum of squares	Variance ratio F	Probability P	Significance level
A	2	364.66	182.33	15.50	0.0005	highly significant
B	3	4788.17	1596.05	135.69	0.0000	highly significant
A*B	6	65.78	10.96	0.93	0.5066	insignificant
Error	12	141.16	11.76			
Total	23	5359.76				

4.3.1 Effect of specimen capping method (factor A)

The analyses of variance made in Tables 5-7 show that the effect of factor A on compressive strength is highly significant. In this particular case, the effect is significant at a level of less than five tenth of a per mil. This means that the probability of the effect being due to some random occurrence and not being a property of the material is less than five in ten thousand!

For cylindrical specimens, the compressive strength main effect A is untroubled by two factor interactions, Table 7. However, two factor interaction A*B has to be accepted as having occurred for the strength response for cubes, Table 6.

Classification of the main effects' means into significantly different groups was made by using Tukey's multiple comparison procedure. Tukey's method is based on the studentized range statistic, and it is the most useful pairwise comparison procedure *Statistix* /10/ performs. The comparison test was performed by using rejection level $\alpha = 0.01$. The results are presented in Tables 8-10.

Table 8. Tukey's pairwise comparison of means of Y by factor A. Error term used A*B*C*D, 36 DF; $\alpha = 0.01$.

Level of factor A	Mean (MPa)	Homogeneous groups	Test parameters	
3	89.07	I	Critical Q value	4.399
1	84.91	I	Critical value for comparison	2.130
2	83.80	I	Standard error for comparison	0.685

Table 9. Tukey's pairwise comparison of means of Y by factor A; cubes only. Error term used A*B*C*D, 32 DF; $\alpha = 0.01$.

Level of factor A	Mean (MPa)	Homogeneous groups	Test parameters	
3	94.34	I	Critical Q value	4.433
1	92.23	...I	Critical value for comparison	1.674
2	86.42	I	Standard error for comparison	0.534

Table 10 Tukey's pairwise comparison of means of Y by factor A; cyliders only. Error term used A*B*D, 18 DF, $\alpha = 0.01$.

Level of factor A	Mean (MPa)	Homogeneous groups	Test parameters	
2	78.56	I	Critical Q value	4.687
3	78.53	I	Critical value for comparison	5.619
1	70.28	...I	Standard error for comparison	1.695

For cubes the Tukey's test indicates that all three means are significantly different from each other in such a way that the highest strengths are achieved with ground specimen surfaces and the lowest with sulphur capped specimen surfaces. Alternatively, for cylindrical specimens the Tukey's test classifies the main effect in only two groups; these are the sulphur capped or ground cylinders which give higher strengths than the sawn cylinders.

4.3.2 Effect of specimen size and type (factor C)

The analyses of variance made in Tables 5 and 6 show that the effect of factor C on compressive strength is highly significant at a level of less than one tenth of a per mil. This means that the probability of the effect being due to some random occurrence and not being a property of the material is less than one in ten thousand!

When cylindrical specimens are analyzed alone (Table 7), no interactions A*C or B*C can, naturally, exist. However, two factor interaction (B*C) has to be accepted as having occurred for the strength response for cubes, Table 6.

As shown before, classification of the main effects' means into different groups was made by using Tukey's multiple comparison procedure. The comparison test was performed by using rejection level $\alpha = 0.01$. The results of the multiple comparison for the capping method effect are presented in Table 11.

Based on the pairwise comparison shown in Table 11, the Tukey's test indicates that all the three means are signifigantly different from each other. These groups are 100 mm cubes which give the highest strengths, 150 mm cubes which give the second highest strengths, and the ø150·h300 mm cylindrical specimens which give the lowest compressive strengths.

Table 11 Tukey's pairwise comparison of means of Y by factor C. Error term used A*B*C*D, 36 DF; $\alpha = 0.01$.

Level of factor C	Mean (MPa)	Homogeneous groups	Test parameters	
1	92.21	I	Critical Q value	4.399
2	89.78	...I	Critical value for comparison	2.130
3	75.79	I	Standard error for comparison	0.685

4.3.3 Interactions between various effects

One of the main motivations for carrying out factorial experiments is that interactions between factors may be investigated. Interactions between main factors are complex relationships among the effects of these factors, so that they are not independent in their effects of the response being measured /6,11/.

The results of this experimental program have been used to study the interactions A*B, A*C and B*C. The analyses of variance given in Tables 5-7 show that all the effects of these interactions on compressive strength are highly significant. In these particular cases, the F-test indicates that the effects are significant at a level of less than seven tenth of a per mil. This means that the probability of the interaction being due to some random occurrence and not being a property of the material is less than seven in ten thousand! The relevant interaction diagrams are shown in Figs. 1-3.

*Interaction A*B*
This interaction for the cube test data is illustrated in Fig. 1. It may be noted in Table 7 that for cylinders the interaction A*B is not significant, whereas for cubes the significance level is extremely high, Table 6.

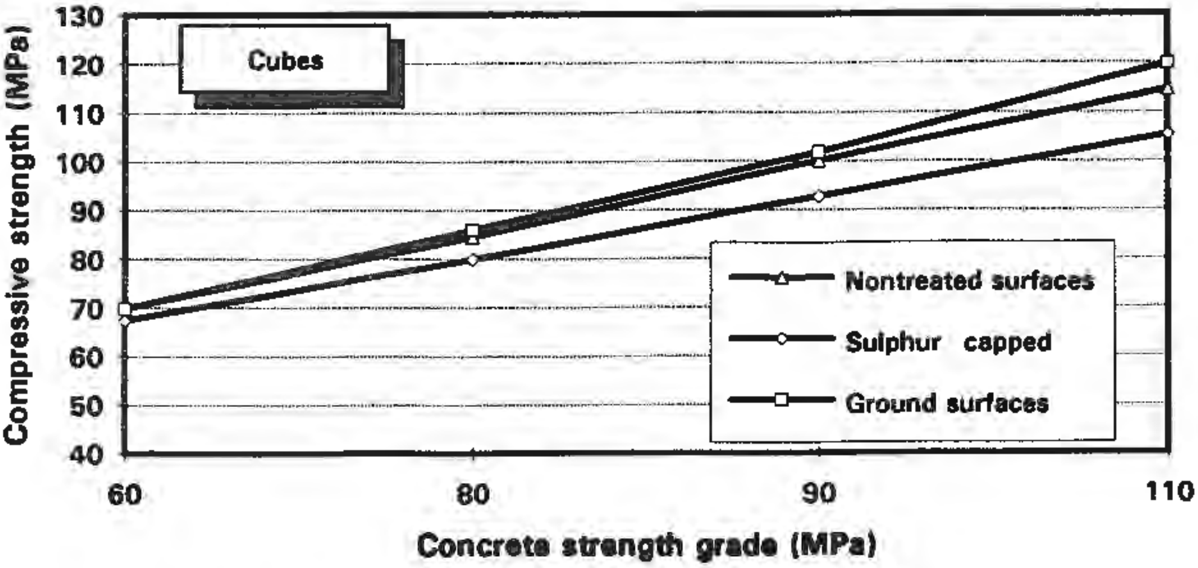

Fig. 1. **Specimen capping method (A) and concrete strength grade** (B) interaction for compressive strength for cubical specimens.

If no interaction occurred, the responses of compressive strength to concrete strength grade with different specimen surface treatment methods would be parallel to one another. Interactions between the two factors are indicated by the lack of parallelism apparent in the diagram.

Thus, for cylindrical specimens there is no interaction A*B, and for cubical specimens, the relationships between the two factors can be interpreted as follows:

- The lowest compressive strengths in all the concrete strength grades studied are achieved with the cubes with sulphur capped surfaces.
- The highest strengths in all the strength grades studied are achieved with the cubes with ground surfaces.
- The difference in strengths between the cubes with ground and nontreated surfaces increase with increasing strength grade, but it is only nominal at strength grades ≤90 MPa.

*Interaction A*C*
This interaction for the whole set of data is illustrated in Fig. 2. It is evident that the effect of specimen surface treatment method on the compressive strength of cubes is different from that of cylindrical specimens. As already mentioned, interactions between the two factors are indicated by the lack of parallelism apparent in the diagram.

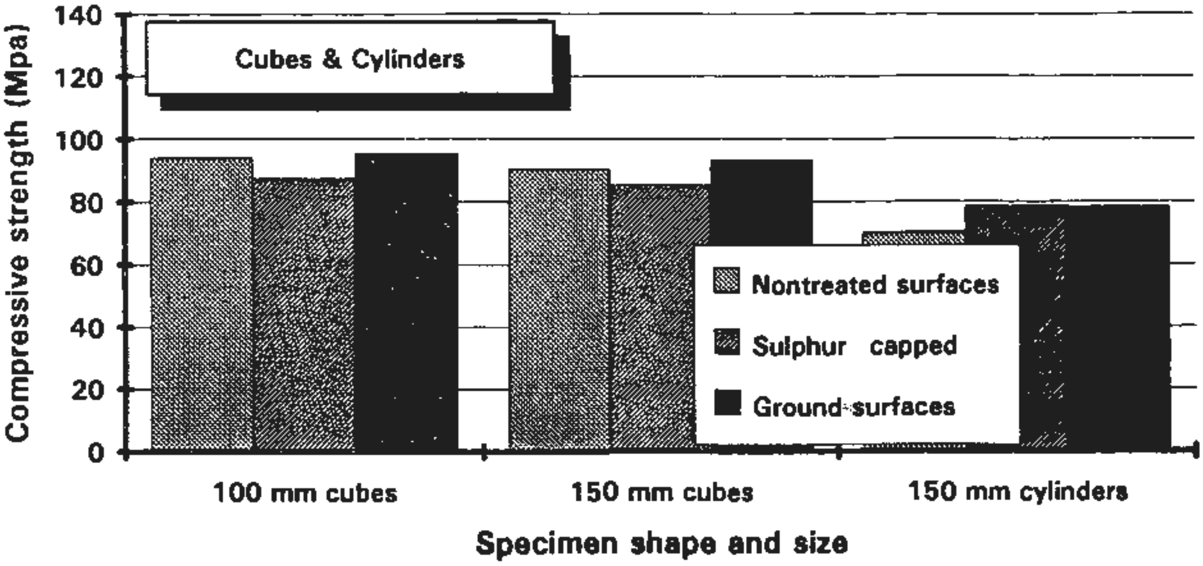

Fig. 2. Specimen capping method (A) and specimen type (C) interaction for compressive strength; the whole test data.

The relationships between the two factors can be interpreted as follows:

- With cubes, the highest compressive strengths are achieved with ground specimen surfaces, and the lowest with sulphur capped specimen surfaces.
- With cylinders, the highest compressive strengths are gained with ground or sulphur capped specimen surfaces, and the lowest with sawn specimen surfaces.

*Interaction B*C*
This interaction for the whole set of strength data is illustrated in Fig. 3.

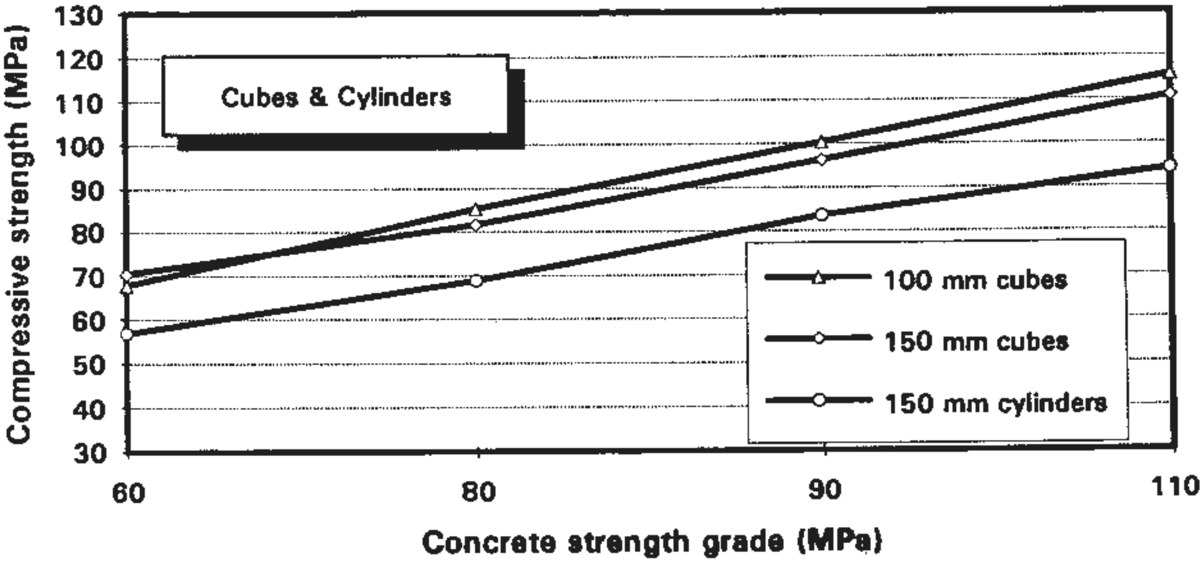

Fig. 3. Concrete strength grade (B) and specimen type (C) interaction for compressive strength; the whole test data.

It may be noted in Table 7 that for cylinders the interaction B*C is not significant, whereas for cubes the significance level is extremely high, Table 6.

Again, the interactions between the two factors are indicated by the lack of parallelism apparent in the diagram. The relationships between the two factors can be interpreted as follows:

- The lowest compressive strengths in all the concrete strength grades studied are achieved with the cylindrical specimens.
- With the strength grades 80, 90 and 110 MPa, the 100 mm cubes give higher compressive strengths than the 150 mm cubes.
- However, with the strength grade 60 MPa, the 150 mm cubes give higher compressive strengths than the 100 mm cubes.

4.4 Overall average values of variation

The present experiment was conducted in well-controlled laboratory conditions. Thus, it was not surprising to find out that the overall level of quality control was excellent, the overall average value of variation being as low as 2.0%. However, the main factors, i.e specimen surface treatment method (A), concrete strength grade (B) and specimen size and shape (C), had a distinct effect on the achieved variation levels.

For 100 mm and 150 mm cubes, the coefficient of variations shown in Table 4 can be interpreted as follows:

- When explained with factors (B) and (C), the lowest average values of coefficient of variations (0.8%) were gained with ground specimens, the second lowest (1.3%) with sulphur capped specimens, and the highest (1.9%) with nontreated specimens.
- When explained with factors (A) and (C), the lowest average values of coefficient of variations (0.5%) were achieved with 80 MPa's grade, the second lowest (0.8%) with 90 MPa's grade, the second highest (1.4%) with 110 MPa's grade, and the highest (2.7%) with 60 MPa's grade.
- When explained with factors (A) and (B), the average values of coefficient of variations for the 150 mm cubes (1.0%) were sligthly lower than those of the 100 mm cubes (1.7%).

Alternatively, for ø150·300 mm cylinders, the coefficient of variations shown in Table 4 can be interpreted as follows:

- When explained with factor (B), the lowest values of coefficient of variations (1.0%) were achieved with ground specimens, the second lowest (1.5%) with sulphur capped specimens, and the highest (7.9%) with sawn specimens.

- When explained with factor (A), the lowest values of coefficient of variations (1.9%) were gained with 90 MPa's strength grade, the second lowest (3.4%) with 110 MPa's grade, the second highest (3.9%) with 60 MPa's grade, and the highest (4.7%) with 80 MPa's grade.

From a practical point of view, it can be seen that all but one of the treatment combinations shown in Table 4 yielded compressive strength results of excellent repeatability. This one exception was the ø150·300 mm cylindrical specimens tested on sawn surfaces. Excluding this exception, the average values of coefficient of variation for 100 mm cubes (1.7%), 150 mm cubes (1.0%) and ø150·300 mm cylinders (1.3%) are approximately equal. This suggests that approximately the same number of specimesn of either type can be used to obtain the same degree of accuracy. However, if the lowest possible coefficent of variation is needed, grinding of the test specimen compression surfaces is advisable.

5. CONCLUSIONS

An extensive statistical test program was conducted in order to determine effects and possible interactions of the specimen size, shape and end conditions on the compressive strength of high-strength concrete. The main conclusions drawn from the analysis were as follows:

The *effect of specimen end condition* on the compressive strength of high-strength concrete was found to be statistically highly significant in such a way that:

With cylindrical specimens the highest average strengths were obtained with ground or sulphur capped surfaces. This effect was the same in all the strength grades studied, thus no interactions between these two factors were observed. The coefficient of variation averaged 1.0% for cylinders with ground surfaces, 1.5% for sulphur capped cylinders and 7.9% for cylinders with sawn surfaces.

Alternatively, for cubes the highest average strengths were reached with ground specimens, the second highest with nontreated specimens and the lowest with sulphur capped specimens. Differences in the strength response between the various specimen end conditions increase with increasing strength grade, thus indicating a strong interaction between these two factors. The lowest average values for coefficient of variation (0.8%) were gained with ground cubes, the second lowest (1.3%) with sulphur capped cubes and the highest (1.9%) with nontreated cubes.

The *effect of specimen size and shape* was also found to be statistically highly significant in such a way that:

The highest average strengths were obtained with 100 mm cubes, the second highest with 150 mm cubes and the lowest with ø150·300 mm cylinders. In cylindrical specimens this effect was found to be free of interactions. However, in cubes a strong interaction with concrete strength grade was observed. With the 60 MPa strength grade, the 150 mm cubes gave higher strengths than the 100 mm cubes, but with the strength grades of 80, 90 and 110 MPa, the case was the opposite. The coefficient of variation averaged 1.7% for

100 mm cubes, 1.0% for 150 mm cubes and 3.5% for ø150 mm cylinders, respectively. The overall average coefficient of variation obtained was 2.0%, indicating an excellent level of quality control.

As a ***practical conclusion,*** the statistical experiment shows that when the highest possible mean values and the lowest possible coefficent of variations are needed, grinding of the test specimen load-bearing surfaces is necessary.

However, if higher values of variation are allowed, high-strength concrete cylinders of ø150·300 mm can, **in controlled laboratory conditions**, be tested on high-quality sulphur capping compound, and high-strength concrete cubes of 100 or 150 mm on machined mould faces, respectively.

6. REFERENCES

1. Ipatti, A., A bibliography on high-strength concrete 1930-1990. Imatran Voima Oy, Concrete and Soils Laboratory. Report DLB1-G310-0119. Vantaa, April, 1991, 70p.

2. Ipatti, A., High-strength concrete - A new material for power plant construction. (In Finnish). Imatran Voima Oy, R&D-notes, IVO-B-13/91, 94p.

3. Holland, T.C., Testing high-strength concrete; A checklist of recommended practices. Concrete Construction, June 1987, pp. 534-536.

4. Rosenbaum, D.B., Higher strengths tricky to test. ENR, January 18, 1990, pp. 56-58.

5. High Strength Concrete, State of the Art Report. FIP, SR 90/1; CEB Bulletin d'Information No. 197. Published by the Fédération Internationale de la Précontraite, London, 1990. 61p.

6. Ipatti, A., Effect of size, shape and end condition of test specimen on compressive strength of high-strength concrete. Imatran Voima Oy, Research reports IVO-A-10/92. Vantaa, December 1992, 46 + 4p.

7. ACI Committee 363, Research needs for high-strength concrete. ACI Materials Journal, Nov. 1987. pp. 559-561.

8. Simons, B.P., Getting what was asked for with high-strength concrete. Concrete International. October, 1989. pp. 64-66.

9. Lessard, M., Aitcin, P.- C., Testing high performance concrete. In: High performance concrete: From material to structure. Edited by Y. Malier, E&FN Spon. London, 1992. pp. 196-213.

10. User's Manual. Statistix, Version 4.0. Edited by J. Siegel (Analytical Software, St. Paul, 1992).

11. Orr, D.M.F., Factorial experiments in concrete research. ACI Journal, October, 1972, pp. 619-624.