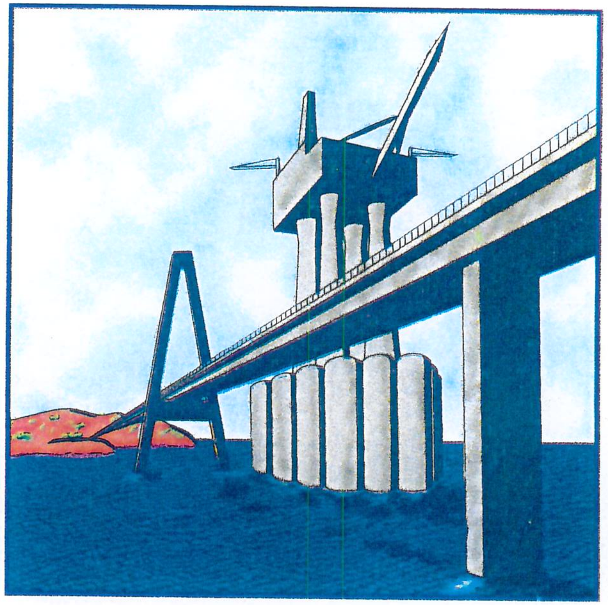
5th International Symposium on

Utilization of High Strength/ High Performance Concrete

20 - 24 June 1999
Rica Park Hotel
Sandefjord, Norway



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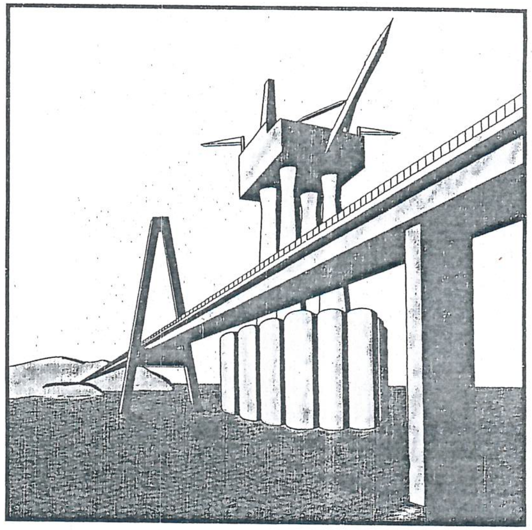

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A STATISTICAL EVALUATION OF SPECIMEN SIZE AND SHAPE EFFECTS ON COMPRESSIVE STRENGTH OF THE VHSC AND VHSFRC

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SUMMARY

In this paper the effects of specimen size and specimen shape on the compressive strength of the material are examined. Tests on cylindrical and cubic specimens of various sizes were performed. Two concrete mixes are examined, one having a maximum aggregate size of 3 mm, and the other having a maximum aggregate size of 15 mm. Both of them had in common: aggregate/binder ratio of 2, a silica fume/binder ratio of 0.2 and randomly dispersed steel micro fibers of 0, 2, 1 and 4% by volume. Eight different specimen types of moulds with four different high strength concrete compositions were considered. The compressive strengths of all specimen types and the conversion factors between them were evaluated and compared.

INTRODUCTION

In civil engineering the determination of the failure stress of the material used in the constructions is of primary importance. The experimental results that can be found in literature and referred to ordinary concrete (i.e. [1]) indicate clearly that the failure stress (apparent) of the concrete decreases with the geometric dimensions of the test sample. This is one of the aspects of the size effect, characteristic of the heterogeneous and fragile materials as concrete and rocks, effect of primary importance when it comes to the «translation» of the strength of the material determined in laboratory to the material used in the construction of structures of real dimensions. Therefore the failure strength of the material with which a real structure is composed cannot be considered that obtained from usual laboratory tests on specimens of limited dimensions. This effects have been attributed in the past to several reasons; among these the influence of the confinement due to the plates of the test machines on the strength and the failure of the specimens, the difference in temperature and humidity between the surface and the core of a sample that generate tensions and differences in the degree of maturation of the specimens [2].
The codes, giving informations regarding the dimensions of the specimens to be tested to compression in order to evaluate the failure strength of concrete, try to guarantee significant dimensions for the determination of this mechanical characteristic.
The first rational approach to the problem is due to Weibull [3] that, on a statistical basis, determined the strength of a structure in the basis of the probability of failure associated to the defect of critical dimensions. The decreasing strength with the dimensions is due to the increasing probability of the presence of these defects in the structures of big geometric dimensions. Later on, Neville [4] suggested that the size effect in the concrete could depend on

the probability of finding micro cracks having a critical orientation and dimension, probability that grows with geometric dimensions.
So, the first problem that is met, in the characterization of a material is the individuation of the optimal dimensions of the specimens for the compression tests. This is important specially in the case of very high strength concrete, because, as it can be intuited, the high strength of the material determines very high values of compressive failure loads, when the dimensions of the specimens are those used for ordinary concrete. Further on, the presses used in official laboratories for the tests on constructions materials could result non compatible conserving for very high strength concrete the typical dimensions of those used for ordinary concrete.
The problem, on the basis of results obtained in a series of experimental compressive tests on very high strength plain and fiber reinforced concrete specimens, of cubical and cylindrical shapes of different dimensions is examined. The variation of compressive strength is examined, in relation to the dimension of the specimens and of the fiber content. The work has the purpose to suggest the optimal dimensions of the specimens for the compression tests and to individuate the correlation that exists between results obtained with cubical and cylindrical specimens.

VERY HIGH STRENGTH CONCRETE, FIBER-REINFORCED AND NOT

The mechanical behavior of the materials of high and very high strength is very different from that of the normal concrete.

Typically, a normal concrete is a non homogeneous material, that evidences differences of elastic properties between the aggregates and the cement paste. Furthermore, it is characterized by a low and not perfect adhesion between the paste and the aggregate. The failure, in elements made with these materials, occur always along irregular surfaces that generally interest relevant volumes of material. Commonly, the aggregates are not involved in the failure and an enucleation of the aggregates is observed. From a macroscopic point of view this is traduced in an appreciable "ductility" of the material (Fig. 1).
The high and very high strength materials are more homogeneous. In the first place, the maximum dimension of the aggregates is diminished, in order to the reduce the probability of defects in the aggregates.

Furthermore, using aggregates of high quality and shape, their strength and the strength of the paste are similar and an optimal interfacial adhesion is obtained. In elements with these materials, the fractures that develop are more regular and interest both the paste and the aggregate, without an enucleation of the aggregate.

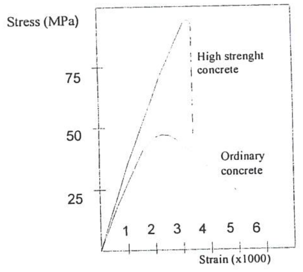

Figure 1 - Compressive constitutive law σ–ε

The macroscopic behavior of these materials results much less ductile with much more explosive and catastrophic failures. The post-critical behavior is very difficult to point out because a drastic reduction in the bearing capacity is experienced (Fig. 1).

All of these can be anyway corrected with the addition of an opportune quantity of reinforcing fibers, that, specially in presence of traction stresses, confer to the material a notable ductility and an adequate tenacity. (i.e. [5]).

MATERIALS AND TESTING EQUIPMENTS

The materials used for this study present basically two different mixes. The first, commonly defined DSP (Densified Systems containing homogeneously arranged, ultra fine Particles), was proposed by the first time by H. Bache [6]. It is about very high strength malts containing quartz sand, silica fumes and steel micro fibers. The second differs only for the type and dimension (3-6 mm) of the calcareous crushed aggregate.

Mix designs for this study were defined as shown in Table 1.

Table 1 - Mix designs, kg/m^3

	MIX 1 - Series no. 1			MIX 2 - Series no. 2	
mix reference definition	2/0%F	2/2%F	2/4%F	1/0%F	1/1%F
Portland cement CEM I 52.5 R	709	658	607	770	770
Micro silica, uncompacted	144	131	118	86	86
Natural sand (0-3 mm), silic.calcar.	-	-	-	543	512
Crushed aggregates (3-6 mm) silic.-calcar.	-	-	-	817	770
Quartz aggregates (0-3 mm)	1412	1316	1220	-	-
Acrylic superplasticizer (30% solid)	36	40	40	39	39
Steel micro fibers	0	160	320	0	78
Total water	191	177	163	215	213
Water/binder	0.225	0.225	0.225	0.25	0.25

As is well known, the main functions of the microsilica (characterized by a particle size distribution of two orders of magnitude finer that normal Portland cement) are to fill the voids and to produce secondary hydrates by pozzolanic reaction. The result was material characterized by an excellent compactness that produce a reduced porosity and improved mechanical properties.

The specimens, prepared using steel or plastic moulds and consolidated with a high frequency vibrating table, were unmoulded after 24 hours and cured in water at a temperature of 20 °C till the test (28 days).

The testing system consisted of universal testing machine Controls with a maximum capacity of 3000 kN.
The load has been applied following the standard procedures according the Italian UNI norms (UNI code 6132).

EXPERIMENTAL RESULTS

In Table 2, the mean, characteristic, and design (CEB model) cubic and cylindrical strength values and the standard deviations, determined from the tests results over sets of 12 specimens, with mix 1, for each different geometry (40, 50, 70, e 100 mm), and for each different content of fibers (0%, 2%, 4%) are reported.

Table 2 - Mean, characteristic, and design cubic and cylindrical strength values with MIX 1

Curing		7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	28days
Side (mm)	Fibers	s_{R7}	s_{R28}	R_{cm7}	R_{cm28}	V_{R7}	V_{R28}	R_{ck7}	R_{ck28}	R_{cd}
40	0%	8,81	5,28	91,50	138,33	0,10	0,04	76,43	129,30	102,8087
40	4%	3,18	20,59	124,00	144,11	0,03	0,14	118,56	108,90	74,35
50	0%	4,68	7,76	102,80	132,18	0,05	0,06	94,80	118,91	92,32
50	2%	3,67	6,28	122,00	153,73	0,03	0,04	115,72	142,99	113,35
50	4%	16,96	11,93	115,60	156,99	0,15	0,08	86,60	136,59	103,75
70	0%	0,24	16,45	102,70	136,43	0,00	0,12	102,30	108,30	76,97
70	2%	2,08	6,05	117,30	158,60	0,02	0,04	113,74	148,25	117,88
70	4%	6,43	17,00	121,40	157,96	0,05	0,11	110,40	128,89	93,55
100	0%		11,47		138,71		0.08		119,10	89,63
100	2%		11,28		156,42		0,07		137,13	104,69
100	4%		14,03		161,76		0.09		137,77	103,13
Curing		7 days	28 days	7 days	28 days	7 days	28 days	7 days	28 days	28days
Diam.	fibers	s_{R7}	s_{R28}	f_{cm7}	f_{cm28}	V_{R7}	V_{R28}	f_{ck7}	f_{ck28}	f_{cd}
ϕ 40	4%		11,63		140,63		0,08		120,74	90,89
ϕ 50	4%		18,09		135,12		0,13		104,19	72,34
ϕ 100	4%		6,41		135,84		0,05		124,88	98,29

In Table 3, the analogous parameters for the Mix 2, also referring to 12 specimens, for each different geometry, and for each different content of fibers (0%, 1%) are reported.

Table 3 - Mean, characteristic, and design cubic and cylindrical strength values with MIX 2.

Side (mm)	% fibers	R_m [MPa]	s_{R28} [MPa]	V_{R28}	R_{ck} [MPa]	R_{cd} [MPa]
40	0%	136.76	15.06	0.110	111.98	97.94
40	1%	147.78	6.34	0.043	137.34	131.43
50	0%	145.41	8.54	0.058	131.37	123.32
50	1%	145.57	3.51	0.024	139.79	136.52
70	0%	145.49	7.80	0.053	132.65	125.38
70	1%	143.01	4.28	0.029	135.96	131.98
100	0%	133.79	4.67	0.034	126.10	121.75
100	1%	135.84	6.74	0.049	124.75	118.48
Diameter (mm)	% fiber	f_m [MPa]	s_{R28} [MPa]	V_{R28}	f_{ck} [MPa]	f_{cd} [MPa]
40	0%	107.63	21.06	0.195	72.97	53.35
40	1%	100.74	13.54	0.134	78.47	65.86
70	0%	114.29	8.53	0.074	100.24	92.30
70	1%	123.22	4.86	0.039	115.22	110.69
100	0%	139.03	3.20	0.023	133.76	130.02
100	1%	130.63	1.69	0.012	127.85	126.27

In the tables, the symbols used have the following meaning:

- f_c, R_c: cylindrical strength and cubical of the concrete thought as random variables;
- $f_{c,m}$, $R_{c,m}$: medium strength found, respectively, for the cylindrical and cubical specimens;
- s_f, s_R: standard deviations read, respectively, for the cylindrical and the cubical specimens;
- V_f, V_R: coefficients of variation found, respectively, for the cylindrical and cubical specimens.

DISCUSSION

As it can be observed, from the confront of the results from the statistical analysis on the mix 1 specimens, reported in Figures 2 and 3, the mean compressive cubic strength resulted to be practically not related to the dimensions. Thus, it can be denoted that it is not necessary for these

materials to consider big sided cubic specimens to evaluate a significant mean compressive strength. All this is related to the microstructure of the material that has little aggregate's dimensions (maximum diameter 3.2 mm).
Therefore, it results in accordance to what is suggested about the minimum dimension of the specimens in relation to the maximum diameter of the aggregates used in the mixture. The experimental results evidence how the quantity of fibers, in the presence of simple compression, increments in a non significant way the strength of the material, contrary to the traction bending strength where a strength increment of 100% with a little quantity of reinforcing fibers [5] can be observed.

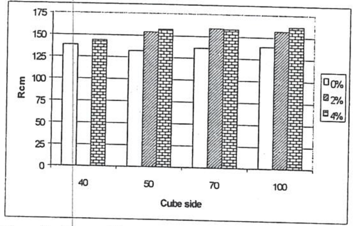

Figure 2 - Mean cubic strength MIX I

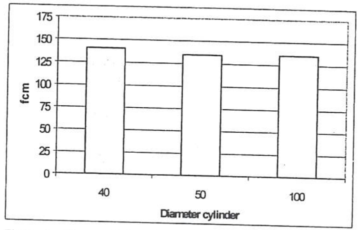

Figure 3 - Mean cylindrical strength MIX 1 (4%)

Furthermore, the statistical analysis of the tests results evidence that the standard deviation results limited in all the examined cases (figure 4).

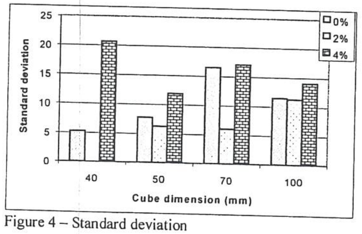

Figure 4 – Standard deviation

This is also due to the good quality of the well vibrated and very geometrically regular specimens.

Anyhow, the standard deviation tends to reduce in the fiber reinforced specimens and in the specimens of greater dimensions.
In the first case, the reason can be attributed to the higher ductility of the fiber reinforced material, thus less sensible to geometric defects.

In the second case instead, the reasons are a smaller sensibility of the specimens of bigger dimensions to the geometric defects, and also because they can be compacted better, than those of smaller dimensions.

The rupture in the material without reinforcement fibers are typically explosive contrary to the fiber reinforced materials that happens in a more gradual way that can be controlled better in a strain controlled test.
The results of the statistic analysis of the compressive tests with mix 2 specimens, reported in table 3, and illustrated in Figures 5 and 6, show the strength in function of the dimension and shape of the specimens, and of the fiber content.

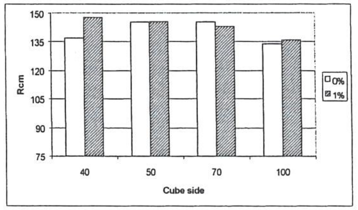

Figure 5 - Mean cubic strength MIX 2

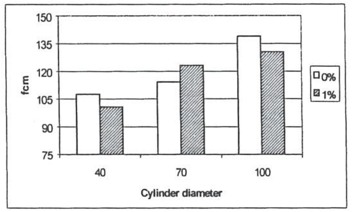

Figure 6 - Mean cylindrical strength MIX 2

The comparison of the statistical study results, confirms what has already been observed referring to the specimens with mix 1.
In particular, even in this case, the results evidence that between cubic specimens of different sizes the mean strength is almost identical (figure 5), while in the case of the cylinders (figure 6), a slight size effect leads to the growth of the strength.
The standard deviation results for all the sample types, except for those of 40 mm dimension, even smaller, that denotes a high quality guarantee. Even in this case, as it has already been esteemed for the mix 1, the presence of an adequate content of fibers generally reduces the value of the standard deviation. This fact, added to the high value of the mean strength, leads to very reduced values of the variation coefficient V_R, (it is commonly considered, for the ordinary concrete aged in situ, approximately 15%). In this specific case, except for the specimens of 40 mm dimension, not greater values than the 7 % are found (figure 7 e 8).

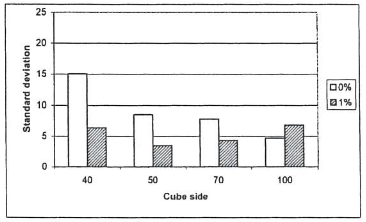

Figure 7 – Standard deviation cubes MIX 2

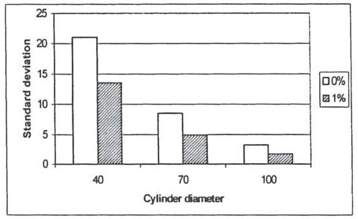

Figure 8 – Standard deviation cylinders MIX 2

Another interesting aspect is the ratio between the cylindrical and cubic strength.
The importance of such aspect is evidenced by the fact that, in many countries as United States and France, the reference strength is the cylindrical one, while in other countries, as Italy, Germany, and Belgium, the use of cubic specimens is common.

Usually, it is affirmed that the ratio between the cylindrical and cubic characteristic strength for the concrete, in function of the class, is included between 0.8 and 0.83 [7]. Tests made on materials with strength between 60 and 130 MPa [8-9] have evidenced that in this case, such ratio assumes values between 0.90 and 0.99.

Prior to the suggestion of an useful comparison that allows to esteem the shape effect, it is important to observe that the shape correlation coefficient k_c $[k_c=k_{cil/cub}=(f_c/R_c)]$ between the cylindrical and cubic compressive strength values (28 day) is function of the fractile considered strength.

Figure 9 evidences the behavior of the shape coefficient in function of k, for the cubic and cylindrical specimens, of 70 mm dimension with mix 2 and 1% fiber content, limiting k to values between –3 e 3. Usually, k assumes the values 1.645 e 2.576, respectively, for the fractile 5% and for the fractile 0.5%, and that is assumed positive for fractiles inferior to the fractile 50% (medium value).

$$\frac{f_c}{R_c}=\frac{f_{cm}-k\cdot\sigma_f}{R_{cm}-k\cdot\sigma_R}=\frac{f_{cm}}{R_{cm}}\cdot\frac{1-k\cdot V_f}{1-k\cdot V_R}.$$

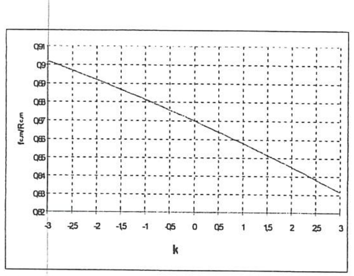

Figure 9 - The shape coefficient with variations of the considered fractile with $V_f > V_R$

Generally, for these materials such circumstance is related to the eventuality that the variation coefficient relative to cylindrical specimens (V_f) is generally higher than that relative to cubic specimens (V_R). In fact, the condition $R_{c,m}>f_{c,m}$, with, in general two very similar standard deviations values, leads to the relation $V_f>V_R$.

Otherwise, in the case in which $V_f=V_R$, the trend is constant, while in the case $V_f<V_R$ the trend is increasing.

The smallest value of the shape coefficient for the design strength has an important influence in the security measure, when, as it happens generally, the cylindrical characteristic strength is determined in relation to the shape coefficient relative to the characteristic strength (5% fractile).

Next, in Table 4, for the specimens with mix 1 and with 4% fibers, the values of the shape coefficient determined for the characteristic strength (fractile 5%) and for the design strength, determined with the CEB criteria [10-12] are reported.

Particularly significant is the ratio between the two characteristic values (5%), being that, for example, the Italian codes [13] prescribe clearly that the ratio to be taken into consideration (that is 0.83 for the ordinary concrete and 0.85 for HSC) is relative to the two characteristic strengths R_{ck} e f_{ck}.

Table 4 - Shape coefficient with 4% fiber MIX 1

diam/side	R_{cm28}	R_{ck28}	R_{cd}	f_{cm28}	f_{ck28}	f_{cd}	k_{ccm}	k_{cck}	k_{ccd}
40	144,11	108,9	74,35	140,63	120,74	90,89	0.97	1.1	1.22
50	156,99	136,59	103,75	135,12	104,19	72,34	0.86	0.76	0.69
100	161,76	137,77	103,13	135,84	124,88	98,29	0.84	0.9	0.95

In figure 10, for a better highlight, the values assumed by the shape coefficient in relation to the considered fractiles for cubic and cylindrical specimens with mix 1 and with 4% of fibers and of different dimensions (40, 50, 100mm) are reported.

In such case, as can be seen in Table 4, the correlation coefficients between the mean strengths (at 28 days) k_c are superior in all the cases to 0.84, assuming values, that in the case of specimens with dimension 40 mm, are near to one (Figure 10).

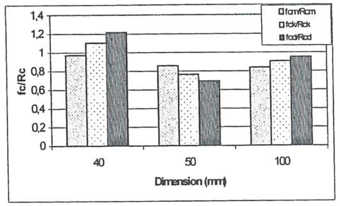

Figure 10 - Shape effect MIX1 4% fibers

The trend of the shape coefficient, tends to grow for the specimens of dimension 40 and 100 mm, and tend to decrease with the specimens of dimension 50mm. Similarly, in Table 5 and 6, and figure 11 and 12, the values assumed by the shape coefficient in relation to the fractiles considered for the cubic and cylindrical specimens of different dimensions (40, 50, 70, and 100 mm) with mix 2 and added of 0% and 1% of fiber contents have been reported.

Table 5 - Shape coefficient with 0% fiber MIX 2

diam/side	R_{cm28}	R_{ck28}	R_{cd}	f_{cm28}	f_{ck28}	f_{cd}	k_{ccm}	k_{cck}	k_{ccd}
40	136.76	111.97	97.94	107.63	72.97	53.35	0.78	0.65	0.54
70	145.49	132.65	125.38	114.29	100.25	92.3	0.78	0.75	0.73
100	133.79	126.1	121.75	139.03	133.76	130.78	1.03	1.06	1.07

Table 6 - Shape coefficient with 1% fiber MIX 2

diam/side	R_{cm28}	R_{ck28}	R_{cd}	f_{cm28}	f_{ck28}	f_{cd}	k_{ccm}	k_{cck}	k_{ccd}
40	147.77	137.34	131.43	100.74	78.47	65.86	0.68	0.57	0.50
70	143.02	135.97	131.97	123.22	115.22	110.7	0.86	0.84	0.83
100	135.85	124.75	118.48	130.63	127.85	126.28	0.96	1.02	1.06

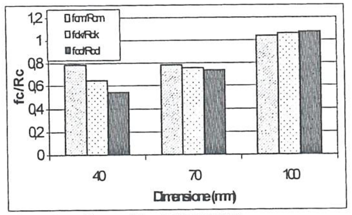

Figure 11 – Shape effect MIX2 0% fibers

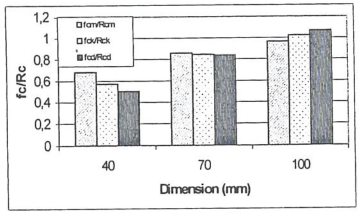

Figure 12 - Shape effect MIX2 1% fibers

In both cases, the results evidence clearly that the shape correlation coefficient is function of the fractile of the strength considered.

In particular, in the case of 100 mm specimens the variability of the shape coefficient, with the k fractile, results to be very low and at the same time values of the shape coefficient. are very high.

CONCLUSIONS

On the basis of the experimental results, it can be concluded that:

1. Regarding the considered geometry important variations of the compressive strength for the different dimensions, are not observed;
2. Regarding the fiber content, the compressive strength is lightly influenced;
3. The ratio between cylindrical and cubic strength, in the case of the 100 mm specimens results to be much higher (even greater than one) than that commonly accepted in the ordinary concrete.
4. For what concerns the safety factor, regarding the 100 mm specimens, variations of the shape coefficient k_c in relation to the strength fractile considered (50%, 5%, 0.5%) are not observed,

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