ISBN 82-91341-25-7

5th International Symposium on Utilization of High Strength/High Performance Concrete
20 - 24 June 1999, Rica Park Hotel, Sandefjord, Norway
Volume 1

Norwegian Society of Chartered Engineers

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Proceedings
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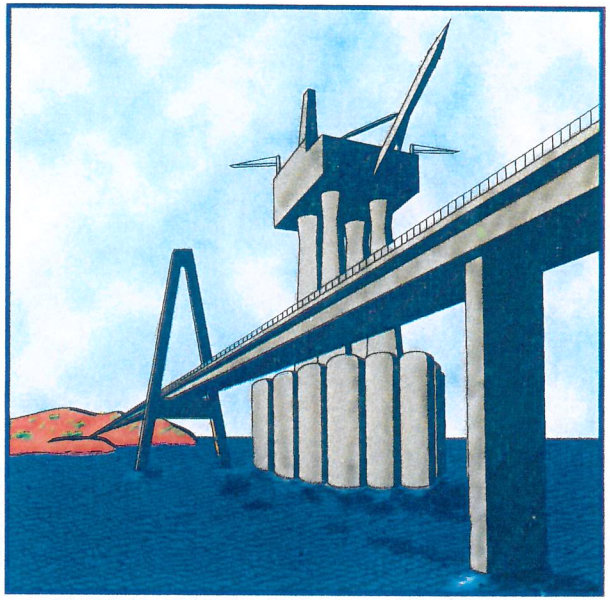

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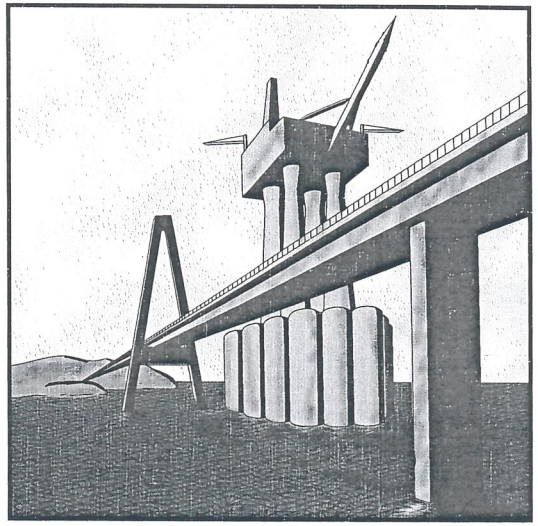

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CHARACTERISTIC COMPRESSIVE STRENGTH OF VERY HIGH STRENGTH CEMENT-BASED MATERIALS

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SUMMARY

In this paper, the result of 228 compression tests performed on very high strength cement-based material specimens are discussed. The considered material is a very high performance mortar, having a maximum aggregate size of 3 mm, an aggregate/cement ratio of 2, silica fume, an acrylic superplasticizer and randomly dispersed micro-fibers whose contents are 0, 2 and 4% by volume.
A statistical description of the compressive strength is derived and the characteristic compressive strength values as a function of the micro-fibers volume content and of other parameters have been reported.
The results obtained put in evidence that the quality level of high performance concrete (and its components) used for structural applications influence deeply the design considerations and the final performances.

INTRODUCTION

The use of a material for structural applications requires a complete knowledge of its mechanical performances. In particular, compressive and tensile strengths are fundamental properties, as well as other properties but only for particular applications (for ex., impact strength, wear and fatigue resistance). In these more recent years, it is also required that a structural material, including concrete, maintains its performances for a long time, in other words that it has a good chemical and physical durability. The concrete performances are generally correlated in a positive way, so that is recognized the improvement of a determined property as associated to the improvement of other properties/performances: for example, the increase of the concrete compressive strength is followed by an increase of the tensile strength [1-2].
In a such way, the global performance behavior can be estimated with reference to a single significant property.
In the case of normal concrete, all the norms and standards classify the material grades as a function of characteristic compressive strength (from the structural point of view), see for ex. [3-7]. Other than the quality and properties of its composition, this strength (and the more well-known characteristic compressive strength, at 28 days) assumes the significance of fundamental parameter for the behavioral characterization of concrete. However, it is important to underline that for a good durability it is necessary to have a "good" concrete with reference to its physical characteristics (low porosity, low permeability, ...).
In this work the problem of the evaluation of very high strength concrete (VHSC) characteristic compressive strength is discussed, with particular reference to the possibility of incorporation of fibers to primarily increase the tensile/bending strength. This study is also aimed to put in evidence the effects of several process parameters (curing time, specimen dimensions, types of mold) on this fundamental property.

MATERIALS AND EXPERIMENTAL EQUIPMENTS

The cement-based materials used for this investigation are very high performance mortars, obtained with:
- Portland cement (CEM I 52.5 R, with a Blaine fineness of 4590 cm2/g;
- Grey microsilica in the form of a dry, not dense powder having a surface area of 20 m^2/g (B.E.T. method);
- natural crystalline quartz sand of high purity (99% SiO2), with dimensions 0-3 mm;
- acrylic copolymer superplasticizer, 30% solid content
- carbon steel micro-fibers, length 6 mm, and diameter 0.15 mm.

All the mixtures have:
- aggregate/binder ratio 2;
- superplasticizer/cement ratio 0.02;
- water/binder ratio 0.22;
- microsilica/binder ratio 0.2;
- fiber content: 0, 2 or 4% by volume.

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 molds and consolidated with a high frequency vibrating table, were unmolded 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 6132).

CHARACTERISTIC COMPRESSIVE STRENGTH

It is known that the statistical distribution that best approximates the behavior of the random variable "concrete strength" (R) is the log-normal distribution; such distribution is used principally because it excludes from the domain of the density of distribution function the values for $r<0$: these values have not significance for the material strength. It must be observed that, when modeling the random variable R (concrete strength) with a normal distribution, it is possible to obtain $P[R<0]$ values next to zero ($<10^{-4} \div 10^{-5}$) and the error must be considered negligible. Of course, this fact depends on the value both of the strength which represents the mean μ_R and of the value assumed by the standard deviation σ_R. For what concerns the data collected for the high strength

concrete (high values of μ_R) produced with high quality production control (low values of σ_R) it can be expected that the normal distribution approximates in a very satisfactory way the density of distribution function of the random variable R [8].
Assumed that $f_R(r)$ is a normal distribution (acceptable hypothesis in this case), the aim of this study is the determination, for each set of specimens, of the mean value and the standard deviation of the distribution; this problem is solved by means of the inferential statistics.
The control of the concrete quality level is made measuring the compressive strength of a certain number of specimens (cubic or cylindrical) prepared during the construction of the structural elements. It is known that the bigger the number is taken, the better the quality of the statistical study will result [8-10]. Besides, the curing conditions expected for the specimens allow to obtain a better interpretation of the quality level with reference to what happens in the actual (in field) situation: as a matter of the fact, the structure is exposed to a series of external factors that can influence the level of quality and that is considered in the design phase by introducing the safety factor γ_C.
The reference value is not the minimum absolute value of the compressive strength, but the value called "characteristic strength" (R_{ck} for cubic specimens, f_{ck} for cylindrical ones) that has a 5.10^{-2} probability of being lowered using a statistical model which represents the frequency histogram referred to the population of measures of the compressive strength, Fig. 1.

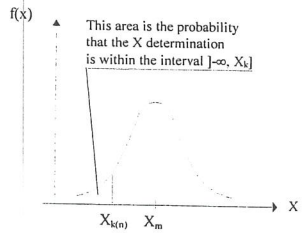

Figure 1 - Gauss density of probability

The characteristic value is obtained from the mean value by subtracting k times the standard deviation. The k value depends on the probability that is requested to the value of R_{ck} (or f_{ck}) to be lowered. In the specific case (requested probability equal to 5.10^{-2}), the k value is 1.645, in accordance with the indications given by [10]. Because of the quite limited number of specimens (12 for each set), the value of k_n (the dependence on the number of tests is evidenced by giving to the k parameter the n subscript) is equal to 1.71.

The standard deviation estimated is given by the following expression:

$$s=\sqrt{\frac{\Sigma(R_{ci}-R_{cm})^2}{n-1}},$$

where R_{ci} is the strength value measured for the i test, n is the total number of tests performed, R_{cm} the mean compressive strength. It is evident that the smaller the value of s, the closer the characteristic value will be to the mean value, thus the material offering more granted performances.
Besides, it is important to put in evidence that a "material No. 1" which has a higher value of R_{cm1} than the other "material No. 2" (R_{cm2}) is not granted to be of higher quality level. As a matter of the fact, when two materials are considered, with their corresponding first and second order moments (R_{cm1}, s_1, R_{cm2}, s_2) it can also happens that even if $R_{cm2}>R_{cm1}$ it can be $R_{ck2}<R_{ck1}$, if $s_2>s_1$. That is, although the material No. 2 presents a greater mean value than the material No. 1, it does not assure a quality level higher than the other latter (low guarantee material). Being $R_{ck}=R_{cm}-k_n.s$, in order to have $R_{ck2}>R_{ck2}$, it must be $R_{cm2}-k_n.s_2>R_{cm1}-k_n.s_1$.

Therefore, with reference to the structural reliability, the real improvement of the performance level can be obtained only increasing, for a given probability, the R_{ck} value. It is also necessary to consider the curing conditions of both test specimens and structural elements: sometimes it could be convenient to perform "pilot" tests to make a comparison between the strength of specimens cured together with the produced elements and the reference strength of specimens produced at the same time, but cured in controlled conditions (for example, 20°C, in water).

To consider the influence of external factors on the strength of the real structure – factors which can reduce the structure performances – it is possible to refer these considerations to the approach proposed by the semi-probabilistic method [5, 10, 11] to the limit states and to introduce the safety factor γ_c, which is the product of three terms, each having different meanings:
- γ_{c1} which takes into account the randomness and the errors made especially when the reinforcing steel is placed. Normally, $\gamma_{c1}=1.1$;
- γ_{c2} which considers the differences in strength existing between the in-situ concrete and the concrete tested in laboratory: $\gamma_{c2}=1.1$;
- γ_{c3} to reduce the strength from the fractile 5% to the fractile 0.5%: its value depends on the statistical distribution assumed to model the concrete as random variable.

In the case of normal distribution, the security coefficient γ_c is:

$$\gamma_c=\gamma_{c1}\cdot\gamma_{c2}\cdot\gamma_{c3}=1.1\cdot1.1\cdot\frac{1-1.645\cdot V_f}{1-2.576\cdot V_R}$$

in which the coefficients 1.645 and 2.576 are dependent on the properties of the normal distribution, V_R is the variation coefficient, for the cylindrical or cubical specimens.
After these necessary theoretical considerations, the results obtained from the experimental program made on plain and fiber-reinforced high performance cement-based materials will be analyzed.

RESULTS AND DISCUSSION

Tabs. 1 and 2 show the values calculated on the basis of statistic parameters (mean value, standard deviation, variation coefficient) for each set of 12 specimens, with reference to the statistic evaluation of experimental results of compression tests performed on cubic specimens, by varying several parameters: cube sides (40, 50, 70 and 100 mm), fiber content by volume (0, 2 and 4%), curing time (7 and 28 days) and, finally, mold material (steel, PVC, polystyrene). In particular, in Table 2 the results obtained with cubic (side: 40 mm) and cylindrical (diameter: 40 mm) specimens prepared with different types of moulds are shown. In this particular case, results are referred to a fiber content of 4% by volume.

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.

Table 1 – Compressive strengths for cubes

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

Table 2 – Cylindrical and cubic strengths as a function of different mold materials

Diameter (mm)	Fibers	f_{cs} (steel mold)	s_{cs}	f_{cpvc} (PVC mold)	s_{cpvc}	V_{cs}	V_{cpvc}
40	4%	140.25	11.63	99.29	13.87	0.083	0.14
Side (mm)	Fibers	R_{cs} (steel mold)	s_{cs}	R_{cpol} (polystyrene mold)	s_{cpol}	V_{cs}	V_{cpol}
40	4%	144.10	20.59	100.17	9.84	0.143	0.098

The comparative analysis of these results has been made in the Figures 3-10. For a direct comparison of the results obtained with the cubes, Figs. 2-4 show the influence of fiber content on the mean compressive strength, on the characteristic strength (5% fractile) and on the design strength (calculated according to the FIB-CEB model, [5]), respectively defined as R_{cm}, R_{ck} and R_{cd}.
The comparison of standard deviations are shown in Fig. 5.

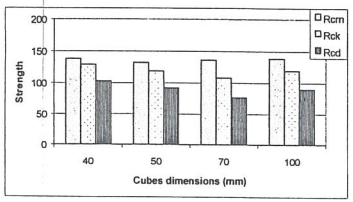

Figure 2 – Mean, characteristic and design strength for cubic specimens (0% fibers)

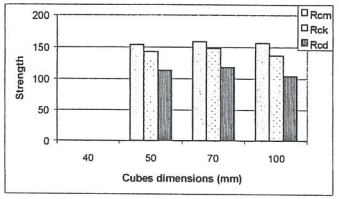

Figure 3 – Mean, characteristic and design strength for cubic specimens (2% fibers)

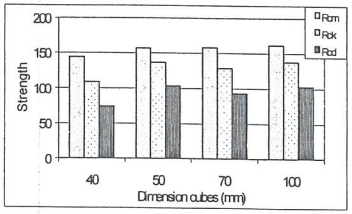

Figure 4 – Mean, characteristic and design strength for cubic specimens (4% fibers)

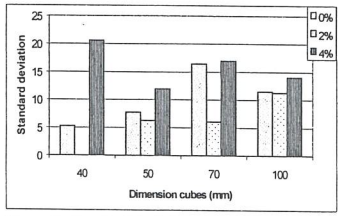

Figure 5 - Standard deviations: a comparison

The results put in evidence the remarkable fact that there are negligible dimensional effects over the mean compressive strength and there is no dependence on fiber content. Slight differences are registered for the plain and fiber-reinforced materials: that is clear passing from 0% to 2% by volume of fibers, but the fiber content increment from 2% to 4% do not determine any significant increase of the mean compressive strength. Particularly, in the case of 70 mm cubes, the mean strength for 2% fiber-reinforced material is higher than the corresponding value for 4% content. Furthermore, the results obtained with not reinforced specimens have a higher dispersion than the values corresponding to the fiber-reinforced specimens (lower standard deviations).
The presence of fibers, perhaps, determines a control in the damage process during the compression test, so the peculiar brittleness of very high strength concrete is reduced: the integrity of specimens is maintained up to the peak load, without any particular evident macro-breaks. On the contrary, in the case of plain materials, the loading process can cause the gradual ejection of splinters from the specimen, when the 70-80% of maximum load is reached, with a reduction of original specimen transverse section (section to which is conventionally referred the breaking strength), reduction quantified near to 20%.

The higher standard deviation is also influenced by the surface defects and voids existing in the specimens. It is also true that when the fiber content by volume is 4%, the greater quantity of fibers can determine a reduced homogeneity in the bulk and a consequent increase of standard deviation (observed for 70 mm and 100 mm sided specimens). Such a circumstance can make negligible the slight increase of mean compressive strength, passing from 2% to 4% of fiber content (exception for 70 mm cubes). This is very important for the characteristic strength, but also in reference to the other relevant performances offered by the material: by increasing the fiber content in the concrete, there is not any other improvement of mechanical properties other than the bending strength. In this specific study, for all the specimen dimensions, it always verified that the design strength of 4% fiber reinforced materials is lower than the design strength for 2% fiber content.
Then, the presence of fibers determines an increase of ultimate strength, together with the bending strength and finally a higher material quality (reduction of standard deviation) up to a maximum optimal content of fibers.

Figs 6-8 show the influence of curing time on compressive strength. In particular, for all the cases, the 28 days strength is 20-25% higher than the 7-days strength; besides, it is not dependent on the fiber content and on the specimen dimensions.

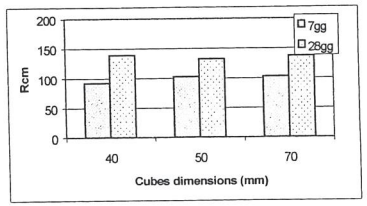

Figure 6 – Mean strength as a function of curing time (0% fibers)

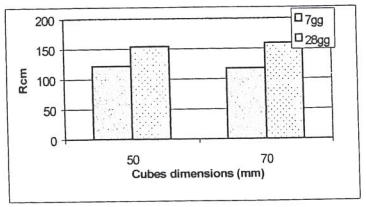

Figure 7 – Mean strength as a function of curing time (2% fibers)

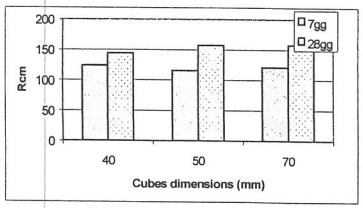

Figure 8 – Mean strength as a function of curing time (4% fibers)

Other than the considerations before, in order to have high or very high strength materials, it is absolutely necessary to make a good material compaction as it is possible to obtain specimens (or elements) free of macroscopic defects.
From this technological point of view, it is clear that the use of steel molds (instead of plastic molds) allows to obtain the best mechanical performances, Figs. 9-10: the characteristic and design strengths are deeply influenced by the types of mold used.

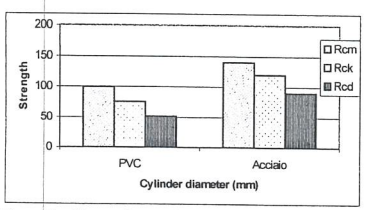

Figure 9 – Mean, characteristic and design strength as a function of mold types (0% fibers, cylindrical specimens)

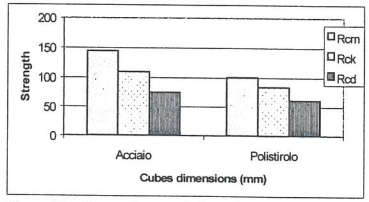

Figure 10 – Mean, characteristic and design strength as a function of mold types (0% fibers, cubic specimens)

CONCLUSIONS

The experimental results enable us to notice what follows:

1. The presence of fibers, other than determining an increase of the ultimate strength due to the confinement effect, determines an improvement of material performances in the sense of a more granted quality, but only up to a certain volume content (about 2%);
2. The standard deviations of the fiber-reinforced materials (2% and 4%) are lower than the corresponding value for the plain material;
3. The standard deviation, referred to the specimens containing 2% by volume of fibers, is lower than 7% of the mean values (variation coefficient < 7%);
4. Higher fiber contents (4%) can determine higher values of standard deviation (70 mm and 100 mm sided specimens), thus making the scarce increment of the mean strength negligible;
5. In order to obtain the best compaction of materials considered as well as the best mechanical performances, the use of steel moulds is required.

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