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PRELIMINARY PROGRAM

ON THE CORRELATION BETWEEN THE MODULUS OF ELASTICITY AND THE COMPRESSIVE STRENGTH IN VHSC

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1. INTRODUCTION

The determination of the modulus of elasticity used for the production of structural members is of crucial importance in civil engineering, both for functional (serviceability limit states – SLS) and for safety reasons (ultimate limit states – ULS). As it is well-known, the modulus of elasticity can be determined with monoaxial static tests (in compression or tension conditions for the tangential and/or secant modulus) or with non-destructive evaluations (dynamic-mechanical modulus).

The experimental results available in literature, together with the more recent standards and recommendations, both for normal and for high strength concrete [1-6] point out that the modulus of elasticity E_c is correlated with the compressive strength of concrete. The suggested relationships, defined after experimental tests, can be well-referred only to the mix design utilized, so they are purely indicative if used with different compositions.

The modulus of elasticity for concrete depends on the modulus of elasticity both of the paste and of the aggregates used, other than their proportions in the mix design [7].

The modulus of elasticity for cement paste essentially depends on its porosity and consequently on the water/binder ratio [8], but also on mineral additions (microsilica, for example) and/or on chemical admixtures (water reducers and superplasticizers) which can be present in the mix, which allow to obtain a denser matrix. If we reflect upon the correlation between the water/binder ratio and the compressive strength as well as upon the correlation between the water/binder ratio and modulus of elasticity (for the same mix design), we can understand why all the relationships proposed for the modulus of elasticity are referred to compression strength, which is much easier to determine and which any other parameter is usually referred to.

The influence of the modulus of elasticity of aggregates is very relevant on the determination of the modulus of elasticity of concrete, not necessarily on the compressive strength: some experimental tests [7] seem to demonstrate that different concretes possessing the same values of compressive strength, prepared with different types of aggregates, have very different values of modulus of elasticity.

The need of determining proposals of relationships between the modulus of elasticity and the compressive strength for high/very high strength concretes is due to the fact that in most of standards and recommendations these materials are considered as ordinary concrete (up to 60 MPa about) and the suggested correlations are not valid beyond this limit. In fact, the mechanical behaviour of these very high strength materials is very different in comparison with that of normal concrete [9-10].

An ordinary concrete is typically a non-homogeneous composite, characterized by clearly different elastic properties both of aggregates and of paste and by a weak paste-aggregate interfacial zone. Cracks inside this material propagate along non-regular surfaces involving relevant volumes of material. Aggregates are not involved in this fracture mechanism and their enucleation from the matrix is observed. From a macroscopic point of view, the ductility of ordinary concrete is referred to this mechanism (Fig. 1, curve a). The introduction of mineral additions (normally silica fume) and of a superplasticizer allow to reduce the water/binder ratio and obtain consequently a more homogeneous material (High/Very High Strength Concrete – HSC/VHSC). The consequent effect is that relevant stresses are transmitted also to the aggregates, so the crack propagation involve the aggregates too. In this case, the stress-deformation curve is typically more brittle, with an increase of slope and the post-peak behaviour is observed with difficulty (Fig. 1, curve c - VHSC). On the contrary, the initial part of the same curve is more linear. The shape of the stress-strain curves is closely related to the nature of concrete components, especially of the aggregates [7]: several studies have shown that high strength concretes of equal strength but prepared with different aggregates can have significantly different moduli of elasticity [11-12].

In the following paragraph, the most recent correlations between strength and modulus of elasticity, included in national standards or proposed in literature, will be mentioned. After, there will be described the results obtained by compressive tests, made on cylindrical specimens (height/diameter = 2) of very high strength concrete, also fiber-reinforced – which have been previously interested by a load-unload history (30% of the failure load) – which permitted to determine the beginning of the ascending branch of the stress-strain curve and having, from this, the elastic modulus.

Finally, the correlation between the measured compressive strength and the estimation of elastic modulus is discussed, and the comparison with expressions from the literature and from the national and international codes analysed.

2. PROPOSED CORRELATIONS BETWEEN MODULUS AND COMPRESSIVE STRENGTH

2.1. MODELS SUGGESTED IN STANDARDS AND NORMS

2.1.1. MC 90 C.E.B. F.I.P. [1]

The following correlation is proposed for the modulus of elasticity at 28 days of curing, for concrete classes not exceeding the 100 MPa: $E_{ci} = E_{c0}\left[\left(f_{ck} + \Delta f\right) / f_{cm0}\right]^{0.3}$, where E_{ci} = modulus at 28 days, f_{ck} = characteristic cylindrical compression strength, $\Delta f = 8$ MPa, $f_{cm0} = 10$ MPa, $E_{c0} = 22$ MPa. When concrete strength is more than 50 MPa, the C.E.B. suggests an alternative expression, similar to (1): $E_{ci} = E_{c0}\left[\left(f_{ck} / f_{cm0}\right)\right]^{0.3}$.

2.1.2. A.C.I. 363 [3]

The following correlation is proposed by the American Concrete Institute, valid for concrete strength up to 83 MPa: $E_c = 3320\sqrt{f_c^{'}} + 6900$, where $f_c^{'}$ = mean cylindrical compression strength.

2.1.3. NS 3473-1992 (Norwegian Standard) [6]

In this standard is suggested this correlation, valid for concrete strength up to 94 MPa: $E_c = 9500(f_{cc})^{0.3}(\rho / 2400)^{1.5}$, where f_{cc} = cylindrical compression strength, r = concrete density. This expression is also valid for concrete containing lightweight aggregates (LWA).

2.1.4. Dutch Norms [6]

The following proposed correlation is valid for concrete cubic strength up to 105 MPa: $E_c = 35900 + 40 f_{cck}$, where f_{cck} = mean cubic compression strength (150 mm sided cube).

2.1.5. Italian Norms [13, 14]

Italian norms allows the use of concrete having a characteristic cubic compressive strength up to $R_{ck} = 55$ MPa, but it is possible to use the same correlation up to 75 MPa, after approval of the committee called "Consiglio Superiore dei Lavori Pubblici" – Ministry of Public Works [14]. It is allowable also to use the two C.E.B. correlations, for f_{ck} up to 80 MPa. For the modulus of elasticity, the two following correlations are valid: $E_c = 5700\sqrt{R_{ck}}$ N/mm^2 (standard curing - UNI 6556-1976) and $E_c = 5100\sqrt{R_{ck}}$ N/mm^2 (steam cured).

2.1.6. Other Norms

Other norms (German and EC-2, ENV206, for ex.) do not provide correlations but the direct values of modulus of elasticity, as a function of compressive strength (concrete grades):

Table 1: *E_{cm} in German norms – DIN 1045 - Updated 1995* –[15]

Concrete Grades	B 65	B 75	B 85	B 95	B 105	B 115
Ecm (GPa)	40.5	42	43	44	44.5	45

Table 2: *EC-2 Eurocode (ENV 206)* [4]

Concrete Grades	C12 C15	C16 C20	C20 C25	C25 C30	C30 C35	C35 C40	C40 C50	C45 C55	C50 C60
Ecm (GPa)	26	27,5	29	30,5	32	33.5	35	36	37

2.1.7. General comments

The above-mentioned correlations are referred to both cubic and cylindrical strength (mean or characteristic values).

These differences provoke further discrepancies among the different obtained values, for the difficulty to estimate the correlation factor k_{cc} (cylindrical/cubic ratio). In fact, in many countries (Germany, Italy, Belgium, for example) is accepted the cubic strength, in other countries (U.S.A., Canada, France) the cylindrical strength. The kcc values are not unique, but ranges from 0.8-0.83 (ordinary concrete) to 0.9 and more (high strength concrete). Recent experimental works seem to indicate values close to 1 for very high strength concrete (more than 100 MPa)

[16]. The above-mentioned correlations are shown in Figure 2: the discrepancies among the curves are clear (curves adapted to the characteristic cylindrical strength f_{ck}, according to the specific recommendations of each standards).

In particular, Figure 2 shows that the Italian and the French correlations overestimate the modulus even for medium strength concrete, with increasing difference when considering high strength concrete.

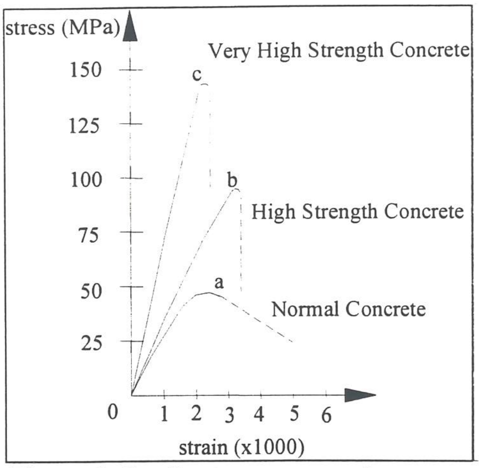

Figure 1. *Qualitative stress-strain curves for normal and high strength concrete*

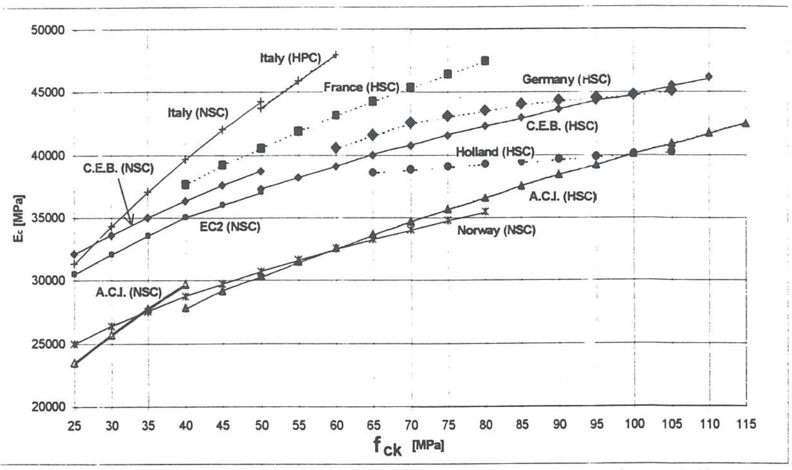

Figure 2. *A comparison among the different correlations proposed*

2.2. MODELS SUGGESTED IN LITERATURE FOR HPC

The differences between the results obtained from the models proposed in standards and codes can be easely explained with the influence of nature of the coarse aggregate on the elastic properties of HPC [11]. This can be attributed to the highly dense hydrated cement phase and the very strong bond between cement paste and aggregate, that allow to obtain a very homogeneous composite material, similar to the natural rocks. Other than aggregate characteristics, the water/binder ratio is very important too.

Researchers have tried to proposed mathematical models considering the respective moduli of elasticity of each component of concrete (considered as two-phase material, composed of mortar and coarse aggregate) and the corresponding fractional volumes. Baalbaki et al. [17] have reported and evaluated these models, considering a series of concrete having a cylindrical compressive strength of about 100 MPa, and moduli of elasticity ranging from 24 to 42 GPa. The two-component relationships were compared with the ACI 363, MC 90 (CEB) and NS correlations.

Main conclusions of this study are that in the case of HPC modulus of elasticity cannot always be predicted using the existing mathematical models, as a function of compressive strength. According to the authors, the best and the most reliable way to define this value remains the direct measurement. An evaluation of correlations proposed by ACI, NS and MC, as well as of mathematical models, provides estimates with less than 20 percent difference.

It seems clear that is necessary to introduce in the relationships a parameter which takes in direct consideration the type of aggregate used in HPC.

Gutierrez et al. [7] have recently presented an extended experimental work, after which three correlations were finally proposed, with reference to some models proposed in above-cited standards (M. C. 90 and C.E.B.-F.I.P., ACI 363) and in other norms (BS 8110). The formulae proposed in these international codes and standards models are quite different: proportional to the cube root of strength (MC 90) or to the square root (ACI), or linear (BS).

In this study, regressions of the square root, cube root and the straight line versions were evaluated: after imposition of passing through the origin (which would be more strictly correct), the only expression which ensure a good correlation coefficient was the formula of the cube root.

The correlation was related to the modulus of elasticity of aggregates and the following formula was finally proposed: $E_c = 0.85 \cdot \alpha_E \left[(f_{ck} + \Delta f)/f_{cm0}\right]^{1/3} \cdot \alpha_\beta$, where: E_c is the modulus at 28 days (MPa), f_{ck} is the characteristic cylindrical strength, Δf=8 MPa, f_{cm0}=10 MPa, α_E=2.15 · 10^4 MPa. α_β is a parameter that varies from 0.7 to 1.2, according to the aggregate type (basalt, limestone, quartzite, sandstone) [7].

The previous expression presents a better correlation coefficient if mean strength f_{cm} is used instead of characteristic strength, for concrete strength lower than 80 MPa.

The authors stated that the minimum compressive strength for aggregates used for HPC is 100 MPa.

The values proposed for α_β are reasonably conservative, so the real modulus in general would be greater than those calculated with this correlation.

Finally the following formula resumes the proposed model: $E_c = \alpha_\beta 8480\sqrt[3]{f_{cm}}$ (*).

It is important to remark that according to this model, concrete with 100 MPa of strength produced with diabase aggregate will have a modulus of 58 GPa, produced with sandstone aggregates will have a modulus of 23 GPa [7].

According to the proposal, in those applications where the modulus of elasticity need not to be determined precisely, a value of $\alpha_\beta=1$ can be assumed, but errors could occur. In the other hand, in projects where the deformability of structure is relevant, the choice of aggregates for preparing concrete is very important. Particularly, when the deformability is in excess and can bring to reach the ultimate limit state (ULS), this choice becomes primary and essential. In these cases, may be important to refer to a characteristic value of modulus of elasticity (above all, when is derived from a correlation containing the mean compressive strength). To solve the problems of deformability control, the following path can be followed: evaluation of E_c for the desired strength, then calculation of α_β from (*), finally definition of the more appropriate types of aggregates, using the following equation: $\alpha_\beta = 0.1485\sqrt{E_a}$, where E_a is the modulus of elasticity for the aggregate to be chosen [7].

Other proposed correlations are cited in [18].

2.3. MODELS SUGGESTED FOR FIBER-REINFORCED CONCRETE

Experimental studies performed for the evaluation of modulus of elasticity of fiber-reinforced concrete are based on the Voight model, expressed as follows: $E_c = E_f V_f + E_m(1-V_f)$, where E_c, E_f and E_m are respectively the modulus of elasticity of the fiber-reinforced concrete, of the fibers and of the matrix; Vf is the percent volume content of fibers [19].

Fibers inside the concrete (considered as matrix) are randomly dispersed, then it is necessary to introduce a correction factor η_0 to take account of reinforcement efficiency and fiber length: $E_c = \eta_0 \cdot E_f V_f + E_m(1-V_f)$ [19]. More advanced models developed for fiber reinforced composites include, in addition, the properties of the interface between the two materials, whether the fibers are discontinuous or not, the distribution and orientation of the fibers, the aspect ratio (length to diameter) of the fiber, and the like.

In general, it was observed that the effect of adding fibers is small, with reference to the resulting stiffness of composite, even when the volume content of added fibers is high [18].

3. MATERIALS

3.1 MATERIALS, MIX DESIGNS AND SPECIMENS

Mix designs for this study were defined as shown in Table 3.

Cylindrical specimens of diameter=100 mm and height=200 mm were prepared in steel moulds and water cured at 20°C until 28 days.

3.2 TESTING EQUIPMENTS

A standard oleodynamic testing machine (Galdabini – 3000 kN) was used for the tests. The modulus of elasticity was determined by applying three axial inductive extensometers (gage length 50 mm) at 120° and using a data acquisition system (UPM 60). In each test, three loading cycles to 30% of the compressive strength of concrete were applied to the specimens and the initial stress-strain curve was derived, for calculation of the modulus of elasticity.

Table 3. *Mix designs, kg/m³*

	Series no. 1		Series no. 2		
mix *reference definition*	**1/0F**	**1/1F**	**2/0F**	**2/2F**	**2/4F**
Portland cement CEM I 52.5 R	770	770	709	658	607
Microsilica, uncompacted	86	86	144	131	118
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)	39	39	36	40	40
Steel microfibers	0	78	0	160	320
Total water	215	213	191	177	163
Water/binder	0.25	0.25	0.225	0.225	0.225

4. RESULTS AND DISCUSSION

Experimental results obtained from the mix series no. 1 and 2 are summarized in Tabs. 4 and 5 (unreinforced concrete) and in Table 6 (fiber-reinforced concrete). Values of modulus for series no. 1 (siliceous-calcareous aggregates) are lower than the value of modulus obtained from the series no. 2 (quartz aggregates), even if the strength values are higher (135 MPa instead of 110-120 MPa). Besides, as expected, there is not a strong influence of fibers on the values of modulus. It is clear that any attempt to apply any correlation proposed before could lead to different results. If these results, transformed into characteristic values, are singularly referred to the correlations proposed by the norms, the values of series no. 1 appear to have a good correspondence with the Norwegian norm and are overestimated with the ACI (HSC) norm correlation. The values of series no. 2 appear to have a very good correspondence with the CEB and DIN (Germany) norm correlations.

On the contrary, using the correlation proposed by Gutierrez [7], which takes into account the quality of the aggregates quality (through the α_β coefficient), it is possible to calculate from f_{cm} the corresponding E_c values with excellent accuracy, so that the differences between experimental and calculated values are almost negligible (Table 6). In the case of series no. 2 (quartz aggregates), it was assumed $\alpha_\beta = 1.15$ as suggested, whereas for the series no. 1 values of 0.91, 0.94 and 1 (suggested if E value is unknown) were assumed and in any case the differences are not higher than 10%. It is demonstrated the influence of coarse aggregates quality on the calculations.

Finally, the values of modulus of fiber-reinforced concrete evaluated with the Voight's models are shown in Table 7. The modified Voight's model seems to be more accurate than the simple model.

Table 4. *Series no. 1*

	1/0F		1/1F	
No.	Rc (MPa)	Ec (MPa)	Rc (MPa)	Ec (MPa)
100 a	132.4	41593	131	39161.7
100 b	137.3	39916	132.6	39212.2
100 c	136.4	41905	128.5	38223
100 d	132.8	40966	135.8	38882
100 e	-	-	139.1	41659
100 f	-	-	142.2	40696
100 g	-	-	135.8	37741
Mean values	**135**	**41095**	**135**	**39368**

Table 5. *Series no. 2*

	2/0F		2/2F		2/4F	
No.	Rc (MPa)	Ec (MPa)	Rc (MPa)	Ec (MPa)	Rc (MPa)	Ec (MPa)
100 a	109	44875	72	48099	114	44743
100 b	114	44071	136	47389	127	44563
100 c	99	46362	121	45242	121	45874
100 d	114	46416	123	44846	117	44775
Mean values	**109**	**45431**	**113**	**46394**	**120**	**44989**

Table 6. *E_{cm} values using Gutierrez's relationship*

Mix	**f_{cm} (MPa)**	**E_{cm} experim. (MPa)**	**E_{cm} calculated (MPa) (α_β)**	**ΔE, %**
1/0F	135	41095	39588 (0.91) 40891 (0.94) 43502 (1)	-3.7 -0.5 +5.8
1/1F	135	39368	39588 (0.91) 40891 (0.94) 43502 (1)	-0.4 +3.8 +10.4
2/0F	109	45431	46517	+2.4
2/2F	113	46394	47102	+1.5
2/4F	120	44989	48077	+6.8

Table 7. *Fiber-reinforced concrete*

Mix	**Ecm calculated**	**Ec, Voight's model**	**Ec, Voight's model modified**
1/1F	39368	42634	41474
2/2F	46394	48422	46102
2/4F	44989	51414	46773

5. CONCLUSIONS

On the basis of tests executed it can be derived that:

- there are many correlations between modulus of elasticity and compressive strength, proposed in standards, recommendations and in literature: these differences are evident, even if the range of high/very high strength concrete is considered;
- even the modulus for high/very high strength concrete is strongly depentent on the nature of (coarse) aggregates;
- the best reproducibility was obtained not using a correlation proposed by norms, but using the correlation proposed by Gutierrez, which takes into account the aggregates quality;
- fibers do not influence the values of modulus even when relatively high contents by volume are used;
- further experimental work is needed to confirm this results.

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SUMMARY

In this paper the problem of the evaluation of the modulus of elasticity for high and ultra high strength concrete (with and without fibers) is discussed. Different equations for the correlation between the compressive strength and the tangent elastic modulus at the origin, proposed by various national and international codes and by the literature are analyzed and a comparison between the various proposals is also shown. Subsequently, the experimental results for modulus obtained by compressive tests performed on cylindrical specimens 100x200 mm of very high strength concrete, also fiber reinforced, are reported. Finally, the correlations between the measured compressive strength and the modulus of elasticity are discussed with reference to the tests.

The results seem to demonstrate that is impossible to evaluate the modulus of very high strength concrete from the measured values of strength, as it is strongly dependent on the nature of coarse aggregates.

ZUSAMMENFASSUNG

In dieser Arbeit wird das Bewertungsproblem des Elastizitätsmoduls von hochfestem und ultrahochfestem Beton besprochen. Es werden hier diverse Korrelations-Gleichungen zwischen der Druckfestigkeit und dem ursprünglichen Schubelastizitätsmodul analysiert, welche durch verschiedene nationale und internationale Code sowie durch die Literatur vorgeschlagen werden, und es wird ihre Gegenüberstellung aufgezeigt. Es werden dann die experimentellen Resultate der erzielten Elastizitätsmodule auf zylindrischen Prüfstücken von 100x200 mm aus hochfestem und ultrahochfestem, auch faserverstärktem Beton vorgetragen. Und schliesslich werden die Korrelationen zwischen der Druckfestigkeit und dem Elastizitätsmodul unter Bezugnahme auf die durchgeführten Prüfungen besprochen.

Die Resultate scheinen zu beweisen, dass es nicht möglich ist, das Elastizitätsmodul von ultrahochfestem Beton aus den gemessenen Festigkeitswerten zu bewerten, da dieses in hohen Grade von der Natur des groben Zuschlags abhängig ist.

RÉSUMÉ

Ce document traite le problème de l'évaluation du module élastique de bétons à haute et très haute résistance. Il analyse et ensuite compare différentes équations de corrélation entre la résistance à la compression et le module d'élasticité tangent à l'origine proposées par des codes nationaux et internationaux ainsi que par la littérature. Ce document reporte également les résultats expérimentaux de module élastique obtenus sur des éprouvettes cylindriques 100x200 mm de bétons à haute et très haute résistance, même fibro-renforcés. Les corrélations entre la résistance à la compression et le module d'élasticité sont enfin discutées par rapport aux essais effectués.

Les résultats semblent montrer qu'il n'est pas possible d'évaluer le module élastique de bétons à très haute résistance à partir des valeurs de résistance mesurées car ce module dépend fortement de la nature du granulat gros.

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