Cement & Concrete Composites 24 (2002) 263–267

Cement & Concrete Composites

www.elsevier.com/locate/cemconcomp

Differences in instantaneous deformability of HS/HPC according to the kind of coarse aggregate

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Abstract

In the analysis of concrete structures the knowledge of real values of modulus of elasticity is of great importance, particularly at displacements or losses of prestressing consideration. For two-dimensional problems the Poisson's ratio is important too. Recommendations from the Standards can inform us roughly about these values but usually in the range of classes of ordinary concrete only. In general, greater the strength of concrete greater the differences in modules of elasticity for similar classes of concrete are. In the first row material factors have to be taken into consideration. To explain the range of variations the results of tests for high-strength/high-performance concrete manufactured with different components, particularly various kinds of coarse aggregates are presented. These results are compared with some other tests and with basic recommendations.

Keywords: Coarse aggregates; Concrete deformations; High-strength/High-performance concrete; Modulus of elasticity; Poisson's ratio

1. Introduction

The significant development of high-performance concrete manufacturing and application, which occurred in the last decade in many countries, caused new problems in structural design. In the analysis of serviceability limit states, and also in some cases of ultimate limit states, the proper estimation of mechanical properties of materials has to be done in design process.

Apart from special structures, usually prototypes in certain areas, designers are not aware what particular components would be used in the structure designed and, consequently, they have to take values from the codes or other general recommendations. Even in the range of ordinary concrete the international codes or the national standards recommends values or expressions leading to relatively large differences in such basic properties, like modulus of elasticity, E_c, or Poisson's ratio, ν_c.

Most of the present tests of HS/HPC show that many factors influencing these properties should be taken into account. This is because the greater number of components must be used, and some of them are influencing each other. On the other side, the components may have significantly different properties from country to country, sometimes from region to region. It must be considered for manufactured components, like cements or admixtures, as well as for natural components, like fine or coarse aggregates.

2. Background information

2.1. Modulus of elasticity

Since most international codes and national standards express the modulus of elasticity as a function of compressive strength these formulas may be more or less correct for the certain range of mixes and specific methods of testing only. Such a situation known from ordinary concrete is much more complex for high-performance concrete because additional factors influence mechanical properties of hardened concrete.

Taking into account the basic equations from update international recommendations one may see the variety of expressions; to compare some of them the unified units are introduced (modulus E_c in GPa, and compressive strength f_c in MPa):

- Eurocode 2 [1]: $E_c = 9.5(f_{ck} + 8)^{1/3}$,
- CEB-FIP MC90 [2]: $E_c = 10(f_{ck} + 8)^{1/3}$,

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0958-9465/02/$ - see front matter
PII: S0958-9465(01)00013-0

- ACI 318-99 [3] – general: $E_c = 4.73\sqrt{f'_c}$ for normal density concrete, and more detailed as affected by concrete density: $E_c = 0.043\sqrt{f'_c \times \rho_c^3}$ (for density range $\rho_c = 2300$–2500 kg/m^3),
- ACI 363-92 [4]: $E_c = 3.32\sqrt{f'_c} + 6.9$ (for concrete up to 83 MPa).

These expressions were compared many times to each other and with test results by many authors, e.g. [5–8]. On the basis of these comparisons different corrections were proposed, but still the expressions as a function of compressive strength were proposed.

From the analysis of many series of concrete tested in various research centres it was stated that modulus of elasticity of high-performance concrete should be considered mainly in aspects of the three following groups of factors:

- kinds and amounts of chemical admixtures and mineral additives of cementitious materials,
- shapes, sizes, curing regimes and method of testing of specimens,
- kind and amount of course aggregate.

Unfortunately, test results from different laboratories are not quite comparable. The methods and conditions of testing were not the same, and variables were assumed from more than one group mentioned above.

In the tests presented in this paper the influence of coarse aggregates was mainly considered, while other factors were assumed similar for all groups of series of concrete specimens.

In testing the modulus of elasticity there are also different rules in use. Commonly used values of secant modulus of elasticity are taken from various ranges of stresses in measured stress–strain relation. The widest range was assumed in ACI 318 recommendations, with a stress from zero to a compressive stress $0.45f'_c$. Most of the European standards based on the RILEM recommendations (1972) where the range was assumed from a stress 0.5 MPa to $0.33f_{cm}$. The results of the differences may be significant for normal-strength concrete (NSC) (with more curved stress–strain diagrams) while for HPC the influence of range of stresses may be usually neglected, as the diagrams are more linear.

All results of tests presented in this paper refer to the range of 0.5 MPa to $0.33f_{cm}$.

2.2. Poisson's ratio

Recommendations for Poisson's ratio in the recent codes are either neglected at all (ACI 318) or given in the form of approximate range of possible values. Two parallel documents published by CEB-FIP gave significantly different values: CEB-FIP MC90 [2] recommended the general range of ν_c from 0.1 to 0.2, while FIP/CEB report for high-strength concrete [9] proposed the range 0.18–0.24. The simplest approach presents Eurocode 2 [1], recommending similarly like many national standards $\nu_c = 0.2$ as the only value for concrete.

The experimental basis for Poisson's ratio is much smaller than for modulus of elasticity; these tests were usually recognized as being of second rank [10].

3. Experimental program

3.1. Mix proportions

The tests on influence of the kind of coarse aggregate on basic mechanical properties of concrete modulus of elasticity and *Poisson's* ratio were divided into two steps.

In the first step of investigation there were two groups of serial tests undertaken – series of specimens of high-strength concrete with predicted 28-days compressive strength 80 MPa, and for comparison series of NSC about 40 MPa. In each series there were 6 specimens tested after 28 days.

The following constituent materials were used in the series:

- *coarse aggregate*: three most common in Europe kinds of aggregates used for HPC were used: basalt (B), granite (G), and natural rounded gravel (O) quartzitic in majority; the same aggregates were used in comparable series of NSC;
- *fine aggregate*: river quartz sand, additionally washed;
- *cement*: commercially available Portland cement without additives CEM-I-42.5 was used in HPC and CEM-I-32.5 in NSC (former notation of cements CP45 and CP35 respectively);
- *additive*: silica fume (SF) commercially available in Poland;
- *admixture*: superplastisizer (SP) – sulfonated polymers-based, Rheobuild-2000.

The mix proportions for these series of concrete are presented in Table 1.

In the second step similar tests were done using specimens produced in the laboratory during almost 2 years, as accompanying specimens at production of concrete elements for other experimental tests. All these concretes were produced with use of the same materials but mix recipes were somewhat different, according to required mean compressive strength of concrete in the range from 35 to 100 MPa. There were 9 series of concrete with basalt, 9 series with granite and 5 series with natural rounded gravel. Similarly to the series from the first step of tests there were 6 specimens in each series tested after 28 days (with tolerance +1 day in some cases).

Table 1
Mix proportions for specimens of HPC and ordinary concrete, in (kg/m^3)

Mix sign	Kind of coarse aggregate	Portland cement		Water	Sand	Coarse aggregate		SF	SP	Density
		I-32.5	I-42.5		0–2	2–8	8–16			
B_1	Basalt	–	500	123	565	444	1008	50	15	2705
G_1	Granite	–	500	123	491	325	989	50	15	2493
O_1	Nat. gravel	–	500	123	180	1081	540	50	15	2489
B_2	Basalt	324	–	167	483	820	820	–	–	2614
G_2	Granite	324	–	167	483	714	734	–	–	2422
O_2	Nat. gravel	324	–	167	193	1158	579	–	–	2421

3.2. Test specimens

All specimens were cylindrical Ø150 × 300 mm, cast in plastic moulds and compacted in the same manner using poker vibrator. Specimens were cured under the same regime: after 1 day removed from the moulds, next 6 days were moist-cured under polyethylene sheet. Then air-dried up to testing at $60 \pm 5\%$ RH at controlled temperature $20 \pm 2°C$.

3.3. Instrumentation

The specimens were loaded using 3000 kN hydraulic testing machine equipped in control of a rate of stroke. The computer for data acquisition was used to collect strains for selected levels of load. The speed of stresses increment was controlled and assumed as about 0.3 MPa/s.

Longitudinal and transverse strains were measured using electrical resistance strain gauges 75 mm long, mounted at the midheight of the specimens. Two longitudinal and two transverse gauges were glued on the opposite sides of each cylindrical specimen.

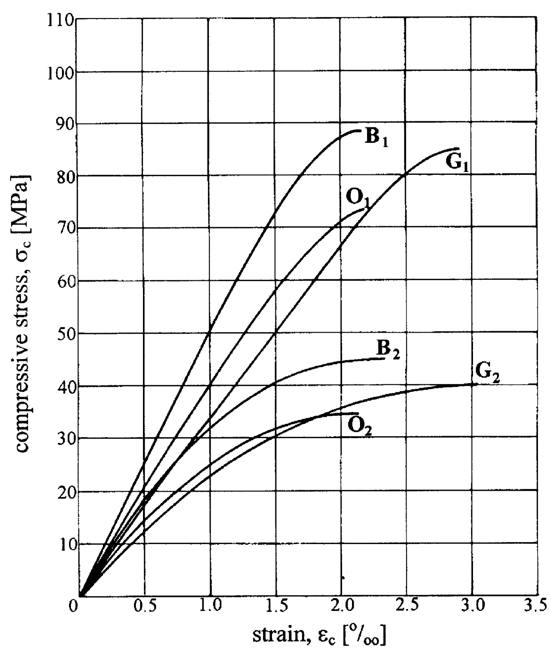

Fig. 1. Comparison of characteristics' $\sigma_c - \varepsilon_c$ for concretes described in Table 1; tests after 28 days.

4. Test results and discussion

4.1. Characteristics $\sigma_c - \epsilon_c$

The main aim of tests was determination of modulus of elasticity, E_c, and Poisson's ratio, v_c. Therefore, data from measurements were recorded for the rising part of $\sigma_c - \varepsilon_c$ diagrams only.

For the first group of concretes (presented in Table 1) the diagrams are presented in Fig. 1. Each diagram was built on the basis of six measured individual characteristics, as a mean one for the series of specimens.

Although these two groups of concrete mixes B_1, G_1, O_1 and B_2, G_2, O_2 were proportioned to obtain the same strengths, the differences in characteristics were visible in all basic properties. Particularly significant are differences in modules of elasticity, and in strains, ε_{c1}, corresponding with the peak point of diagram (ε_{c1} is not the ultimate strain).

Another set of results was recorded in the second step of testing. Various concrete mixes, designed for different compressive strengths, were produced with use of exactly the same three kinds of coarse aggregates as in the first step. The diagrams presented in Fig. 2 separately for different aggregates may be compared with corresponding groups in Fig. 1.

It is visible that the values of strains, ε_{c1}, corresponding with the highest point of stress–strain diagrams, are very similar in concrete with the same coarse aggregate, almost irrespective of the compressive strengths. Significantly greater are the values for granite aggregate (ε_{c1} over 3.0×10^{-3}) than for basalt (about 2.3×10^{-3}) or for natural rounded gravel (about 2.2×10^{-3}). The results showed once more that the

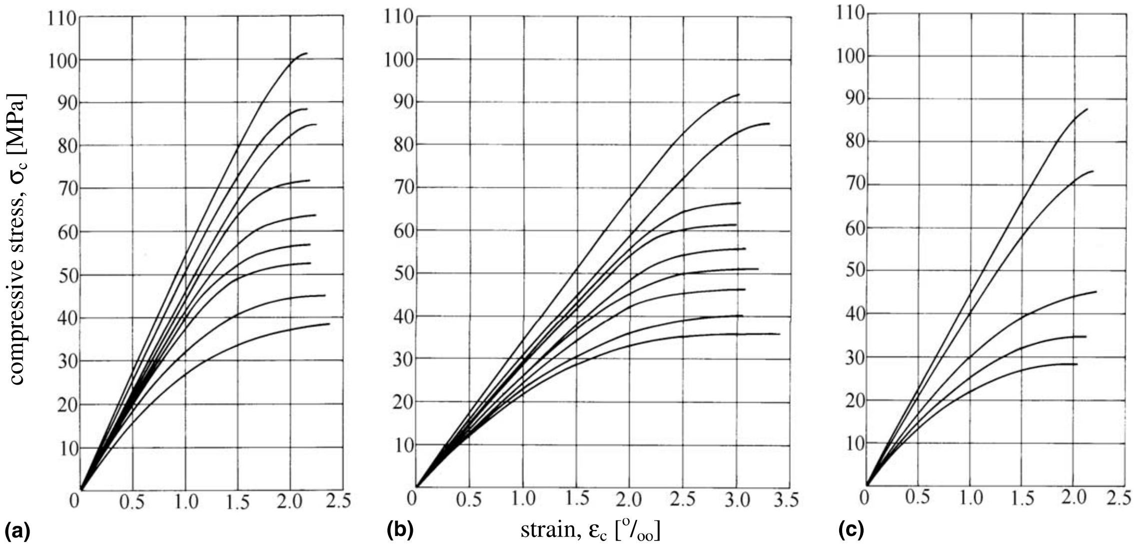

Fig. 2. Diagrams of relation $\sigma_c - \epsilon_c$ for concretes of various strengths produced from 3 different coarse aggregates: (a) nine series with basalt, (b) nine series with granite, (c) five series with natural rounded gravel.

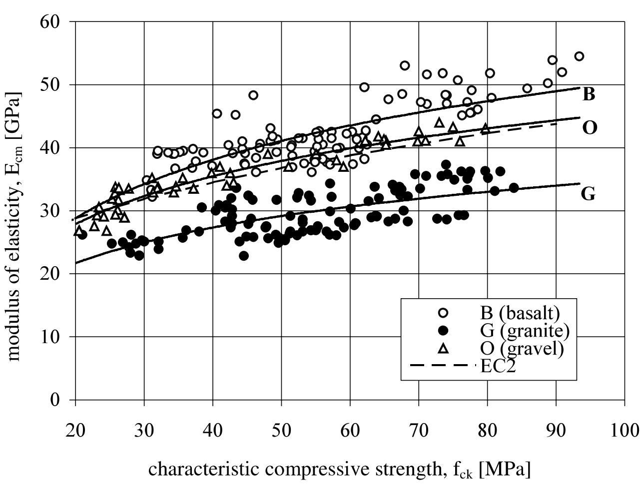

Fig. 3. Test results of secant modulus of elasticity; comparison of mean values for the three groups of concrete with the EC2 recommendation.

former opinion "the higher compressive strength the lower strain at the peak stress" was wrong. Unfortunately, such an opinion was presented not long ago in serious publications.

4.2. Modulus of elasticity

All results of modulus of elasticity tests for concrete with three kinds of coarse aggregates are presented in Fig. 3. These results are shown in function of characteristic compressive strength, f_{ck}. Three curves in this graph B, G and O calculated for different aggregates give the most spectacular illustration of the influence of the kind of coarse aggregate on the modulus of elasticity. For comparison, there is also introduced the dashed line according to Eurocode 2 [1] recommendations.

Table 2
Coefficients proposed for HPC produced with different coarse aggregate to the basic values recommended in Eurocode 2

Kind of coarse aggregate	Proposed coefficients	Coefficients recommended in CEB-FIP MC90 [2]
Basalt (crushed)	1.13	1.15
Granite (crushed)	0.79	–
Rounded quartzitic gravel (natural)	1.03	1.00

On the basis of the experimental results the approximate coefficients were proposed for practice as a correction for the particular aggregate to the basic values recommended in Eurocode 2. This proposal is valid for the aggregates available in Poland (and in Central Europe) and limited to the range of concrete classes (characteristic strengths) from 60 to 90 MPa (Table 2). In the Table there are also presented, for comparison, values of coefficients proposed by CEB-FIP MC90 [2] for some kinds of aggregates, based probably on the results of tests from research centres in Western Europe.

4.3. Poisson's ratio

For the first time (probably), such a big set of results for *Poisson's* ratio was obtained from tests done in the same conditions. The values of Poisson's ratio were measured always for the level of stresses corresponding with $0.33f_{cm}$ (mean value of compressive strength in

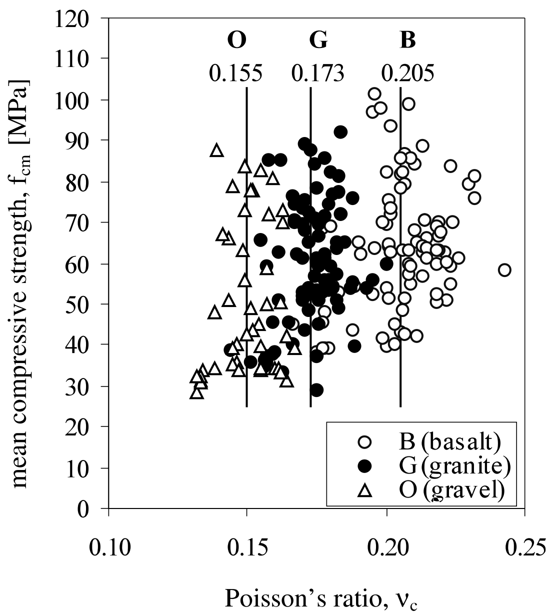

Fig. 4. Poisson's ratio test results with mean values for the three groups of concrete.

each series of six specimens). These results are presented in Fig. 4 together with the mean values, ν_{cm}, for each group of specimens with the same coarse aggregate (two results from each specimen were obtained). All results from testing concretes with mean compressive strength of 30–100 MPa are collected together in Fig. 4 because it was observed that results are irrespective of the compressive strength.

The significant differences are visible between the three groups. It may be useful for the selection of a kind of concrete in those situations when Poisson's ratio has to be taken into consideration in analysis (two-dimensional problems).

5. Conclusions

The target of tests presented in the paper was to clarify the real influence of a kind of coarse aggregate on the basic mechanical properties of concrete, particularly HPC. The tests were limited to those kinds of aggregates, which are in common use in Poland (and other countries in Central Europe) at production of HPC.

The following conclusions can be drawn from the tests:

(i) The stress–strain characteristics for the wide range of concrete strength showed the significant differences in the strains at the maximum stress between the groups of concretes with various kinds of coarse aggregate. These strains for each group are almost the same and independent of the strength. The deformability at compression of concrete with granite aggregate was the greatest in the range of aggregates considered.

(ii) The kind of coarse aggregate has a significant effect on the modulus of elasticity. In comparison with Eurocode 2 recommendations the values are in reality greater of about 13% for basalt aggregate while for aggregate from crushed granite are smaller even about 21%. The third kind of aggregate used in tests – natural rounded gravel – showed the values very close to those recommended (3% greater in fact).

(iii) Similarly, major differences were stated in the values of Poisson's ratio. Mean values for concrete with basalt were the greatest, $\nu_c = 0.205$, while significantly smaller for concrete with granite, $\nu_c = 0.173$, and for concrete with natural gravel, $\nu_c = 0.155$.

The results confirmed, that at design or analysis of responsible structures, particularly those with HPC, the properties recommended in the standards are too rough even for initial calculations. Designers have to be aware of the differences and have to cooperate with the laboratory of contractor to obtain the real data for the concrete with the kind of coarse aggregate available in the region.

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