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THE QUALITY OF HIGH-PERFORMANCE CONCRETES AS A FUNCTION OF THEIR HARDENING TIME

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In the paper, the results of the author's investigations on the long-term variation of some technological properties of cement concrete are presented. The experiments were carried out using basalt aggregate, natural sand, Portland cement CEM I 42.5 R, acrylic superplasticizer and silica fume. By adding superplasticizer, the amount of water in the concrete mix was reduced by 19–22% whereby the water-binder ratio was reduced from 0.40 to 0.29–0.32. All the tested concretes meet the compressive strength requirements of the adopted classification of HPCs (compressive strength of at least 60 MPa after 28 days of hardening). Long-term testing has confirmed that compressive strength as a function of time is steadily increasing. The increase is rapid in the first days of hardening. Logarithmic curves are a good approximation of the relationship between compressive strength and hardening time. The investigations have demonstrated that superplasticizer and silica fume significantly reduce the water absorption of the concrete. Also increasing in time is the modulus of elasticity. The concrete modified with superplasticizer and silica fume seems to be more brittle than the reference concrete.

1. INTRODUCTION

High-performance concretes (HPCs) are new generation materials which are increasingly used in building engineering. Generally, HPCs and ordinary concretes are produced in a similar way, however in the case of HPCs the components must be of consistently high quality and their recipe proportions have to be followed very strictly. The components and the concrete mix must be continuously monitored at all the stages of concrete production. The choice of major components, superplasticizers and silica fume must ensure good workability of concrete mix and result in characteristics of the concrete guaranteeing its durability. The intensification of research into high-performance concretes and their applications is observed globally, also in Poland.

2. Overview of papers on quality and performance of HPCs during their hardening time

The results of research on the quality of HPCs are reported in numerous papers published in Poland [2–8, 10–14, 19, 25] and abroad [1, 9, 15, 17, 20–24].

High-performance concretes are described in [2], where one can find some information on the composition, technology and mechanical properties of HPCs and VHPCs (very high-performance concretes), as well as $\sigma - \varepsilon$ diagrams for cement slurry, aggregate, ordinary concrete and HPCs.

Concrete deforms nonlinearly due to micro-cracks. The differences between the modulus of elasticity of the matrix and that of the aggregate result in the stress concentration in the contact layer between them, whereby a network of micro-cracks develops even under a small load.

When the difference between the rigidity of the matrix and that of the aggregate in HPCs is smaller in comparison with ordinary concrete, then as a result the stress pattern is more homogenous and stress concentrations are reduced. Since fewer micro-cracks are formed, HPCs cracks more rapidly. The typical performance of ordinary concrete and HPCs specimens is illustrated in Fig. 1 by curves $\sigma_c - \varepsilon_c$.

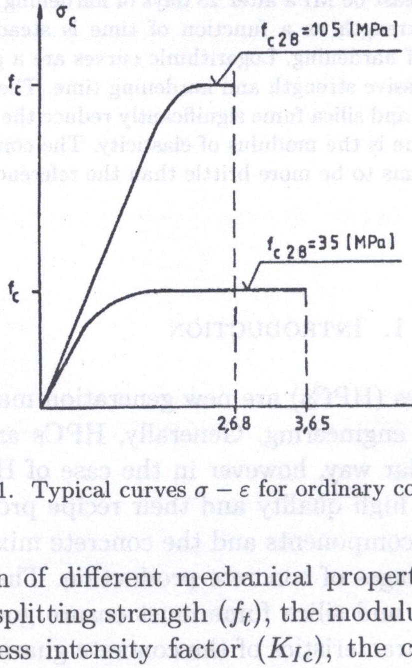

FIG. 1. Typical curves $\sigma - \varepsilon$ for ordinary concrete and HPCs [2].

A comparison of different mechanical properties: the compressive strength (f_c), the tensile splitting strength (f_t), the modulus of elasticity (E), the critical value of the stress intensity factor (K_{Ic}), the cracking energy (G_f) and the parameters which are characterizing the size of the micro-cracks zone around the crack's tip (c_f, l_0) for ordinary concretes and HPCs can be found in Fig. 2.

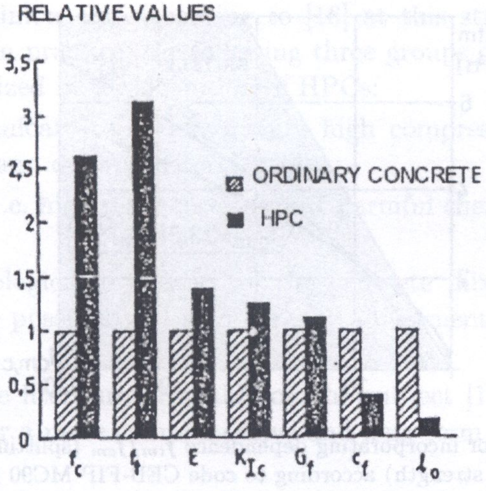

FIG. 2. Comparison of different mechanical properties of ordinary concretes and HPCs [2].

The author of [10] suggests a classification of new generation concretes and points out that neither standards nor recommendations for introducing HPCs into the building industry exist. Two proposals for extending the design code's regulations concerning nonlinear structural analysis and brittleness of concrete are presented in Figs. 3 and 4. One proposal relates to model dependencies $\sigma - \varepsilon$ (Fig. 3) and the other to usability (important for limit state analysis) – a generalized relationship between mean tensile splitting strength and mean compressive strength (brittleness of concrete) (Fig. 4).

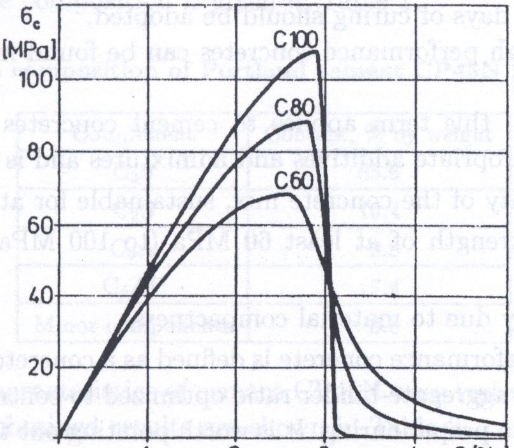

FIG. 3. Proposal for $\sigma - \varepsilon$ relationships to be used in nonlinear structural analysis according to code CEB-FIP MC90 for concretes C60–C100 [10].

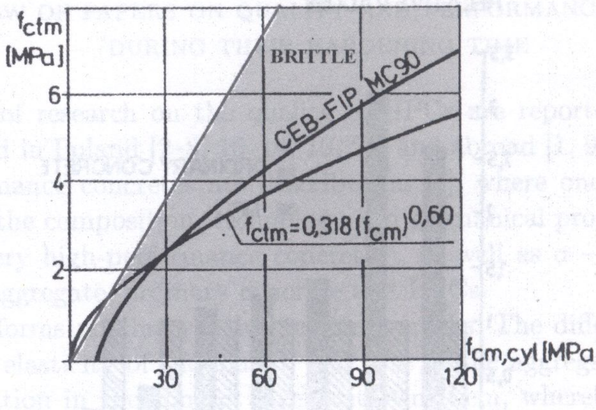

FIG. 4. Proposal for incorporating dependence f_{tm}/f_{cm} (splitting strength/compressive strength) according to code CEB-FIP MC90 [10].

Material brittleness (k) is defined as a ratio of mean tensile splitting strength of concrete (f_{tm}) to mean compressive strength of concrete (f_{cm}). Materials are considered to be brittle, when their $f_{tm}/f_{cm} \leq 0.125$. Brittle materials include ordinary concrete, ceramics, glass and cast iron. The lower the ratio (k), the more brittle the material.

According to the authors of [14], the compressive strength of HPCs determined after 365 and 730 days is an evidence of their long-term strength. The quality of HPCs assessed on the basis of the compressive strength determined after 28 days of hardening gives the structure a wider safety margin. If the HPCs are to be used for the construction of high buildings, the compressive strength determined after 90 days of curing should be adopted.

Definitions of high performance concretes can be found in many papers, for example in [2, 9, 15].

According to [2], this term applies to cement concretes based on natural aggregates with appropriate additives and admixtures and is characterized by:

a) good workability of the concrete mix, sustainable for at least one hour;
b) compressive strength of at least 60 MPa (to 100 MPa) after 28 days of hardening;
c) good durability due to material compactness.

In [9, 15] high performance concrete is defined as a concrete with a low water-binder ratio and the aggregate-binder ratio optimized to control the dimensional stability, subjected to proper curing. It is worth pointing out that a generally accepted definition of high performance concretes does not exist. HPCs can be also defined as a material with improved one or more characteristics, e.g. durability, compressive strength, abrasion resistance, etc.

In the author's opinion and according to [16] at this stage of introducing HPCs into construction practice, the following three groups of material properties should be emphasized in the definition of HPCs:

a) beneficial mechanical properties, mainly high compressive strength and reduced instant and delayed deformability;

b) high durability, i.e. high resistance to most harmful chemical and physical effects;

c) beneficial technological properties of the concrete mix, a quick gain in strength and the possibility of a wide-range adjustment of the rheological properties.

The analysis of the literature available on the subject [1–17, 19–26] shows that there is a need for a more comprehensive and long-term study of technical properties of HPCs.

The author's research presented in this paper is aimed at filling in the gaps in knowledge about how some properties of HPCs develop in time, also in the aspect of building practice.

3. TESTS AND THEIR RESULTS

3.1. *Materials*

The following basic concrete components were used for the tests: a) 8–16 mm, 4–8 mm and 2–8 mm basalt aggregate from the Wilcza Góra quarry; b) 0–2 mm washed sand from the Mietków Mine; c) Portland cement CP45N (CEM I 42.5 R) [29–32] from the Górażdże Cement Plant and the tap water. The cement's phase composition is given in Table 1.

Table 1. Phase composition of Portland cement CP45N (CEM I 42.5 R).

Component	Content, % by weight
C_3S	65.6
C_2S	10.4
C_3A	9.8
C_4AF	7.4
Minor components	6.8

The strength characteristics of cement CP45N were tested according to standard [29] and the obtained results are shown in Table 2.

The tested cement compressive strength after 28 days of curing was by 5% lower than the requirement specified in standard [29]. It is worth pointing out that according to the current, revised standard [30, 31], the observed strength characteristics of the binder still correspond to the Portland cement strength class CEM I 42.5 R.

Table 2. Strength characteristics of Portland cement.

Characteristic	Test results [MPa]	Standard requirements [29]
Compressive strength of standard mortar after 3 days	22.3	minimum 20 MPa
Compressive strength of standard mortar after 7 days	32.9	–
Compressive strength of standard mortar after 28 days	42.6	minimum 45 MPa

The aggregates were experimentally combined into an optimum aggregate composition – characterized by the maximum compactness and by minimum amount of water absorbed by the aggregate [8, 25, 27–28]. The voids (v) determined for the combined and compacted aggregates and the calculated Kuczyński grading index (U_K) [27–28] were respectively 21.1% and 6.60. The composition of aggregates is considered to be very good when $6 \leq U_K \leq 7.5$ [27, 28].

The aggregate mixture composition is given in Table 3.

Table 3. Amounts of aggregates in optimum aggregate composition.

No.	Type of aggregate	Amount of particular aggregate as a percentage of total aggregate
1.	basalt aggregate 8/16	36.4
2.	basalt aggregate 4/8	24.2
3.	basalt aggregate 2/4	9.1
4.	natural sand 0/2	30.3
Total:		100.0 %

In the experiments an ordinary acrylic superplasticizer (without formaldehydes) having a strong liquefying effect was used. Its dry substance content in the water solution was 33% and the superplasticizer's density at a temperature of +20°C was 1.140 g/ml. The manufacturer's recommended superplasticizer percentage is 0.5–1.2% (33% water solution), but for HPCs it can be as much as 3.0% relative to the mass of cement.

A reactive additive – silica fume powder – was used in amounts of 3% or 7% to modify the concrete mix. The manufacturer's recommended percentage of this additive is 2–10% of the mass of cement.

The superplasticizer and the silica fume used as the components of the tested concrete mixes come from one manufacturer, form a compatible system, interact well with the applied Portland cement and seem to be a good choice for the production of HPCs.

3.2. *Characteristics of concrete mixes*

Four concrete mixes were made using Portland cement, basalt aggregates, washed sand, and addition of superplasticizer and silica fume. All the mixes had identical plastic consistency (measured with a slump of approximate 2.5 cm [33]). The same amount of cement, i.e. 450 kg/m^3, was always used. Quality test results for the mixes (denoted by M1 to M4) are shown in Table 4, in which the reference mix (M1) contained only the basic components.

In the case of mix M2, superplasticizer was added to the basic composition in the amount of 2% by weight of cement and a certain amount of water was removed from it to preserve the initial consistency. The water removed from the mix was replaced with an appropriate amount of the component aggregates at a ratio given in Table 3. As a result, the water-cement ratio (W/C) of the mixes decreased.

In the case of the other two mixes (M3 and M4), respectively 3 and 7% (relative to the mass of cement) of silica fume and a considerable amount ($2.5 \div 3.0\%$) of superplasticizer were added to the basic composition to remove a certain amount of water and thus to reduce the W/C ratio while preserving the initial consistency (a slump of approximate 2.5 cm).

The above amounts of superplasticizer are still safe to use since they do not result in the air entrainment of concrete mixes (Table 4).

In addition, several concrete mixes were made, differing in their superplasticizer and silica fume contents and in the consistence classes. They will be the subject of a separate report.

3.3. *Characteristics of concretes*

Compressive strength (f_c), water absorption (n_w) and modulus of elasticity (E) of concrete prepared as mixes M1, M2, M3, M4 (shown in Table 4) were determined at different times during cement hardening. The specimens used for all the determinations were cured in a climatic chamber at a temperature of 18°C (±2°C) and a relative air humidity of 95% (±5°C).

For each type of concrete and age of testing (in a range of 3 days to 5 years) compressive strength was determined using 9 cube specimens with a 10 cm side. The average compressive strength test results are shown in Fig. 5. In addition, the dispersion of results in the form of standard deviation was calculated. The obtained results are given in the Figs. 5 and 6.

Moreover, the compressive strength of each type of concrete after 28 days was determined using 9 cube specimens with a 15 cm side.

Table 4. Composition and characteristics of concrete mixes containing superplasticizer and silica fume.

Concrete mix	Amount of superplasticizer (33% water solution) as percentage of the mass of cement (and per 1 m^3)	Amount of silica fume as percentage of the mass of cement(p_k) (and per 1 m^3)	Amount of cement, in kg/m^3 (C)	Amount of water, in kg/m^3 (W)	Amount of aggregate, in kg/m^3 (K)	$\frac{W}{C+p_k}=\frac{W}{S}$	Reduction of water amount, in kg (%), relative to initial amount of water in mix M1	Concrete mix consistency as measured by slump, in cm	Air content, in %	Density, in kg/m^3
M1	0.0%	0.0	450	180	2033	0.400	–	2.5	0.4	2663
M2	2.0% (9.0 kg)	0.0	450	146	2084	0.324	34 (18.9)	2.5	0.1	2689
M3	2.5% (11.2 kg)	3.0% (13.5 kg)	450	140	2096	0.302	40 (22.2)	2.5	0.2	2711
M4	3.0% (13.5 kg)	7.0% (31.5 kg)	450	140	2069	0.291	40 (22.2)	2.5	0.2	2704

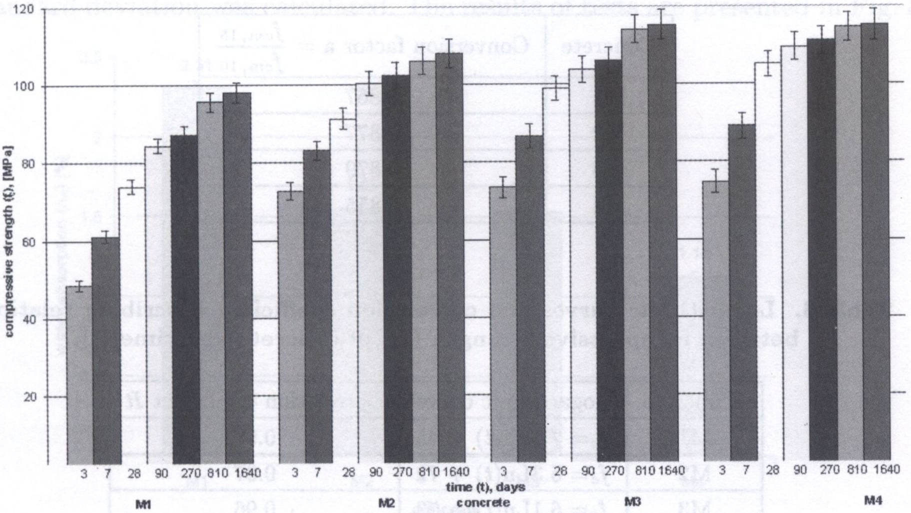

FIG. 5. Comparison of compressive strength versus time for HPCs.

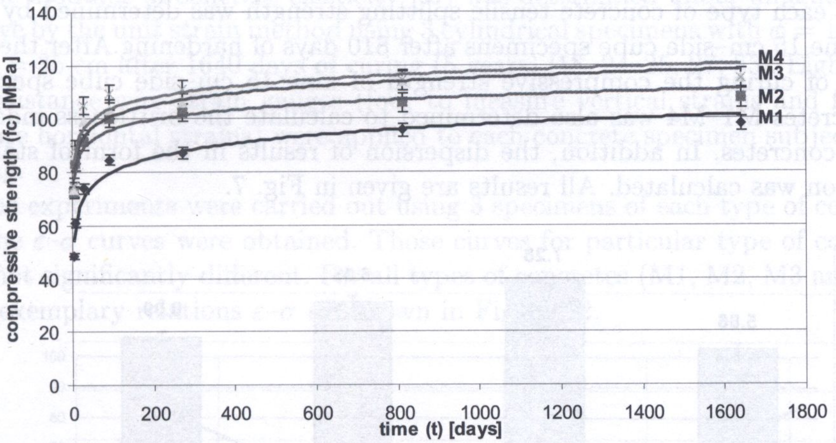

FIG. 6. Correlation between compressive strength f_c [MPa] of concretes nd time (t) [days].

The ratio (a) of mean compressive strength determined on cubes with 15 cm side ($f_{cm,15}$) to mean compressive strength determined on cubes with 10 cm side ($f_{cm,10}$), is given in Table 5.

The empirical relations between compressive strength and concrete hardening time are shown in Fig. 6. Logarithmic curves and correlation coefficient describing those relations for each type of concrete are given in Table 6.

Table 5. Compressive strength conversion factors for HPCs after 28 days of hardening.

Concrete	Conversion factor a = $\dfrac{f_{cm,\,15}}{f_{cm,\,10}}$
M1	0.867
M2	0.877
M3	0.879
M4	0.855

Table 6. Logarithmic curves and correlation coefficient describing relation between compressive strength (f_c) of concrete and time (t).

Concrete	Logarithmic curve	Correlation coefficient R
M1	$f_c = 7.6\mathrm{Ln}(t) + 45$	0.98
M2	$f_c = 5.3\mathrm{Ln}(t) + 72$	0.97
M3	$f_c = 6.1\mathrm{Ln}(t) + 73$	0.96
M4	$f_c = 5.8\mathrm{Ln}(t) + 77$	0.92

For each type of concrete tensile splitting strength was determined by splitting nine 15 cm–side cube specimens after 810 days of hardening.After the same period of curing the compressive strength of nine 15 cm–side cube specimens of concretes M1–M4 was also determined to calculate the brittleness index (k) of the concretes. In addition, the dispersion of results in the form of standard deviation was calculated. All results are given in Fig. 7.

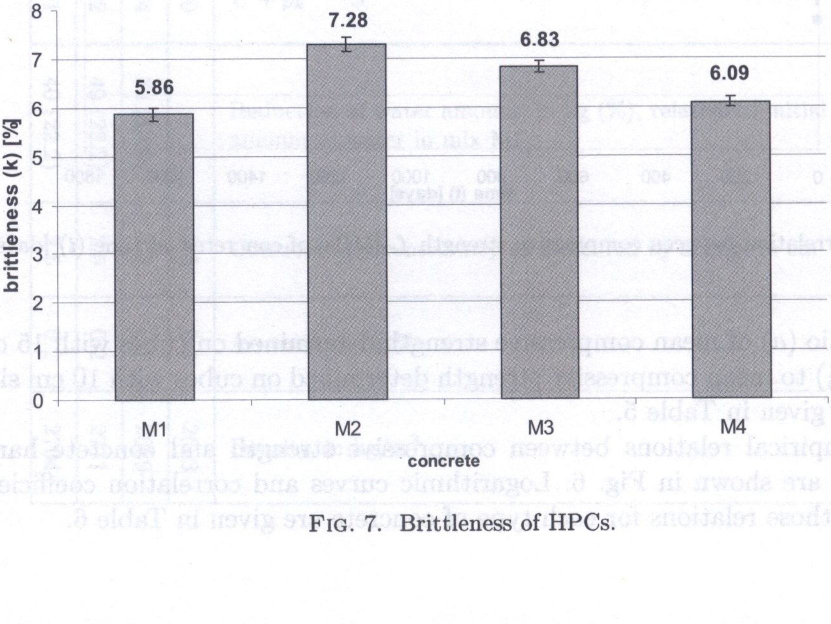

FIG. 7. Brittleness of HPCs.

Water absorption (n_w) was determined using five 10 cm–side cube specimens after 28 days of hardening [33]. Additionally, the dispersion of results in the form of standard deviation was calculated. The results of tests are presented in Fig. 8.

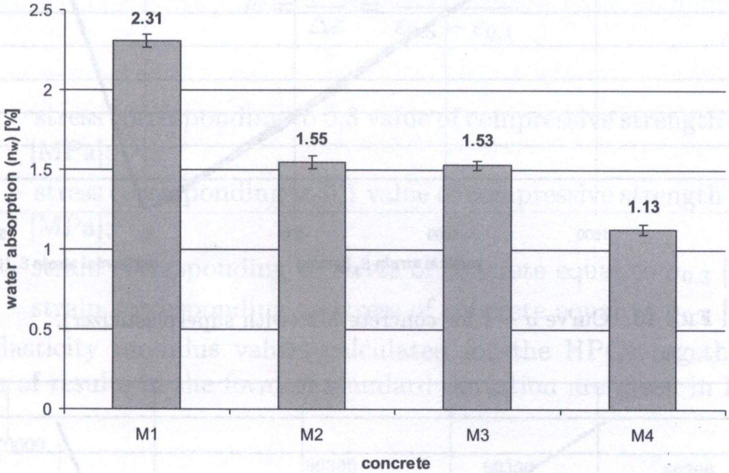

FIG. 8. Water absorption of HPCs.

The modulus of concrete elasticity (E) was determined under uniaxial compressive by the unit strain method using 3 cylindrical specimens with $\phi = 11.3$ cm and $h = 35$ cm after 1640 days of curing (5 years) [18, 24–25, 27, 35]. Eight electric resistance wire strain gauges (four to measure vertical strains and four to measure horizontal strains) were applied to each concrete specimen subjected to loading.

The experiments were carried out using 3 specimens of each type of concrete and the ε–σ curves were obtained. Those curves for particular type of concrete were not significantly different. For all types of concretes (M1, M2, M3 and M4) some exemplary relations ε–σ are shown in Figs 9–12.

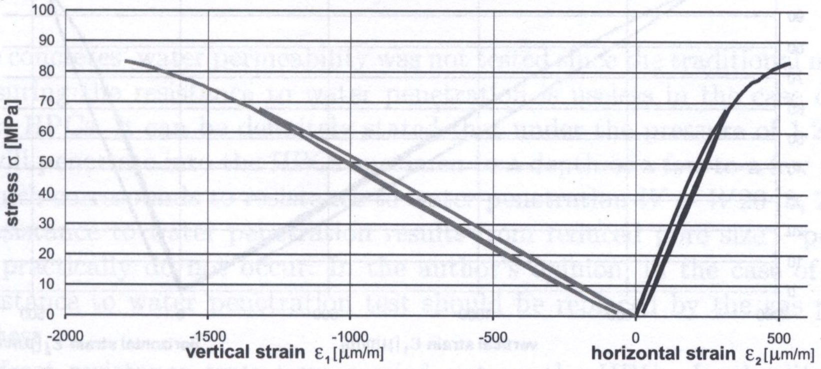

FIG. 9. Curve $\sigma - \varepsilon$ for reference concrete M1.

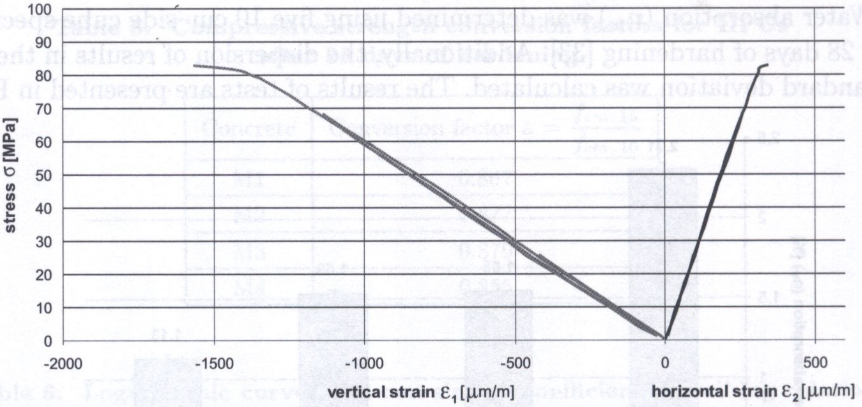

FIG. 10. Curve $\sigma - \varepsilon$ for concrete M2 (with superplasticizer).

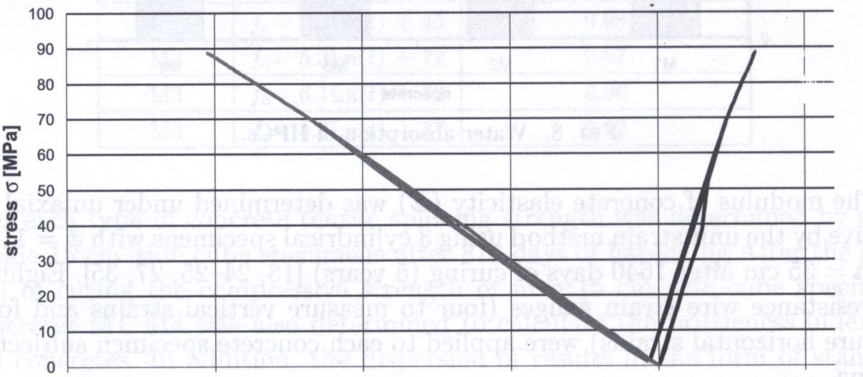

FIG. 11. Curve $\sigma - \varepsilon$ for concrete M3 (with superplasticizer and 3% of silica fume).

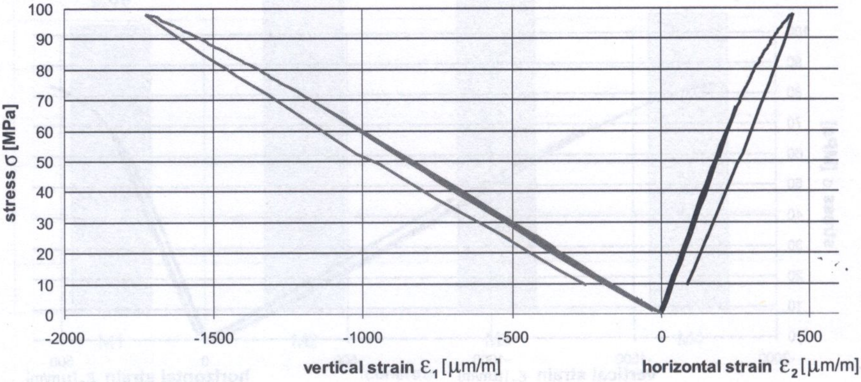

FIG. 12. Curve $\sigma - \varepsilon$ for concrete M4 (with superplasticizer and 7% of silica fume).

The modulus of elasticity was calculated for stress from $0.1f_{cm}$ to $0.3f_{cm}$. It was obtained from the following formula:

$$E = \frac{\Delta\sigma}{\Delta\varepsilon} = \frac{\sigma_{0.3} - \sigma_{0.1}}{\varepsilon_{0.3} - \varepsilon_{0.1}} \tag{3.1}$$

where:

$\sigma_{0.3}$ – stress corresponding to 0,3 value of compressive strength ($\sigma = 0.3f_{cm}$) [MPa];

$\sigma_{0.1}$ – stress corresponding to 0,1 value of compressive strength ($\sigma = 0.1f_{cm}$) [MPa];

$\varepsilon_{0.3}$ – strain corresponding to stress of concrete equal to $\sigma_{0.3}$ [µm/m];

$\varepsilon_{0.1}$ – strain corresponding to stress of concrete equal to $\sigma_{0.1}$ [µm/m].

The elasticity modulus values calculated for the HPCs together with the dispersion of results in the form of standard deviation are given in Fig. 13.

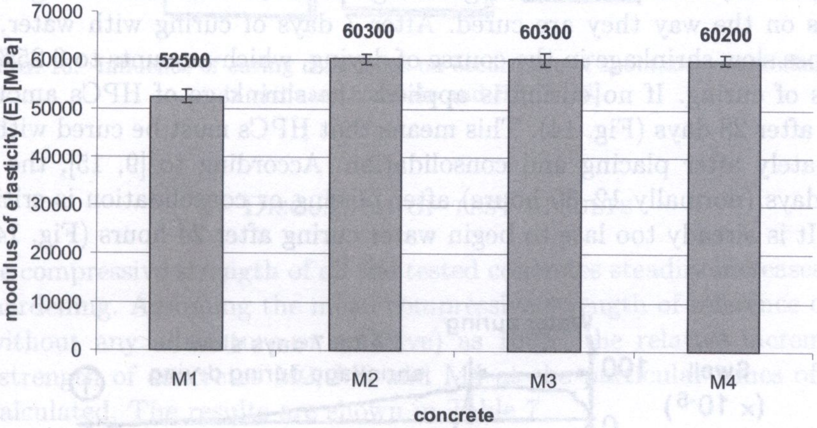

FIG. 13. Modulus of elasticity of HPCs.

The concretes' water permeability was not tested since the traditional method of measuring the resistance to water penetration is useless in the case of very compact HPCs. It can be definitely stated that under the pressure of 1.2 MPa, water will penetrate into the HPCs specimen to a depth of a few to a few tens of mm, which corresponds to resistance to water penetration $W > W20$ [8, 24–25]. Such resistance to water penetration results from reduced pore size – pores > 10 µm practically do not occur. In the author's opinion, in the case of HPCs the resistance to water penetration test should be replaced by the gas permeability test.

No frost resistance tests were carried out on the HPCs. In the literature [2, 9, 10, 15–16, 24–25], views on this subject are divergent. What can definitely be stated is that the HPCs would have a high degree of resistance to frost if an air entrainment admixture, compatible with superplasticizer and silica fume, was added to their composition. It should be noted, however, that the introduction of an additional 1% of air into concrete mixes lowers the strength of the concrete by about 5%.

The results of water absorption tests carried out on the concretes showed that water fills their capillary pores in a small degree. The HPCs' water absorption is in a range of 1.13–2.31% and therefore they can be regarded, in the author's and other researchers' opinion [24–25], as extraordinarily freeze/thaw resistant. The degree of freeze/thaw resistance of HPCs (F_{HPCs}) is bigger than the degree of freeze/thaw resistance of ordinary concretes after 150 cycles of freeze/thaw (F150); $F_{HPCs}>F150$. In the author's opinion, judging by the increase in HPCs' strength in time, its freeze/thaw resistance should be tested later than after 28 days of hardening, e.g. after 90 days.

The shrinkage of the HPCs was not tested. According to the literature [1–2, 8–9, 11, 15–16, 24–25], the shrinkage of high performance concretes significantly depends on the way they are cured. After 7 days of curing with water, HPCs undergoes slow shrinkage in the course of drying, which amounts to 0.25‰ after 28 days of curing. If no curing is applied, the shrinkage of HPCs amounts to 0.40‰ after 28 days (Fig. 14). This means that HPCs must be cured with water immediately after placing and consolidation. According to [9, 15], the period of 2–3 days (normally 12–36 hours) after placing or consolidation is critical for HPCs. It is already too late to begin water curing after 24 hours (Fig. 14).

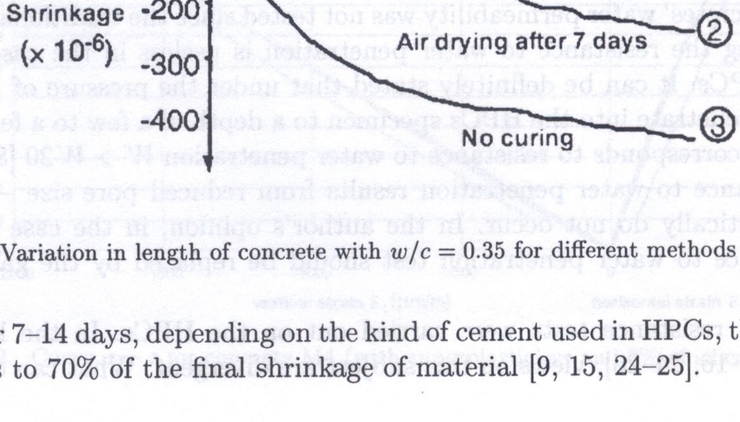

FIG. 14. Variation in length of concrete with $w/c = 0.35$ for different methods of curing [15].

After 7–14 days, depending on the kind of cement used in HPCs, the shrinkage amounts to 70% of the final shrinkage of material [9, 15, 24–25].

Curing conditions may contribute to the occurrence of autogeneous shrinkage. The latter does not occur if water is supplied to the exterior of ordinary concrete and HPCs (Fig. 15).

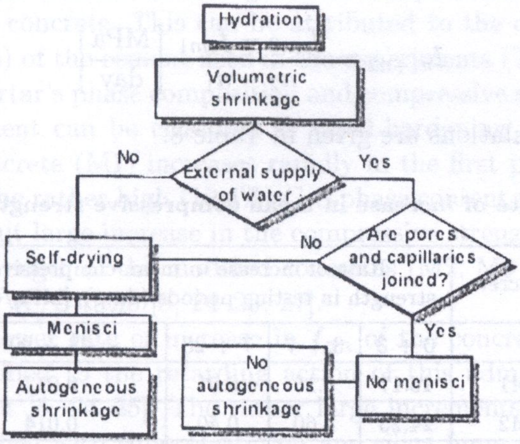

FIG. 15. Influence of curing conditions on occurrence of spontaneous shrinkage in ordinary concrete and HPCs [15].

4. DISCUSSION OF TEST RESULTS

The compressive strength of all the tested concretes steadily increases during their hardening. Assuming the mean compressive strength of reference concrete M1 (without any admixture or additive) as 100%, the relative increments in mean strength of concretes M2, M3 and M4 at the particular times of testing were calculated. The results are shown in Table 7.

Table 7. Relative increments in mean compressive strength (f_{cm}) of HPCs.

Concrete	Increments in compressive strength of concretes containing superplasticizer and silica fumes relative to mean compressive strength of reference concrete at times of testing, %						
days	3	7	28	90	270	810	1640
M2	150	136	124	118	117	111	110
M3	151	142	134	123	121	119	117
M4	154	149	142	130	127	120	117

In addition, the rate of increase in mean compressive strength ($I_{n1 \div n2}$) up to 90 days in periods: 0–3 days ($n_2 = 3$, $n_1 = 0$), 3–7 days ($n_2 = 7$, $n_1 = 3$), 7–28 days ($n_2 = 28$, $n_1 = 7$) and 28–90 days ($n_2 = 90$, $n_1 = 28$) was calculated for all the tested HPCs. The rate is a ratio of the difference between mean compressive strength of concrete at the age of n_2 days (f_{cm2}) and at the age of n_1 days (f_{cm1}) to the number of days in the period. It was calculated from the following formula:

$$I_{n1 \div n2} = \frac{f_{cm2} - f_{cm1}}{n_2 - n_1} \left[\frac{\text{MPa}}{\text{day}}\right] \tag{4.1}$$

The results of calculations are given in Table 8.

Table 8. Rate of increase in mean compressive strength for HPCs.

Concrete	Rate of increase in mean compressive strength in testing periods (days), [MPa/day].			
	0 ÷ 3	3 ÷ 7	7 ÷ 28	28 ÷ 90
M1	16.17	3.15	0.61	0.017
M2	24.23	2.60	0.40	0.014
M3	24.27	3.30	0.59	0.008
M4	24.90	3.60	0.76	0.002

The classes of the concretes after 28 days of hardening determined (using cube specimens with a 15 cm side) according to Polish Standard PN-EN 206–1 [34] are given in Table 9.

Table 9. Classes of concretes determined according to Polish Standard PN-EN 206-1 [34] after 28 days of hardening.

Concrete	Classes
M1	C50/60
M2	C60/75
M3	C60/75
M4	C70/85

The results of the long-term testing of the HPCs' compressive strength show that the largest increase in this strength in the modified concretes occurred within 3 days: the increment in f_{cm} is by 50–54% larger in comparison with that of the reference concrete and the rate of increase in compressive strength in the period of 0–3 days is very high – 24–25 MPa/day – in comparison with 16 MPa/day observed in the unmodified concrete.

As time passes, increments in f_{cm} of the concretes containing superplasticizer and silica fumes become smaller, but are still relatively large, e.g. 36–49% after 7 days and 24–42% MPa after 29 days, in comparison with those of the reference concrete. The rate of increase in strength for all the tested concretes is 2.60–3.60 MPa/day and 0.40–0.76 MPa/day in the periods of respectively 3–7 days and 7–28 days.

The characteristic increase in strength after 3 days of hardening is observed for the unmodified concrete. This can be attributed to the chemical properties (phase composition) of the cement used in the experiments (Table 1). According to the standard mortar's phase composition and compressive strength [24–27, 29] (Table 2), the cement can be classified as rapid-hardening cement. Hence the strength of the concrete (M1) increases rapidly in the first period of hardening and subsequently the rather high (10.4%) C_2S phase content (Table 1) is responsible for the slow but large increase in the compressive strength. The increase in the compressive strength of the modified concretes (M2, M3 and M4) is mainly due to the reduced W/C ratio [8, 24–25, 27].

The relatively lower rate of increase in f_{cm} of the concrete with superplasticizer can be ascribed to the retarding action of this admixture on the time of set of the cement [8, 24–25]. The rather large increments in the strength of the concretes modified with superplasticizer and silica fume are due to both the reduction of W/C and the action of the silica fume. As a result of physical interactions and pozzolanic reactions, p_k favourably modifies the microstructure of the cement slurry and that of the transition layer, reducing porosity and increasing adhesion to the filler. Consequently, the concrete's compactness increases and its strength improves [5, 8, 24–26].

Regardless of the type of concrete, the obtained strength characteristics corresponded to the adopted classification of HPCs (compressive strength of at least 60 MPa to 100 MPa after 28 days of hardening). After 28 days of hardening concrete M1 received class C50/60 and the modified concretes (M2, M3 and M4) received classes which were higher of 2–3 classes than the reference concrete (Table 9). Similar tendencies in the change of f_{cm} are observed after 5 years: f_{cm} of the modified concretes is by 10–17% higher (Table 7), which according to the standard classification [34] places them 1–2 classes higher than the reference concrete.

Superplasticizer and silica fume additions lower the brittleness index of HPCs. The effect of superplasticizer on brittleness was found to be stronger in the case of concrete M2. If larger amounts of silica fume are added to concretes M3 and M4, the latter become less brittle than the concrete modified with superplasticizer (Fig. 7).

The water absorption of all the concretes (M1, M2, M3 and M4) is low, ranging from 1.13% to 2.31%. If superplasticizer or superplasticizer and silica fume are introduced into concrete mixes and at the same time water is removed from them to preserve their initial plastic consistency, n_w decreases considerably – by 33–49% – relative to the water absorption of concrete M1. This is mainly due to a reduction of the mix W/C caused by the superplasticizer and to an improvement in the concrete's compactness brought about by adding superplasticizer and silica fume [5, 8, 9, 24–26].

According to standard [33], the water absorption of concrete should not be higher than:

- 5% for concretes exposed to the elements,
- 9% for concretes protected against the elements.

All the tested concretes (M1–M4) have a very high modulus of elasticity (E) after 5 years of curing – within a range of 52500-60300 MPa. This is due to the use of basalt aggregate with apparent grains density (G) equal to 3014 kg/m^3, produced from rock having high compressive strength (271 MPa on average in the deposit), which constitutes about 48% of the material's total volume. The increase in E of the modified concretes (M2–M4) by about 15% relative to the reference can be ascribed to their high aggregate content, the removal of water and good adhesion between the matrix and the aggregate. Moreover, the modulus of elasticity increases with the compressive strength of concrete (f_c). Silica fume by reducing the porosity of the transitional structure, increases adhesion of matrix to the aggregate [5, 9, 24–25]. The obtained modulus of elasticity (E) are correlated with the $\varepsilon - \sigma$ curves shown in Figs. 9–12.

For concretes whose compressive strength is in a range of 80-140 MPa ,the modulus of elasticity (E) and compressive strength (f_c) are interrelated by the following expression [24]:

$$E_B = 3.65(f_c)^{0.5}. \tag{4.2}$$

Using the experimentally determined values of E and f_c and formula (4.2), the factors of proportionality between the parameters were calculated for each type of concrete. The following equations describe the $E - f_c$ relation for the tested concretes:

$$\text{concrete M1} \quad E_{B1} = 5.30\,(f_c)^{0.5}, \tag{4.3}$$

$$\text{concrete M2} \quad E_{B2} = 5.80\,(f_c)^{0.5}, \tag{4.4}$$

$$\text{concrete M3} \quad E_{B3} = 5.60\,(f_c)^{0.5}, \tag{4.5}$$

$$\text{concrete M4} \quad E_{B4} = 5.62\,(f_c)^{0.5}. \tag{4.6}$$

For the HPCs the proportionality factor (Eqs. 4.3–4.6) describing the $E - f_c$ dependence after 5 years of hardening was calculated (with the possibly smallest error) from an appropriate system of inequalities. The equation which describes (with an accuracy of ±4.6%) the $E - f_c$ dependence for all the four tested HPCs after 1640 days of hardening in laboratory conditions has this form:

$$E_{HPCs} = 5.54(f_c)^{0.5}. \tag{4.7}$$

Equations (4.3)–(4.6) describing the relation between E and f_c are shown in Fig. 16. Points on the graph are representing experimentally obtained mean values of compressive strength and modulus of elasticity, tested after 5 years of curing of analyzed concretes M1–M4 (curves 1–4). The summarized relation $E - f_c$ (Eq. (4.7)) for HPCs is represented on the graph by the curve 5.

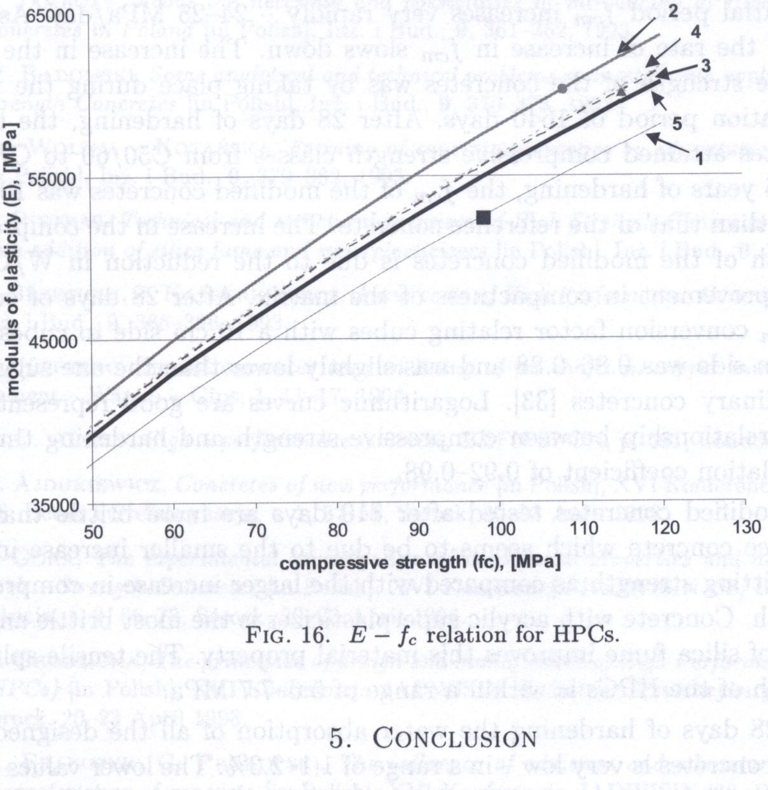

FIG. 16. $E - f_c$ relation for HPCs.

5. CONCLUSION

From the tests on the quality of HPCs with superplasticizer and silica fume additives the following conclusions can be drawn:

1. By modifying concrete mixes with acrylic superplasticizer (33% water solution) in the amount of 2–3% relative to the mass of cement it is possible to reduce the water content by 34–40 kg/m^3 ($\sim$ 19–22%) and to lower the W/B (Water/Binder) ratio from 0.40 (the reference) to 0.29–0.32 (concrete with superplasticizer and silica fume) while preserving the initial plastic consistency of the mix.

2. The compressive strength of all the tested concretes after 28 days of curing was in a range of 64–90 MPa (on 15 cm cubes) and in a range of 74–150 MPa (on 10 cm cubes) and the concretes comply with requirements of the adopted classification of HPCs [1–2, 9–10, 15–16, 24–25].

3. Long-term testing (3 days to 5 years) has clearly shown the effect of the increase in time of the compressive strength of HPCs. As a result of intensive physico-chemical processes taking place in hardening concrete, all the tested concretes modified with acrylic superplasticizer and silica fume acquired considerable strength (48–75 MPa) already after 3 days of curing. The f_{cm} of the modified concretes was observed to be by 50–54% higher than that of the reference concrete after 3 days of curing. Within this initial period f_{cm} increases very rapidly – 24–25 MPa/day. As time passes, the rate of increase in f_{cm} slows down. The increase in the compressive strength of the concretes was by taking place during the whole observation period of 1640 days. After 28 days of hardening, the tested concretes attained compressive strength classes from C50/60 to C70/85. After 5 years of hardening, the f_{cm} of the modified concretes was 10–17% higher than that of the reference concrete. The increase in the compressive strength of the modified concretes is due to the reduction in W/C and the improvement in compactness of the matrix. After 28 days of curing, the f_{cm} conversion factor relating cubes with a 10 cm side to cubes with a 15 cm side was 0.86–0.88 and was slightly lower than the one suggested for ordinary concretes [33]. Logarithmic curves are good representation of the relationship between compressive strength and hardening time, at a correlation coefficient of 0.92–0.98.
4. The modified concretes tested after 810 days are more brittle than the reference concrete which seems to be due to the smaller increase in tensile splitting strength as compared with the larger increase in compressive strength. Concrete with acrylic superplasticizer is the most brittle and addition of silica fume improves this material property. The tensile splitting strength of the HPCs is within a range of 5.6–7.7 MPa.
5. After 28 days of hardening the water absorption of all the designed and tested concretes is very low – in a range of 1.1–2.3%. The lower values of n_w in the modified concretes are the result of a reduction in W/C and the tightening of the matrix, particularly in the case of a 7% silica fume addition.
6. The modulus of elasticity of the HPCs after 5 years of curing was very high, up to 52000–60000 MPa. The equation for elasticity modulus E in relation to the compressive strength of HPCs was found: $E_{HPCs} = 5.54 (f_c)^{0.5}$ with an accuracy of ±5%. The fact that the concretes have high f_c and E values can be exploited in the design of building structures, e.g. the cross-sections of columns can be reduced to obtain more slender and lighter structures, spans can be made longer, material consumption can be reduced, structures can be loaded at earlier age. When changing the cross-sections of structural elements, one should bear in mind that the structure must be properly braced.

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