To the problem of the methodology for evaluating the effectiveness of the use of superplasticizers in concretes

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Abstract. Based on the analysis of the effect of various superplasticizers on the compressive and tensile strengths of concrete hardened under different conditions for three months, it was concluded that to estimate the effectiveness of superplasticizers it is not enough to compare the relative strength indicators of concrete only (fₙ₀/f₂₈; fₜ = f(f); f = f(W/C)) without taking into account the effect of the superplasticizer on the water content in the concrete mix and the cement content. The assessment methodology is given. It is shown that provided the required design parameters for durability are ensured, analysis of only data on the increase in compressive and tensile strengths in time can lead to erroneous conclusions. A reliable assessment should be made taking into account the influence of the superplasticizer on the composition and cost of the concrete mix, shrinkage, creep and E-modulus of concrete.

1. Introduction
Concrete mixes with superplasticizers (SP) are widely used in construction due to the possibility of obtaining the required properties, as concrete mixes, and concrete [1-4]. High-performance SP based on polycarboxylate ethers are represented on the market by numerous manufacturers and brands. To choose a SP in each specific case, it is important to take into account a variety of factors, in particular, the water-reducing capacity, the influence of SP on the formation of the structure and properties of cement stone and concrete [5-7]. Ignoring some factors when choosing SP may lead to an unreliable assessment of the feasibility of its application. When choosing an effective SP to solve a specific problem, it is impossible to separate technical and economic issues. When assessing the effect of SP on the properties of concrete, one should not operate only with relative indicators and ignore the influence of SP on the concrete composition and water content of the concrete mix with the required mobility. The article shows that if during evaluating the effectiveness when comparing the various SP you pay attention on the technical side of problem only it may lead to an incorrect conclusion.

2. Methodology
The compressive strength of concrete and tensile strength on splitting was determined on samples-cubes 100x100x100 mm at the age of 28 and 90 days. The transition from tensile strength on splitting $f_{tt}$ to axial tensile strength $f_t$ was made according to the formula $f_t = 0.93 \cdot f_{tt}$. Samples were made from concrete mix with slump 220-240 mm (S5 in accordance with EN 206). The water content ranged...
from 157 till 198 kg/m³, the content of the additive was from 2.8 till 4.72 l/m³ (from 0.8 to 1.05% by weight of cement). The cement content in the series 1 was 350 kg/m³, in the series 2 - 450 kg/m³. Curing the samples until the test was carried out:

- in normal conditions (hereinafter NC) according to GOST 10180-2012 (temperature 20+2 °C, relative humidity more than 95%);
- in environmental conditions (hereinafter EC) at a temperature of from 20 to 29 °C and a relative humidity from 51 till 85%.

For the manufacture of concrete mix next cements were used:
- CEM I 42.5 «Novoroscement», Proletary plant (C₃S = 62.1%; C₂S = 17.3%; C₃A = 5.2%; C₄AF = 13.4%, R₂O = 0.77%) with activity 52.9 MPa;
- CEM I 42.5 «Verkhnebakansky cement plant» (C₃S = 61.5%; C₂S = 16.9%; C₃A = 3.6%; C₄AF = 15.2%, R₂O = 0.6%) with activity 51 MPa.

Cements do not differ by mineralogical composition and activity. The specific surface of cements was 3100-3200 cm²/g.

As aggregates next materials were used:
- sand with size module 2.1;
- crushed stone 5-20 mm (granite, granodiorite (42%), diabase (37%).

SP based on polycarboxylate ethers produced «BASF Building systems» were used:
- Мaster Glenium 115, рН 5.5-7.5;
- Мaster Glenium ACE430, рН 3.5-7.5.

According to [8], these admixtures have practically no effect on the porosity and strength of the cement stone of the studied cements under normal hardening conditions.

3. Results

In figure 1 the dependence between the compressive strength \( f \) of the tested concretes and the value of W/C, type of cement and SP, conditions and duration of hardening was given.

![Figure 1](attachment:image.png)
In figure 2 the dependence between the tensile strength $f_t$ and the compressive strength $f_c$ of the tested concretes taking into account the type of cement and the additive the conditions and duration of hardening was given.

![Figure 2](image.png)

**Figure 2.** Dependence between the tensile strength of concrete $f_t$ and the compressive strength $f_c$, the type of cement and admixtures, the conditions and duration of hardening.

VB (P) 115 (430) NC (EC) 28 (90) – respectively cement VB, P; SP Master Glenium 115, Master Glenium ACE430; NC – normal conditions, EC – environmental conditions; $T$ – according to the formula $f_t = 0.29 \cdot f_c^{0.6}$ [9]; EN 1992-1-1 – according to the formula $f_{ctm} = f_c^{2/3}$.

In table 1 formulas describing the dependence of the compressive strength $f_c$ on the value of W/C were given. In table 2 formulas describing the dependence of the tensile strength $f_t$ on the compressive strength $f_c$ were given.

**Table 1.** Formulas describing dependence between the compressive strength $f_c$ and the value of W/C.

| Hardening conditions | Formula of strength at the age of 28 days | Formula of strength at the age of 90 days |
|----------------------|------------------------------------------|----------------------------------------|
| NC                   | $f_c = \frac{35.2}{(W/C)^{0.6}} \cdot 1 - R^2 = 0.041$ | $f_c = \frac{42.2}{(W/C)^{0.6}} \cdot 1 - R^2 = 0.626$ |
| EC                   | $f_c = \frac{39.1}{(W/C)^{0.6}} \cdot 1 - R^2 = 0.234$ | $f_c = \frac{35.7}{(W/C)^{0.6}} \cdot 1 - R^2 = 0.875$ |

a – the value $1 - R^2$ characterizes the proportion of dispersion that cannot be explained by regression.

**Table 2.** Formulas describing dependence between the tensile strength $f_t$ and the compressive strength $f_c$.

| Hardening conditions | Formula of strength at the age of 28 days | Formula of strength at the age of 90 days |
|----------------------|------------------------------------------|----------------------------------------|
| NC                   | $f_t = 0.26 \cdot R_c^{0.7}$; $1 - R^2 = 0.75^b$ | $f_t = 0.1 \cdot R_c^{0.72}$; $1 - R^2 = 0.74$ |
| EC                   | $f_t = 0.018 \cdot R_c^{1.3}$; $1 - R^2 = 0.45$ | $f_t = 0.022 \cdot R_c^{1.25}$; $1 - R^2 = 0.875$ |

b – the value $1 - R^2$ characterizes the proportion of dispersion that cannot be explained by regression.
4. Discussion
From data on figure 1 and in table 1 we may concluded:
- the compressive strength of concrete is unambiguously determined by the value of W/C only for concrete NC curing at the age of 28 days. In other cases the strength of concrete depends not only of the W/C value, but also of the hardening conditions and age. With increasing age of concrete the influence of other factors than W/C increases;
- at the age of 28 days, the studied hardening conditions have practically no effect on the strength of concrete. The maximum decrease in strength in EC is noted for the composition VB115 is 8%, and the increase in strength for the composition VB430 is 10%;
- data about the change in the strength of concrete after curing for 90 days in NC and EC are presented in table 3:

| Hardening conditions | Concretes compositions |
|----------------------|------------------------|
|                      | VB 115                |
|                      | VB 430                |
|                      | P 115                 |
|                      | P 430                 |
| NC                   | 0.935/1.07\(c\)       |
|                      | 1.08/1.23             |
|                      | 0.96/0.89             |
|                      | 1.18/1.24             |
| EC                   | 0.98/0.81             |
|                      | 1.04/1.03             |
|                      | 0.91/0.95             |
|                      | 1.09/1.11             |

- cement content 350/450 kg/m\(^3\).

From data presented in table 3 it is obvious that the SP Master Glenium 115 adversely affects on the increase in strength during prolonged hardening for both cements.

- the tensile strength of concrete after 28 days of hardening in NC is associated with a compressive strength by dependence, similar to the well-known formula \( f_{ctm} = 0.3 \cdot f^{2/3} \) (EN 1992-1-1). But in addition to compressive strength (i.e. the values of W/C), another factors that the formula does not take into account are influenced. Adhesion between cement stone and aggregates may influence on the tensile strength of concrete. Evaluation of the adhesion strength of cement stone with aggregate according to the method [10] showed adhesion values from 0.73 to 1.54 MPa;
- in other cases, the tensile strength of concrete depends not only on the magnitude of compressive strength (W/C), but also from hardening conditions, concrete age, type of SP. With increasing concrete age the dependence between tensile strength and compressive strength becomes more linear, and with a decrease in W/C increases more intensely;
- all cases are characterized by a strong influence on the ratio of tensile strength and compression of another factors that are not taken into account in the formula \( f_{t} = a \cdot f^{x} \);
- at the age of 28 days the tensile strength of concrete during hardening in the EC is lower than when hardening in NC for concrete with a cement content of 350 kg/m\(^3\), with a cement content of 450 kg/m\(^3\), the hardening conditions practically do not affect the tensile strength of concrete;
- at the age of 90 days the decrease in tensile strength after hardening in the EC is from 7 to 26% relative to concrete cured in NC;
- data about change the strength of concrete after curing during 90 days in NC and EC are presented in table 4:

| Hardening conditions | Concretes compositions |
|----------------------|------------------------|
|                      | VB 115                |
|                      | VB 430                |
|                      | P 115                 |
|                      | P 430                 |
| NC                   | 0.89/1.11\(d\)        |
|                      | 1.01/1.49             |
|                      | 1.14/1.09             |
|                      | 1.22/1.17             |
| EC                   | 0.84/1.10             |
|                      | 1.23/1.0              |
|                      | 0.92/1.08             |
|                      | 1.31/1                |

- cement content 350/450 kg/m\(^3\).

Obviously from the point of view of increasing the tensile strength of concrete during long period, the use of SP Master Glenium ACE430 is preferable.
From an economic point of view cement content for obtaining concrete with required strength is an important indicator. In figure 3 it is shown the dependence between the compressive strength of concrete and the W/C with taking into account the type of SP after 28 days of curing in NC.

![Figure 3](image_url)

**Figure 3.** The influence of W/C and type of SP on the compressive strength of concrete after 28 days of curing in NC.

It is obvious that in case of using the SP Master Glenium ACE430 we have an advantage. But concrete mixes with required workability were obtained with different water content: mixtures with Master Glenium ACE430 had the water content from 191 till 198 l/m³, and mixtures with Master Glenium 115 had the water content from 157 till 174 l/m³, which predetermined different cement content. In figure 4 the cement contents for the studied cements with admixtures to obtain concretes of classes C40/50 and C55/67 were given.

![Figure 4](image_url)

**Figure 4.** Cement content for concrete classes C40/50 and C55/67.

From fig. 4 it is obvious that depending from the hardening conditions the type of cement and SP concrete class C40/50 can be obtained with cement content from 321 till 371 kg/m³, and class C55/67 - from 446 till 517 kg/m³, and less content cement provides the use of SP Master Glenium 115. Since
the prime cost of the concrete mix is largely determined by the cement content, it is obvious that preference should be given to the concrete compositions with SP Master Glenium 115.

5. Conclusion
Comparing the efficiency of concretes made with various SP only on the basis of a comparison of the relative indicators of concrete properties \(f_{90}/f_{28}; f_t = f(f; f = f(W/C))\) without taking into account the effect of the SP on the water and cement content in the concrete mix can lead to erroneous conclusions. A reliable assessment should be made taking into account the influence of the SP on the composition and cost of the concrete mix, shrinkage, creep and E-modulus of concrete [11 - 24].

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