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Calculation of plastic viscosity of concrete mixture using the modified empirical formula

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Abstract. Nowadays various types of viscometers are being designed to measure the rheological properties of cement paste and fresh concrete. Most of them are very expensive and require specific knowledge about their usage. Then in practice usually the empirical formulas are used to calculate the main rheological properties – yield stress (Pa) and plastic viscosity (Pa·s). Therefore, in the literature, there are some formulas which can't be used to calculate analytically plastic viscosity of concrete mixture, e.g. it cannot estimate the influence of different chemical admixture on plastic viscosity of concrete. The paper focuses on the modification of the empirical formula to calculate the plastic viscosity of fresh concrete mixture. In this paper the way of viscosity formula modification was described. For an empirical formula modification, the coefficients which describe the influence of different chemical admixture on plastic viscosity of concrete mixture were used. Coefficients $K_{calc.}$ were calculated as a ratio between different viscosity values of cement pastes obtained without and with certain chemical admixtures. Viscosity of cement paste was obtained by using rotational viscometer Rheotest RN4. Coefficients describe the change in cement pastes viscosity when adding different type (superplasticizer, viscosity modifying agent, air-entraining agent and air voids removing agent) and amount of chemical admixture.

Keywords: concrete mixture, empirical formula, plastic viscosity

1. Introduction

Concrete is the most popular material which is used in construction field nowadays. Estimation of rheological properties of concrete mixtures and optimization of their compositions are important tasks in the modern construction technology. Rheological parameters according to Bingham model can be calculated according to the equation (1) [1,2]:

$$\tau = \tau_0 + \eta \cdot \bar{\gamma} \tag{1}$$

where: τ – shear stress, Pa; τ_0 – yield stress, Pa; $\bar{\gamma}$ – shear rate, s^{-1}; η – plastic viscosity, Pa·s.

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Various type of viscometers are being used to determine the rheological parameters of fresh concrete They measure the shear stress at varying shear rates [3,4]. However, most of them are very expensive and require specific knowledge to use them. An alternative approach for modelling the rheological behaviour of fresh concrete was proposed. The values of yield stress and plastic viscosity are correlated to the slump value and the flow time, respectively [5-13]. According to scientist [5], the relation between the yield stress τ_0 and the slump flow *S* does not depend on the mould geometry. The study [12] presented the comparative analysis of various viscosity models including Hu, Ferraris and De Larrard and of Toutou. The calculations were based on changes of plastic viscosity of concrete mixture depending on relative solid concentration (Φ- the solid volume of concrete /Φ*- maximum solid concentration of mixture) of mixtures. According to authors, the proposed models assume that the concrete is divided into two scales: paste (water, cement, additives and superplasticizers) and aggregate (sand and gravel). The model takes in-to the account the effect of additives and the superplasticizers (content and type).

The plastic viscosity is defined as the proportional coefficient between shear stress and shear rate under a state of steady shear, and it is greatly affected by colloidal particle interaction forces including Brownian forces, hydrodynamic forces and viscous forces be-tween particles [11]. The changes in cement paste viscosity have a great effect on the plastic viscosity values of fresh concrete. Due to this assumption, the change of cement paste viscosity adding different type and amount of chemical admixtures was established.

The aim of the study was to determine the possibilities of modification of empirical formula which could estimate the influence of different chemical admixture on the plastic viscosity of fresh concrete.

2. Materials and methodology

The Portland cement CEM II/A-LL 42. R confirming to the European standard EN 197-1 was used for the test. Physical and mechanical properties of Portland cement are presented in Table 1.

Table 1. Physical and mechanical properties of Portland cement

Property	Value
Specific surface area, m^2/kg	410
Particle density, kg/m^3	3.05
Normal consistency of cement paste, %	26.5
Volume stability, mm	0.8
Initial setting time, min.	195
Compressive strength after 2 days / 28 days, MPa	27.1 / 54.0
Loss on ignition, %	5.05
Insoluble materials, %	-
SO_3, %	2.48
Cl^-, %	0.015
Alkalis, calculated by Na_2O equivalent, %	<0.8

Two different sizes of fine aggregate from “Kvesu” quarry were used in this study: sand fraction 0/1with bulk density 1520 kg/m^3, fineness module 1.78 and sand fraction 0/4 with bulk density 1710 kg/m^3, fineness module 2.62. Sieve analysis of the fine aggregate is conducted according to EN 12620 and presented in Table 2. Gravel fraction 4/16 and bulk density 1327 kg/m^3 was used as the coarse aggregate. Sieve analysis of the fine aggregate and coarse aggregate are conducted according to EN 12620 and presented in Table 2.

Cement pastes were mixed in the laboratory in forced type mixer „Automix“. Cement was dosed by weight, water and different chemical admixtures were dosed by volume. The plasticizing admixture was mixed with water and poured into the mixer. Remaining admixtures were dozed directly to the cement paste.

Concrete mixtures were mixed for 3 minutes in the laboratory in forced type concrete mixer. Only dry aggregates were used for concrete mixtures. Cement and aggregates were dosed by weight while on the other hand, water and different chemical admixtures were dosed by volume. 90% of water was instantly poured into the mix. The plasticizing admixture was mixed with 10% of remaining water and poured into the mixer. Remaining admixtures were dozed directly to the mix.

Table 2. Sieve analysis of the fine and coarse aggregates

Diameter of the sieve's mesh, mm	The amount of poured out material, %		
	Sand fraction 0/1	Sand fraction 0/4	Gravel fraction 4/16
16.0	100.00	100.00	98.80
8.0	100.00	100.00	42.10
4.0	100.00	95.10	4.30
2.0	99.80	81.80	1.00
1.0	99.10	54.60	0.52
0.500	77.40	12.40	0.44
0.250	2.20	0.70	0.36
0.125	0.50	0.30	0.32
0.000	0.00	0.00	0.00

The description of chemical admixtures which were used in this study are presented in Table 3.

Table 3. Description of chemical admixtures

	Glenium SKY628	Rheomix 880	Rheomatrix 100	Microair G (LP)
Purpose	Superplasticizer	Air voids remover	Viscosity modifier	Air entrainer
Compound-based	Polycarboxylate ether	Propoxylate-etoxylate	Synthetic copolymer	Modified resin
Dosage, %	0.6-1.8	0-0.3	0-1.1	0-0.3
Density, g/cm^3	1.06-1.10	0.97 – 0.02	1.0-1.02	0.98-1.04
Viscosity, mPa·s	-	<600	-	-
pH	-	-	6-9	9-11
Chloride quantity, %	<0.1	-	<0.1	<0.01

The slump of the concrete mixture was evaluated according to standard EN 12350-2 and the density - according to standard EN 12350-6.

The rheological properties of cement pastes were obtained using rotational viscometer Rheotest RN4. The plastic viscosity values of cement paste are presented in Table 4. Viscometer consists of measuring drive with quick acting coupling rotor or cone and measuring cup coupling, connecting cable for control unit connection and stand with a temperature-controlled plate guide. For the test was used the cylinder measuring system which consists of the measuring cup (assembled) with coupling and cylinder rotor. General technical data of equipment: torque 0.1 to 150 mNm; speed range 0 to 1000 rpm; frequency: 0.001...10 Hz; viscosity 1…107 mPas; share rate 0.13...1300 s^{-1}.

Concrete mixture`s rheological property yield stress was evaluated according to equation (2). The yield stress of non-vibrated concrete mixture was calculated according to its fresh technological parameters: density and slump [13]. This equation was adjusted according to the standard cone which is used to evaluate the slump of the concrete mixture.

$$\tau_0 = \frac{0.00815 \cdot \rho_m}{\left(\sqrt{\frac{0.498}{30-SL}} - 0.001724 - 0.024\right)^2}; \tag{2}$$

where: τ_0 – yield stress of concrete mixture, Pa; ρ_m – density of concrete mixture, kg/m^3; SL – slump of concrete mixture, cm.

Second mixture`s rheological property – plastic viscosity was evaluated according to equation (3). Plastic viscosity is established by the concentration of aggregates which are used in the concrete mixture [13].

$$\eta_b = \eta_v \cdot \exp\left(\frac{a_c \cdot \rho_v}{\rho_v + \frac{V}{C} \cdot \rho_c - b_c \cdot \rho_v} + \frac{a_{sm}\left(1-\varphi_{st}-\varphi_o-\frac{V}{\rho_v}-\frac{C}{\rho_c}\right)}{1-\varphi_{st}-b_{sm}\left(1-\varphi_{st}-\varphi_o-\frac{V}{\rho_v}-\frac{C}{\rho_c}\right)} + \frac{a_{st} \cdot \varphi_{st}}{1-b_{st} \cdot \varphi_{st}}\right); \tag{3}$$

where: η_v – dynamic viscosity of water in 20 °C, Pa·s; φ_o – air content of concrete mixture, %; V, C – water and cement quantities in concrete mixture (1 m^3); ρ_v, ρ_c – densities of water and cement, kg/m^3; φ_{st} – volume concentration of coarse aggregate in concrete mixture; a_c, a_{sm}, a_{st} – factors describing the form of cement, fine and coarse aggregate`s particles ($a_c = 2.6$; $a_{sm} = 2.5$; $a_{st} = 2.6$); b_c, b_{sm}, b_{st} – factors describing the density distribution of cement, fine and coarse aggregate respectively in cement paste, mortar and concrete mixture.

The empirical formula (3) was modified by a coefficient $K_{calc.}$ that describes the influence of different chemical admixture on the plastic viscosity of concrete mixture (4).

$$\eta_b = \eta_v \cdot \exp\left(\frac{a_c \cdot \rho_v}{\rho_v + \frac{V}{C} \cdot \rho_c - b_c \cdot \rho_v} + \frac{a_{sm}\left(1-\varphi_{st}-\varphi_o-\frac{V}{\rho_v}-\frac{C}{\rho_c}\right)}{1-\varphi_{st}-b_{sm}\left(1-\varphi_{st}-\varphi_o-\frac{V}{\rho_v}-\frac{C}{\rho_c}\right)} + \frac{a_{st} \cdot \varphi_{st}}{1-b_{st} \cdot \varphi_{st}}\right) \cdot K_{calc.} \tag{4}$$

where: $K_{calc.}$ – the coefficient which describes the change in mixture`s plastic viscosity when using different type and content of chemical admixture.

3. Results and discussions

Coefficient $K_{calc.}$ was calculated as a ratio between different viscosity values of cement pastes obtained without and with certain chemical admixtures. Table 4 shows the calculated coefficient`s $K_{calc.}$ values. Rheological properties of the yield stress (Eq. 2) and the plastic viscosity (Eq. 4) with different type and content of chemical admixture were analysed.

The content of chemical admixture was gradually increased. The dosage of superplasticizing admixture based on polycarboxylate ether varied in the range from 0.6 to 1.4% of cement mass, the dosage of air voids removing admixture based on propoxylate-etoxylate – from 0.05 to 0.3%, dosage of viscosity modifying admixture based on synthetic copolymer – from 0.1 to 1.1% and dosage of air entraining admixture based on modified resin – from 0.05 to 0.3% (Table 4). In addition, the content of superplasticizing admixture was constant (1.4% of cement) and content of air voids removing admixture, viscosity modifying admixture and the air-entraining admixture was gradually increased, respectively. During the research, W/C ratio was constant 0.47.

Table 4. Coefficients describing the change in cement paste viscosity when adding different type and amount of chemical admixture

No.	Chemical admixture content, %	Plastic viscosity of cement paste, Pa·s	Calculated coefficient, $K_{calc.}$
Superplasticizing admixture alone			
1	0	0.506	-
2	0.6	0.093	0.184
3	0.8	0.093	0.183
4	1.0	0.043	0.085
5	1.2	0.039	0.077
6	1.4	0.039	0.077
Superplasticizing admixture (1.4 %) and air voids removing admixture			
1	0	0.039	0.077
2	0.05	0.043	0.085
3	0.10	0.036	0.071
4	0.15	0.043	0.085
5	0.20	0.043	0.085
6	0.25	0.043	0.085
7	0.30	0.032	0.063
Superplasticizing admixture (1.4 %) and viscosity modifying admixture			
1	0	0.039	0.077
2	0.1	0.032	0.063
3	0.3	0.032	0.063
4	0.5	0.032	0.063
5	0.7	0.032	0.063
6	0.9	0.034	0.067
7	1.1	0.046	0.091
Superplasticizing admixture (1.4 %) and air entraining admixture			
1	0	0.039	0.077
2	0.05	0.029	0.057
3	0.10	0.029	0.057
4	0.15	0.029	0.057
5	0.20	0.029	0.057
6	0.25	0.030	0.059
7	0.30	0.032	0.063

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Concrete mixture compositions are given in Table 5.

Table 5. Compositions of the concrete mixture.
Amount of materials for 1m^3 of concrete mixture

Materials	Unit	Concrete mixture compositions						
		BA4-0	BA4-1	BA4-2	BA4-3	BA4-4	-	-
Portland cement	kg	380	380	380	380	380	-	-
Water	l	178	178	178	178	178	-	-
Gravel fraction 4/16	kg	986	986	986	986	986	-	-
Sand fraction 0/4	kg	574	574	574	574	574	-	-
Sand fraction 0/1	kg	286	286	286	286	286	-	-
Superplasticizer	l	2.15	2.87	4.03	4.30	5.02	-	-
W/C	–	0.47	0.47	0.47	0.47	0.47	-	-
		BA5-0	BA5-1	BA5-2	BA5-3	BA5-4	BA5-5	BA5-6
Portland cement	kg	380	380	380	380	380	380	380
Water	l	178	178	178	178	178	178	178
Gravel fraction 4/16	kg	986	986	986	986	986	986	986
Sand fraction 0/4	kg	574	574	574	574	574	574	574
Sand fraction 0/1	kg	286	286	286	286	286	286	286
Superplasticizer	l	5.02	5.02	5.02	5.02	5.02	5.02	5.02
Air voids remover	l	-	0.20	0.39	0.59	0.78	0.98	1.18
W/C	–	0.47	0.47	0.47	0.47	0.47	0.47	0.47
		BA6-0	BA6-1	BA6-2	BA6-3	BA6-4	BA6-5	BA6-6
Portland cement	kg	380	380	380	380	380	380	380
Water	l	178	178	178	178	178	178	178
Gravel fraction 4/16	kg	986	986	986	986	986	986	986
Sand fraction 0/4	kg	574	574	574	574	574	574	574
Sand fraction 0/1	kg	286	286	286	286	286	286	286
Superplasticizer	l	5.02	5.02	5.02	5.02	5.02	5.02	5.02
Viscosity modifier	l	-	0.38	1.14	1.90	2.66	3.42	4.18
W/C	–	0.47	0.47	0.47	0.47	0.47	0.47	0.47
		BA7-0	BA7-1	BA7-2	BA7-3	BA7-4	BA7-5	BA7-6
Portland cement	kg	380	380	380	380	380	380	380
Water	l	178	178	178	178	178	178	178
Gravel fraction 4/16	kg	986	986	986	986	986	986	986
Sand fraction 0/4	kg	574	574	574	574	574	574	574
Sand fraction 0/1	kg	286	286	286	286	286	286	286
Superplasticizer	l	5.02	5.02	5.02	5.02	5.02	5.02	5.02
Air entrainer	l	-	0.19	0.38	0.57	0.76	0.95	1.14
W/C	–	0.47	0.47	0.47	0.47	0.47	0.47	0.47

As shown at Table 6, the slump of concrete mixture with different type and content of chemical admixture varied in the range from 220 to 260 mm and the density of concrete mixture – from 2360 to 2400 kg/m^3. The consistency of concrete mixture varied in the S5 (≥220±30 mm) class range according to standard EN 12350-2.

Table 6. Technological properties of the concrete mixtures

Technological property	Unit	Concrete mixture compositions						
		BA4-0	BA4-1	BA4-2	BA4-3	BA4-4	-	-
Density	kg/m^3	2360	2390	2360	2400	2400	-	-
Slump	mm	240	240	220	260	250	-	-
		BA5-0	BA5-1	BA5-2	BA5-3	BA5-4	BA5-5	BA5-6
Density	kg/m^3	2400	2390	2390	2380	2390	2390	2380
Slump	mm	250	220	250	250	240	250	250
		BA6-0	BA6-1	BA6-2	BA6-3	BA6-4	BA6-5	BA6-6
Density	kg/m^3	2400	2390	2390	2380	2370	2380	2360
Slump	mm	250	240	250	240	230	230	230
		BA7-0	BA7-1	BA7-2	BA7-3	BA7-4	BA7-5	BA7-6
Density	kg/m^3	2400	2390	2400	2390	2370	2370	2380
Slump	mm	250	250	250	260	240	250	260

The yield stresses of different compositions of concrete mixtures were calculated according to their fresh technological parameters: density and slump (Table 6) using equation (2). The plastic viscosity values of concrete mixtures with different type and content of chemical admixture were evaluated according to modified equation (4). Figure 1 – Figure 4 shows the influence of different type and content of chemical admixture on yield stress and plastic viscosity of the concrete mixture.

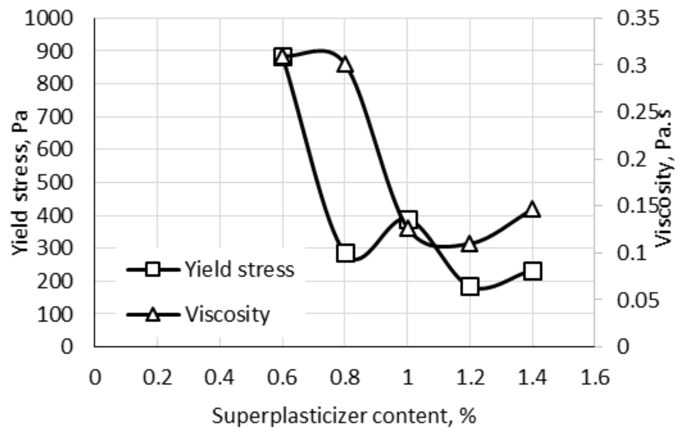

Figure 1. The dependence between superplasticizer content and mixture`s (BA4) yield stress and plastic viscosity

As can be obtained from Figure 1, the increase of superplasticizer content from 0.6 to 0.8% of cement mass in mixture composition decreased the yield stresses of fresh concrete from about 884 to 286 Pa (about 3.1 times). Further increase of superplasticizer content from 0.8 to 1.4% of cement mass in mixture composition showed that the yield stresses decreased about 1.2 times. The increase of superplasticizer content from 0.6 to 1.4% of cement mass in mixture composition gradually increased the plastic viscosity of fresh concrete from about 1.4 to 1.9 Pa.s (about 1.4 times). The superplasticizer based on polycarboxylate ether had a significant influence on fresh concrete rheological properties. This could be due to its adsorption effect on cement particles surface and dispersants to avoid particle segregation.

Figure 2 illustrates the relation between air voids removing admixture content and mixture`s yield stress and plastic viscosity. The increase of air voids removing admixture content from 0 to 0.3% of cement mass in mixture composition hadn't any significant influence on yield stresses of fresh concrete – yield stresses varied in the same range from about 234 to 233 Pa. The addition of air voids removing admixture of 0.3% of cement in mixture composition resulted in the decrease of plastic viscosity about 12% compared to viscosity without this admixture. Complex of chemical admixtures – superplasticizer (constant content) based on polycarboxylate ether and air voids removing admixture based on propoxylate-etoxylate hadn't any significant effect on yield stress and plastic viscosity values of fresh concrete.

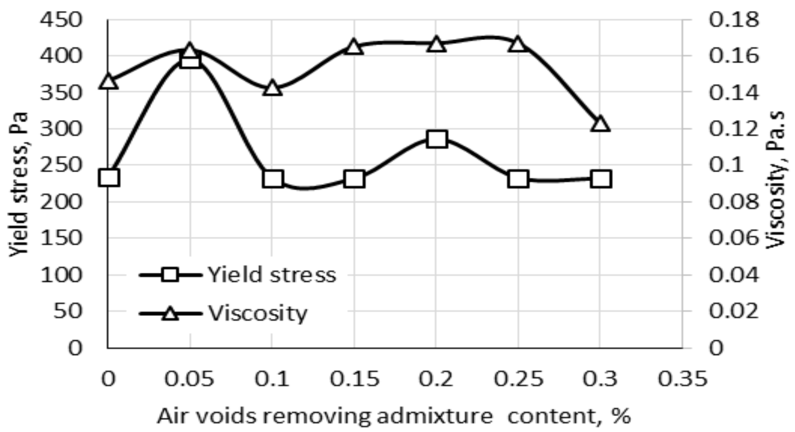

Figure 2. The dependence between air voids removing admixture content and mixture`s (BA5) yield stress and plastic viscosity

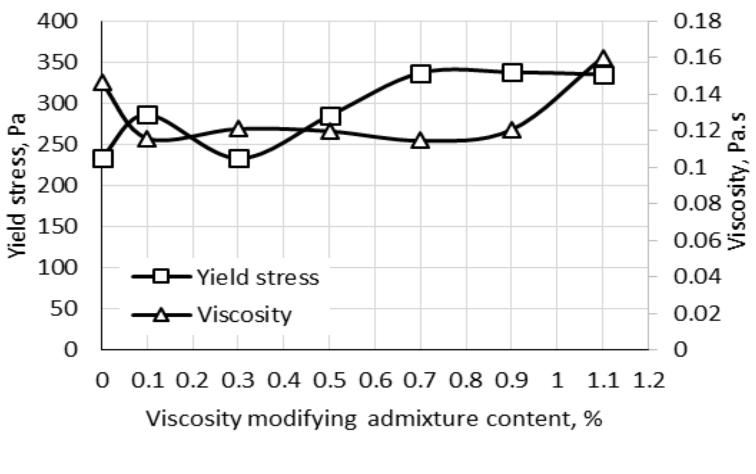

Figure 3. The dependence between viscosity modifying admixture content and mixture`s (BA6) yield stress and plastic viscosity

As can be seen from Figure 3, the increase of viscosity modifying admixture content from 0 to 1.1% of cement mass in mixture composition increased both the yield stresses of fresh concrete from about 234 to 335 Pa (about 1.4 times) and plastic viscosity of fresh concrete from about 0.14 to 0.16 Pa·s (about 0.9 times).

The complex of chemical admixtures – superplasticizer (constant content) based on polycarboxylate ether and viscosity modifying admixture based on synthetic copolymer increased the yield stress and plastic viscosity values of fresh concrete.

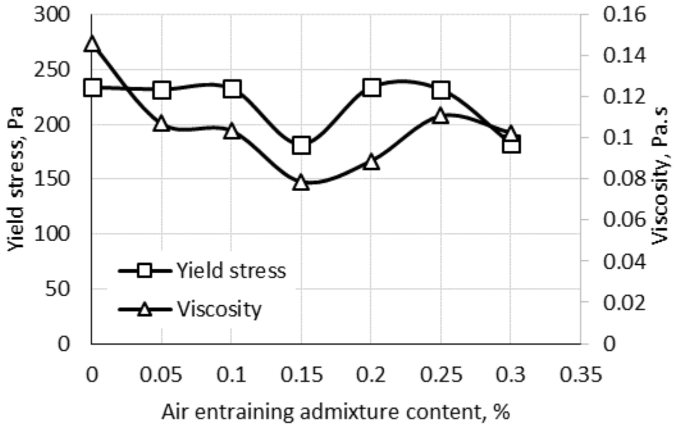

Figure 4. The dependence between air entraining admixture content and mixture`s (BA7) yield stress and plastic viscosity

Figure 4 illustrates the dependence between the air-entraining admixture`s content and mixture`s yield stress and plastic viscosity. The increase of air entraining admixture content from 0 to 0.3% of cement in mixture composition decreased both the yield stresses of fresh concrete from about 234 to 183 Pa (about 1.3 times) and plastic viscosity of fresh concrete from about 0.15 to 0.10 Pa·s (about 1.5 times). The complex of chemical admixtures – superplasticizer (constant content) based on polycarboxylate ether and air-entraining admixture based on modified resin decreased the yield stress and plastic viscosity values of fresh concrete.

To verify the obtained results, the modified empirical formula must be examined in future works and additional experiments are needed to be performed with other concrete mixtures compositions and different types of chemical admixtures.

4. Conclusions

Based on the modified empirical formula, plastic viscosity values of the fresh concrete mixture were calculated using different type and amount of chemical admixture. Coefficients $K_{calc.}$ were calculated as a ratio between different viscosity values of cement pastes obtained without and with certain chemical admixtures. Coefficients describing the change in cement paste viscosity adding the different type of solutions including superplasticizer, viscosity modifying, air-entraining and air voids removing agent were calculated. The change in cement paste viscosity adding different type and amount of chemical admixture was equated to the change in concrete mixture viscosity. To verify the obtained results, the modified empirical formula must be examined in future works and additional experiments are needed to be performed with other concrete mix-compositions and different types of chemical admixtures.

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