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Usability of mortar for predicting shear strength development at rest of fresh self compacting concrete

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HIGHLIGHTS

- Mortars can be used in the SCC design and for the optimal selection of materials.
- Mortars can be used for control influence of technological factors on the SCC rheology.
- g_s determines rheological parameters important for the shear strength at rest.
- A_T determines the rheological parameters relevant to formwork pressure.
- A_T and g_s depends on w/c ratio, the type of HRWR and cement.

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ABSTRACT

Determining the relationship between the rheological parameters of the model mortar and the rheological parameters of SCC (Self-Compacting Concrete) was the aim of the work. The static yield stress and the thixotropy coefficient A_T were determined, which are important due to the development of the shear strength at rest and the formwork pressure generated during SCC casting. Shear strength of SCC reflected as static yield stress g_s at rest develops mainly due to a self-compaction ability of SCC. And in the longer term, g_s develops due to the progressive hydration of the cement and the disappearance of the HRWR impact (loss of fluidity). The static yield stress g_s depends on w/c ratio, the type of HRWR (High Range Water Reducers) and cement. SCCs with a higher w/c ratio develop static yield stress g_s faster, but up to 40 min the influence of w/c ratio decreases. The stiffening of SCC due to thixotropy increases the shear strength of SCC, but at the same time, it slows down the self-compaction of concrete. Thixotropy coefficient A_T depends primarily on w/c ratio, and with the same w/c, on the type of cement and HRWR. The thixotropy coefficient A_T increases in the initial period of SCC being at rest. The SCC with higher w/c ratio are characterized by higher thixotropy coefficient A_T but at the same time by lower static yield stress g_s. The significance of the thixotropic effect for shear strength disappears in time.

1. Introduction

Self-compacting concrete (SCC) is characterized by specific rheological properties thanks to which it is able to flow and compact under its own weight, fill the formworks with reinforcement, ducts, boxouts etc., while maintaining homogeneity European Concrete Standard EN 206–1 and [1]. The technological, economic and ecological benefits of using SCC have been confirmed by a great number of applications in all kinds of constructions, engineering structures and infrastructure [12]. However, the use of SCC is not always without problems, with unpredictable formwork pressure highlighted as one of the key problems involving the excessive use of SCC [1-4]. In effect of its high flowability, SCC can generate much higher formwork pressure than CVC (Conventional Vibrated Concrete). Nowadays, when using SCC, vertical formworks are usually designed assuming the possibility of full hydrostatic pressure. For example, this approach is presented in the standard DIN 18,218 2010 and [5]. Rheological properties of SCC are listed as the main factor influencing formwork pressure [3], alongside its density, casting technique and formwork characteristics.

Rheological behaviour of SCC is usually characterized by the Bingham model parameters - yield stress and plastic viscosity [1,3,6-8]. As a common method to obtain yield stress, an equilibrium flow curve is plotted as the equilibrium shear stress – shear

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rate relationship. Since the publication of the Bingham model in 1922 [6], many models have been proposed to describe the equilibrium flow curve. However one of the most common models for cementitious materials is still the Bingham model. Some researchers[7-9] argue that as a linear model, it is unable to capture shear thinning and shear thickening behaviors that can be observed in cementitious materials. Bingham model is generally applicable for finding the flow properties of concrete and in certain cases, the flow curve obtained for SCC mixes using the Bingham model gives a negative value of yield stress which is physically not possible. So it is proposed the Herschel-Bulkley or a modified Bingham model then provides a good description of non-linear flow behavior. With each models, a measure of yield stress can be obtained. In our case, a good fit of the results to the Bingham model was obtained. Material parameters of Bingham model correctly characterize the behaviour of SCC when it is at steady state within the range of the evaluated shear rate interval. Thus, the yield stress according to the Bingham model is then referred to as the dynamic yield stress [3,7,10]. The dynamic yield stress defines the load at which SCC changes from the state of motion to the state of rest. Plastic viscosity defines the ability of SCC to flow in the steady state. The measurements of the dynamic yield stress and plastic viscosity are well founded for the purposes of SCC casting, since these parameters determine its flowability, segregation resistance and self-deaeration (self-compaction) ability. The studies summarized in [13] prove that the dynamic yield stress correlates very well with the slump flow of SCC and plastic viscosity with the flow time of SCC according EN 12350–8 Testing Fresh Concrete - Part 8: Self-Compacting Concrete - Slump-Flow Test and [11]. An example of such a correlation obtained for the Viskomat XL rheometer in the research study [12] is shown in Fig. 1 - slump flow is inversely proportional to the value of dynamic yield value g, and the time t_{500} is proportional to plastic viscosity h.

When SCC is left at rest in the formwork, it builds-up structure and develops shear strength which increases with time. The shear strength relates to the value of stress that has to be exceeded in the SCC for it to go from the state of rest to the state of motion [3]. This stress is later referred to as static yield stress [7]. The higher is the static yield stress of SCC, the higher is its ability to carry vertical load, and thus lower pressure on the formwork. In the case of SCC, the increase of static yield stress occurs as a result of the overlapping processes, i.e. self-compaction of the mixture, chemical hydration process of cement, loss of the High Range Water Reducer (HRWR) action in time [3]. The last two phenomena affect the dynamic yield stress and plastic viscosity and are referenced to workability loss. Other effects also have an influence on the static yield stress, among which thixotropy is of particular interest [3,7,13-16]. The thixotropy of SCC can be characterized by the thixotropy coefficient A_T [3]. Thixotropy is associated primarily with the presence of some HRWR, viscosity modifying admixtures (VMA) and thixotropic admixtures (TA) whose polymers are characterized by an extensive spatial structure and high molecular weight. Whereby admixtures can bind solid phase grains in the grout left to rest into a stiff structure [3]. The workability loss of SCC is in general an irreversible process, while thixotropy is reversible - under the influence of external load the said effect may completely or partially disappear [3,13-16]. Typical behaviours of SCC under the increasing and decreasing load are presented in Fig. 2.

The control of the rheological properties of SCC is crucial for its effective use. Therefore, a large number of studies have been devoted to this problem. However, these studies only concern the rheological properties of SCC in steady state and the influence of material and technological factors on the dynamic yield stress and plastic viscosity. Basing on them, in [1,3,19-28] it was found that these rheological parameters of SCC depend on paste volume in concrete, w/c ratio, aggregate type and grading, type and properties of cement, type and content of superplasticizer, presence of mineral additives and that of other admixtures, mixing method and temperature. Therefore the character of the influence of these factors on dynamic yield stress and plastic viscosity of SCC and its changes in time is generally well recognized. Little attention has been devoted to the problem of time dependent structural behaviour of SCC at rest, and the impact of material and technological factors on the value of static yield stress and thixotropy coefficient A_T of SCC is less documented. As demonstrated in the references [3,10,29-37,38-42], the most important factors influencing the value of static yield and thixotropy coefficient A_T are w/c ratio, the quantity and type of HRWR, as well as cement content and composition, the presence and type of mineral admixtures and the presence of VMA and TA admixtures. And although there is no doubt that through an appropriate selection of materials and mix design, shear strength and the development of the shear strength of SCC when it is resting in the formwork can be controlled, the nature of the impact of these factors on static yield value and thixotropy coefficient A_T has not been recognized satisfactorily, because it indicates various contradictions in the obtained results. For example, the prevailing view is that by using lower w/c ratio and higher addition of HRWR is obtained higher shear strength [38,39,41,42], but other studies, e.g. [40], indicate the opposite trend. Therefore, a large number of data in terms of rheological behaviour and the parameters of SCC at rest state still have to be collected.

Due to a large number of factors affecting the rheological properties of SCC and their complex interactions, it is difficult to predict the performance and robustness of SCC in specific technological

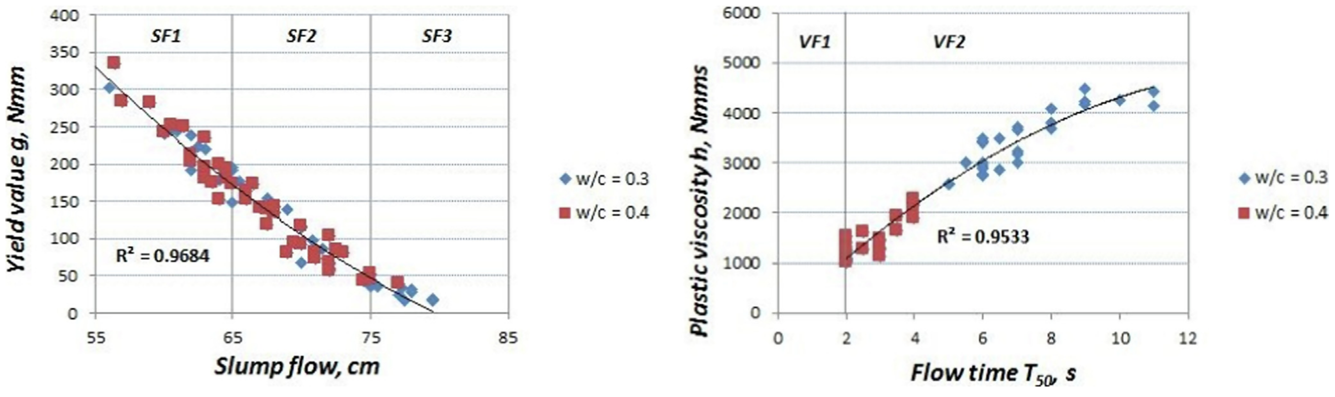


Fig. 1. Dependencies: slump flow vs. yield value g and flow time T_{50} vs. plastic viscosity h determined by rheometer Viskomat XL [12].

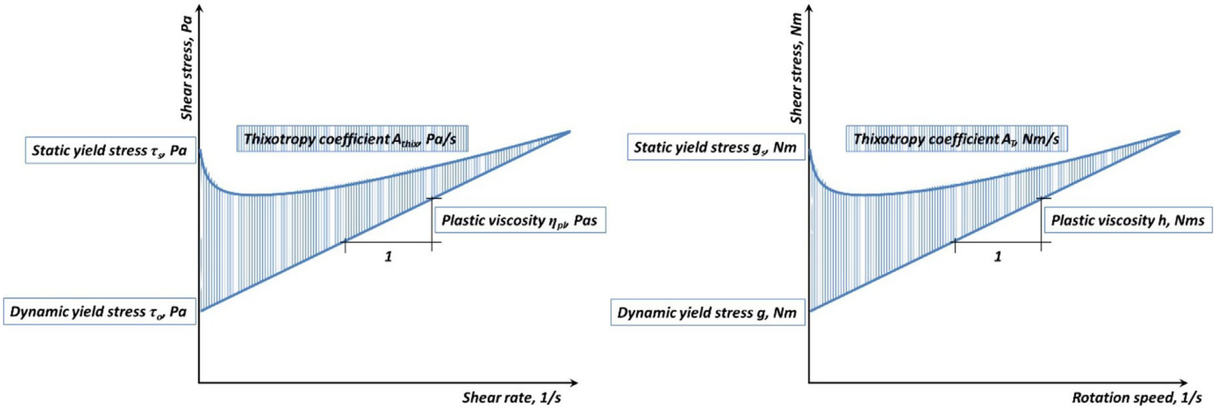


Fig. 2. Typical behavior of SCC under the increasing and decreasing shear rate and parameters characterizing its rheological properties [1718].

conditions. As a consequence, the process of designing and optimizing the SCC composition due to its rheological properties always involves the necessity to carry out experimental research, and it is usually done in a wide range. Time- and material-consuming rheological tests involving the influence of various constituents of the composition conducted on fresh concrete can be replaced by testing model materials. From the physical point of view, there is no difference in the structures of mortar and concrete - mortar can be considered as concrete without coarse aggregate, and the phenomena that occur inside are of similar nature [23,25,43-46]. Numerous studies have demonstrated that testing mortars allows to predict the rheological properties of fresh concrete [46], especially in the case of SCC, which is usually characterized by high mortar content [12,23,25,43,44,45,47,48,49]. However, these studies only focused on the rheological parameters of the materials in the steady state, i.e. the dynamic yield stress and plastic viscosity. Taking into account the above and the information presented earlier, concerning the lack of unequivocal results of the influence of composition factors on the static yield stress and thixotropy coefficient A_T of SCC, further research is necessary in this area.

Therefore the objective of this study was to verify whether, basing on the rheological tests of a model mortar, can be predicted rheological parameters of SCC, important due to its shear strength development at rest, and for formwork pressure generated during its casting - i.e. the static yield stress and the thixotropy coefficient A_T. Because SCCs of different mix designs have been used in the study, the significance and nature of the impact of the selected factors: w/c ratio, cement type and HRWR type on the rheological properties of SCC have been analysed also.

2. Experimental details

2.1. Research program

To meet the objectives of the study, the rheological properties of SCC with different composition and rheological properties of the corresponding model mortars were determined. The following rheological parameters were measured: dynamic yield stress and plastic viscosity (characterizing rheological properties in steady state) as well as static yield stress and thixotropy coefficient A_T (characterizing rheological properties in the state of rest) (Fig. 2). The mixtures having two different w/c ratios of 0.30 and 0.40 were prepared with the target slump flow of 650 ± 30 mm (SF1 - SF2 class according EN 12350–8 Testing Fresh Concrete - Part 8: Self-Compacting Concrete - Slump-Flow Test and [11]). Such SCCs are recommended by [12] for casting vertical elements such as walls and columns. The SCCs were characterized by the same volume of cement paste (360 dm/m^3)- the amount of cement and water was adjusted to the assumed w/c ratio. To obtain a wide range of variability of rheological properties of SCC, different cements (CEM I, CEM III/A, CEM V/A) and HRWR (carboxyl ethers SP1, SP2, SP3, SP4, SP5) were used. To obtain the target initial slump flow, HRWR dosage was experimentally adjusted. The amount of HRWR added to SCC with the w/c = 0.4 and 0.3 was on average 1% and 2.1% of the cement mass, respectively. At the same time, the amount of HRWR added to SCC with CEM I and CEM V was higher than that added to SCC with CEM III - on average 1.8% and 1.1% of the cement mass, respectively. The tests were carried out for 30 different SCCs, and the research program, the mix designs of SCCs and model mortars are presented in Table 1. The statistical analyses were performed using the Statistica® 13.1.

2.2. Concept of model mortars

The composition of model mortar should be adjusted to take into account the specifics of the structure of SCC, especially the impact of capillary cohesion and contact friction among aggregate, phenomena's which have significant influence on the changes of rheological properties of SCC in time and shear strength development in rest. In work [12] different methods of adjusting mortar composition were discussed and evaluated. It was established that optimal method of adjusting model mortars proportioning is the method assuring of the equal concrete and mortar dispersion ratio [12]. It has the best rheological correlation between mortar and SCC as a function of the time and temperature and it seems that they will also be useful for evaluation of shear strength development of SCC in rest. These mortar composition was based on the assumption of equal concrete and mortar dispersion ratio (2) (3) (4) (5), with a structure that well reflects the structure of concrete.

$$D_c/D_m = 1 \tag{1}$$

where: D_c – concrete dispersion factor, m; D_m – model mortar dispersion factor, m

The concrete dispersion ratio is following:

$$D_c = \frac{V_{cp,mix}}{S_a\hat{A}\cdot M_{aggr}}, m \tag{2}$$

where: $V_{cp,mix}$– the volume of cement paste in the fresh concrete, m^3; S_a – specific surface of aggregate, m^2/kg; M_{aggr} – the mass of the aggregate in the concrete mix (sand and coarse aggregate), kg

Table 1
Research program and proportioning of mortars and concretes (C - cement; W - water; S - sand 0–2 mm; A - coarse aggregate 2–8 mm).

Codes		Variables			Composition								
					Concrete					Mortar			
Concrete	Mortar	C	SP	w/c	C,kg/m^3	W,kg/m^3	SP, %C	S, kg/m^3	A, kg/m^3	C, kg/m^3	W,kg/m^3	SP, %C	S, kg/m^3
B1	Z1	CEM I	SP1	0,3	572	172	3.00	884	780	757	227	3.00	1346
B2	Z2	CEM I	SP2		580	174	2.00			767	230	2.00	
B3	Z3	CEM I	SP3		566	170	3.75			752	226	3.75	
B4	Z4	CEM I	SP4		580	174	2.00			767	230	2.00	
B5	Z5	CEM I	SP5		584	175	1.50			773	232	1.50	
B6	Z6	CEM III	SP1		573	172	1.75			757	227	1.75	
B7	Z7	CEM III	SP2		579	174	1.00			765	230	1.00	
B8	Z8	CEM III	SP3		567	170	2.50			750	225	2.50	
B9	Z9	CEM III	SP4		577	173	1.25			762	229	1.25	
B10	Z10	CEM III	SP5		577	173	1.25			762	229	1.25	
B11	Z11	CEM V	SP1		555	167	2.50			734	220	2.50	
B12	Z12	CEM V	SP2		559	168	2.00			739	222	2.00	
B13	Z13	CEM V	SP3		551	165	3.00			729	219	3.00	
B14	Z14	CEM V	SP4		555	167	2.50			734	220	2.50	
B15	Z15	CEM V	SP5		559	168	2.00			739	222	2.00	
B16	Z16	CEM I	SP1	0,4	508	203	1.00	884	780	672	269	1.00	1346
B17	Z17	CEM I	SP2		510	204	0.75			674	270	0.75	
B18	Z18	CEM I	SP3		502	201	2.00			664	266	2.00	
B19	Z19	CEM I	SP4		510	204	0.75			674	270	0.75	
B20	Z20	CEM I	SP5		510	204	0.75			674	270	0.75	
B21	Z21	CEM III	SP1		502	201	0.75			664	266	0.75	
B22	Z22	CEM III	SP2		504	202	0.50			666	266	0.50	
B23	Z23	CEM III	SP3		501	200	1.25			660	264	1.25	
B24	Z24	CEM III	SP4		502	201	0.75			664	266	0.75	
B25	Z25	CEM III	SP5		502	201	0.75			664	266	0.75	
B26	Z26	CEM V	SP1		489	196	1.50			646	258	1.50	
B27	Z27	CEM V	SP1		493	197	0.75			652	261	0.75	
B28	Z28	CEM V	SP2		487	195	1.75			644	258	1.75	
B29	Z29	CEM V	SP3		492	197	1.00			650	260	1.00	
B30	Z30	CEM V	SP4		492	197	1.00			650	260	1.00	

The model mortar dispersion ratio is following:

$$D_m = \frac{V_{cp,m}}{S_s\hat{A} \cdot M_s}, m \tag{3}$$

where: $V_{cp,m}$ – corrected volume of cement paste in the mortar calculated according (4), m^3; S_s – static specific surface area of sand, m^2/kg; M_s – the mass of the sand in the concrete mix, kg

Corrected volume of cement paste in the mortar is following:

$$V_{cp,m} = V_{cp,mix}\frac{S_a \cdot M_{aggr}}{S_s\hat{A} \cdot M_s}, m^3 \tag{4}$$

Dispersion ratio concept is presented in details in [50], the method of calculating composition of in [12]. In general, dispersion ratio D is formulated as ratio of volume of continuous dispersing phase (cement paste) to specific surface of dispersed phase (sand + coarse aggregate). If simply the coarse aggregates is removed from concrete, aggregate surface is reduced. With unchanged cement paste volume dispersion ratio of mortar is then larger than of concrete. Such mortar is more fluid, shows a tendency for segregation, sedimentation and capillary cohesion and contact friction among aggregate disappear or are extremely weak. To have the same concrete and mortar dispersion ratio it is necessary to subtract a volume of cement paste $V_{cp,m}$ (4) adequately to reduced surface by removed coarse aggregate. It can be calculated from the condition of equality D_c (2) and D_m (3). Usefulness of such model mortars for predicting influence of time and temperature on SCC rheological parameters - dynamic yield stress and plastic viscosity - was proven in [12].

2.3. Materials and mix design

SCC was designed according to the method presented in [26]. The mix designs of SCC and model mortars are presented in Table 1. All SCCs are characterized by the same volume of cement paste (360 dm/m^3) and aggregate. The assumed variation of rheological properties was obtained through a significant differentiation of the w/c ratio and that of the cement and HRWR type. Basic properties of the cements and HRWRs are presented in Tables 2 and 3. Date obtained from the manufacturer of cement and admixture. Cement was characterized using XRF by manufacturer. Natural sand of 0–2 mm and coarse aggregate of 2–8 mm were used, and the combined grading of aggregate is presented in Fig. 3. The particle size distribution of cement is presented in Fig. 4.

2.4. Measuring method of rheological properties of SCC and mortars

The measurements of rheological properties have been performed using rotational rheometers: Viskomat NT (Schleibinger Instruments) for the mortars and Viskomat XL(Schleibinger Instruments) for fresh concrete [51]. The Viskomat NT is a true speed controlled viscometer driven by a high precision synchron motor. Each rotation is resolved whithin 200.000 steps. It allows ramping from 0.001 rpm to 400 rpm in both directions to record flow curves and yield points. The torque up to ± 250 Nmm or ± 500 Nmm is measured by a special transducer. The operation principle of the viskomat XL is near the same as for the Viskomat NT. The Viskomat XL has a torque range from 0.0.10000 Nmm with a resolution of 0.05 Nmm and accuracy better then 0.02 Nm. The speed may be 0.0001 to 80 rpm in both directions, clockwise or counter clockwise. As option also an oscillating or shear stress controlled mode is possible. The theoretical basis and the rules involving rheological measurements with the application of rotational rheometers are generally discussed in [3,43,44]. Since measurement constants were not determined for these rheometers, the results are presented using rheological constants in equivalent units - g [Nmm], h [Nmms], g_s [Nmm] and A_T [Nmm/s], corresponding to dynamic

Table 2
Properties of cement. Date obtained from the manufacturer of cement.

Cement	Ingredients, [%]							Specific surface,[m^2/kg]	Density, [g/cm^3]
	SiO_2	CaO	Al_2O_3	Fe_2O_3	MgO	Na_2O_{eq}	SO_3		
CEM I 42.5 R,	21.6	64.4	4.5	2.2	1.3	0.40	3.1	333	3.10
CEM III/A 42.5 N-HSR/NA	30.2	52.2	6.4	1.8	3. 5	0.8	3.3	385	3.00
CEM V/A 32.5 (S-V) R-LH	29.2	49.3	9.5	2.8	2.4	1.3	2.2	338	2.88

Table 3
Properties of superplasticizers. Date obtained from the manufacturer of admixture.

SP	Major constituentaccording producer	Density, [g/cm^3]	Concentration, [%]
SP1	carboxyl ether	1.07	30.1
SP2	carboxyl ether	1.06	32.0
SP3	carboxyl ether	1.04	19.6
SP4	acrylic polymer	1.07	27.9
SP5	carboxyl ether	1.08	38.0

yield stress, plastic viscosity, static yield stress and thixotrophy coefficient A_T, respectively. It should be noted, that Banfill et al., in [52] found that different rheometers gave very different values of yield stress and plastic viscosity for the same concrete, even if the measurement with these instruments gave the values directly in fundamental units. Altogether it proves that when using different rheometers, it is possible to describe rheology of fresh concrete well enough, regardless of whether it was in physical units or equivalent to physical ones.

The references [3,13,30,53,54,55,56] indicate three main approaches to the measuring of the rheological parameters of SCC at rest: (i) measuirng the loopcurve of hysteresis, (ii) measuring the static yield stress at constant shear speed and (iii) mixed measurements, combining the procedures (i) and (ii). The approach (i) allows to determine a full rheological profile of the mix. The presence and the magnitude of the thixotropic effect may be determined on the basis of the analysis of the loopcurve of hysteresis, as an area between the upper curve and lower curve of the loop of hysteresis and expressed as the thixotropy coefficient A_T. Since the shear speed changes during the measurement, using such a method for the definition of static yield stress is difficult. The approach (ii) allows to determine static yield stress, but since the measurement is conducted at very low and constant shear rate, it is not possible to determine other rheological parameters of the concrete mix. The best solution, which combines the advantages of both measurement methods, is the approach (iii), which was adopted in the following research. The procedure is presented in Fig. 5. This procedure, inspired by the procedures used in [53,55], consists of two phases - (i) measuring shear resistance at an extremely low shear speed and measuring the histeresic loop-curve (ii). In (i), it is possible to measure the static yield stress, and in (ii) – the dynamic yield stress, plastic viscosity and thixotrophy coefficient A_T.

The SCC and model mortars were prepared in planetary mixers of the capacity of 30 dm^3 and 2 dm^3 respectively, using analogous mixing procedures. Portland cement, sand and gravel were dry mixed in the mixer for 30 sec. Next, water containing HRWR was added. The total mixing time was 5 min. The measurements of the rheological parameters of SCC and model mortars were performed using the sequence shown in Fig. 5. Immediately after the completion of mixing, three measuring vessels were filled with SCC (or model mortar) and rheological parameters were measured at 5, 20 and 40 min after the completion of mixing. Next, the SCC (or model mortar) was remixed at 75th minute. Then, two measuring vessels were filled with SCC, and rheological parameters were measured at 80 and 100 min after the completion of mixing. It was not possible to carry out further measurements for the majority of mixtures due to their rapidly progressing stiffening.

In general, the rheological measurements were performed without repetition. However, for the selected SCCs and model mortars, series of 4 repeats were made (20% of mortars and 10% of SCC). The average coefficients of variation V for g and h of the mortars were V_g = 4,6% (V_{gmax} = 6.5%) and V_h = 4,1% (V_{hmax} = 7.1%), and of the SCC - V_g = 6,5% (V_{gmax} = 8.5%) and V_h = 5,8% (V_{hmax} = 7.5%), respectively. The average coefficient of variation V for g_s was V_{gs} = 6.1% ($V_{gs\ max}$ = 8.9%) for the mortars and V_{gs} = 7.9% (V_{gsmax} = 9.4%) for the SCC, and the coefficient of variation V for A_T was V_{AT} = 6.2% (V_{ATmax} = 9.3%) for the mortars and V_{AT} = 7.3% (V_{ATmax} = 11.3%) for the SCC. The average coefficients of variation V for the measure-

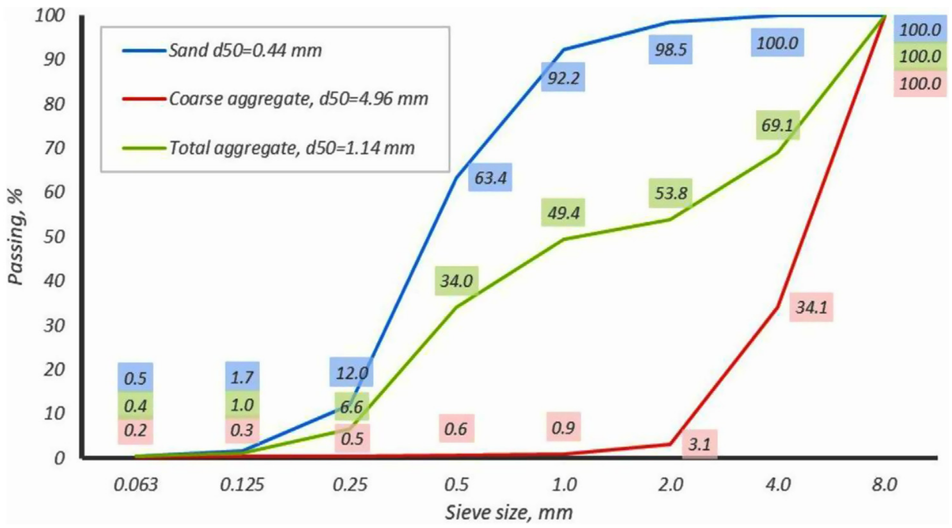


Fig. 3. Sieve analysis for sand (model mortars) and aggregate (SCC).

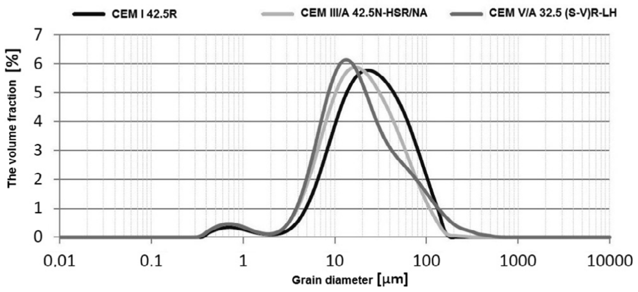


Fig. 4. The particle size distribution of cement.

ments of all rheological parameters are clearly lower than 10%. It allows us to assess the repeatability of the performed rheometer measurements as good.

3. Results and discussion

The relationship between the rheological parameters of model mortars and SCC is presented in Fig. 6. The rheological properties of SCC and those of the corresponding model mortars are presented in Figs. 7 - 10. All tested SCCs were characterized by an initial flow of 650 ± 30 mm. The SCCs with w/c = 0.3 were stable and did not show bleeding (VSI 0 according [57]). The SCCs with w/c = 0.4 were also stable, but bleeding was sometimes visible (VSI 0 - VSI 1 according [57]), so these SCC may show a tendency towards faster sedimentation.

3.1. The suitability of mortars for the prediction of rheological properties of SCC

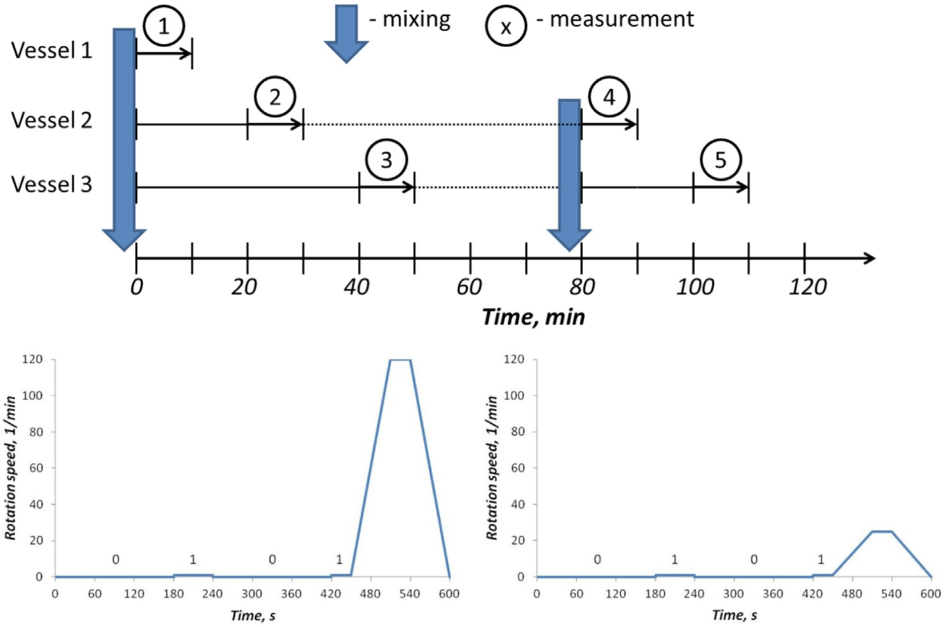
The obtained results clearly show that there is a compatibility between the rheological parameters of model mortars and SCC. It has been confirmed that the measurements of the rheological properties of model mortars can be used for predicting the rheological properties of SCC in both steady and rest states. The relationship between the rheological parameters of model mortars and SCC can be described by the linear functions shown in Fig. 6. At the same time, the values of the rheological parameters of SCC are clearly higher than those of model mortars. Thus, the obtained linear functions allow to convert the measured values of the rheological parameters of model mortars into the rheological parameters of the SCC of the analogical volume of mortar and coarse aggregate sized up to 8 mm. However, it should be emphasized that the relationship between the rheological parameters of model mortars and SCC does not depend on mortar components and composition. The slope coefficients of these functions depend on the volume of mortar in the SCC and on the grain size of the aggregate, as demonstrated in [24]. For the mixtures with different mortar volume and/or with different aggregate, the slope coefficients must be determined experimentally.

3.1.1. Rheological properties of SCC at steady states

The main aim of the work is to correlate the rheological parameters of the model mortar and SCC in the rest state, however, for comparison, the correlation of rheological parameters of the model mortar and SCC in the steady state was also presented. The coefficients of determination R^2 for the linear relationship between dynamic yield stress g and plastic viscosity h of the model mortar and SCC are respectively $R^2 = 0.94$ and 0.96, which means that the rheological properties of SCC in steady state can be well predicted based on the measurements of these properties on the model mortar. This fully confirms the findings from the previous research, for example [12,49] and by other researchers in [23]. It should be noted that the obtained relationships for dynamic yield stress g and plastic viscosity h for model mortars and SCC are consistent with the relationships obtained in [12] not only in nature, but also quantitatively, as the regression coefficients in the linear equations are analogous. The average deviation of the measured parameters dynamic yield stress g and plastic viscosity h of SCC from the values of these parameters calculated from the relations presented in Fig. 6 amounts to 11.9% (max. 29.1%) and 9.0% (max. 29.6%), respectively.

3.1.2. Rheological properties of SCC at rest states

The coefficients of determination R^2 for the linear relationship between static yield stress g_s and thixotropic coefficient A_T are $R^2 = 0.88$ and 0.86, respectively. This is less than in the case of



Procedure for testing mortar – Viskomat NT
Procedure for testing concrete – Viskomat XL

Fig. 5. Measuring sequence and procedures used.

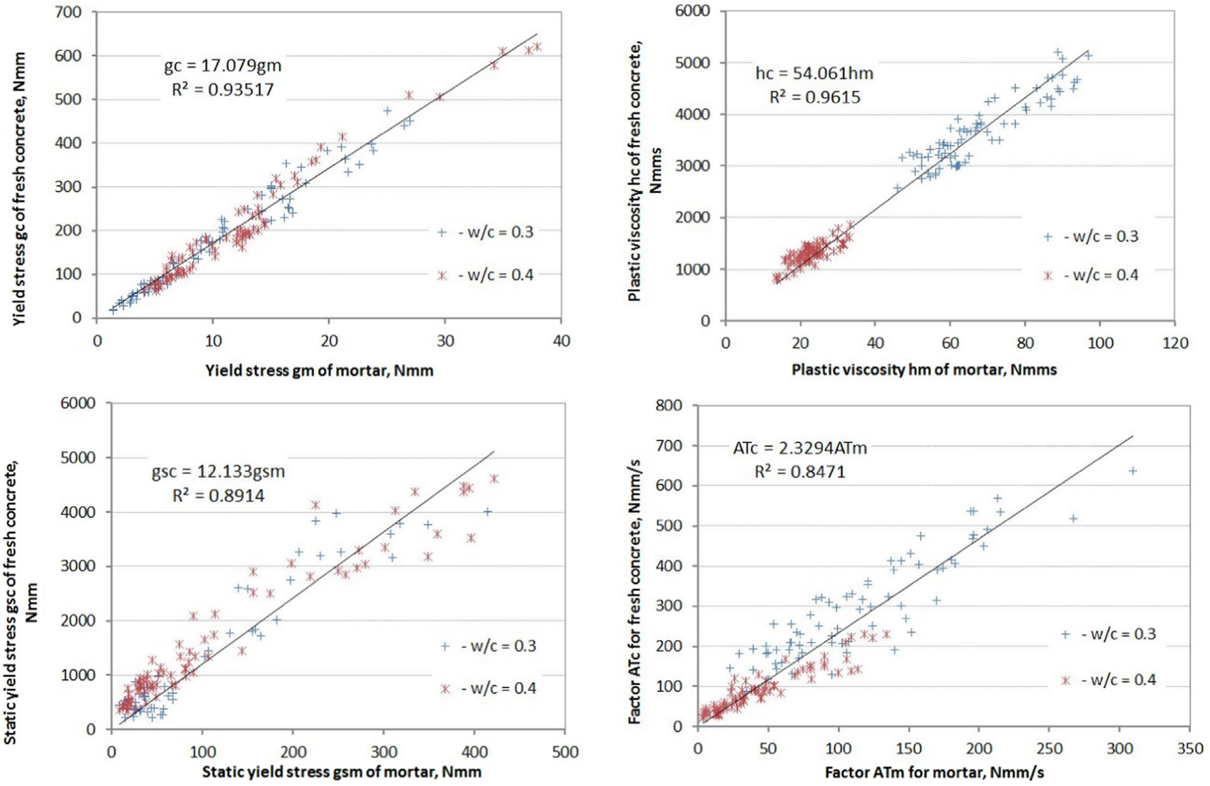


Fig. 6. Rheological parameters of model mortar versus rheological parameters of fresh SCC with coarse aggregate sized up 2–8 mm.

dynamic yield stress g and plastic viscosity h, but it can be still considered as good. The average deviation of the measured parameters static yield stress g_s and thixotropic coefficient A_T of fresh concretes from the values of these parameters calculated from the relations presented in Fig. 6 amounts to 20.1% (max. 42.6%) and 25.3% (max. 87.6%, median 21.3%), respectively. All this indicates that when using model mortars, it is possible to investigate a complex influence of different material and technological factors on the rheological properties of SCC not only in steady state, but also in rest state.

3.2. The impact of SCC mix design on its rheological properties at rest

The nature of the influence of the w/c ratio, HRWR and cement type on all rheological parameters and its changes in time is analogous, both for SCC and model mortars. The results are presented in Figs. 7-10. The results of ANOVA involving the influence of w/c ratio, cement and HRWR type on the rheological properties of SCC and its changes in time are presented in Table 4 and 5 and Fig. 10.

3.2.1. Rheological properties of SCC at steady states

In compliance with the assumptions, SCCs were obtained with the slump flow within the range from 620 to 680 mm, which corresponds to dynamic yield value g within the range from 200 to 20 Nmm, respectively. As it can be expected, the SCC with w/c = 0.4 has a significantly shorter time t_{500} than the SCC with w/c = 0.3 0–1-2 s and 3–6 s, respectively, and plastic viscosity h within the range of 1000–2000 Nmms and 3000–5000 Nmms. The plastic viscosity h is also influenced by HRWR type and by cement type, but the said effects occur mainly in the case of SCC with w/c = 0.3. Over time, dynamic yield value g and plastic viscosity h of SCC increase, initially relatively slowly, accelerating significantly after 80 min. The range of changes of dynamic yield value g is usually higher for the SCC with w/c = 0.4, while the range of changes of plastic viscosity h is higher for the SCC with w/c = 0.3. In general, higher amount of HRWR needed to reach the targeted slump flow of the SCC with lower w/c is conducive to the acquisition of SCC with stable rheological properties over time. The type of HRWR is very important in terms of the flowability loss of SCC, and during its selection we should take into account technological requirements, including the pressure of SCC on the formwork. Usually SCC is designed to keep its flowability as long as possible – in this case HRWR SP1 should be the first choice. In the situation when SCC is designed in line with the formwork pressure, maintaining flowability for a long time is not an advantage – in that case HRWR SP5 should be the first choice. In this study, the use of different cements insignificantly affects the workability loss of SCC. The increase in dynamic yield value g and plastic viscosity h over time results from the progressive process of cement hydration and from the decay of HRWR impact, and its range depends of course on the properties of these components. The mechanism of workability loss was mentioned earlier; it has been discussed in detail in numerous works, including e.g. [1,3,19-29], and the obtained research results are in compliance with them.

3.2.2. Rheological properties of SCC at rest states

The static yield stress g_s of the SCC is initially from 2 to even more than 20 times higher than dynamic yield stress g (on average 10 times), depending on the composition of the SCC. The reason why static yield stress is higher than dynamic yield stress is because static yield stress corresponds to well-connected microstructure it mean an undisturbed, whilst dynamic yield stress corresponds to a damaged microstructure. Differences between both values confirm the existence of more than one microstructural level [29]. As shown in [29] differences increase when w / c ratio decreases and the amount of plasticizer increases. However, in these studies the influence of the type of cement and time

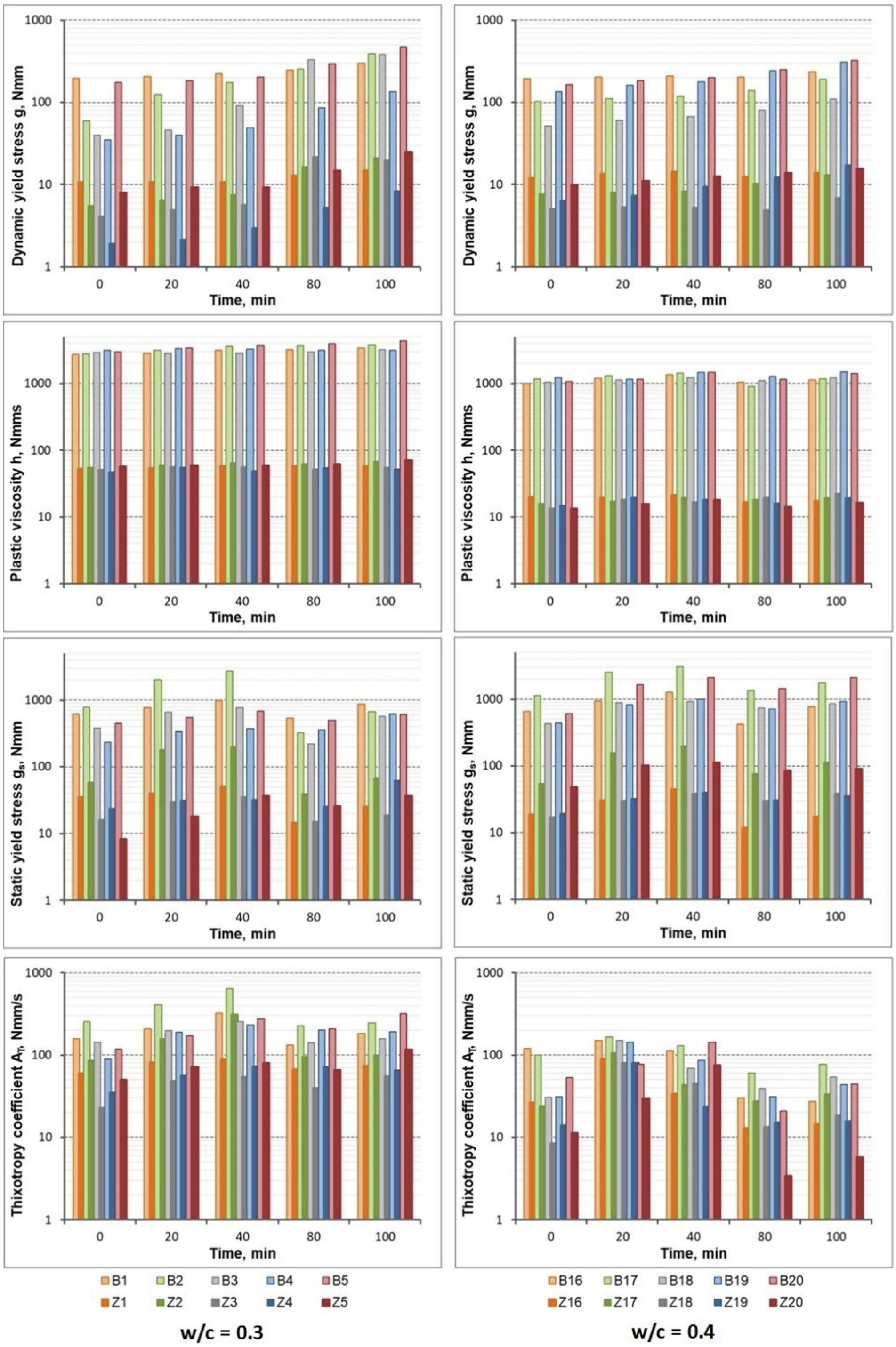


Fig. 7. Rheological properties of SCC and of model mortars with CEM I. SCC and model mortars design according Table 1.

was not investigated and the tests were presented on cement pastes. As it was demonstrated by ANOVA in Fig. 10, the static yield stress g_s depends primarily on w/c ratio, and then on the type of cement and HRWR. SCC with w/c = 0.4 is characterized by an average of 2 times higher static yield stress g_s than SCC with w/c = 0.3. As already stated, static yield stress g_s depends on the type of cement and HRWR, but basing on tested mortars, it cannot be confirmed that there are explicit impact trends. The static yield stress g_s of the SCC left at rest increases in time, and this increase is faster than that of dynamic yield stress g. While the increase of dynamic yield stress g over 40 min is on average 50%, and it can be mostly considered to be insignificant due to the flow and self-compacting ability of SCC, the increase in static yield stress g_s is more significant, and it is on average 350% (g_s increases from 1.5 to 14 times, depending on the SCC mix design). The static yield stress g_s usually does not increase linearly, and its increase is faster during the first 20 min of being at rest. As indicated by ANOVA, after 40 min the static yield stress g_s depends on the type of HRWR and cement, and w/c at that moment is a less significant factor. Again, no explicit trends of the influence type of HRWR and cement can be indicated. It should be noted that this influence is very significant - depending on cement and HRWR type, the static yield stress g_s

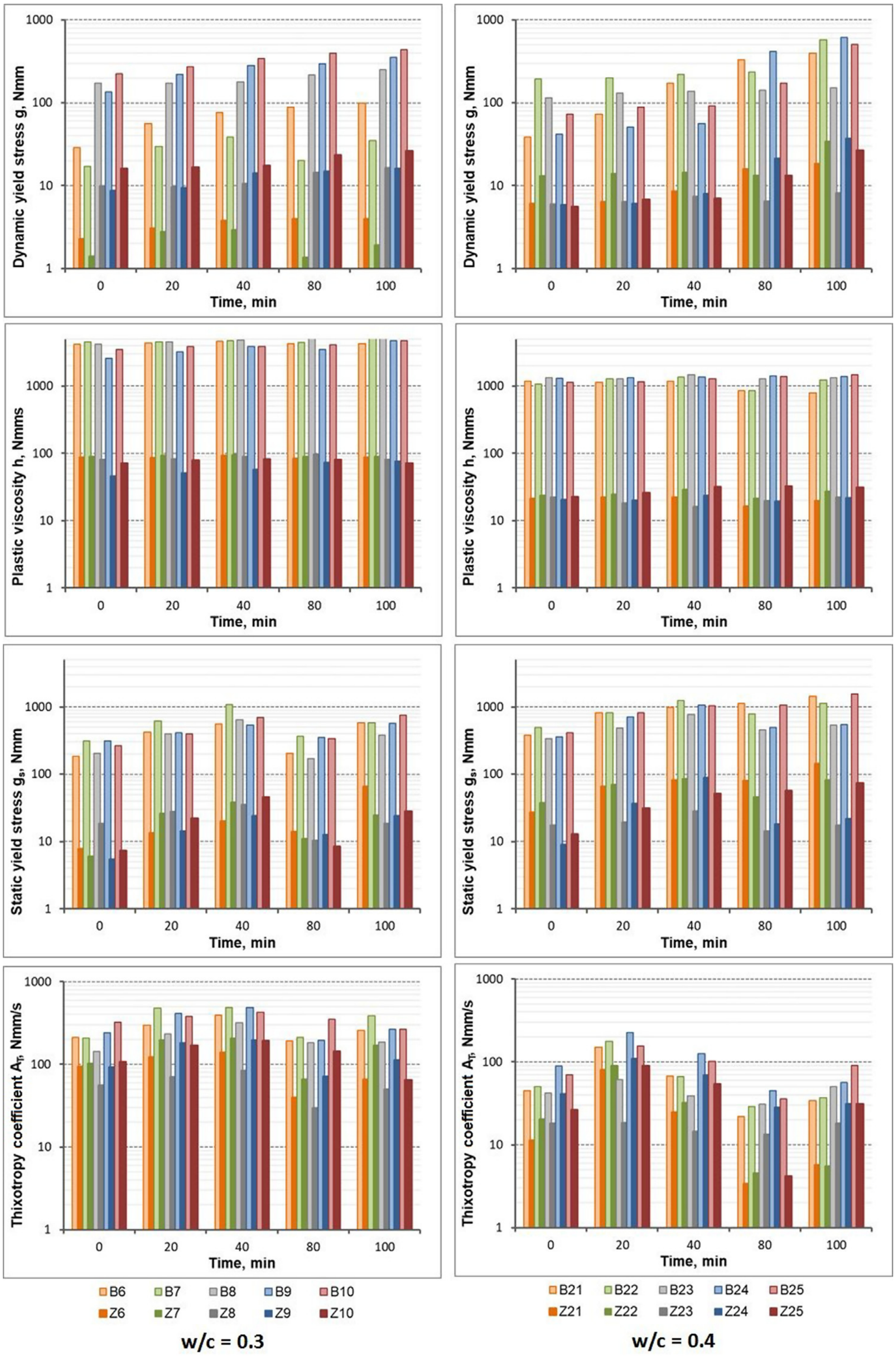
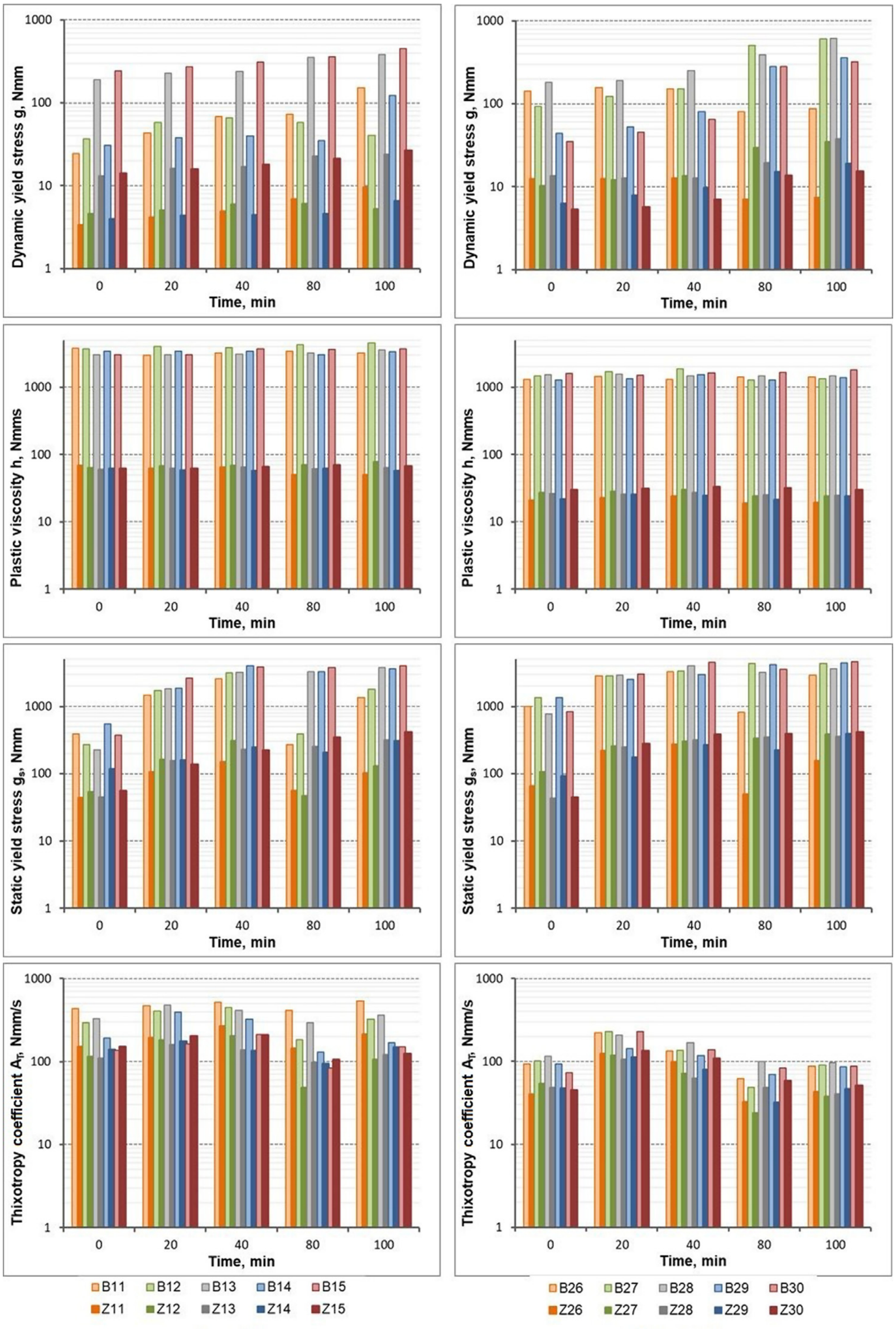


Fig. 8. Rheological properties of SCC and of model mortars with CEM III. SCC and model mortars design according Table 1.

after 40 min can be from 400 to 4000 Nmm (difference by 1000%). The influence of w/c ratio on static yield stress g_s decreases in time, which means that although SCC with w/c = 0.40 faster develops shear strength than SCC with w/c = 0.3 and with the same volume of cement paste, but in a longer time their shear strength may be similar. Since the tests were carried out over 40 min at rest only, the nature of static yield stress g_s changes over longer times requires further studies.

The thixotropy coefficient A_T after 5 and 40 min depends primarily on w/c ratio, and with the same w/c, on the type of cement and HRWR (ANOVA in Fig. 10). The thixotropy coefficient A_T of the SCC at rest increases initially (20 min), and it is clearly faster for the SCC with w/c = 0.3. Over longer time (40 min) the rise of thixotropy coefficient A_T slows down, and in the case of the SCC with w/c = 0.4, it can even decrease (probably due to the decay of the HRWR action). In general, the A_T thixotropy coefficient A_T of the SCC with w/c = 0.3 is higher than that of the analogous SCC with w/c = 0.4. The type of HRWR and cement has impact on thixotropy coefficient A_T, and this impact is much more visible in the case of SCC with w/c = 0.3. However, basing on the conducted research,



w/c = 0.3 **w/c = 0.4**

Fig. 9. Rheological properties of SCC and of model mortars with CEM V. SCC and model mortars design according Table 1.

it is not possible to indicate explicit trends. However, we can argue that by an appropriate selection of cement and HRWR type, the thixotropy effect of SCC can be controlled.

The contribution of thixotropy to shear strength development seems ambiguous. The stiffening of SCC due to thixotropy increases the shear strength of SCC, but at the same time, it slows down the self-compaction of concrete (the SCC with higher w/c ratio are characterized by higher thixotropy coefficient A_T but at the same time by lower static yield stress g_s). The significance of the thixotropic effect for shear strength disappears in time.

In general, the SCCs with lower w/c are characterized by higher thixotropy coefficient A_T and by lower static yield stress g_s development in time. With the same volume of cement paste, the SCCs with w/c = 0.3 are characterized by lower volume of water and higher amount of cement than the mixtures with w/c = 0.4. Their structure is more compact, and more HRWR is needed to fluidize them. As a result, they are characterized by high plastic viscosity h. The more compact the structure and higher plastic viscosity h, the higher thixotropy coefficient A_T, whereof value is also related to the amount and type of HRWR. With a higher amount of HRWR, thixotropy coefficient A_T is not only higher but it also decays more

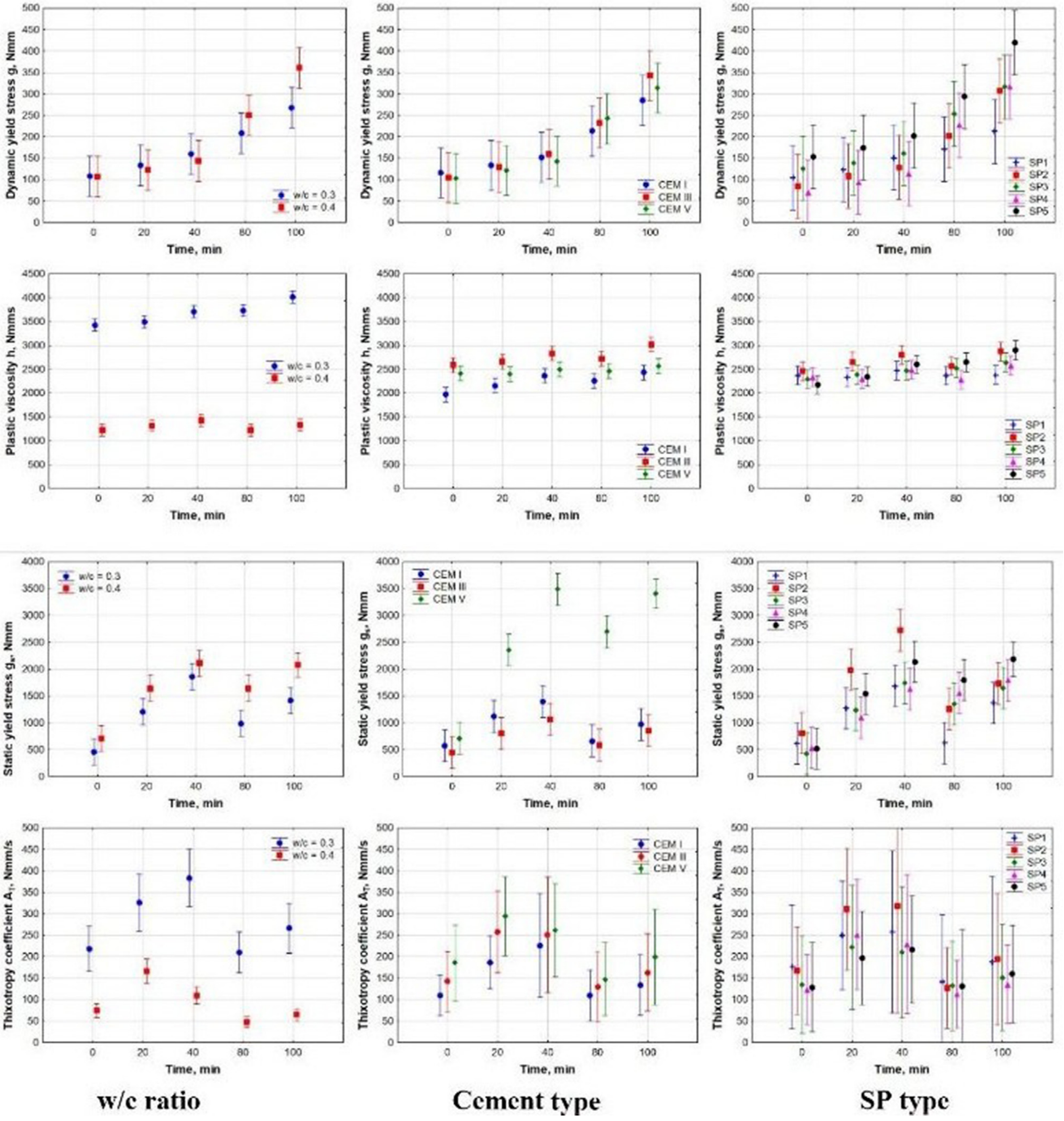


Fig. 10. ANOVA for influence w/c ratio, cement type and SP type on rheological parameters of SCC and its changes in time.

Table 4
ANOVA of influence of time, w/c ratio, cement type and HRWR type on rheological parameters of SCC.

Factor	Dynamic yield stress g		Plastic viscosity h		Static yield stress g_s		Thixotropic coefficient A_T	
	F-ratio	p	F-ratio	p	F-ratio	p	F-ratio	p
Time	25.49	0.000	10	0.000	38.3	0.000	30.0	0.000
w/c ratio	2.09	0.152	3573	0.000	34.2	0.000	424.2	0.000
Cement	0.29	0.749	7	0.000	217.4	0.000	16.5	0.000
HRWR	5.35	0.001	60	0.000	8.4	0.000	6.1	0.000

slowly, due to the longer-lasting impact of HRWR. All this is conducive to the acquisition of a stable, thixotropic, stiffening mixture (especially when HRWR with viscosity enhancing properties is used), but with slow sedimentation of grains, and thus with slower increase of static yield stress g_s. To obtain a given fluidity, the mixtures with w/c = 0.4 require the application of a smaller amount of HRWR, they also have a distinctly lower plastic viscosity h and thixotropy coefficient A_T. These SCCs faster undergo sedimentation and compacting (which is manifested by faster increase of static yield stress g_s) and they do not display thixotropic effect. It should

Table 5
ANOVA of influence of w/c ratio, cement type and SP type on rheological parameters of SCC after 5 and 40 min.

Factor	Static yield stress g_s				Dynamic yield stress g			
	after 5 min		after 40 min		after 5 min		after 40 min	
	F-ratio	p	F-ratio	p	F-ratio	p	F-ratio	p
w/c ratio	29.50	0.001*	2.83	0.081	45.11	0.000*	141.3	0.000*
Cement	10.82	0.005*	67.72	0.000*	7.25	0.008*	2.18	0.099
HRWR	7.67	0.008*	4.95	0.026*	1.03	0.447	10.29	0.006*

p - significance level, the criterion is 0.05, * denotes significant influence of factor

be noted that thixotropy coefficient A_T can be useful to assess the resistance of SCC to segregation.

A repeated mixing destroys the structure of SCC, but when left at rest again, the SCC rebuilds its structure. Immediately after the repeated mixing, the static yield stress g_s is higher than the one after 5 min. When left for 20 min at rest, the SCC increases its static yield stress g_s, but this increase is slower than the one initially observed. At the same time, the thixotropy coefficient A_T after remixing is lower than the one after 5 min, and its increase in time is small. Such a character of static yield stress g_s and thixotropy coefficient A_T changes can be explained by the flowability loss of SCC (a progressing cement hydration and the decay of HRWR impact) and its reduced ability to self-compact (in general, slower sedimentation of aggregates). Since the tests after remixing were carried out over 20 min at rest only, the nature of static yield stress g_s and thixotropy coefficient A_T changes over longer times requires further studies.

As demonstrated by the research, by an appropriate selection of w/c of the mixture, type of cement and HRWR, it is possible to control the properties of SCC at rest. The selection of cement and HRWR has not been possible so far without experimental verification. As demonstrated above, such studies can be carried out with the use of mortars.

4. Conclusions

Model mortars can be used in the SCC design process for the optimal selection of materials and mix design. As well as in during the process production of SCC for quality control to detect variations in different deliveries of materials and for control influence of variable technological factors on the rheological properties.

With respect to the suitability of mortars for the prediction of rheological properties of SCC at steady and rest states, the following conclusions can be drawn:

- Linear relations were determined, allowing to convert the values of rheological parameters obtained in the measurements of the model mortar into the rheological parameters of SCC.
- Model mortars, whereof composition is based on the assumption of equal concrete and mortar dispersion ratio, can be used to predict rheological properties of SCC.
- Model mortars can be used to predict rheological properties of SCC in both steady (dynamic yield stress g and plastic viscosity h) and in rest state (static yield stress g_s and thixotropy coefficient A_T) and to predict the changes of these parameters in time.
- The nature of the influence of materials and technological factors such as w/c ratio, cement and SP type on the rheological parameters of SCC and model mortars is the same.
- However, further tests are required, involving SCCs of different mortar volume as well as aggregates of different type and grading.

With respect to the impact of SCC mix design on its rheological properties at rest, the following conclusions can be drawn:

- The static yield stress g_s is much higher than dynamic yield stress g, and its increase in time is much faster.
- The static yield stress g_s does not increase linearly; its increase is faster during the first 20 min of mixture being at rest.
- In the case of SCC with a constant volume of paste, the static yield stress g_s depends on w/c ratio, the type of HRWR and cement.
- SCCs with a higher w/c ratio develop static yield stress g_s faster, but up to 40 min the influence of w/c ratio decreases.
- Thixotropy coefficient A_T depends primarily on w/c ratio, and with the same w/c, on the type of cement and HRWR. The lower the w/c ratio, the higher thixotropy coefficient A_T.
- The thixotropy coefficient A_T increases in the initial period of SCC being at rest. Over longer periods of time, especially in the case of SCC with a higher w/c, thixotropy coefficient A_T may decrease.
- Shear strength of SCC (reflected as static yield stress g_s) at rest develops mainly due to a self-compaction ability of SCC and, in a longer time, due to a progressing cement hydration and the decay of HRWR impact (flowability loss).

Ethical statement

The authors confirm that the manuscript is not under review or published elsewhere. The authors state that the research was conducted according to ethical standards. There is no ethical concern.

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CRediT authorship contribution statement

Jacek Gołaszewski: Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Supervision, Software, Validation, Writing - review & editing. **Grzegorz Cygan:** Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing. **Michał Drewniok:** Conceptualization, Methodology, Software, Data curation, Writing - original draft, Software, Validation, Writing - review & editing. **Aleksandra Kostrzanowska–Siedlarz:** Conceptualization, Methodology, Software, Data curation, Writing - original draft, Visualization, Investigation, Software, Validation, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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