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Research paper

Influence of temperature on rheological properties of self-compacting mortars and concretes in rest state

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Abstract: The rheological properties of fresh mortars and self-compacting concretes (SCC) at rest – the static yield value g_s and the thixotropy factor A_T – at temperatures from 10 to 30°C were investigated. The static yield value g_s and the thixotropy factor A_T of SCC depends on the temperature and the w/c ratio. Immediately after casting, the static yield value g_s of the SCC is the higher the higher the temperature and/or w/c ratio are. Thixotropy factor A_T of fresh SCC depends mainly on w/c ratio – the higher w/c ratio the lower A_T is. The increase in temperature of SCC reduces thixotropy factor A_T, but the effect is insignificant. During the 40 minutes that the SCC remain at rest, the static yield value g_s increases and this increase is faster for mixes with a higher w/c ratio. Thixotropy factor A_T of SCC left in rest first increases over time, but then, after just 20 to 40 minutes, begins to decrease. Temperature does not affect static yield value g_s and thixotropy factor A_T changes in time. The nature of the effect of temperature on the rheological properties of mortars and SCC is analogous. It was proven that model mortars can be used to predict the effect of temperature on the rheological properties of SCC both in the flow phase and at rest and to predict changes in these parameters over time. The implications of the temperature effect on the rheological properties of SCC in terms of formwork pressure were also discussed.

Keywords: mortar, rheology, rest state, self-compacting concrete, temperature

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1. Introduction

The development of the rheological properties of fresh self-compacting concrete (SCC) is of fundamental importance for its effective use in practice [1–3]. First and foremost, the rheological properties determine workability, flowability, passing ability, self-compactness ability and segregation resistance of fresh SCC. Secondly, the rheological properties of SCC, together with the casting and formwork characteristics, are decisive in controlling lateral pressure of SCC on the formwork [4–6]. Typical rheological behavior of a fresh SCC under the load and parameters characterizing its rheological properties are presented in Fig. 1 [3]. The rheological properties of fresh SCC during pouring processes, i.e. when it is in the flowing state, are usually characterized by the Bingham model material parameters – dynamic yield stress and plastic viscosity [3]. The dynamic yield stress expresses the load at which SCC stops flowing and goes to rest. The plastic viscosity expresses the flowability of SCC in the steady flow state. In order to achieve high flow and passing ability while minimizing the risk of segregation, SCC mixtures are usually designed to have as low a dynamic yield stress as possible and, at the same time, a moderate or high plastic viscosity [1–3]. After pouring, when left at rest, the fresh SCC compacts and loses workability [3–7]. As a result, it builds-up structure and develops shear strength which increases with time. Shear stress required to get the SCC flow again, i.e. for it to go from a state of rest to a state of flow, is referred to as the static yield stress [3, 8]. The higher the static yield stress of the SCC, the higher its ability to carry vertical loads and thus the lower the lateral pressure on formwork [3–7]. The rheological properties of SCC at rest may be also influenced by other effects, among which thixotropic stiffening is attributed particular importance [3, 9, 10]. The thixotropic stiffening is reversible and, under external loading, the effect can disappear. The thixotropic stiffening ability of a mixture is characterized by the thixotropy factor A_T, which is defined as the area between the increasing and decreasing flow curve (Fig. 1) [3, 11].

Due to the importance of controlling rheological properties in SCC technology, a large number of studies have been devoted to the problem, which is still the subject of intensive research e.g. [12–16]. It is worth noting here that the majority of the research to date is related

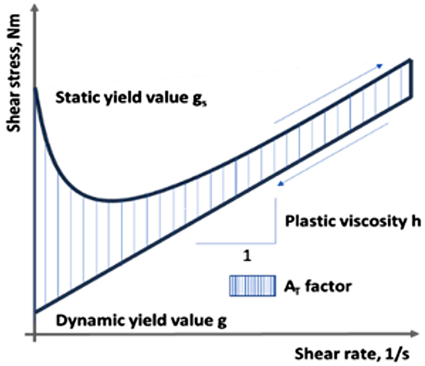

Fig. 1. Behaviour of fresh SCC under the increasing and decreasing load and parameters characterizing its rheological properties

to the rheological properties of SCC in the flow phase, and therefore refers to the dynamic yield stress and plastic viscosity. These studies have identified the most important material and technological factors influencing the rheological properties of SCC and the nature and extent of their influence. Problems of rheological properties of fresh SCC have been widely discussed and summarized in monographic studies, e.g. [1–3, 17]. Studies on the influence of material and technological factors on the rheological parameters of SCC at rest are limited and indicates various contradictions in the obtained results [3, 9, 10, 18–24].

The analysis of literature shows that one of the most important factors influencing the rheological properties of fresh SCC is temperature. Its influence has been the subject of numerous studies, e.g. [3, 25–30], oriented primarily on the workability of fresh SCC and thus on the rheological properties in the flow state. They show that the effect of increasing temperature on the fresh SCC workability is mainly due to the overlapping effects of accelerating the cement hydration process and increasing the degree of superplasticizer (SP) adsorption on the cement and its hydration products. The effect of temperature on dynamic yield stress and plastic viscosity is significant and its nature and range depends mainly on the type, properties and amount of cement, the type, properties and amount of SP, the type of mineral additives, the w/c ratio and the volume of the cement paste. However, no clear trends in the influence of these factors can be identified. The effect of temperature on the rheological properties of SCC at rest has not been systematically studied, with only few studies confirming that it is significant [3]. Therefore, a research in terms of rheological parameters of SCC at rest state, especially static yield stress development, still have to be made.

The large number of factors influencing the rheological properties of SCC, their complex interactions and the absence of a clear trends of influence means that the process of designing and optimizing the composition of SCC usually involves expensive and labour – intensive experimental studies. Numerous works, e.g. [3, 31–40], have shown that testing model mortars makes it possible to predict the rheological properties of fresh concrete. The possibility applies especially to rheological properties of fresh SCC in both the flow and rest states, e.g. [37, 38]. However, there is lack of research on the possibility of predicting the effect of temperature on the rheological properties of a concrete mixture at rest based on the testing of mortars.

The primary objective of the study was to determine the influence of temperature and time on the rheological properties of fresh SCC at rest. In addition, the study verified whether the rheological parameters of fresh SCC at rest – the static yield value and the thixotropy factor A_T – could be predicted from tests on a model mortar. The study also determined the effect of temperature on the rheological properties of fresh SCC in the flow state, providing additional data in this respect. The implications of the temperature effect on the rheological properties in terms of controlling formwork pressure were also discussed.

2. Experimental

In the study, the influence of temperature in range from 10 to 30°C on rheological properties of fresh SCC was investigated. This range of temperature variation is due to the general rules of concrete technology. Rheological parameters of fresh SCC and model mortars were measured for temperature 10, 20 and 30°C. Proportioning of concretes were designed according to the method presented in [41], with slump flow ranged from 600 to 750 mm and flow time T_{500} from 2 to 10 s. In this way, fresh SCC with significantly different rheological properties in the flow phase were obtained. This allows a more comprehensive analysis of the temperature influence on the rheological properties of SCC at the rest state. All tested SCC have the same volume of cement paste, the variability in the fresh SCC properties was controlled by the use of different w/c ratio, SP dosage and cement type. The compositions of the model mortars were determined assuming the same concrete and mortar dispersion ratio, using the method presented in [37,38].

The research plan and compositions of SCC and model mortars used are presented in Table 1. Properties of the cements used are presented in Table 2. Natural sand of 0–2 mm and coarse aggregate of 2–8 mm were used, the combined grading of aggregate is presented in Fig. 2. Polycarboxylate ether based superplasticizer HRWR with a density of 1.07 g/cm^3 and a concentration of 32% was used, based on the recommendations outlined in [42].

Table 1. Research plan and proportioning of SCC and model mortars

Variables		**SCC concrete**						**Mortar**				
Cement type	**w/c**	**Mix**	**C**	**W**	**FA**	**CA**	**SP**	**Mix**	**C**	**W**	**FA**	**SP**
			kg/m^3				**%C**		**kg/m^3**			**%C**
CEM I	0.3	SCC1	594	178.2	885	785	3	M1	760	228	1390	3
CEM III		SCC2	584	175.2			1.8	M2	747	224		1.8
CEM V		SCC3	563	168.9			2.5	M3	720	216		2.5
CEM I	0.4	SCC4	512	204.8			1	M4	674	270		1
CEM III		SCC5	504	201.7			0.8	M5	663	265		0.8
CEM V		SCC6	488	195.2			1.5	M6	638	256		1.5

Table 2. Properties of cements

Cement type	**Cement constituents, %**							**Specific surface, cm^2/g**	**Density, g/cm^3**
	SiO_2	**CaO**	**Al_2O_3**	**Fe_2O_3**	**MgO**	**Na_2O_e**	**SO_3**		
CEM I 42.5	21.6	64.4	4.5	2.2	1.3	0.40	3.1	3330	3.10
CEM III/A 42.5N	30.2	52.2	6.4	1.8	3.5	0.8	3.3	3850	3.00
CEM V/A 32.5 (S-V)	29.2	49.3	9.5	2.8	2.4	1.3	2.2	3380	2.88

The rheological parameters of the fresh SCC were determined using a Viskomat XL rheometer and of the model mortars using a Viskomat NT rheometer. These rheometers are characterized in detail in [38]. The theoretical fundamentals and rules for rheological measurements with rheometers are presented in [3]. A specially developed procedure of measuring rheological properties was used, shown in Fig. 3 and explained and discussed in detail in [38]. It allows determination of the static yield stress g_s (by measuring shear stress at an extremely

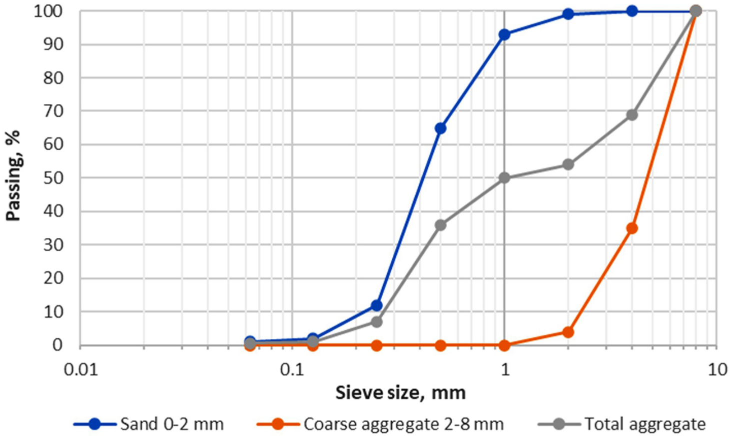

Fig. 2. Sieve analysis for aggregate used in SCC and model mortars

low shear rate), the thixotropy factor A_T as the area between the increasing and decreasing flow curve and dynamic yield stress g and plastic viscosity h at a decreasing shear rate, assuming that rheological behavior of fresh concrete or mortar is characterized by the Bingham model.

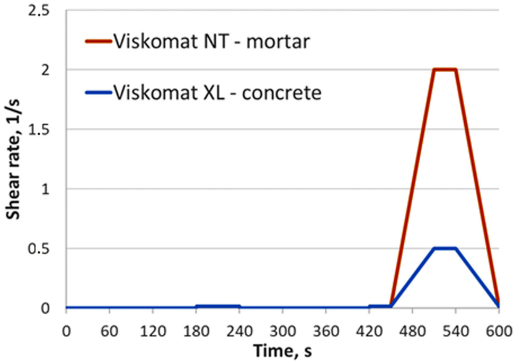

Fig. 3. Procedure of measuring of rheological properties of SCC

Measurement constants have not been defined for Viskomat rheometers, so results are presented using conventional rheological constants: dynamic yield stress g [N·mm], plastic viscosity h [N·mm·s], static yield stress g_s [N·mm] and thixotropy ratio A_T [(N·mm)/s]. The rheological measurements were generally performed without repetition, but for the selected fresh SCC and mortar the coefficients of variation V for rheological parameters were investigated. The coefficients of variation V for g, h, g_s and A_T of fresh SCC were $V_g = 6{,}1\%$, $V_h = 6{,}2\%$, $V_{gs} = 8.1\%$, $V_{AT} = 8.9\%$ respectively and for mortar $V_g = 4{,}7\%$, $V_h = 4{,}2\%$, $V_{gs} = 6.1\%$, $V_{AT} = 7{,}2\%$ respectively. Repeatability is analogous to that obtained in the study [38]. As they are clearly less than 10%, this makes it possible to consider the repeatability of the performed rheometer measurements as good.

The SCC and model mortars were prepared in planetary mixers. Cement, sand and coarse aggregate were dry mixed in the mixer for 30 sec. Next, water and HRWR was added. The total mixing time was 5 minutes. The temperature of the ingredients was chosen so that at the end of the mixing a mixture with a given temperature could be obtained. Immediately after end of mixing three measuring vessels were filled with a SCC or a model mortar and placed in a climate chamber to maintain the desired temperature. The rheological parameters were measured at 0, 20 and 40 minutes after the end of mixing. These rheometers have a cooling-heating system with which the temperature of the mixture can be controlled during the measurement.

3. Results and discussion

The influence of temperature on basic technological properties of fresh SCC directly after end of mixing is presented in Table 3. The influence of temperature and time on rheological parameters of fresh SCC and of the corresponding model mortars in flow state are presented in Fig. 4 and rest state in Fig. 5.

Table 3. Properties of fresh SCC

Mix	**Temperature, °C**	**Slump flow, mm**	**T_{500}, s**	**VSI**	**Air content, %**	**Density, kg/m^3**
Testing method		EN 12350-8		ACI 237R-07	EN 12350-7	EN 12350-6
SCC1	10	520	8	0	6	2296
	20	640	5	0	4.8	2325
	30	710	4	0	3.3	2362
SCC2	10	640	9	0	7	2280
	20	750/	9	0	3.9	2334
	30	750	7	0	2	2403
SCC3	10	640	10	0	6	2272
	20	720	8	0	4.2	2301
	30	710	6	0	4	2320
SCC4	10	530	4	0	5.9	2256
	20	620	3	1	4.4	2282
	30	690	2	1	3.5	2313
SCC5	10	620	6	0	7.4	2193
	20	740	2	1	5.1	2255
	30	710	2	1	4.6	2260
SCC6	10	610	4	0	8.2	2156
	20	630	2	1	5	2236
	30	710	2	1	4.5	2243

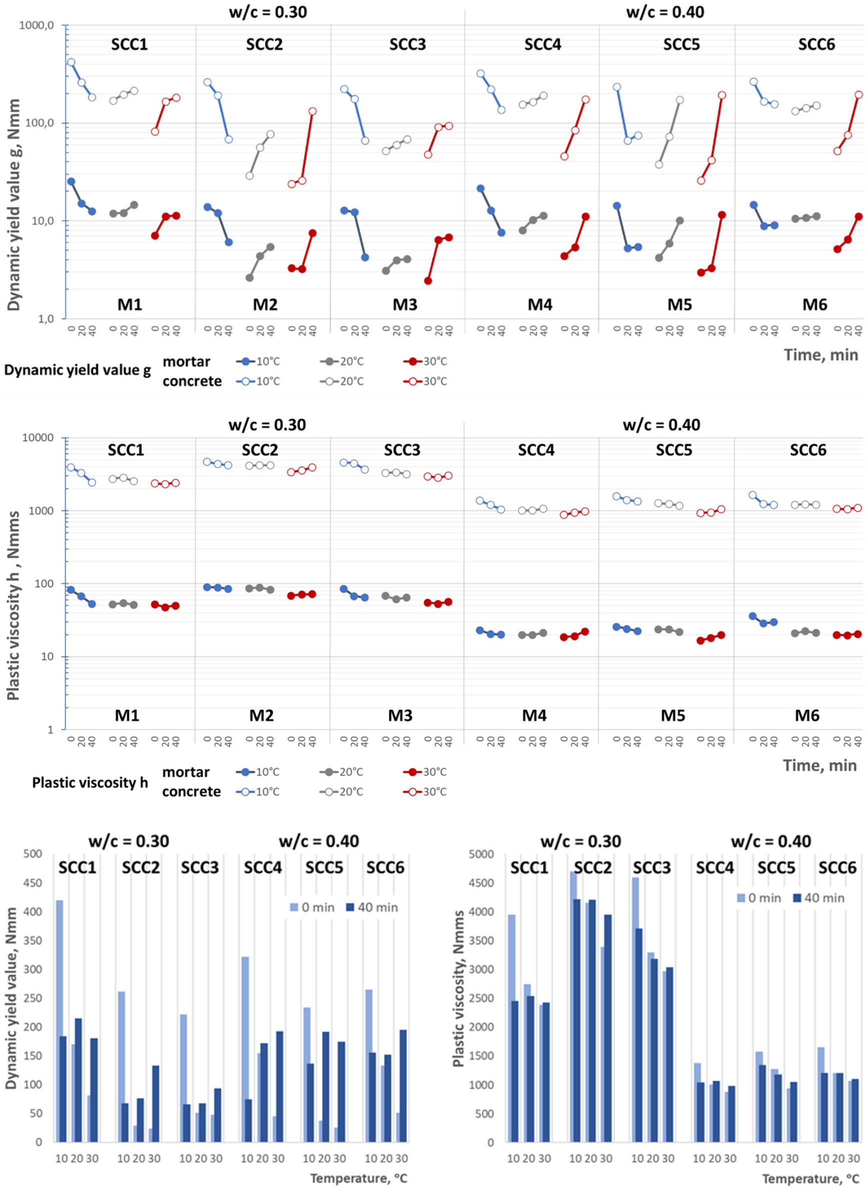

Fig. 4. Influence of temperature and time on fresh SCC and model mortars rheological parameters in the flow state – dynamic yield value *g* and plastic viscosity *h*

Tested SCCs were characterized by a flow in the set out scope. The flowability of the fresh SCC clearly decreases as its temperature decreases. Fresh SCCs with w/c = 0.4 show a tendency to slight bleeding at temperature 20 and 30°C being stable at 10°C, while SCCs with w/c = 0.3 were stable at all temperatures. The air content in fresh SCC increased with the

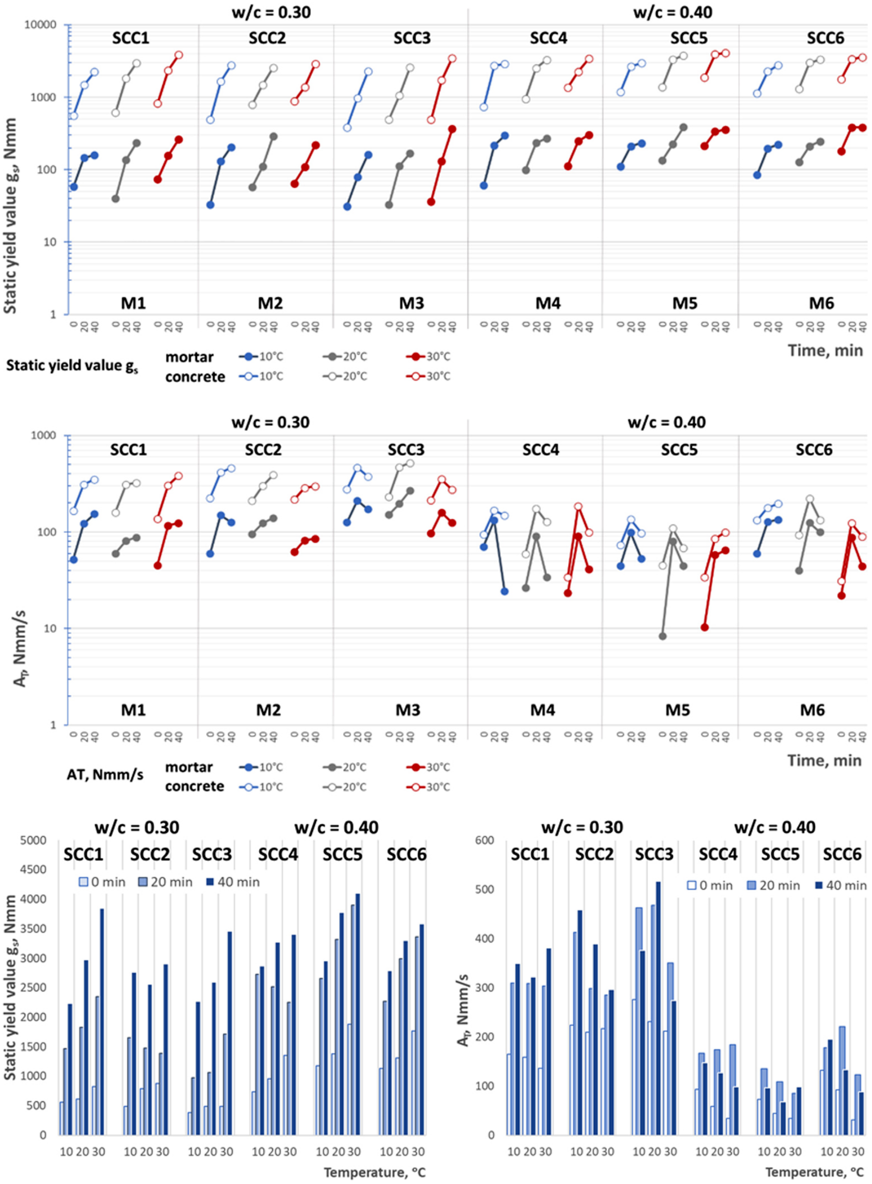

Fig. 5. Influence of temperature and time on fresh SCC and model mortars rheological parameters in the rest state – static yield value g_s and thixotropy factor A_T

decreasing temperature, the difference in the air content between fresh SCCs at temperature 10 and 30°C was on average about 3%. Density of SCC with w/c = 0.3 was about 3% higher than of SCC with w/c = 0.4. As the temperature increases, the density of fresh SCC increases about 1.5% for each 10°C increase. This effect has to be related to the influence of temperature on the consistency and air content in fresh SCC.

3.1. Influence of temperature on rheological properties of fresh SCC

In general, the observed influence of temperature of fresh SCC on its rheological properties in the flow state is in agreement with the state of knowledge. Immediately after mixing the dynamic yield value g and plastic viscosity h of fresh SCC decrease with increasing temperature. As a result, the initial flowability of SCC also increases with increasing temperature (as results in Table 3 indicate). The effect is more pronounced in the case of SCC with cement CEM I and/or with w/c = 0.30. Over a period of 40 minutes, the rheological properties of fresh SCC in the flowing state change depending on temperature. At 10°C the dynamic yield value g and plastic viscosity h decreases and thus SCC flowability increases in time. At 20 and 30°C dynamic yield value g increases in time, the faster the higher the temperature, while plastic viscosity h changes insignificantly. After 40 min the dynamic yield value g of fresh SCC is the highest at 30°C and the lowest at 10°C. In general, fresh SCCs with higher w/c and/or with cement CEM I are more sensitive to temperature influence.

The nature and extent of the effects of w/c ratio and cement type on the rheological properties of SCC at rest are consistent with previous findings and have been discussed in detail in [38]. The discussion of the results therefore focused on the effect of temperature. Immediately after mixing, the static yield value g_s of the fresh SCC is the higher the temperature is; at temperature 30°C is about 1.5 times higher than at temperature 10°C. This effect is mainly due to rheological properties of fresh SCC at flow state – at lower temperature have a higher plastic viscosity h and dynamic yield value g and therefore have lower ability to fast build-up structure.

The static yield value g_s of the SCC increases significantly over a period of 40 min, on average increasing by about 4 times. The nature of the increase in the static yield value g_s of depends mainly on the w/c ratio of fresh SCC, which is in accordance with research [38]. The static yield value g_s of SCC with w/c = 0.30 increases almost linearly. In comparison, the static yield value g_s of SCC with w/c = 0.40 increases rapidly for the first 20 minutes of being at rest, then the increase slows down distinctly. After 40 minutes, the static yield value g_s of SCC with w/c = 0.40 is still higher than that of SCC with w/c = 0.30, but the effect of the w/c ratio decreases over time. In a longer time their static yield stress g_s may be similar.

It should be noted that temperature insignificantly affect the rate of increase of static yield value g_s in time, which during 40 min is 48, 53 and 56 (N·mm)/min at 10, 20 and 30°C respectively. Although the rate of increase of the static yield value g_s in 40 minutes is quite similar, it seems that the nature for this increase at higher and lower temperatures is different. Increase in the static yield value g_s in time at the higher temperature results from a faster flowability loss of SCC due to accelerated cement hydration process. At the same time, at the temperature of 10°C the flowability of the SCC mixture increases in time, and this effect may cause stronger sedimentation and be responsible for increase of the static yield value g_s. The nature of static yield value g_s changes over longer time requires further studies.

The static yield value g_s of fresh SCC is clearly higher than the dynamic yield value g, and temperature has a strong influence on the difference between the two. Immediately after mixing, the static yield value g_s of SCC at 10, 20 and 30°C is on average 4, 10 and 35 times higher than the dynamic yield value g, respectively. Responsible for this is the effect of the rheological properties in the flow state of fresh SCC on its ability to build a structure at rest, which was outlined above. After 40 minutes, the static yield value g_s is about 20 times higher than the dynamic yield value g, but the effect of temperature is insignificant.

The thixotropy factor A_T after 5 min depends primarily on w/c ratio, SCC with w/c = 0.30 are characterized by a clearly higher A_T. The effect of temperature on A_T is lower, but evident. For the first 20 min of being in rest the A_T of the SCC increases, as the temperature of SCC decreases and it is faster for SCC with w/c = 0.30. Over longer time the increase in A_T slows down considerably and for SCC with w/c = 0.40 A_T decreases. Influence of temperature is still visible after 40 minutes, but no clear trends can be established. It should be noted that the higher the plastic viscosity h, the higher the A_T is.

Due to the rheological parameters of SCC pressure on the formwork is determined by (1) dynamic yield value g in the initial phase of casting and next (2) static yield value g_s which defines the ability of SCC to carry vertical load. The higher dynamic and static yield values are the lower pressure on formwork is. The influence of other examined rheological parameters is considerably smaller and ambiguous. Higher plastic viscosity h and/or thixotropy factor A_T contribute to shear strength development, lowering vertical loads or increasing load bearing capacity of SCC. However, in the same time it's slow down the self-compaction, reduces the development of static yield value g_s and delay the structure build-up.

The temperature influences the SCC pressure on the formwork, as it affects the rheological properties of fresh SCC. Initially, the pressure of SCC on the formwork should be directly proportional to its temperature, because dynamic yield value g decreases with increasing temperature. However, SCC at higher temperatures faster build-up a structure capable of carrying loads and obtain higher static yield stress g_s. Thus over time, SCC pressure on the formwork should be inversely proportional to the temperature.

3.2. Usability of model mortars for the prediction of rheological properties of SCC

The relationships shown in Figs. 4 and 5 demonstrate that the nature of the effect of temperature (and of time and w/c ratio) on the rheological properties of model mortars and fresh SCC both in the flow and at rest state is analogous. Although the rheological parameters of fresh SCC are clearly higher than those of model mortars, the direction of their changes under the influence of temperature (and of time and w/c ratio) overlaps. By measuring the rheological parameters of the model mortar, it is therefore possible to determine the nature of the effect of temperature on the rheological parameters of the fresh SCC.

Figure 6 shows a linear functions which allows the rheological parameters obtained in the mortar measurements to be converted into the rheological properties of the fresh SCC. It should be noted that the obtained relationships for rheological parameters in flow and rest state for model mortars and SCC are consistent with the relationships obtained in [38] not only in nature, but also quantitatively, as the regression coefficients in the linear equations are analogous. This shows that the relationship between the rheological parameters of SCC and the corresponding model mortars does not depend on temperature.

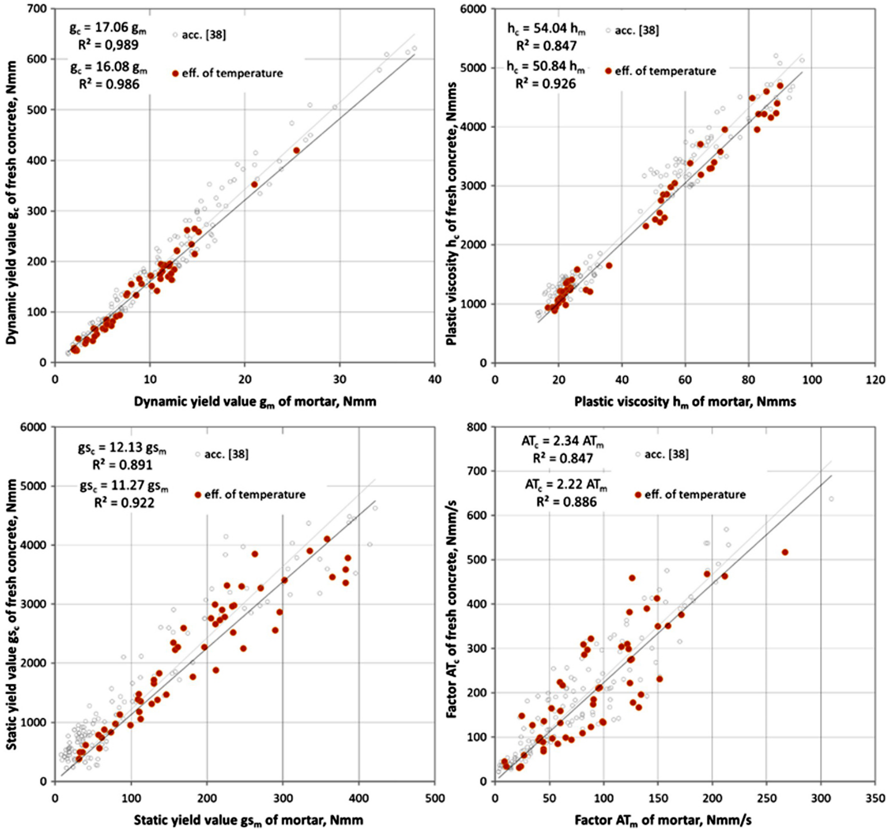

Fig. 6. Rheological parameters of model mortar versus rheological parameters of fresh SCC – effect of temperature

The research was focused on the rheological properties at rest, but the relationships for the mixtures in the flowing state were also determined. The coefficients of determination R^2 for the linear relationship between dynamic yield stress g and plastic viscosity h of the model mortar and fresh SCC are $R^2 = 0.986$ and 0.926 respectively. The average deviations of the calculated dynamic yield stress g and plastic viscosity h of fresh SCC (acc. to the relationships in Fig. 6) from these measured are 14.3% (±20 N·mm) and 6.9% (±160 N·mm·s), respectively. The accuracy of the determination of these parameters is similar to previous studies, for example [31, 37, 38], and confirms the high suitability of the model mortar for predicting the rheological properties of SCC in flow state. The coefficients of determination R^2 for the linear relationship between the static yield stress g_s and thixotropy factor A_T are $R^2 = 0.922$ and 0.886, respectively. The average deviations of the calculated static yield stress g_s and thixotropy factor A_T of fresh SCC from these measured from are 14.8% (±300 N·mm) and 29.7% (±61 (N·mm)/s), respectively. This is somewhat worse than for the rheological parameters in the flow state, but still accurate enough for the design and control of the rheological properties of SCC at rest.

4. Summary and conclusions

The static yield value g_s of fresh SCC depends on the temperature and the w/c ratio. Directly after casting, the static yield value g_s of the SCC is the higher the higher the temperature and/or w/c ratio are. During the 40 minutes that the SCC remain at rest, the static yield value g_s increases and this increase is faster for SCC with a higher w/c ratio. The temperature does not significantly affect the increase in static yield value g_s at this time. The increase in static yield value g_s occurs mainly during the initial period when the mixture is at rest and then slows down considerably.

Thixotropy factor A_T of fresh SCC depends mainly on w/c ratio - the higher w/c ratio the lower A_T. The increase in temperature of fresh SCC reduces A_T, but the effect is insignificant. Thixotropy factor A_T of fresh SCC left in rest first increases over time, but then, after just 20 to 40 minutes, begins to decrease. Temperature does not affect thixotropy factor A_T changes in time.

The relationships obtained for the influence of temperature and w/c ratio on the rheological parameters of SCC in the flow stage confirm the results of previous studies. The dynamic yield stress g and plastic viscosity h of SCC are both initially inversely proportional to temperature. At temperature 10°C a decrease in dynamic yield stress g and plastic viscosity h over time was observed, while at 20 and 30°C the dynamic yield stress g increased with slight changes in plastic viscosity h. These effects were more pronounced for SCC with lower w/c ratios.

Model mortars can be used to predict the effect of temperature changes on the rheological properties of SCC both in the flow phase (dynamic yield stress g and plastic viscosity h) and at rest (static yield value g_s and thixotropy coefficient A_T) and to predict changes in these parameters over time. The nature of the effect of temperature on the rheological properties of model mortars and SCC is analogous. There is a linear relationship between the rheological parameters of the model mortar and SCC which allows the rheological parameters obtained in the mortar measurements to be converted into the rheological parameters of the fresh SCC. By measuring the rheological parameters of the model mortar, it is therefore possible to qualitatively and quantitatively determine the performance of fresh SCC at varying temperatures.

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Wpływ temperatury na właściwości reologiczne samozagęszczalnych zapraw i betonów w stanie spoczynku

Słowa kluczowe: beton samozagęszczalny, reologia, temperatura, zaprawa, stan spoczynku

Streszczenie:

Celem badań było określenie wpływu temperatury i czasu na parametry reologiczne mieszanek BSZ w stanie spoczynku – statyczną granicę płynięcia g_s i współczynnik tiksotropii A_T. Dodatkowo zweryfikowano możliwość wykorzystania badań reologicznych wykonanych na zaprawach modelowych do przewidywania wpływu temperatury na parametry reologiczne mieszanki BSZ w stanie spoczynku. Stwierdzono, że zmieniająca się w zakresie od 10 do 30°C temperatura istotnie wpływa na statyczną granicę płynięcia g_s mieszanki BSZ w stanie spoczynku. Im temperatura mieszanki jest wyższa, tym statyczna granica płynięcia g_s mieszanki jest większa i szybciej wzrasta w czasie. Wzrost statycznej granicy płynięcia w czasie wynika najpierw z samozagęszczenia mieszanki BSZ, a następnie z postępującego procesu hydratacji i utraty efektu działania SP. Statyczna granica płynięcia g_s jest znacznie, nawet o rząd wielkości większa od dynamicznej granicy płynięcia. Współczynnik tiksotropii A_T maleje ze wzrostem temperatury, przy czym wpływ temperatury na współczynnik tiksotropii A_T nie jest istotny w porównaniu do wpływu w/c. Wykazano, że charakter wpływu temperatury na właściwości reologiczne zapraw modelowych i mieszanek BSZ w spoczynku jest analogiczny. Zaprawy modelowe mogą być wykorzystywane do prognozowania wpływu temperatury na właściwości reologiczne mieszanki BSZ w stanie spoczynku. Wyznaczono zależności liniowe pomiędzy parametrami reologicznymi zapraw i mieszanek betonowych w stanie spoczynku. Przedyskutowano mechanizm wpływu temperatury na właściwości reologiczne mieszanki BSZ w stanie spoczynku w aspekcie ich wpływu na parcia na deskowania. W wyższej temperaturze mieszanka BSZ charakteryzuje się większą statyczną granicą płynięcia g_s i szybszym jej wzrostem, co powoduje, że parcie mieszanki BSZ na deskowania tym mniejsze, im większa jest jej temperatura.

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