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Effect of W/C and superplasticizer type on rheological parameters of SCC repair mortar for gravitational or light pressure injection

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ABSTRACT

The influence of pressure on the yield stress and plastic viscosity of SCC repair mortars was investigated using an adapted Marsh cone with cylindrical shear paddles. Twelve mortars proportioned with water over cement ratios from 0.45 to 0.55 and either Polycarboxylate ether (PCE), polyacrylate (PA) or polynaphtalene sulfonate (PNS) high-range water-reducing admixture (HRWRA) were prepared. Test results show that the exerted pressure, W/C and HRWRA type strongly influence the rheological response: the yield stress is mainly affected by HRWRA residual concentration, except for PCE mortars where sulfate ion concentration can play an important role. Plastic viscosity is mainly affected by solid friction between particles, the latter is influenced by HRWRA dosage and W/C. PA appears to be the most accurate HRWRA for light pressure injection, with less sensitivity to changes in pressure or W/C than PNS or PCE superplasticizers.

1. Introduction

Self-consolidating or self-levelling mortars (SCC mortars) are now being used worldwide for repair and consolidation of masonry, structural crack injection to façade refurbishment and protection in both maintenance and new construction projects. These very fluid materials are also used for filling purposes while being used in preplaced aggregate concrete (PAC) where coarse aggregate is placed in forms, and grout is injected. This type of cementitious material must have excellent flowability and, at the same time, adequate segregation resistance independently of the casting method (pouring or pumping) [1].

To drastically enhance workability of self levelling mortars, high-range water-reducing admixtures (HRWRA) are incorporated into the cement mixture. Such water-soluble organic polymers can enhance flowability of cement paste by dispersing the cement particles into the interstitial solution, thus reducing the inter-particle friction among cement grains and decreasing the degree of water entrapment among flocculated particles.

The cement hydration process was also shown to reduce dispersion efficiency of the HRWRA due to some intercalation of the HRWRA into the hydration products [2–5]. Interaction between cement, viscosity-enhancing agents (VEA) and HRWRA can also lead to loss in fluidity or delay in set time, depending on the concentration and type of admixtures [6–9]. For example, Sonebi [10] found that, on grouts made with 100% CEM I 42.5 N cement complying with European EN 197-1 standards, 0.40 W/B and 1% HRWRA, an addition of 0.04% of diutan gum as VEA resulted in the reduction of the mini slump value from 123 to 90 mm, corresponding to a 8.6 times increase in yield stress. The effect on apparent viscosity (μ_{app}), measured at a constant shear rate of 5.1 s^{-1}, was an increase of μ_{app} from less than 1 Pa s to 4.7 Pa s.

The level of pressure exerted on the concrete, or the mortar, when cast can also influence its flow properties. Such is the case when the material is not poured but pumped by the bottom of the formwork, a technique which is in use to fill thin walled steel boxes columns for multiple storey buildings in order to reduce craneage requirements on site [11]. Other techniques consist in injecting the material under low pressure, such as gravitational injection of SCC repair mortars used to fill cracks in walls or cavities inside ancient masonry walls or bridges, or under ceramic tiles to rehabilitate ancient floors. But when a system of particles having a wide range of sizes and densities is fluidified by a liquid, the particles tend to segregate along the flow direction according to the differences in the properties of the particles [12,13]. Hence, dynamic segregation may occur within concreting pipes while the SCC is pumped, due to the low yield stress used as design parameter.

As a SCC mortar is, in general, characterized by a low yield value and a relatively high viscosity, it is also essential to ensure adequate cohesion and stability of the material to avoid dynamic segregation while the concrete is pumped or static segregation once the concrete is cast into place and until the onset of hardening. The low yield value is essential to enhance spreading of the concrete away from the discharge location, while the viscosity is

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Table 1
Mortar mixture proportioning.

Materials	W/C = 0.45	W/C = 0.475	W/C = 0.5	W/C = 0.525	W/C = 0.55
CEM I cement (kg/m^3)	648	638	628	618	609
Water (kg/m^3)	301	308	314	320	325
Limestone filler (kg/m^3)	244	240	236	232	229
Sand (kg/m^3)			990		
PNS	0.69	0.62	0.51	0.47	0.45
PA	0.51	0.44	0.38	0.31	0.29
PCE	0.22	0.21	0.19	0.19	0.19

HRWRA dosages are expressed in% of solid content over cement mass.

needed to maintain a homogeneous dispersion of solid particles during the handling, the placement, as well as the period of rest into the formwork as long as the SCC mortar has not set. A highly flowable mortar that does not possess sufficient viscosity can undergo segregation, especially when it flows between closely spaced obstacles such as reinforcing bars.

Cementitious material deformability and stability is mainly related to their yield stress and plastic viscosity. While literature usually considers the behavior of concrete as hydrostatic when under pressure, i.e. linked to its specific gravity and the height of poured material [14,15], few data are available on the variation of the rheological parameter with pressure exerted on the material as during the injection phase of highly flowable repair mortars or mortars for PAC. However, the exerted pressure, needed to maintain a continuous flow, may lead to instability of the material within the injection pipes. The proposed work aims at highlighting the behavior of SCC mortars made with different HRWRAs and W/C, monitoring the variation of the yield stress and plastic viscosity, when a light gradient of pressure is exerted on the material to simulate gravitational injection of SCC repair mortar.

2. Materials and mixture proportioning

Rheological parameters were determined to monitor the variation of yield stress and plastic viscosity with pressure on mortars extracted from SCC mix designs. As the original SCC mixture was proportioned with a sand containing about 7% in weight of limestone fillers, a concrete equivalent mortar mixture (CEM) [16] would have led to an over dosage in standardized sand since the specific area of the fillers is important. Consequently, mortars designed from the original SCC mixtures taking into account the binder, the liquid phase (water and admixtures), and the fraction of sand retained on the 2 mm sieve, were used in this investigation. The cut-off of sand fraction at 2 mm for mortar was chosen to enable the assessment of the fluidity of the system without the risk of blockage inside the 8 mm opening nozzle of the modified Marsh cone [17].

The testing program was carried out using mortars made with a CEM I 52.5 N cement containing about 97% of clinker. Crushed limestone filler, showing a 2.71 specific gravity, was added to complete the paste volume to 600 L/m^3. The mortar mixtures were proportioned using crushed limestone sand with a fineness modulus of 2.60 and a 2.66 specific gravity.

The water content was determined to achieve W/C of 0.45–0.55, by steps of 0.025.

A polycarboxylate ether (PCE), a polyacrylate (PA) and a polynaphtalene sulfonate (PNS) were selected as HRWRAs. Their solid content, in mass, were 33%, 35% and 33%, respectively. The dosage rates of the HRWRA were determined to obtain the same initial mini-slump flow of 450 mm on mortars.

This non-air entrained mixtures were proportioned to achieve an air fraction inferior to 2% of the mortar volume.

Table 2
Characteristics of the CEM I 52.5 N cement.

Chemical composition (%) (Bogue)		Physical characteristics	
SiO_2	20.5	Blaine fineness, m^2/kg:	428
Al_2O_3	4.4	Specific gravity:	3.13
Fe_2O_3	2.3	Setting time (Vicat), min	
CaO	63.3	• Initial	209
MgO	2.1	• Final	247
NaO_2 Eq.	0.66	Compressive strength, MPa	
Clinker	97	2 d	37
Limestone filler	3	7 d	52
		28 d	63

Table 1 summarizes the mixture proportioning of the mortar mixtures. The chemical and physical characteristics of the cement are summarized in Table 2.

3. Test methods

The mortars were prepared in batches of 15 L using a four paddle mixer having a helicoidal motion, and rotating at a speed of 175 rpm. The mixing procedure consisted in homogenizing the cement, the sand and the limestone filler in the mixer for 30 s. Then the water was gradually introduced for 60 s with the mixer rotating. Mortar was then mixed during 60 s. After a rest period of 90 s, the HRWRA was introduced and the mixing was resumed for an additional 60 s.

At the end of mixing, the sample column was filled and the remaining height *H* (which is the distance between the surface of the mortar and the upper side of the column) was measured to evaluate the initial pressure existing at the nozzle of the Marsh cone (Fig. 1).

The afflux time through the 8-mm opening for a flow of 1000 mL was monitored until the sample column was emptied. Each 1000 mL corresponds to a variation of 5.6 cm of mortar inside the column, or a variation of pressure of 1.17–1.24 kPa, depending on the specific gravity of the tested mortar. It is noteworthy that the pressure gradient, which is the specific gravity of the mixture divided by a 1 m height, is kept constant during the test. The shearing of the samples due to the flow of mortar inside the column erases any restructuration at rest to focus on non-reversible evolution of fluidity with pressure.

When flow time measurements were ended, the sample column was refilled and the remaining height *H* measured to evaluate the initial pressure existing at the nozzle of the Marsh cone (Fig. 1). Therefore, as the pressure gradient due to the specific gravity of the mixture is known, the variations of pressure existing within the sample can be calculated.

A torque is applied on the mortar until a continuous rotating movement of the paddle axis is seen, which corresponds to the moment when the yield stress permitting continuous shearing is

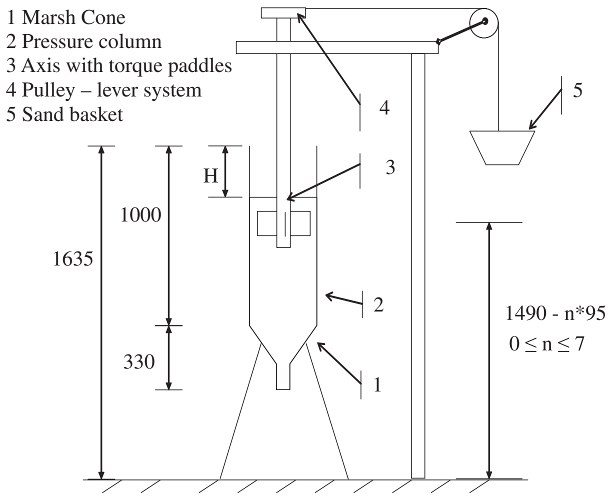

Fig. 1. Scheme of the apparatus (dimensions in mm).

reached. This torque monitoring was done every 9.5 cm from the upper surface of the mortar within the column, which corresponds to a step of variation of pressure of 2.0–2.1 kPa, depending on the specific gravity of the tested mortar. Hence the yield stress (τ_0, which refers to the resistance of the material to initiate the flow, can be calculated [18]. It is noteworthy that a stability criterion on the yield stress [19] was employed for mortar mixtures to verify if no segregation can occur during testing. Indeed, segregation of the mortars inside the sampling column can alter the torque measurement and, hence, the τ_0 calculation. The minimal value of the yield stress below which segregation occurs can be expressed as $\tau_0 = (\rho a - \rho f) \cdot g \cdot D\text{max}/K_0$, where ρa and ρf are the specific gravities of the aggregates and the paste respectively (kg/m^3), g the gravity constant, Dmax the maximal size of the aggregates, and $K_0 = 18$ a constant suggested by Bethemont [19]. This threshold stress has been calculated for each of the tested mixtures and is given in Table 3.

As the afflux time through an 8-mm opening for a flow of 1000 mL was monitored, the rate of flow Q (mL s^{-1}) can be calculated, using the flow time measurements t_v, as follows:

$$Q = \frac{1000}{t_v} \tag{1}$$

The rate of flow in a cylinder having a radius R, and taking as a hypothesis that inertia effects are negligible and the flowing velocity at the fluid/cylinder interface is equal to zero, the Buckingham–Reiner equation for a Bingham fluid having a yield stress τ_0 and a plastic viscosity μ can be expressed as:

$$Q(P) = \frac{\pi \cdot A \cdot R^4}{8 \cdot \mu(P)} \left[1 - \frac{4}{3}\left(\frac{2 \cdot \tau_0(P)}{A \cdot R}\right) + \frac{1}{3}\left(\frac{2 \cdot \tau_0(P)}{A \cdot R}\right)^4\right] \tag{2}$$

where A is the pressure gradient calculated as the ratio between the existing pressure at the cone opening and the remaining height of mortar in the column. It is worth noting that the pressure gradient A is quite constant as it corresponds to the pressure exerted by a 1-m high column of mortar, so directly linked to the specific gravity of the tested material. In the study presented herein, the value for R was taken as 4 mm which corresponds to the radius of the opening of the cone as the measured value of Q is mainly dependent on the dimensions of the outlet of the Marsh cone.

To calculate the plastic viscosity from the monitoring of the rate of flow, the τ_0 values are derived by regression analysis using the yield stress–pressure data computed, and assuming an exponential response.

Replicates were made and tested for mixtures randomly. Repeatability experiments showed a maximal relative deviation of 10% on τ_0, and 7 on plastic viscosity.

4. Results and discussions

4.1. Effect of W/C on variations in yield stress with pressure

As shown on Figs. 2a–2c, an exponential increase in yield stress is observed with increasing pressure on mixtures made with various W/C, independently of the HRWRA type. This variation of τ_0 with pressure can be expressed as:

$$\tau_0(P) = \tau_0(P = 0) \cdot e^{k \cdot P} \tag{3}$$

where P refers to the differential pressure exerted on the investigated mixture and k is an experimental constant given in Table 3 for the tested mixtures. This exponential response was preferred to a linear one to match the literature as regards the effect of pressure on rheology of cementitious materials [18]. The behavior of concrete is usually considered as hydrostatic when under pressure, i.e. linked to its specific gravity and the height of poured material [14,15]. The expected expression of the variation of τ_0 with the exerted pressure is usually taken as $\tau_0(P) = K \cdot \rho \cdot g \cdot z$, where K is a coefficient which is close to 1 for SCC materials [14], ρ refers to the specific gravity of the mixture, g is the gravitational acceleration and z the depth below the top of the material. The deviation from linearity in yield stress vs. pressure may be due to the consolidation

Table 3
Summary of experimental data obtained in this investigation.

Data	W/C = 0.45			W/C = 0.475			W/C = 0.5			W/C = 0.525			W/C = 0.55		
HRWRA	PNS	PA	PCE	PNS	PA	PCE	PNS	PA	PCE	PNS	PA	PCE	PNS	PA	PCE
Slump flow diameter (mm)	445	440	480	450	440	480	450	440	480	440	430	455	425	445	430
Specific gravity of the mortar	2.213	2.212	2.210	2.205	2.204	2.202	2.196	2.195	2.194	2.187	2.187	2.186	2.179	2.178	2.178
Specific gravity of the paste	1.978	1.976	1.973	1.963	1.961	1.959	1.948	1.946	1.944	1.933	1.931	1.930	1.918	1.916	1.915
Threshold segregation stress (Pa)	0.64	0.64	0.64	0.67	0.68	0.68	0.71	0.71	0.71	0.75	0.75	0.75	0.78	0.78	0.78
Initial yield stress $\tau_0(P = 0)$ (Pa)	23.7	18.0	32.5	27.9	20.3	41.6	38.9	24.5	56.2	39.7	45.3	56.2	44.9	54.0	60.2
k (kPa^{-1})	0.05	0.05	0.09	0.06	0.06	0.05	0.05	0.06	0.05	0.07	0.08	0.05	0.08	0.06	0.06
R^2 on exponential regression for $\tau_0(P)$ data	0.83	0.99	0.95	0.98	0.99	0.93	0.99	0.96	0.99	0.99	0.99	0.99	0.96	0.99	0.99
Increase in rate of flow with pressure (mL s^{-1}/kPa)	1.02	1.12	1.45	1.03	1.07	1.29	1.28	1.28	1.51	1.92	2.05	2.00	2.22	2.33	2.62
Initial plastic viscosity $\mu(P = 0)$ (Pa s)	0.05	0.95	0.15	0.01	0.76	0.02	0.01	0.38	0.01	0.04	0.20	0.12	0.05	0.02	0.25
Increase in plastic viscosity $\Delta\mu$ (kPa^{-1})	0.28	0.42	0.61	0.25	0.37	0.21	0.28	0.17	0.20	0.35	0.12	0.10	0.39	0.18	0.13
R^2 on exponential regression for $\mu(P)$ data	0.99	0.86	0.92	0.97	0.86	0.99	0.97	0.82	0.85	0.99	0.97	0.81	0.96	0.99	0.98

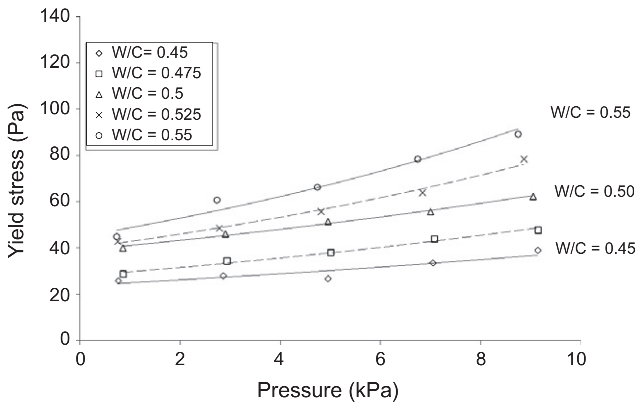

Fig. 2a. Variation of yield stress with pressure for mortars made with PNS HRWRA.

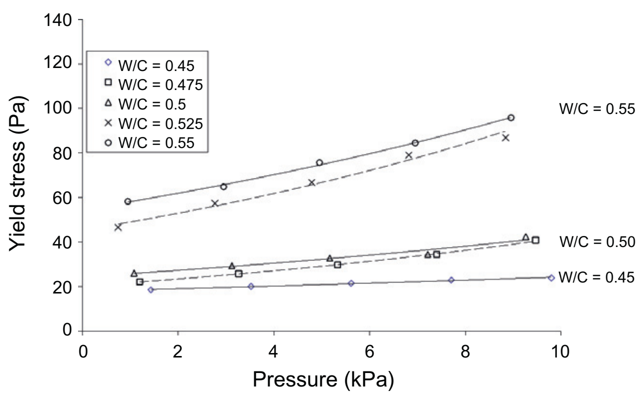

Fig. 2b. Variation of yield stress with pressure for mortars made with PA HRWRA.

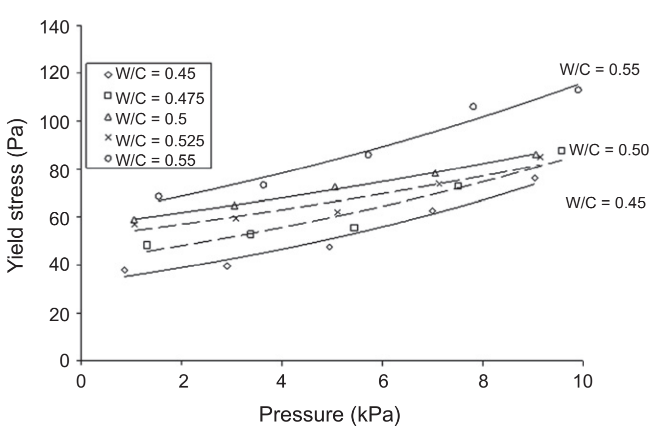

Fig. 2c. Variation of yield stress with pressure for mortars made with PCE HRWRA.

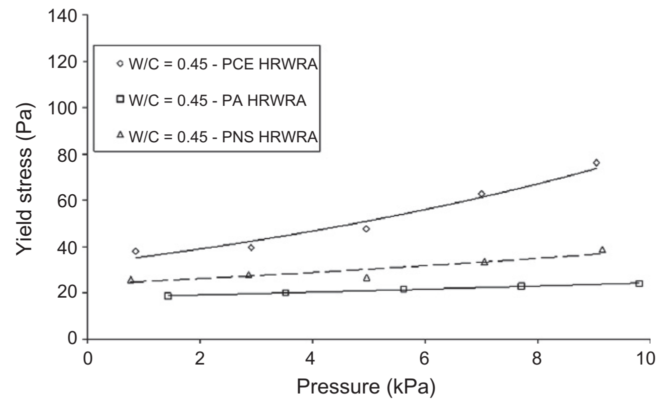

Fig. 3a. Variation of yield stress with pressure for 0.45 W/C mortars made with various HRWRAs.

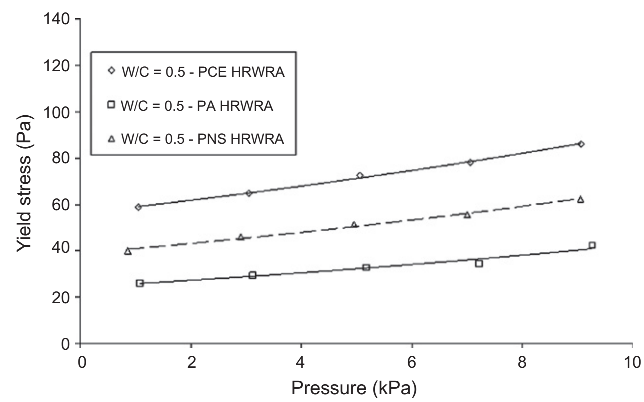

Fig. 3b. Variation of yield stress with pressure for 0.50 W/C mortars made with various HRWRAs.

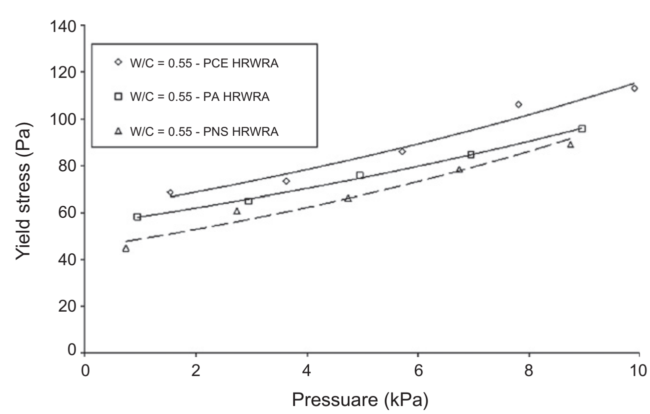

Fig. 3c. Variation of yield stress with pressure for 0.55 W/C mortars made with various HRWRAs.

of the SCC mortar under its own weight. Khayat et al. [20] measured a vertical deformation of 0.3% several hours after casting, denoting thus a consolidation of the material. A calculation made using data obtained on mortars tested herein shows that a 0.3% variation in pressure due to consolidation generates an increasing deviation from linearity with increasing pressure from 0.1% to 7%.

An increase in yield stress with increasing water content is shown, due to the decrease of HRWRA dosage to get the targeted 450 mm slump spread. As shown on Fig. 2a on PNS mixtures, an increase of W/C from 0.45 to 0.55 resulted in a drop in HRWRA demand from 0.69% to 0.45%, expressed on a dry axis, and thus, an increase in initial yield stress ($\tau_0(P = 0)$) from 23.7 to 44.9 Pa occurs (Table 3). As noted in [21], the rheology of cementitious mixes that include HRWRA is affected by the concentration of residual polymer in the pore solution. Higher polymer concentrations in the aqueous phase result in enhancing fluidity. Hence, an increase in water content involves a decrease in HRWRA dosage and, thus, a decrease in polymer concentration, resulting in higher τ_0 values. It is noteworthy that while mixture composition was adjusted to match the same slump spread, no match in yield stress was expected as Mueller and Wallevik [22] observed it: different SCC mixtures with the same slump spread of 620 mm had yield stresses varying from 40 to 80 Pa.

4.2. Effect of HRWRA type on variations in yield stress with pressure

As shown on Fig. 3, and as previously observed on Fig. 2, an exponential increase in yield stress is observed with increasing pressure on mixtures made with various W/C, with R^2 values ranging from 0.83 to 0.99 (Table 3). Apart from the initial variation of τ_0, the exponential shape of the response may be due to the consolidation of the mortar mixture when a gradient of pressure is exerted as previously explained. As demonstrated by Jolicoeur [21], the rheology of cement based materials is influenced by the concentration of free HRWRA remaining in the pore solution. Nevertheless, consolidation due to pressure partly drives away the pore solution, so the free HRWRA concentration decreases with increasing consolidation, i.e. with increasing pressure. Hence, the yield stress increases with increasing pressure, explaining the common exponential shape of the response [18].

On 0.45 W/C mixtures (Fig. 3a), PNS and PA mixtures showed close and similar variations of yield stress with pressure, with a maximal 41% divergence within the 1–10 kPa range of exerted pressure. A switch to PCE HRWRA induces a sharp increase of the yield stress variation with pressure, and almost doubles the initial yield stress value from 23.7 Pa for PNS made mixtures to 32.5 Pa for PCE based mortars. Yamada et al. [23] suggested that the efficiency of dispersion of cement particles is related to the concentration of sulfate ions in the cement paste solution. The adsorption of PCE HRWRA decreases when the sulfate-ion concentration is high in the aqueous phase, thus affecting the degree of retention in fluidity. Yamada et al. [24] noted that a high sulfate-ion concentration in the aqueous phase of cement paste at 20 °C can initially prevent the adsorption of the polycarboxylate polymer onto cement grains for mixtures proportioned with 0.3 W/B and 1% polycarboxylate-based HRWRA, per mass of cement, thus causing fluidity loss [24]. As a low W/C ratio means higher concentrations, this may explain the superior initial yield stress and variation of yield stress with pressure on PCE mortars compared to PNS or PA based mixtures.

When W/C is increased up to 0.50 (Fig. 3b), the differences between the behavior with pressure of the mixtures made with the three types of HRWRA shaded off, except for the initial yield stress which ranges from 24.5 to 56.2 Pa, depending on the HRWRA in use (Table 3). These differences in initial yield stress are mainly due to the HRWRA dosage ranging from 0.19% for PCE mortars to 0.51% for mixtures proportioned with PNS. The higher the HRWRA demand, the higher the residual HRWRA concentration in the pore solution, resulting in a better fluidity [21].

When W/C is increased up to 0.55, the difference between the initial yield stress of the tested mixtures is inferior to 25%, and the evolution of τ_0 with pressure of the tested mixtures are close. As the HRWRA demand is low, the main lubricant responsible for rheologic behavior of the tested mortar is water. As the water content is the same at a fixed W/C ratio, the fact that the three tested mixtures behave the same way with close yield stress values was expected. Nevertheless, when pressure is increased, PCE mixtures have a higher response with pressure than PA or PNS ones, denoting that this HRWRA, sensitive to sulfate concentration, may desorb as pressure partly drives away water, increasing ion concentration.

4.3. Coupled effect of W/C and HRWRA type on variations in rate of flow with pressure

Data presented on Fig. 4 for PNS mortars show that the rate of flow is increasing linearly with increasing pressure. Similar data were obtained on PA and PCE mixtures. An increase in W/C resulted in augmenting the rate of flow as well as the variation of flow with pressure, independently of the HRWRA in use. The higher the W/C, the easier the flow, explaining the presented results. Petit and Wirquin [18] noted that, on 0.50 W/C mortars including variable amount of limestone filler, a limit flow occurred when the exerted pressure is high enough. It is noteworthy that no limit flow was observed on the tested mixtures, denoting that the limit pressure inducing a steady flow was not reached.

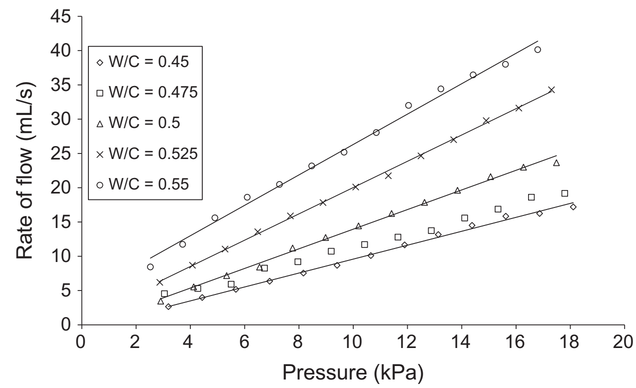

Fig. 4. Variation of rate of flow with pressure for PNS mortars made with various W/C.

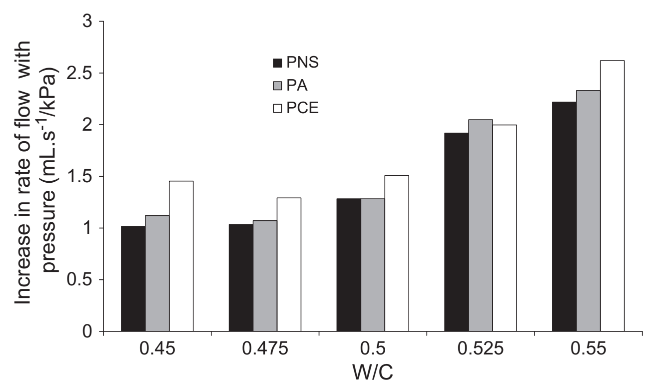

Fig. 5. Variation of rate of flow for mortars made with various HRWRAs and various W/C.

Fig. 5 shows that, when augmenting the water over cement ratio, the increase in rate of flow with pressure (defined as the slope of the rate of flow vs. pressure linear response) remains first constant or even shows a slight decrease before undergoing an increase from W/C of 0.50. When this ratio is below 0.50, it is assumed that, due to the relatively low water content, solid friction between particles drives the flow behavior while an augmentation of water content eases the flow, explaining the increase in rate of flow with W/C. Data obtained on the increase of rate of flow are summarized in Table 3.

4.4. Coupled effect of W/C and HRWRA type on variations in plastic viscosity with pressure

The variation of plastic viscosity was calculated using Eq. (2) and using the τ_0–pressure response. As shown on Fig. 6 for PNS mortars, an exponential like response was observed: when W/C is augmented, i.e. HRWRA dosage decreased to get the targeted 450 mm slump spread, the exerted pressure increases the friction between solid particles of the mortars, thus increasing viscosity and explaining the exponential shape of the μ vs. pressure curve. The plastic viscosity response can be expressed as:

$$\mu(P) = \mu(P = 0) \cdot e^{\Delta\mu \cdot P} \quad (4)$$

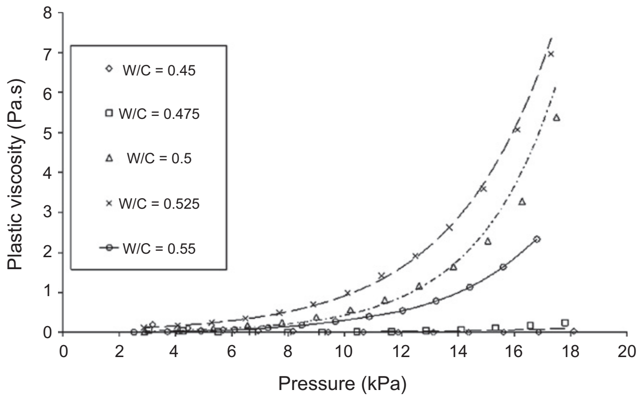

Fig. 6. Variation of plastic viscosity for PNS mortars made with various W/C.

Initial plastic viscosity values ($\mu(P = 0)$), corresponding to μ values when no pressure is exerted on the material, were calculated by exponential regression on the μ vs. pressure curves. Data presented on Fig. 7 show that the initial plastic viscosity of PA mortars are continuously decreasing when increasing the water content. At low W/C, and even if the PA HRWRA deflocculates the cement grains, it is assumed that the deflocculation is not strong enough to avoid interparticle friction, explaining the high values of $\mu(P = 0)$ for W/C inferior to 0.50. When water is increased, and even if it corresponds to a decrease in HRWRA dosage to get the targeted 450 mm slump spread, particles are moved away by the surplus water, and thus, viscosity of the mixture decreases. As for PCE and PNS mortars, a decrease in initial plastic viscosity is first observed up to a W/C of 0.50 before a regain in $\mu(P = 0)$ is seen for higher water contents (Fig. 7). This may be explained as follows: due to their adsorption efficiency, PCE and PNS polymers saturate the surface of the cement grain. An addition of water in the mixture by increasing W/C results in augmenting free water content, easing the flow and, thus, decreasing the $\mu(P = 0)$ response. For W/C over 0.50, HRWRA dosage is low, and so, solid friction between particles can occur, explaining the gain in initial plastic viscosity with exerted pressure.

The variation of the increase of plastic viscosity with exerted pressure ($\Delta\mu$), defined as the exponential coefficient in Eq. (4), is plotted in Fig. 8. For all tested mixtures, $\Delta\mu$ first decreases with increasing W/C up to a limit depending on the HRWRA type. Such limit is 0.475 for PNS mortars, and 0.525 for mixtures prepared with long side chain polymers. The loss of $\Delta\mu$ is more accentuated for PCE mixtures, from 0.61 kPa^{-1} to 0.10 kPa^{-1}, while this loss is only 11% on PNS mortars. The decrease of $\Delta\mu$ observed may be due to the fact that the tested mortars are multiphasic materials. Thus, on increasing shear rate at the nozzle of the Marsh cone (which is related to increasing pressure), phases separate and a layer of water may appear between the mortar and the smooth-walled inner surface of the nozzle, facilitating the flow. It was reported that, if the material of the wall surface cannot disperse particles, the dispersing product tends to form a layer that acts as a lubricant, easing the slippage along the wall form in rheological devices [18,25]. When W/C is augmented, i.e. HRWRA dosage decreased to get the targeted 450 mm slump spread, the exerted pressure increases the friction between solid particles of the mortars, then increasing viscosity. Consequently, $\Delta\mu$ increases when W/C is over 0.475 for PNS mortars, and 0.525 for mixtures prepared with either PA or PCE, as shown on Fig. 8.

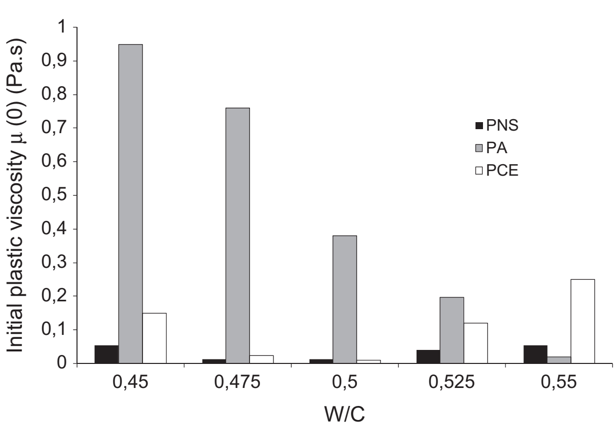

Fig. 7. Variation of initial plastic viscosity for mortars made with various HRWRAs and various W/C.

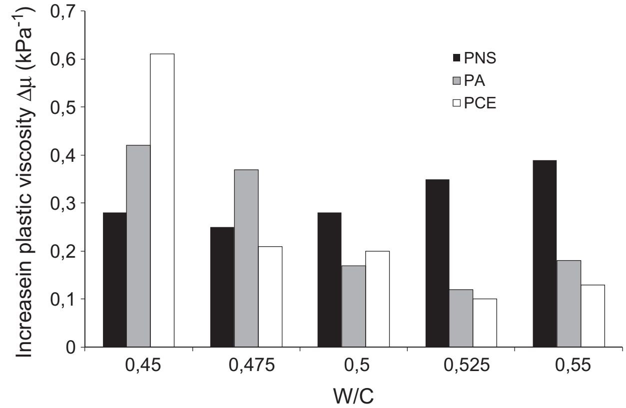

Fig. 8. Variation of increase in plastic viscosity with pressure for mortars made with various HRWRAs and various W/C.

5. Conclusions

The influence of the coupled effect of pressure and W/C and on the evolution of the rheological properties of mortars proportioned with three HRWRA type was investigated. Based on the results presented in this paper, the following conclusions appear to be warranted:

1. An exponential increase in yield stress is observed with increasing pressure on mixtures made at various W/C and various HRWRA.
2. On 0.45 W/C mixtures, polynaphtalene sulfonate (PNS) and polyacrylate (PA) mixtures displayed close and similar variations of yield stress with pressure. A switch to Polycarboxylate ether (PCE) HRWRA induces a sharp increase of the yield stress variation with pressure, and almost double the initial yield stress. This phenomenon may be due to the decrease in the adsorption of PCE HRWRA. When W/C is augmented, the role of water as main lubricant becomes preponderant. Consequently, the differences between the behavior with pressure of the mixtures made with the three types of HRWRA shaded off, except for the initial yield stress.
3. For mortars made with variable W/C, an exponential-like increase of plastic viscosity (μ) is observed when augmenting pressure, due to the increase in solid friction. The plastic viscosity response can be expressed as $\mu(P) = \mu(P = 0) \cdot e^{\Delta\mu \cdot P}$, where $\mu(P = 0)$ represents initial plastic viscosity values corresponding to μ values when no pressure is exerted on the material, and $\Delta\mu$ the variation of the increase of plastic viscosity with exerted pressure.

4. The initial plastic viscosity of PA mortars continuously decreases when the water content increases. Interparticle friction is the main parameter that affects $\mu(P = 0)$. When water is increased, and HRWRA dosage decreased, particles are moved away by the surplus water, and thus, viscosity of the mixture decreases.
5. On mortars proportioned with either PCE or PNS HRWRA, a decrease in initial plastic viscosity is first observed up to a W/C of 0.50 before a regain in $\mu(P = 0)$ is seen for higher water contents. For W/C below 0.50, as these polymers saturate the surface of the cement grain, a rise in W/C results in augmenting free water content, easing the flow and, thus, diminishing the $\mu(P = 0)$ response. For W/C over 0.50, HRWRA dosage is low. Thus, solid friction between particles can occur, explaining the gain in initial plastic viscosity with exerted pressure.
6. The variation of the increase of plastic viscosity with exerted pressure ($\Delta\mu$) is first diminishing with increasing W/C up to a limit depending on the HRWRA type, before showing a gain in $\Delta\mu$. A layer of water may appear between the mortar and the inner surface of the nozzle, facilitating the flow and explaining the initial decrease of $\Delta\mu$. When W/C is augmented and HRWRA dosage decreased, the exerted pressure amplifies the friction between solid particles, increasing viscosity and, consequently, $\Delta\mu$.
7. PA appears to be the most accurate HRWRA for light pressure injection, with less sensitivity to changes in pressure or W/C than PNS or PCE superplasticizers.

References

[1] Warner J. Preplaced-aggregate concrete. Concr Int 2005;27(09):34–8.

[2] Ramachadran VS, Malhotra VM, Jolicoeur C, Spiratos N. Superplasticizers: properties and applications in concrete. In: CANMET, editors, Ottawa; 1998. 404p.

[3] Flatt RJ, Houst YF. A simplified view on chemical effects perturbing the action of superplasticizers. Cem Concr Res 2001;31(8):1169–76.

[4] Flatt RJ, Martys N, Bergström L. The rheology of cementitious materials, MRS bulletin. Mater Res Soc 2004;29(5):314–8.

[5] Fernon V, Vichot A, Le Goanvic N, Colombet P, Corazza F, Costa U, Interaction between Portland cement hydrates and polynaphtalene sulfonates. In: Malhotra VM (Ed.), Proc 5th CANMET/ACI int conf on superplasticizers and other chemical admixtures in concrete. Rome: American Concrete Institute; 1997. p. 225–48.

[6] Khayat KH, Saric-Coric M. Evaluation of the effect of welan gum-superplasticizer interaction on characteristics and of cement grouts. In: Malhotra VM (Ed.), Proceedings, 6th CANMET/ACI international conference on superplasticizers and other chemical admixtures in concrete, ACI SP 195, Nice; 2000. p. 249–68.

[7] Khayat KH, Guizani Z. Use of viscosity-modifying admixture to enhance stability of fluid concrete. ACI Mater J 1997;94(4):332–40.

[8] Khayat KH. Workability, testing, and performance of self-consolidating concrete. ACI Mater J 1999;96(3):346–53.

[9] Khayat KH, Yahia A. Effect of welan gum—high-range water reducer combination on rheology of cement grout. ACI Mater J 1997;94(5):365–72.

[10] Sonebi M. Rheological properties of grouts with viscosity modifying agents as diutan gum and welen gum incorporating pulverized fly ash. Cem Concr Res 2006;36(9):1609–18.

[11] Uy B, Das S. Wet concrete loading of thin walled steel box columns during the construction of a tall building. J Constr Steel Res 1997;42(2):95–119.

[12] Galvin KP. On the phenomena of hindered settling in liquid fluidized beds. In: Honaker RQ, Forrest WR, editors. Advances in gravity concentration. SME; 2003. p. 19–38.

[13] Rubiera F, Hall ST, Shah CL. Sulfur removal by fine coal cleaning processes. Fuel 1997;76(13):1187–94.

[14] Tchamba JC, Amziane S, Ovarlez G, Roussel N. Lateral stress exerted by fresh cement paste on formwork: laboratory experiments. Cem Concr Res 2008;38(4):459–66.

[15] Roussel N. A thixotropy model for fresh fluid concretes: theory, validation and applications. Cem Concr Res 2006;36(10):1797–806.

[16] Schwartzentruber A, Catherine C. Concrete equivalent mortar – a new tool for admixtured concrete design. Mater Struct 2000;33(232):475–82 [in French].

[17] ASTM C 939. Test method for flow of grout for preplaced-aggregate concrete (flow cone method). Annual book of ASTM Standards 04.02.

[18] Petit JY, Wirquin E. Effect of limestone filler content and superplasticizer dosage on rheological parameters of highly flowable mortar under light pressure conditions. Cem Concr Res 2010;40(2):235–41.

[19] Bethemont S, D'aloia Schwartzentruber L, Stefani C, Le Roy R, Rossi P. Stability for a sphere in a complex fluid – segregation of self compacting concrete. Bull Lab Ponts Chaussées 2005;254:61–73 [in French].

[20] Khayat KH, Assad J, Mesbah H, Lessard M. Effect of section width and casting rate on variations of formwork pressure of self-consolidating concrete. RILEM Mater Struct 2005;38:73–8.

[21] Jolicoeur C, Sharman J, Otis N, Lebel A, Simard MA, Page M. The influence of temperature on the rheological properties of superplasticized cement pastes. In: Malhotra VM (Ed.), Proceedings, fifth CANMET/ACI international conference on superplasticizers and other chemical admixtures in concrete, ACI SP 173. Rome: ACI; 1997. p. 379–15.

[22] Mueller FV, Wallevik OH. Effect of maximum aggregate size in air-entrained eco-SCC. In: Shi C, Yu Z, Khayat KH, Yan P (Eds.), Proceedings of the 2nd RILEM symposium on design, performance and use of self-consolidating concrete, RILEM PRO 65, Beijing; 2009. p. 664–73.

[23] Yamada K, Ogawa S, Hanehara S. Controlling the adsorption and dispersing force of a polycarboxylate-type superplasticizer by sulfate ion concentration in aqueous phase. Cem Concr Res 2001;31(3):375–83.

[24] Yamada K, Yanagisawa T, Hanehara S. Influence of temperature on the dispersibility of polycarboxylate type superplasticizer for highly fluid concrete. In: Skarendahl A, Petersson O (Eds.), 1st International RILEM symposium on self-compacting concrete. Stockholm: The publishing company of RILEM; 1999. p. 437–47.

[25] Nehdi M, Rahman M-A. Effect of geometry and surface friction of test accessory on oscillatory rheological properties of cement pastes. ACI Mater J 2004;101(5):416–24.