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Effect of limestone filler content and superplasticizer dosage on rheological parameters of highly flowable mortar under light pressure conditions

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ABSTRACT

The influence of pressure on the yield stress and plastic viscosity of SCC mortars was investigated using an adapted Marsh cone with cylindrical shear paddles. Nine mortars proportioned with various limestone filler content and high-range water-reducing admixture (HRWRA) dosage from 0.65% to 0.85% were prepared. Test results show that when a pressure is exerted on the mortars, the material does not behave as a homogeneous fluid, i.e. having a yield stress depending only on the specific gravity of the mixture and the height of poured mortars and a constant value of plastic viscosity, but as a separative multiphasic material which consolidates, leading to exponential variations of τ_0 and lowering values of μ with pressure. The HRWRA dosage or the limestone filler content has only an effect on the initial value of the yield stress, but has more influence on the variation of plastic viscosity of the mortar with pressure.

1. Introduction

Self consolidating or self levelling cementitious materials are now being studied and used worldwide for building projects. This type of concrete must have excellent flowability and, at the same time, adequate segregation resistance independently of the casting method (pouring or pumping).

To drastically enhance workability of self levelling cementitious materials, 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 [1–4]. 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 the admixtures [5–8]. For example, Sonebi [9] 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 use of limestone filler or the decrease of water over supplementary cementitious materials ratio (W/SCM) can also increase the viscosity of cementitious materials [1,10–14]. The fineness of the SCM is another factor influencing rheology of cement-based material. Partial replacement in volume of cement by limestone filler of 500 to 1000 m^2/kg specific area resulted in an enhancement in fluidity and a reduction of the yield stress [15,16]. For example, Esping [17] found, on self compacting concrete (SCC) made with CEM II/A-LL 42.5 R cement complying with EN 197-1 standards, 0.55 W/C, 0-8 mm natural pit gravel, 8-16 mm crushed granite coarse aggregate, polycarboxylate ether-based HRWRA and limestone filler as SCM, that an increase in limestone filler specific area from 2000 to 6000 m^2/kg resulted in doubling the yield stress and increasing the plastic viscosity from approximatively 35 Pa.s to 50 Pa.s: an excessive addition of SCM can considerably increase water demand due to the increase in specific area, resulting in the stiffening of the material [18]. The mix design should lead to an optimal cement / SCM ratio in order to have a material with very cohesive and unsegregative capacities at rest, and showing a high deformability when moving [19].

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 story buildings in order to reduce craneage requirements on site [20]. Other techniques consist in injecting the material under low pressure, such as gravitational injection of SCC repair mortars used to fill 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

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differences in the properties of the particles [21,22]. Hence, dynamic segregation may occur within concreting pipes while the SCC is pumped, due to the low yield stress used as design parameter.

As an 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 needed to maintain a homogeneous dispersion of solid particles during the handling, the placement, as well as the period of rest into the formwork while 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.

Concrete deformability and stability is mainly related to the yield stress and plastic viscosity of the cementitious material. While literature usually considers the behaviour of concrete as hydrostatic when under pressure, i.e. linked to its specific gravity and the height of poured material [23,24], few data are available on the variation of the rheological parameter with pressure exerted on the material as during the pumping phase of casting or during injection. However, the exerted pressure, needed to maintain a continuous flow, may lead to instability of the material within the concrete pipes. The proposed work aims at highlighting the behaviour of SCC mortars, 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) [25] 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 [26].

The testing program was carried out using mortars made with a CEM I 52.5 N cement containing about 97% of clinker, a polynaphtalene sulfonate (PNS) -based HRWRA, W/C of 0.50, and limestone filler (F).

To design the original SCC mixtures from which the first set of mortars tested in this investigation are derived (mortars '350' to '450'), the cement mass chosen for the tests ranged from 350 to 450 kg/m^3 by steps of 25 kg. Crushed limestone filler was added to complete the binder volume to 185 L, without altering the W/C, and hence the paste fraction. This choice was made to keep the paste-to-aggregate volume ratio constant, thus enabling comparison between the two mixtures in terms of rheology. This non-air entrained SCC mixtures were proportioned in compliance with European EN 206-1 Standard to achieve an air fraction inferior to 2% of the concrete volume. The mortar mixtures are based on SCC mixtures where aggregate particles coarser than 2 mm are excluded from the mixture by sieving. The dosage rates of the HRWRA were determined to obtain the same initial mini-slump flow of 450 mm on mortars.

The second set of mortars (mixtures 0.65% to 0.85%) was designed as a variant of the '400' mixture varying the HRWRA dosage from 0.65% to 0.85% of the cement mass, expressed by active mass of product.

The mortar mixtures were proportioned using crushed limestone sand with a fineness modulus of 2.60, 2.71 specific gravity limestone filler, and PNS-HRWRA of 32% of solid content in mass and incorporated at 0.65% to 0.85%, by mass of cement.

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 liters using a 4 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 during 30 s. Then the water was gradually introduced over 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 gradient of pressure existing at the nozzle of the Marsh cone (Fig. 1).

The afflux time through the 8-mm opening for a flow of 1,000 mL was monitored until the sample column was emptied. Each 1,000 mL

Table 1
Mortar mixture proportioning and experimental data.

Materials	Mortars									
	350	375	400	425	450	0.65%	0.70%	0.75%	0.80%	0.85%
CEM I 52.5 N Cement (kg/m^3)	563	596	628	660	691	628	628	628	628	628
Limestone Filler (kg/m^3)	311	273	236	199	163	236	236	236	236	236
F/C (% in mass)	55	46	38	30	24	38	38	38	38	38
W/C	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
S (kg/m^3)	1055	1022	990	959	929	990	990	990	990	990
PNS-HRWRA (% of cement mass)	1.97	1.67	0.75	0.6	0.51	0.65	0.7	0.75	0.8	0.85
Slump flow diameter (mm)	460	458	457	455	459	430	450	457	490	500
Temperature of the mortar(°C)	25.2	26.2	20.1	21.5	25.2	21.5	23.8	20.1	22.6	20.1
Specific gravity of the mortar	2.25	2.22	2.18	2.16	2.14	2.18	2.18	2.18	2.18	2.18
Specific gravity of the paste	1.96	1.94	1.93	1.92	1.90	1.94	1.94	1.93	1.93	1.93
Threshold segregation stress (Pa)	0.70	0.72	0.73	0.75	0.77	0.72	0.72	0.73	0.73	0.73
Initial Yield stress $\tau_0(P=0)$ (Pa)	4.5	5.8	9.6	10.8	11.6	10.8	12.0	9.6	3.8	1.6
R^2 on exponential regression for $\tau_0(P)$ data	0.98	0.99	0.95	0.99	0.99	0.95	0.93	0.93	0.97	0.81
Initial plastic viscosity $\mu(P=0)$ (Pa.s)	0.2	0.5	1.1	1.3	7.6	4.6	2.7	1.1	0.5	0.4
R^2 on exponential regression for $\mu(P)$ data	0.82	0.86	0.91	0.90	0.99	0.99	0.85	0.91	0.91	0.98

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
		28d:	63

corresponds to a variation of 5.6 cm of mortar inside the column, or a variation of pressure of 1.17 to 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 terminated, the sample column was refilled and the remaining height H measured to evaluate the initial gradient of 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 axis of the paddle is seen, which corresponds to the moment when the yield stress permitting continuous shearing is reached. This torque is created, through a system of pulley and lever, by a basket gradually filled with sand. The measure was done three times and the average mass of sand taken for the torque calculation. This torque monitoring was done each 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 to 2.1 kPa, depending on the specific gravity of the tested mortar.

The most widely used models to describe fresh cement paste behaviours are the Bingham and Herschel-Bulkley models, which take into account the plastic or pseudoplastic behaviour of those concentrated suspensions. In the following theoretical study, the flow is modelled for the Bingham fluid approximation.

The yield stress (τ_0) refers to the resistance of the material to initiate the flow, and the plastic viscosity (μ) refers to the slope of the shear stress-shear rate relationship for a fluid assuming a Bingham response ($\tau = \tau_0 + \mu_p \dot{\gamma}$).

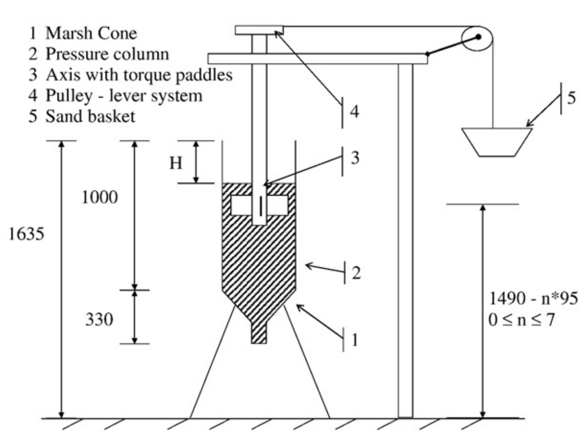

Fig. 1. Scheme of the apparatus.

Two replicates were made and tested for '375' and '400' mixtures. Repeatability experiments showed a maximal relative deviation of 10% on τ_0 , and 5% on plastic viscosity.

4. Theoretical approach to calculate rheological parameter

4.1. Yield stress calculation

As previously noted, a torque is applied on the mortar until a continuous rotating movement of the axis of the paddle is seen, which correspond to the moment when the yield stress permitting continuous shearing is reached. This torque is created, through a system of pulley and lever, by a basket gradually filled with sand. The average mass of sand needed to permit the continuous shearing is converted into force using a gravity constant of 9.81, and multiplied by the 2.5 mm radius of the upper pulley to obtain the torque value. The geometry of the paddles (height a x length b) and the number of paddles (N) are considered to calculate the value of the yield stress from torque monitoring, assuming that, at the very beginning of the rotation of the axis, the stress applied on a paddle is constant and equal to τ_0. Thus, the force F exerted on a paddle is expressed by $F = \tau_0$ a.b, and the torque on each paddle by F.b/2 (the term b/2 is the lever). Consequently, the total torque at a given height of measurement (i.e. at a given pressure) *T(P)* is related to the yield stress at the same pressure τ_0(P) using the following expression (Eq. (1)):

$$T(P) = N.\tau_0(P).\frac{a.b^2}{2} \quad (1)$$

It is noteworthy that a stability criterion on the yield stress [27] 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 $\tau_0 = (\rho a - \rho f).g.Dmax / K_0$ 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 [27]. This threshold stress has been calculated for each of the tested mixtures and is given in Table 1.

4.2. Plastic viscosity calculation

The flow time for a purely viscous fluid t_v is proportional to the viscosity via a function of the cone geometry [28]. As the afflux time through an 8-mm opening for a flow of 1,000 mL was monitored, the rate of flow *Q* (mL.s^{-1}) can be calculated as follows (Eq. (2)):

$$Q = \frac{1,000}{t_v} \quad (2)$$

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 (Eq. (3)):

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

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 of 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 using Eq. (1), assuming an exponential response.

5. Results and discussions

5.1. Effect of limestone filler content on variations in yield stress with pressure

Test results from Fig. 2 and mix proportions given in Table 1 show that an increase in filler content (F/C) from 24% to 55% resulted in increasing HRWRA demand from 0.51% to 1.97% to get the targeted 450 mm slump flow, hence lowering the initial yield stress from 11.6 Pa to 4.5 Pa. Consequently, the '450' mixtures with F/C of 24% exhibited 150% greater values of yield stress than those monitored on the '350' mortars (F/C = 55%), independently of mixture pressure. As reported by Esping [17], the increase in specific area and packing density due to the partial replacement of OPC by limestone filler lowers the slump flow. Consequently, to get the targeted 450 mm slump flow on the mini slump test, the HRWRA dosage was increased. It is note worthy that the W/C was kept constant, thus, an increase in filler content resulted in a decrease in cement, hence a decrease in water dosage. Augmenting HRWRA to keep slump flow the same is similar to increasing the PNS concentration in the aqueous phase, having direct implication on rheological properties [29]. This can explain the decrease in the initial yield stress with increasing filler content [23,29]. Moreover, even if mixture composition was adjusted to match the slump spread to that of the reference mortar, no match in yield stress was expected as Mueller [30] observed that different SCC mixtures with the same slump spread of 620 mm had yield stresses varying from 40 to 80 Pa.

As shown on Fig. 2, an exponential increase in yield stress is observed with increasing pressure on mixtures made with various limestone filler content, with R^2 values ranging from 0.94 to 0.99 (Table 1). This variation of τ_0 with pressure can be expressed as (Eq. (4)):

$$\tau_0(P) = \tau_0(P = 0).e^{k.P} \tag{4}$$

where P refers to the differential pressure exerted on the investigated mixture and k is an experimental constant. The k value for the tested mixtures was $10^{-4}\,Pa^{-1}$. The behaviour of concrete is usually considered as hydrostatic when under pressure, i.e. linked to its specific gravity and the height of poured material [23,24]. The expected expression of τ_0 with the exerted pressure should be $\tau_0(P) = K.\rho.g.z$ where K is a coefficient which is close to 1 for SCC [23], 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 versus pressure may be due to the consolidation of the SCC mortar under its own weight. Khayat [31] 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%.

5.2. Effect of HRWRA dosage on variations in yield stress with pressure

An increase in HRWRA dosage from 0.65% to 0.85% resulted in lowering the initial yield stress ($\tau_0(P = 0)$) from 10.8 Pa to 1.6 Pa, thus increasing the mini slump diameter by 16.3% (Table 1). This well known phenomenon is due to a higher amount of adsorbed polymer onto the surface of the cement grain due to a higher dosage in HRWRA, thus contributing to minimizing interactions between particles through electrostatic repulsive forces. The consequence is a decrease of internal system of electrostatic forces, hence lowering the necessary force to generate the flow known as yield stress. While the mortar designed with 0.85% HRWRA dosage has an initial yield stress close to but above the threshold segregation stress (Table 1), a beginning of segregation was observed on the mortar after 5 min at rest. Nevertheless, for the sake of this investigation, data collected on this mixture were kept.

As shown on Fig. 3, and as previously observed on mortars made with variable limestone filler content (Fig. 2), an exponential increase in yield stress is observed with increasing pressure on mixtures made with various dosages of HRWRA, with R^2 values ranging from 0.81 to 0.99 (Table 1). 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 [29], the rheology of cement based materials is influenced by the concentration of free HRWRA remaining in the pore solution. It is assumed that, due to the high W/C of the mortars tested in this investigation, some HRWRA should be remaining in the pore solution despite of the low dosages in superplasticizer.

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.

5.3. Effect of limestone filler content on variations in rate of flow and plastic viscosity with pressure

Data presented on Fig. 4 show that the rate of flow is increasing linearly with increasing pressure until a point corresponding to 13 kPa where a slow-down of the increase is observed. From this point, the rate of flow tends toward a steady value. Such limit rate of flow is of 45 $mL.s^{-1}$ for mixtures made with low limestone filler content (F/C of

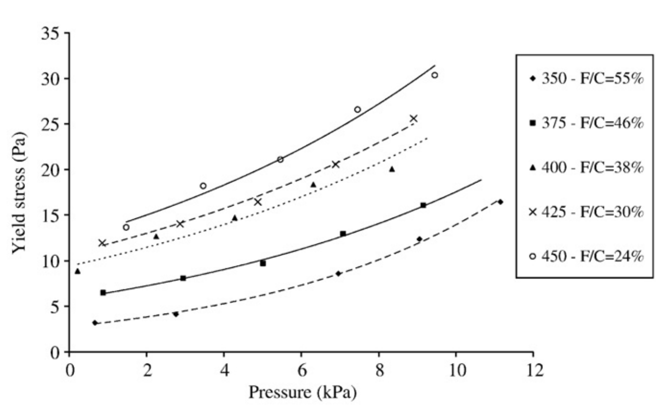

Fig. 2. Variation of yield stress with pressure for mortars made with various limestone filler content.

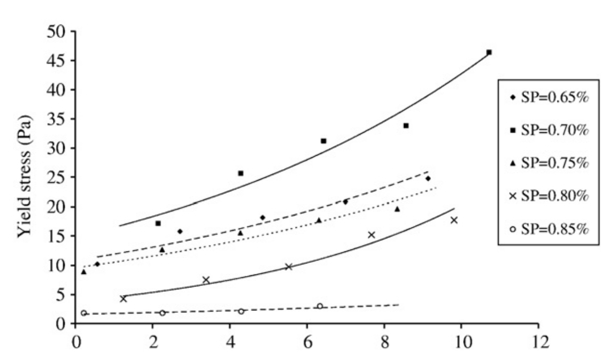

Fig. 3. Variation of yield stress with pressure for mortars made with various HRWRA dosages.

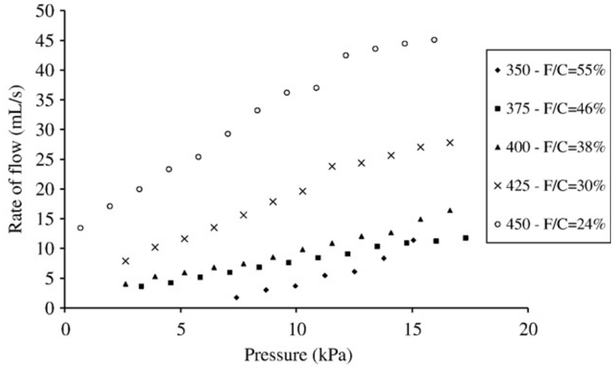

Fig. 4. Variation of rate of flow with pressure for mortars made with various limestone filler content.

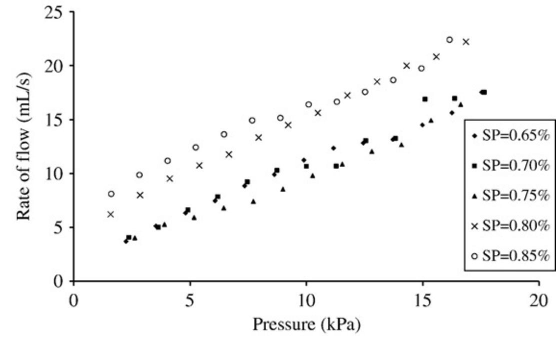

Fig. 6. Variation of rate of flow with pressure for mortars made with various HRWRA dosages.

24%), and is of 28 mL.s^{-1} for mixtures made with 0.30 F/C, and lower with the increase in filler content.

The variation of plastic viscosity, calculated using Eq. (3) and using the τ_0 – pressure response, is presented on Fig. 5. An exponential-like decrease of μ can be observed with increasing pressure, independently of the filler content, and R^2 values on exponential regression range from 0.78 to 0.99. The minimum values of plastic viscosity monitored tend to equal the μ value of water. Such behaviour can be explained by the fact that the tested mortars are multiphasic materials. Hence, 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 [32]. This slippage is more pronounced as the concentration of solid increases [33]. Such observations previously made by researchers on rheometric apparatuses [32,33] may explain the fact that the decrease of plastic viscosity with pressure is more important for mortars made with higher filler content (F/C = 55%) than on mixtures containing 24% to 30% of limestone filler volumetric replacement of OPC. The higher the F/C, the more pronounced the decrease, as shown on Fig. 5.

The use of filler in multiphase cement-based materials aims at enhancing the particle distribution of the powder skeleton, thus reducing the interparticle friction and ensuring a better packing density of the system. The initial plastic viscosity (i.e. the μ value obtained by regression when no pressure is exerted on the mixture) is increasing with the increase in filler content due to the improvement of the packing density [18]. Such initial plastic viscosity is of 0.2 Pa.s for mixtures made with 24% filler content to 7.6 Pa.s for mortars designed with 55% F/C, using an exponential regression to fit the shape of the μ(P) curve (Fig. 5). R^2 values for μ(P) range from 0.82 to 0.99.

5.4. Effect of HRWRA dosage on variations in rate of flow and plastic viscosity with pressure

As for mortars made with various filler contents, the rate of flow of mixtures made with HRWRA dosages from 0.65% to 0.85%, by mass of cement, is linearly increasing (Fig. 6). Contrarily to what was previously noticed of '350' to '450' mortars, no limit rate of flow is observed when filler content is kept constant and the HRWRA dosage varies. It can be assumed that the pressure corresponding to the loss of linearity in the rate of flow-pressure data is not reached yet as, due to the height of the column in the modified Marsh cone presented in this investigation. A maximum of differential pressure of 18 kPa can be obtained, which seems to be insufficient to reveal the point corresponding to the loss of linearity.

When data are plotted in terms of plastic viscosity (Fig. 7), a decrease in the μ value from initial plastic viscosity is first observed, depending on mixture composition, down to 2 mPa.s. Sonebi [9] observed, on grouts made with fixed HRWRA dosage of 1.38% and variable VMA content ranging from 0.04% to 0.08%, that viscosity was reduced with increasing shear rate due to the partial realignment of the polymer chain in the direction of the flow, and dislodging of the intertwined chains of the VMA polymer. Such conclusion can be extended to the data presented on Fig. 7 as shear rate at the outlet of the Marsh cone increases with added pressure, thus reducing the plastic viscosity value. Moreover, the layer of water generated by pressure on the smooth inner surface of the nozzle eases the flow, contributing to decrease plastic viscosity, as previously explained.

Nevertheless, for pressure above 15 kPa for mixtures made with 0.65% and 0.70% HRWRA dosage, and 13 kPa for mortars made with higher HRWRA dosage, an increase in plastic viscosity can be observed, except for the last mortar made with 0.85% HRWRA. Such phenomenon can be explained as follows: when the pressure exerted

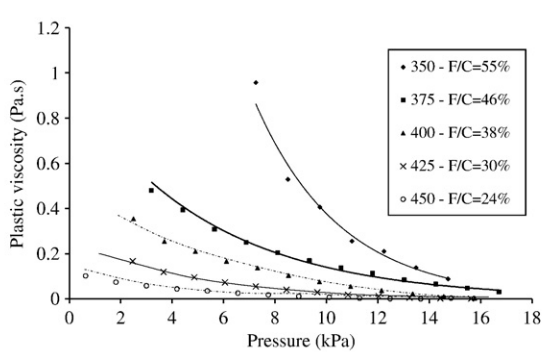

Fig. 5. Variation of plastic viscosity with pressure for mortars made with various limestone filler content.

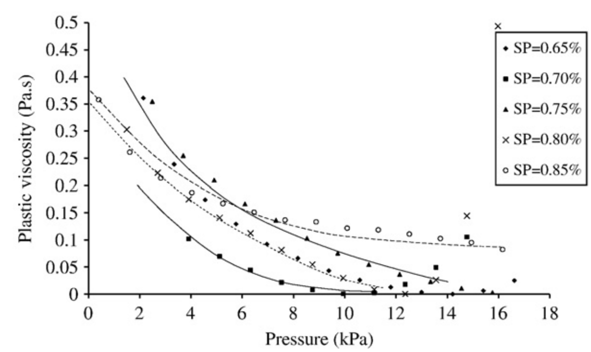

Fig. 7. Variation of plastic viscosity with pressure for mortars made with various HRWRA dosages.

on the material is sufficient, the liquid phase that tended to separate and form a lubrificating layer at the material-nozzle interface recombines with the other materials, thus erasing the interface effect and, hence increasing the μ value. Such increase in plastic viscosity is more affected by higher dosages in HRWRA (Fig. 7). The higher the HRWRA dosage, the sharper the increase in μ after the minimum value and the lower the initial plastic viscosity value, μ(P = 0), decreasing from 4.6 to 0.4 Pa.s^{-1}. Such values of μ at P = 0 are calculated using an exponential regression on the lowering part of the μ(P) response only (Table 1).

As for the μ(P) response for a 0.85% HRWRA dosage, no minimum value is observed and a continuously plastic viscosity decrease is seen with increasing pressure, with higher values of μ than the ones observed on the other tested mixtures, except when pressure is close to zero. It may be due to the light segregation observed which artificially increases the solid content at the bottom of the testing device, hence lowering the fluid and HRWRA content at the outlet of the Marsh cone, so that the mixture behaves as mixtures with variable filler content tested in the first part of this investigation.

The increase in plastic viscosity after a minimum value is not seen on mixtures made with variable filler content, but may occur for superior level of pressure due to their higher solid content compared with mortars proportioned with various HRWRA dosages.

6. Conclusions

The influence of the coupled effect of pressure, HRWRA dosage and limestone filler content on the evolution of the rheological properties of mortars proportioned with PNS -based HRWRA was investigated. Based on the results presented in this paper, the following conclusions appear to be warranted:

1. The proposed modifications on the Marsh cone coupled with torque measurements are adequate to monitor the variations of the yield stress and plastic viscosity with light differential pressure. The estimation of μ is done using the Buckingham–Reiner equation for a Bingham fluid.
2. An exponential increase in yield stress is observed with increasing pressure on mixtures made with various limestone filler contents or various HRWRA dosages. An empirical equation to express the variation of τ_0 with pressure can be $\tau_0(P) = \tau_0(P = 0).e^{k.P}$ where P refers to the differential pressure exerted on the investigated mixture and k is an experimental constant. The deviation from linearity may be due to the consolidation of the SCC mortar under its own weight.
3. On mortars made with various filler contents, the rate of flow increases linearly with added pressure until a point where a slow-down of the increase is observed. From this point, the rate of flow tends toward a steady value. The pressure corresponding to the loss of linearity in the rate of flow-pressure data is not reached for mortars made with variable HRWRA dosages due to the maximum differential pressure of 18 kPa obtained with the modified Marsh cone presented in this investigation.
4. For mortars made with variable filler content, an exponential-like decrease of μ is observed with increasing pressure. The proposed hypothesis to explain such behaviour is related to the fact that the tested mortars are multiphasic materials. Hence, with 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. On mortars made with various HRWRA dosages, a decrease in the μ value is first observed before undergoing subsequent gain in plastic viscosity for pressure above 15 kPa for mixtures made with 0.65% and 0.70% HRWRA dosage, and 13 kPa for mortars made with higher HRWRA dosage. Such phenomenon can be explained as follows: when the pressure exerted on the material is sufficient, the liquid phase that tended to separate and form a lubrificating layer at the material-nozzle interface recombines with the other materials, thus erasing the interface effect and, hence increasing the μ value.

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