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Onset and intensity of shear thickening in cementitious suspensions – A parametrical study

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ABSTRACT

Understanding the intensity and onset of the shear thickening behaviour for cementitious suspensions is of prime importance in high shear processes like mixing and pumping of concrete in construction. In the present study, the onset and intensity of shear thickening of cementitious suspensions were investigated by a parametrical approach (water binder ratio (w/b), high range water reducer (HRWR) dosage, mineral admixture, shear rate) using an appropriate rheological protocol. Results show that, among the mineral admixtures, the suspension with ground granulated blast furnace slag (GGBS) features the highest shear thickening intensity and the earliest onset of shear thickening with respect to HRWR dosage. Moreover, this investigation shows that, among all the investigated parameters, the HRWR dosage influences the intensity and onset of shear thickening profoundly.

1. Introduction

Considering the growing demand for use of high performance concretes in high rise buildings, long distance tunnel applications, mines etc., the pumping of concrete plays a crucial role in properly delivering the material so that it features those requirements which are essential to the successful accomplishment of the intended application (i.e. adequate strength and durability). Rheology is used as an essential tool for designing the concrete suitable for pumping, filling of formwork by free fall and maintaining its stability after placement [1,2]. Rheological behaviour of cement-based systems is affected by several chemical and physical factors [3–6]. Some of the factors are concentration of solids, particle size distribution, fineness, cement chemical composition, water to binder (w/b) ratio, mixing efficiency, shear profile, shearing geometry and the presence of high range water reducers (HRWR). In addition, the use of mineral admixtures to enhance durability and mechanical characteristics complicates the understanding of fresh concrete behaviour. One particular aspect of this rheological behaviour is shear thickening, normally encountered in industries processing concentrated dispersions [7]. Shear thickening is referred as an increase in apparent viscosity with respect to an increase in shear rate. The occurrence of shear thickening is not desirable since more energy is required to increase the flow rate of the material. This phenomenon mainly impacts processes such as mixing, pumping and extrusion, where the applied maximum shear rate may change the flow behaviour. Shear thickening was observed on cement paste sheared at the rate of 150 s^{-1} using a cone and plate geometry, for w/c ratio $<$ 0.40, whereas shear thinning was measured for w/c $>$ 0.40 and Bingham behaviour at w/c 0.40 [8]. Similar behaviour was observed on high performance grouts by Yahia [9]. Rheological study preformed on paste at 0.32 w/c ratio in co-axial cylindrical geometry shows that the onset of shear thickening was observed at lower shear rate (less than 15 s^{-1}) for polyacrylic based superplasticizer for dosage more than 0.30 ml/100 g of cement [10]. Moreover, it was found that intensity of shear thickening increases to 100% at 0.30 ml of superplasticizer/100 g of cement. Further increase in superplasticizer dosage to 0.50 ml/100 g of cement resulted in increase in shear thickening intensity to 200%. Similar increase in apparent viscosity was not observed even at higher dosages of melamine based and lignosulphonate based superplasticizers at 0.32 w/c ratio [10]. This is due to the enhanced steric effect resulting in higher shear-thickening. In cementitious systems with a w/b ratio between 0.22 and 0.26, the use of mineral admixtures such as metakaolin can increase the shear thickening, while the use of micro-silica, below a certain replacement threshold ratio decreases the shear thickening [11]. Ce-

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ment based suspension at a w/c ratio of 0.30 undergo an onset of shear thickening at 150 s^{-1} [12]. With further decrease in w/c ratio to 0.22, onset of shear thickening behaviour can be spotted even at a very low shear rate of 10 s^{-1} [13]. Apart from the factors discussed, the Brownian motion due to thermal randomization energy, colloidal interaction due to charges exhibited by the particles, hydrodynamic interaction due to movement of particles in liquid medium and inertial interaction due to collision between two or more different particles at higher shear rates are responsible for microscopic changes in cement-based suspensions leading to different macroscopic rheological behaviour [14]. More specifically, the onset of shear-thickening of a system is mainly governed by hydrodynamic and inertial interactions [15–17]. Different mechanisms were proposed for the onset of shear thickening. Research by Hoffman [18] developed an order to disordered transformation of particle layers where ordered layer corresponds to the state of easy flow. The formation of particles cluster lead to shear thickening and not ordered layer destruction. Further, the hypothesis of cluster formation was verified through measurements from optical dichroism. On the other hand, dynamic simulation carried out by Brady and Bossis [19] to understand shear thickening shows flow jams due to the consequence of transient cluster formation.

From this information, it is evident that two different mechanisms, i.e. order–disorder transformation and hydro-clustering were considered to be responsible for shear-thickening in cement based suspensions albeit, there is no experimental verification that supports a particular mechanism. Order-disorder transformation is found to be more appropriate for describing shear thickening in suspensions that are mono-disperse and non-Brownian in nature [20]. However, cement based suspensions are poly-disperse. Recent investigation by Rastogi et al. [21,22] shows that state of ordered layer formation vanishes with gradual increase in poly-dispersity. Hence, hydro-clustering mechanism can be considered to be more appropriate in terms of explaining shear thickening behaviour for cement based suspensions. The hydroclustering phenomena is collectively influenced by the increased use of mineral admixtures, chemical admixtures (especially HRWR), low w/b ratio along with higher shear rates. Although studies are available on the effect of the aforesaid parameters individually, interaction of different mineral admixtures, HRWR dosage and solid concentration on shear thickening is not well understood. Hence, this study attempts to understand the interactive effect of these parameters on shear thickening behaviour of cement based suspensions. Though several factors affect the rheological behaviour of cement pastes, the choice of the parameters were made always considering the pumping perspective. In this regard, water to binder ratio, HRWR dosage, mineral admixtures and shear rate are the ones which predominantly affect and govern the aforementioned rheological behaviour. Moreover the experimental activity focused on cement paste, considering that when concrete is pumped through pipes, different layers are formed across the cross-section of pipe due to shear induced particle migration [23]. The layer formed at the periphery of the inside pipe (i.e. at the interface of pipe and concrete) is referred as lubrication layer (LL). This LL is responsible for flow of concrete. Generally, the LL thickness is in the range of few mm and predominantly consists of the cementitious paste phase.

2. Experimental programme

In the present study, the following parameters were varied to understand the shear thickening in cementitious suspensions.

1. Water to binder ratio (w/b)
2. HRWR dosage (% by weight of binder)
3. Mineral admixtures (GGBS, Fly ash, Micro silica)
4. Shear rate

2.1. Materials

Ordinary Portland Cement (OPC) 53 grade complying with ASTM C150/C150M-19a [24], ground granulated blast furnace slag (GGBS) complying with ASTM C989-05 [25], fly ash (FA) complying with ASTM C618-12a [26] and condensed micro silica (MS) complying with ASTM C1240-15 [27] were used. Physical and chemical properties of the materials used are given in Table 1. The particle size distribution of materials used is shown in Fig. 1. Scaning electron microscope (SEM) images are shown in Fig. 2. A poly-carboxylic ester (PCE) based HRWR with a solid content of 29.86% and specific gravity of 1.071 (at 25 °C) was used. To maintain a constant w/b ratio, water correction was done by accounting the water content of HRWR.

2.2. Material combinations and test protocols

The w/b ratio was selected based on concrete grades commonly used (30 MPa to 60 MPa) for most concrete applications in an ur-

Table 1
Physical and chemical properties of binders.

	Ordinary Portland Cement (OPC)	Ground Granulated Blast Furnace Slag (GGBS)	Fly Ash (FA)	Condensed Micro Silica (MS)
SiO_2	22.50	38.80	40.50	85.80
Al_2O_3	5.70	11.20	14.20	1.90
Fe_2O_3	2.20	4.60	14.80	0.60
CaO	60.85	34.20	18.70	0.90
MgO	1.35	9.10	8.20	0.80
Na_2O eq.	0.30	0.34	0.69	0.70
SO_3	2.50	–	–	
Specific gravity	3.10	2.78	2.19	2.20
Mean apparent size (μm)	9.18	3.75	8.88	63.03*
D_{10} (μm)	4.36	0.50	4.73	13.98
D_{90} (μm)	14.92	10.32	13.92	161.31
Surface area (cm^2/g)	4218.40	5526.50	5249.50	–

*Condensed state used as such in order to understand its effect.

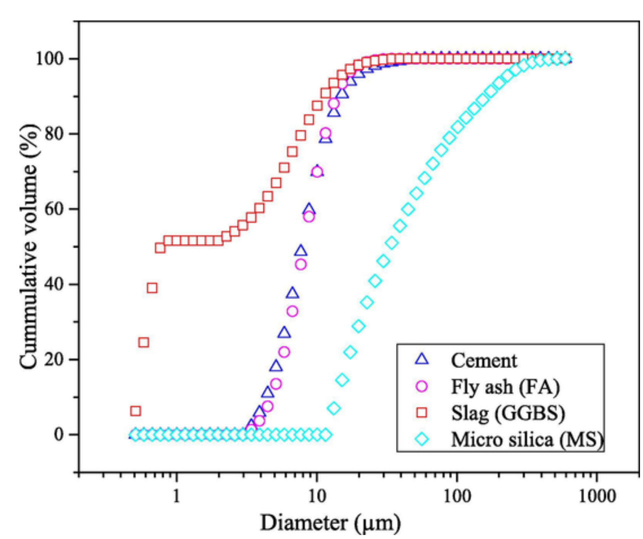

Fig. 1. Particle size distribution of materials.

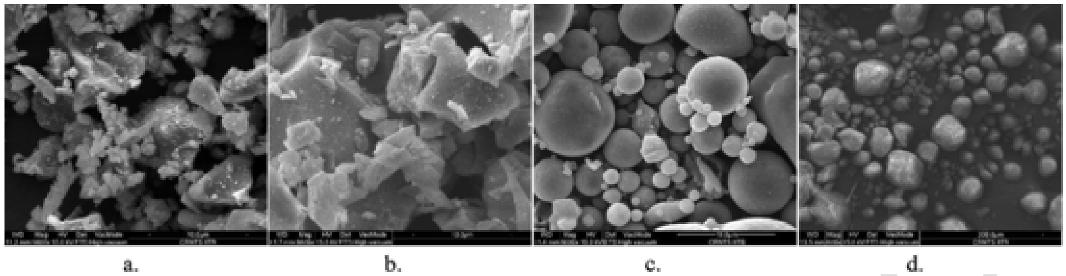

Fig. 2. Scanning electron microscope (SEM) images of binders used in the study a. OPC; b. GGBS; c. FA; d. MS.

ban area (based on inputs from Construction Industries). Further, the employed dosage of mineral admixtures by mass replacement (GGBS – 70%, FA – 25%, MS – 8%) corresponded to the maximum allowable limits as per ACI 211 [28]. For the chosen w/b ratios and mineral admixtures, the chemical admixture (HRWR) was varied from minimal to maximum dosage (till bleeding). The details of all the combination of test parameters are given in Table 2. Cement based suspensions were mixed thoroughly using a planetary shear mixer (ASTM 305) [29]. The mixing protocol is explained as follows. Cement and binder were first dry mixed for 2 minutes for proper homogenization, followed by mixing with 80% of the water corresponding to the selected w/b ratio for 1 minute. Then, the mixer was stopped for 1 minute during which, sides and bottom of the mixing bowl were scrapped, immediately followed by addition of 20% of water along with a required dosage of HRWR. Mixing was carried out for 1 more minute and the mixer was then stopped for 1 minute during which sides and bottom of the mixing bowl were scrapped again to ensure proper mixing. Finally, mixing was continued for 2 more minutes. The mixed paste was used immediately for the rheological investigation. A dynamic shear rheometer was used to this purpose. The rheometer consists of a rotor (paddle shape) and a sample holder that are concentric to each other as shown in Fig. 3. Protruding ribs available inside the cylinder avoids slippage. The following protocol was adopted for all the rheological tests. The pastes were pre-sheared for 1 minute at 315 s^{-1} and rested for a minute. Then, at 10th minute from the moment water is added to paste during mixing, the paste was sheared according to the test protocol linearly from 1 s^{-1} to 300 s^{-1} immediately followed by decreasing the shear rate from 300 s^{-1} to 1 s^{-1} as shown in Fig. 4. Data obtained from the ramp down cycle of the shear profile was used for investigation [30]. The adopted rheological protocol was chosen baased on the maximum shear rate experienced by the lubrication layer (LL) during pumping of concrete. This maximum shear rate depends on the thickness of lubrication layer (LL) and the discharge rate of concrete through the pipe. Based on the information received from site on the pumping, the maximum possible shear rates encountered is around 300 s^{-1}. Hence, the cementitious pastes were sheared at 300 s^{-1}. In addition, an empirical mini-slump investigation was conducted at 12th minute [31]. Mini-slump test results are shown in Table 2. The entire investigation was carried out at a relative humidity and temperature of 60 ± 5% and 25 ± 1 °C respectively.

3. Results and discussion

3.1. Effect of w/b ratio & HRWR dosage on shear thickening

The shear thickening is assessed based on the flow curves for different combination of cement based suspensions at different dosage of HRWR up to a maximum shear rate of 300 s^{-1}. The results obtained are discussed in two aspects i.e. for a given mineral admixture, the effect of w/b ratio, HRWR dosage and shear rate on the viscosity and shear thickening behaviour. Secondly, for a given chemical admixture dosage, the effect of mineral admixture, w/b ratio and shear rate are discussed. Intensity of shear thickening is defined by Eq. (1).

$$Intensity\ of\ shear\ thickening\ (\%) = \frac{\eta_{at\ maximum\ shear\ rate} - \eta_{at\ onset\ of\ shea}}{\eta_{at\ onset\ of\ shear\ thickening}}$$

were, $\eta_{at\ maximum\ shear\ rate}$ – corresponds to the apparent viscosity of the suspension at maximum shear rate (in this study 300 s^{-1}); $\eta_{at\ onset\ of\ shear\ thickening}$ – corresponds to the apparent viscosity of the suspension at the onset of shear thickening (where apparent viscosity reaches a minimum value and starts to increase).

3.1.1. Cementitious suspensions with 100% OPC

Fig. 5 indicates the effect of different w/b ratios on shear thickening for suspension with 100% OPC with different dosage of HRWR. As expected, with an increase in w/b ratio, the apparent viscosity of the suspensions decreased. Initially, suspensions with 100% OPC exhibits complete shear thinning behaviour for different w/b ratios at 0.0% and 0.1% HRWR dosage in the range of the tested shear rates. For a given w/b ratio and at low shear rates, increase in HRWR dosage shows a clear shift in magnitude (higher to lower values) of apparent viscosity. However, at high shear rates, the apparent viscosity reaches a constant value for all w/b ratios at 0.0% and 0.1% of HRWR dosage, with no further increase in apparent viscosity. This clearly indicates no shear thickening behaviour for all w/b ratios at 0.0% and 0.1% dosage of HRWR for the suspension with 100% OPC.

Table 2
Mini-slump values for different suspensions investigated in the experimental program.

Nomenclature	w/b ratio	0.30		0.35			0.40				0.45			
	SP dosage (%bwob*)	0.20	0.30	0.10	0.20	0.30	0.00	0.10	0.20	0.30	0.00	0.10	0.20	0.30
OPC	OPC (100%)	89	136	87	128	148	76	104	134	149	103	138	145	152
GGBS	OPC (30%) + GGBS (70%)	125	145	78	142	150	54	79	137	155	86	100	148	156
FA	OPC (75%) + FA (25%)	125	149	102	133	150	73	107	121	#	99	117	155	#
MS	OPC (92%) + MS (8%)	#	85	57	95	106	65	72	97	120	84	104	115	120

#These mixtures were observed to be either harsh to work in the rheometer or segregated.
* By weight of binder.

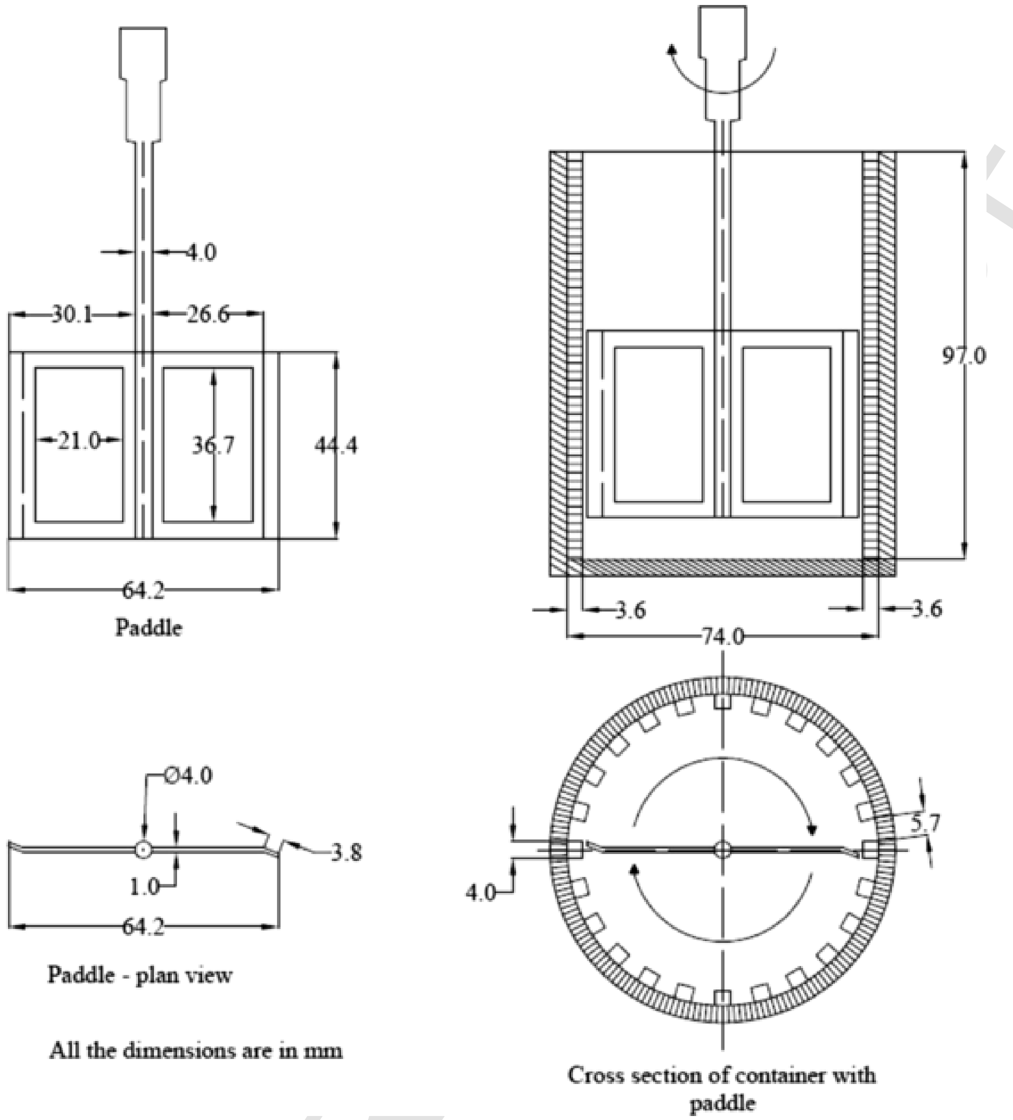

Fig. 3. Schematic diagram of paddle and measuring system.

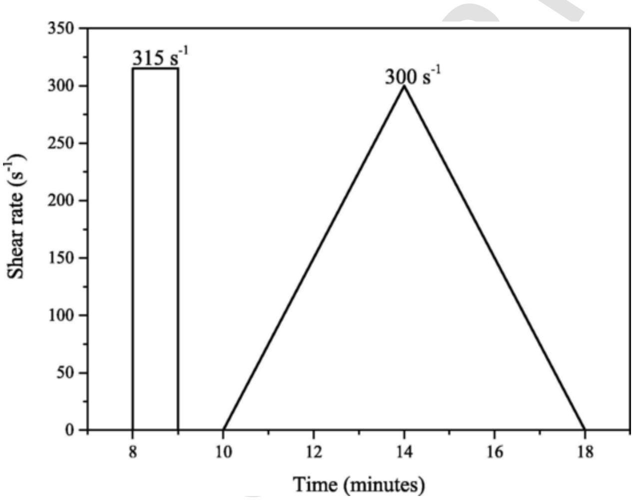

Fig. 4. Rheological protocol adopted in the study.

For 0.0% and 0.1% dosage of HRWR at low shear rates, suspension tends to agglomerate exhibiting high viscosity. Formation of agglomerates results in increased viscosity, as the effective volume fraction of suspension with agglomerate is higher than the volume fraction of the same number of freely moving particles. This could be attributed to the weak electrostatic repulsive forces and steric effects to overcome the attractive forces that lead to the formation of agglomerates entrapping water at a low shear rate. Therefore, the viscosity of the suspension is directly proportional to the size of the agglomerates. Further, as the shear rate increases, competition starts between breakage of bond due to shear induced deformation and reformation of bonds due to attractive forces. Timescale of bond breakage due to shear induced deformation is approximately equal to inverse of shear rate $\dot{\gamma}^{-1}$ [14]. On the other hand, the timescale of bond formation is based on coagulation theory and it accounts to few seconds for dense cementitious suspensions [14].

At similar w/b ratios, increase in HRWR dosage to 0.2% and 0.3%, considerably reduces the apparent viscosity of suspension displaying shear thinning behaviour at low shear rates. Further, an increase in shear rate, increases the apparent viscosity of the suspension experiencing shear thickening behaviour. The intensity of shear thickening increases with an increase in w/b ratio at 0.2% and 0.3% HRWR

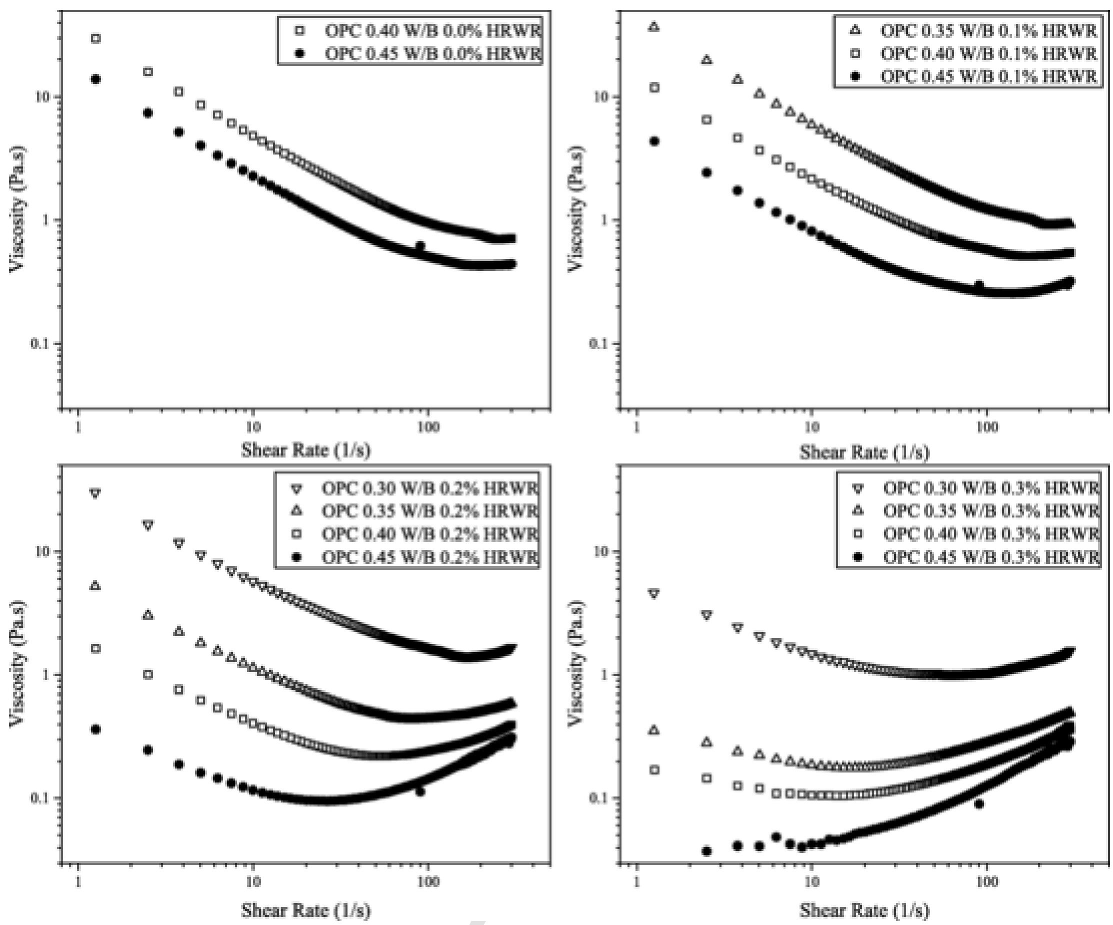

Fig. 5. Effect of w/b ratio & dosage of HRWR on shear thickening of suspension with 100% OPC.

dosage can be observed in Fig. 6. Increase in w/b ratio shifts the onset of shear thickening to the low shear rate at a constant HRWR dosage. Shear thinning behaviour of suspension could not be observed with 0.3% HRWR dosage for w/b ratios equal to 0.40 and 0.45. This could be attributed to the enhanced de-agglomerated state of suspension due to increased dosage of HRWR [12], decreasing apparent viscosity considerably. The pronounced effect of shear thickening at higher shear rate is due to hydrodynamic forces exhibited by the suspension. These forces dominate repulsive forces acting on the particles resulting in increased stress localization. This leads to the formation of hydro-clusters, which ultimately results in a clustered system with disordered state resulting in shear thickening behaviour [32,33]. From Fig. 5, it is also evident that, with an increase in dosage of HRWR, the apparent viscosity of suspension increased at higher shear rates leading to shear thickening at higher w/b ratios, contradicting previous investigations, where shear thickening was observed only for suspension with w/c ratio below 0.40 [8]. Also, at high shear rates, hydrodynamic forces overcome inter-particle repulsive forces forming hydro-clusters thus resulting in shear thickening behaviour and shifting the onset of shear thickening to low shear rates.

3.1.2. Cementitious suspensions with 70% replacement of GGBS

In order to understand the effect of mineral admixtures as replacement of cement, a similar investigation was carried out for 70% mass replacement of GGBS. Replacement of GGBS has a significant effect on shear thickening behaviour as observed from Fig. 7. Similar to 100% OPC, shear thinning behaviour was observed for suspension with 70% replacement of GGBS at 0.0% and 0.1% dosage of HRWR for different w/b ratios, for 0.1% HRWR dosage marginal increase (63.45%) in apparent viscosity was observed for 0.45 w/b at higher shear rates as witnessed in Fig. 8. On the other hand, apparent viscosity increases with increase in shear rate for 0.2% and 0.3% dosage of HRWR at all w/b ratios as observed in Fig. 8. Similar to suspension with 100% OPC, the intensity of shear thickening increases with an increase in the dosage of HRWR as observed in Fig. 8 and the intensity is relatively higher when compared to suspension with 100% OPC (Fig. 9).

For 0.2% and 0.3% dosage of HRWR at similar w/b ratios, suspensions with 70% GGBS exhibit shear thickening behaviour even at low shear rates as observed in Fig. 8. The onset of shear thickening shifts to very low shear rate due to the addition of GGBS at a similar dosage of HRWR and at similar w/b ratio. Increase in apparent viscosity at higher shear rate for 0.3% dosage of HRWR was more or less equivalent to the one observed at similar w/b ratios for 0.2% dosage of HRWR. This shows that further increase in dosage of HRWR intensifies apparent viscosity at higher shear rate causing difficulties in processing when high shear rates are involved. Early onset and higher intensity of shear thickening behaviour observed at 0.2% and 0.3% dosage of HRWR could be due to increase in repulsive forces by Brownian motion apart from electrostatic and steric effects due to their comparatively less particle size and higher replacement. It could also be possible that due to higher presence of Al_2O_3, relative adsorption of HRWR is higher which results in higher steric repulsion [34].

On the other hand, possible reason for an increase in intensity and early onset of shear thickening at very low shear rates could be due to the angular nature of GGBS along with finer particle sizes (Fig. 1 & Fig. 2). The finer particle sizes increases the packing density. Along with higher packing density and angular shape the inter-particle friction increases, inhibiting the free flow of particles at high shear rates

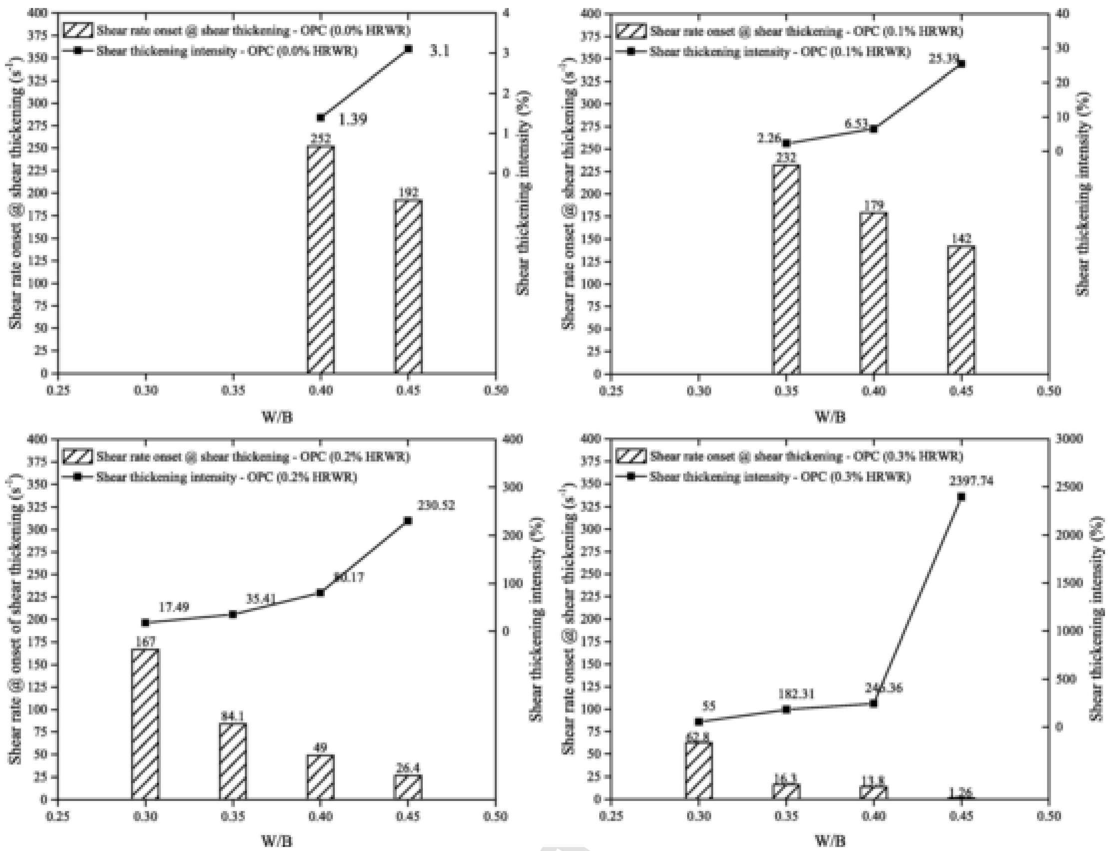

Fig. 6. Shear rate @ onset of shear thickening & shear thickening intensity of suspension with 100% OPC.

[9,35]. Additionally, suspensions with 70% GGBS possess high initial solid volume fraction of 0.537, 0.499, 0.466 and 0.436 corresponding to 0.30, 0.35, 0.40 and 0.45 w/b ratios respectively as shown in Fig. 10. This results in higher inter-particle friction at high shear rates, that tend to form flocculated system and dis-ordered state rapidly.

3.1.3. Cementitious suspension with 25% replacement of FA

Shear rate dependent behaviour exhibited by suspension with 25% replacement of FA for different w/b ratio and different HRWR is shown in Fig. 11. Depsite having the highest solid volume fractions (Fig. 10), the shear thickening behaviour exhibited by suspension with 25% mass replacement of FA was similar to the one exhibited by 100% OPC pastes. However, apparent viscosity exhibited by the suspensions with 25% FA replacement at the low shear rate is considerably lower, due to the spherical shape of FA as depicted from Fig. 2. When compared to suspension with 100% OPC shear thickening intensity was marginally higher for similar w/b ratios and HRWR dosage due to higher solid volume fraction (Fig. 10) as shown in Fig. 9. Further, for similar w/b ratio increase in dosage of HRWR from 0.2% to 0.3% decreases apparent viscosity at low shear rate and shifts the onset of shear thickening to low shear rate as observed in Fig. 12.

Similar to 100% OPC and 70% GGBS suspensions at 0.0% dosage of HRWR, 25% FA suspensions exhibit shear thinning behaviour. This could be due to the formation of clusters at a low shear rate, as the shear rate increases, shear forces overcome attractive inter-particle forces that can de-flocculate the suspension resulting in reduced resistance.

3.1.4. Cementitious suspension with 8% replacement of MS

Intensity and onset of shear thickening exhibited by suspension with 8% mass replacement of MS at different w/b ratios and different HRWR dosages are shown in Fig. 13. At low shear rates, for suspensions with 8% MS, the apparent viscosity of the suspension is observed to be high. As shear rate is increased, the suspension clearly exhibits a shear-thinning behaviour. At a given shear rate and HRWR dosage, with increase in w/b ratio, the suspensions change the behaviour from shear thinning to shear thickening. The intensity of shear thickening increases with respect to increase in w/b ratio with a gradual shift in the onset of shear thickening to low shear rate as observed in Fig. 15. Increase of HRWR dosage from 0.2% to 0.3% results in a significant reduction of apparent viscosity at low shear rates.

Previous investigations have shown that the addition of MS reduces shear thickening behaviour as well as shifts the onset of shear thickening to higher shear rates [26,27]. Although the SVF is higher for MS than OPC, the delayed onset and lower intensity could be due to the condensed nature of MS resulting in the formation of relatively bigger clusters at a low shear rate which keeps on dissociating in size as shear rate increases. Within the range investigated in this study, the maximum shear rate applied is not enough to create sufficient hydrodynamic forces that could overcome the repulsive forces exhibited by the suspension, resulting in comparably less shear thickening intensity as well as in shifting of the onset of shear thickening to higher shear rates. Due to higher flocculation even for higher w/b ratios and higher HRWR dosages, shear thickening is obscured or comparatively less for suspension with 8% MS. This can be understood by comparing the yield stress of all the suspensions at similar w/b ratio and similar HRWR dosage as shown in Fig. 14. Where, bigger particle size of MS (due to high flocculation of the particles) in the suspension results in higher yield stress (253 Pa) even with a 0.3% HRWR followed by the suspensions with OPC (17 Pa), FA (4 Pa) and GGBS (3 Pa).This agrees with previous studies which showed that highly flocculated suspension obscures shear thickening behaviour [37].

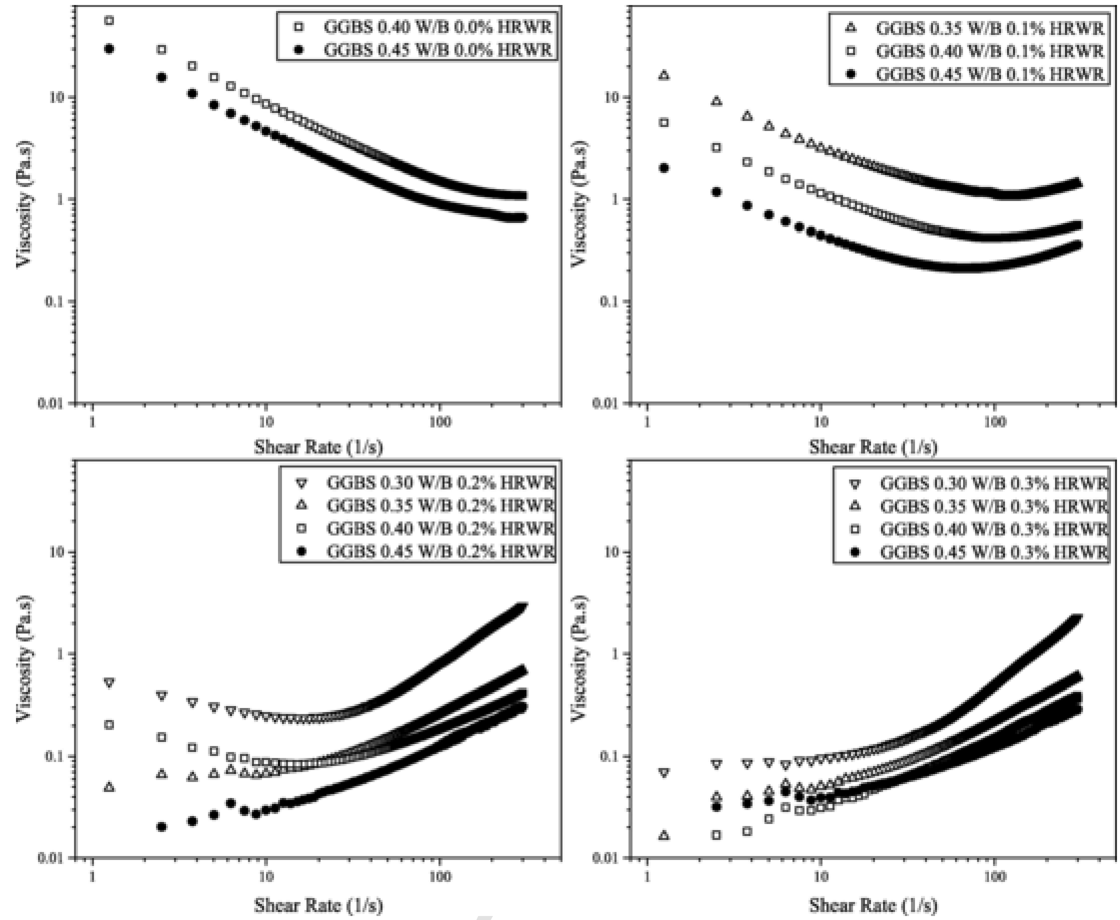

Fig. 7. Effect of w/b ratio & different dosage of HRWR on shear thickening of suspension with 70% GGBS.

3.2. Influence of mineral admixtures on shear thickening

Overall view exhibited by a change in w/b ratio at different HRWR dosage for different percentage replacement of supplementary cement based system is shown in Figs. 16–18. Irrespective of different replacement level of supplementary cementitious materials, increase in w/b ratio decreased the apparent viscosity of all the suspensions at low shear rates, which also clearly exhibited shear thinning behaviour. However, an increase in shear rate leads to shear thickening behaviour of suspensions. The intensity of shear thickening increases with respect to increase in w/b ratio irrespective of supplementary materials used as observed in Fig. 9. As the dosage of HRWR increases, intensity of shear thickening increased and the onset of shear thickening shifts to low shear rates as observed in Figs. 9 and 19 respectively. Specifically, the rate of increase in shear thickening is exorbitantly high for GGBS with increment in HRWR dosage (at all w/b ratios), while shear thickening exhibited by all other suspension increases gradually with respect to increase in HRWR dosage. Moreover, the shear rate at which shear thickening initiates is almost very low for GGBS, irrespective of w/b ratio at a constant HRWR dosage. The onset of shear thickening gradually shifts from high to low shear rate for 100% OPC and 25% FA replacement. Further, the shear thickening exhibited by 8% replacement of MS is very low at all w/b ratios.

In general, shear thinning behaviour exhibited by different suspensions are due to flocculation and de-flocculation of the suspension brought about by balance in attraction due to van der Waal forces, repulsion due to Brownian motion, electrostatic repulsion and steric effect [17,19,20,32,37]. At low shear rates, irrespective of w/b ratio and at 0.1% dosage of HRWR, most of the suspension exhibits shear thinning behaviour due to the formation of clusters because of very high van der Waal forces [37]. Increase in shear rate results in de-flocculation of particles in the suspension that releases water, thereby reducing the effective volume fraction of the suspension as well as the apparent viscosity as observed in Fig. 16.

A further increase in shear rate results in viscous dissipation within the suspension increasing hydrodynamic forces that can overcome repulsive forces. This again leads to assembling of particles in the suspension forming hydro-clusters. Hydro-clusters increase apparent viscosity by localizing shear stress leading to the origin of shear thickening at higher shear rates [37].

On the other hand, when compared with 100% OPC, GGBS based suspension exhibits highest shear thickening intensity due to inertial collision at high shear rates and least apparent viscosity due to the enhanced action of Brownian motion at low shear rates, irrespective of w/b ratios. Enhnaced Brownian motion reduces the formation of bigger size clusters leading to decrease in apparent viscosity at low shear rates. Further, at higher shear rates, GGBS suspensions tend to reach higher apparent viscosity due to the highest initial solid volume fraction and angular shape. This contributes to higher amount of hydro-clusters and high inertial forces (higher collision between particles) causing continuous shear thickening regime [37].

4. Conclusions

The effect of w/b ratio, HRWR dosage and replacement of different supplementary cementitious materials on intensity and onset of shear thickening has been evaluated in this paper by means of a dedicated rheological protocol. From the results discussed above, the follow-

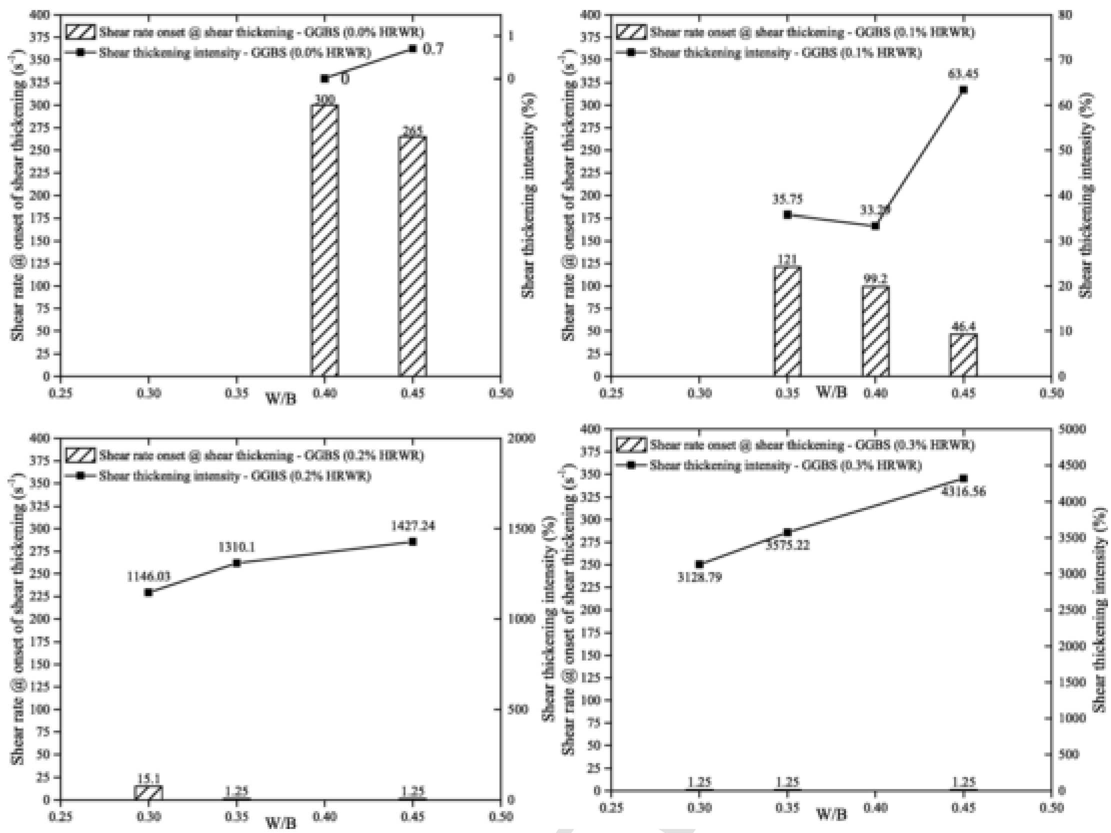

Fig. 8. Shear rate @ onset of shear thickening & shear thickening intensity of suspension with 70% GGBS.

ing conclusions can be drawn:

1. Increase in HRWR dosage increases the intensity of shear thickening as well as reduces the onset of shear thickening to low shear rates irrespective of replacement of OPC with supplementary cementitious materials (GGBS, FA, MS).
2. At 0.0% and 0.1% dosage of HRWR, irrespective of supplementary cementitious materials and w/b ratio, all the suspensions exhibit shear thinning behaviour. However, at 0.2% and 0.3% dosage of HRWR, most of the suspension exhibits shear thickening behaviour.
3. At 0.2% and 0.3% dosage of HRWR intensity of shear thickening is high as w/b ratio increases from 0.30 to 0.45. The onset of shear thickening shifts to low shear rates as well.
4. Suspensions with 70% replacement of GGBS exhibits the highest shear thickening intensity and shifts onset of shear thickening to very low shear rates (less than 15 s^{-1} for 0.2% HRWR dosage at all w/b ratios and almost 0 s^{-1} for 0.3% HRWR dosage at all w/b ratios).
5. Apparent viscosity exhibited by the suspensions with 8% MS replacement is the highest when compared with all other suspensions (irrespective of w/b ratio and HRWR dosage). However, the effect of MS on the intensity of shear thickening is lower.
6. Intensity and onset of shear thickening exhibited by suspension with 100% OPC and suspension with 25% replacement of FA are almost similar except that the apparent viscosity exhibited by suspension with 25% replacement of FA is comparatively less.

Based on the results obtained, it is very clear that among the four parameters (w/b ratio, mineral admixtures, HRWR dosage, shear rate) investigated, the shear thickening behaviour of cement based suspension is greatly influenced by w/b ratio and HRWR dosage. Since the w/b ratio and mineral admixtures are decided upon the required strength and durability, for a process like pumping of concrete (for a given shear rate), adequate attention shall be given while selecting the HRWR and its dosage.

Uncited reference

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CRediT authorship contribution statement

P.V. Ponambala Moorthi: Conceptualization, Methodology, Validation, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization, Project administration, Formal analysis. **Francesco Pra Mio:** Methodology, Validation, Investigation, Data curation, Project administration. **Prakash Nanthagopalan:** Writing - original draft, Writing - review & editing, Supervision. **Liberato Ferrara:** Writing - review & editing, Supervision.

Declaration of Competing Interest

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

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.conbuildmat.2020.118292.

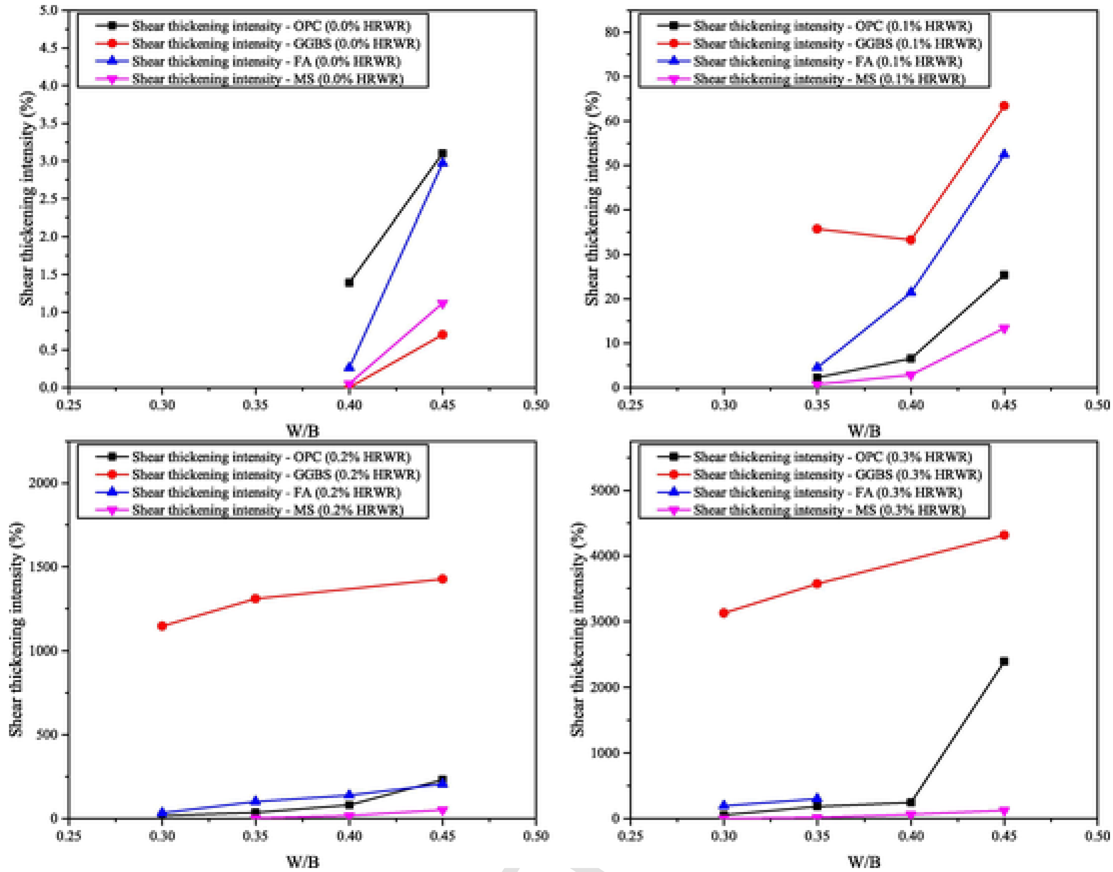

Fig. 9. Shear thickening intensity of different suspensions.

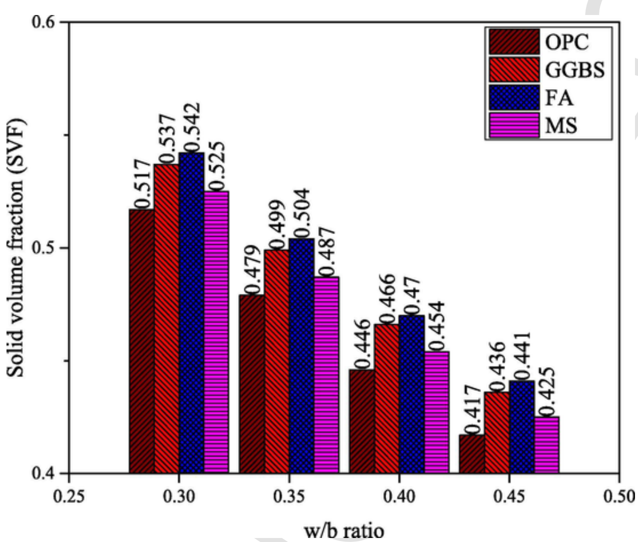

Fig. 10. Solid volume fraction (SVF) of different suspensions at all w/b ratios.

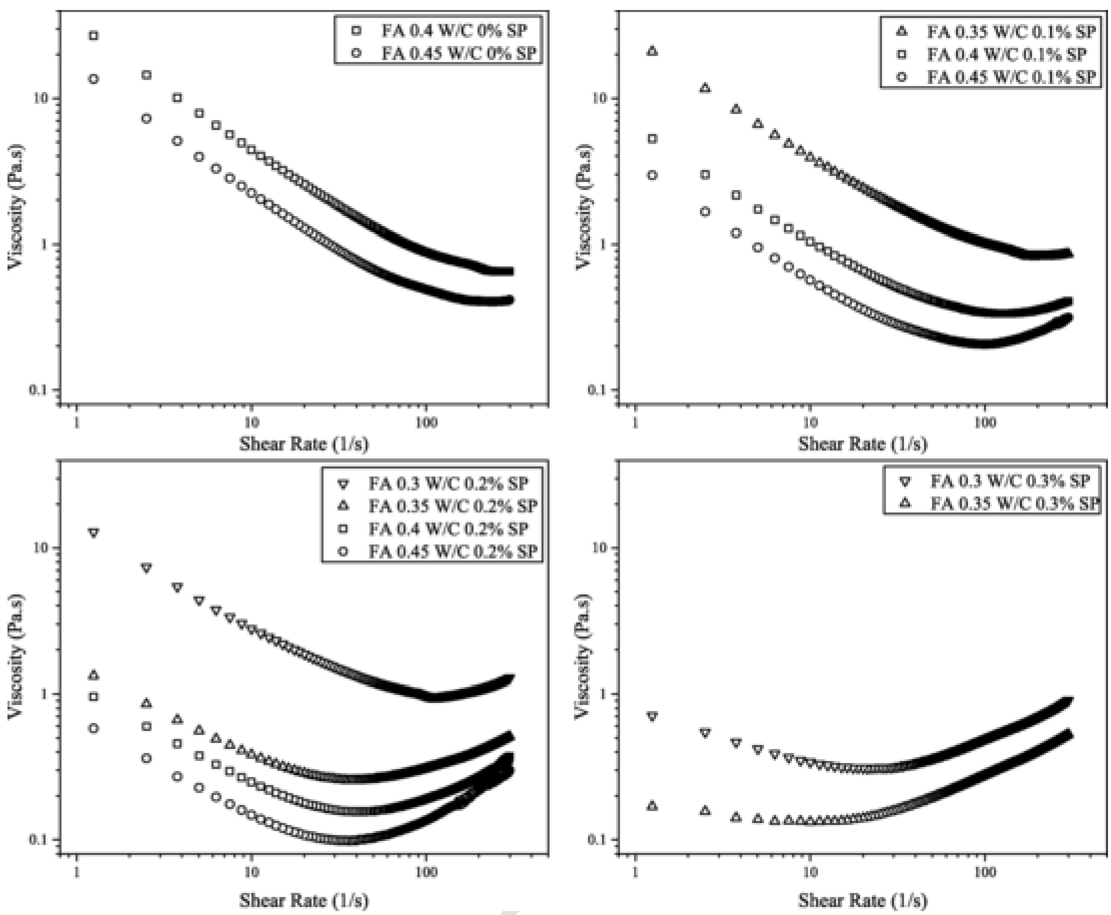

Fig. 11. Effect of w/b ratio & different dosage of HRWR on shear thickening of suspension with 25% FA.

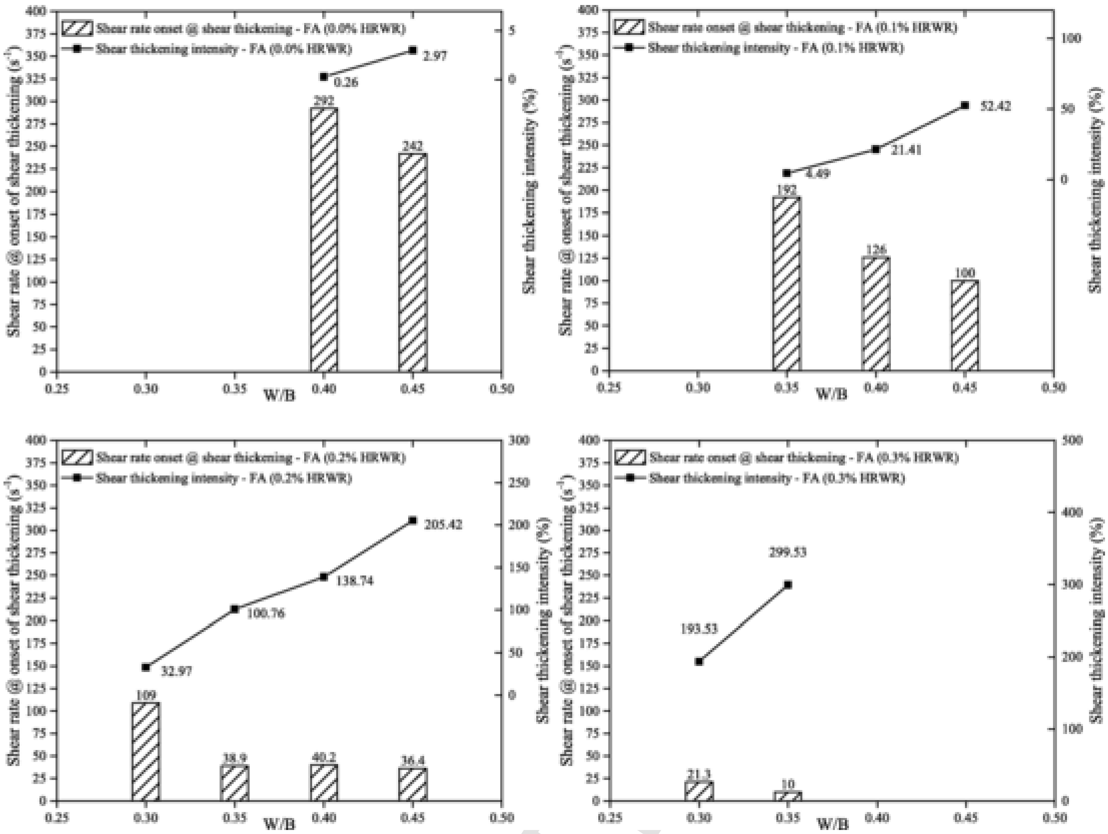

Fig. 12. Shear rate @ onset of shear thickening & shear thickening intensity of suspension with 25% FA.

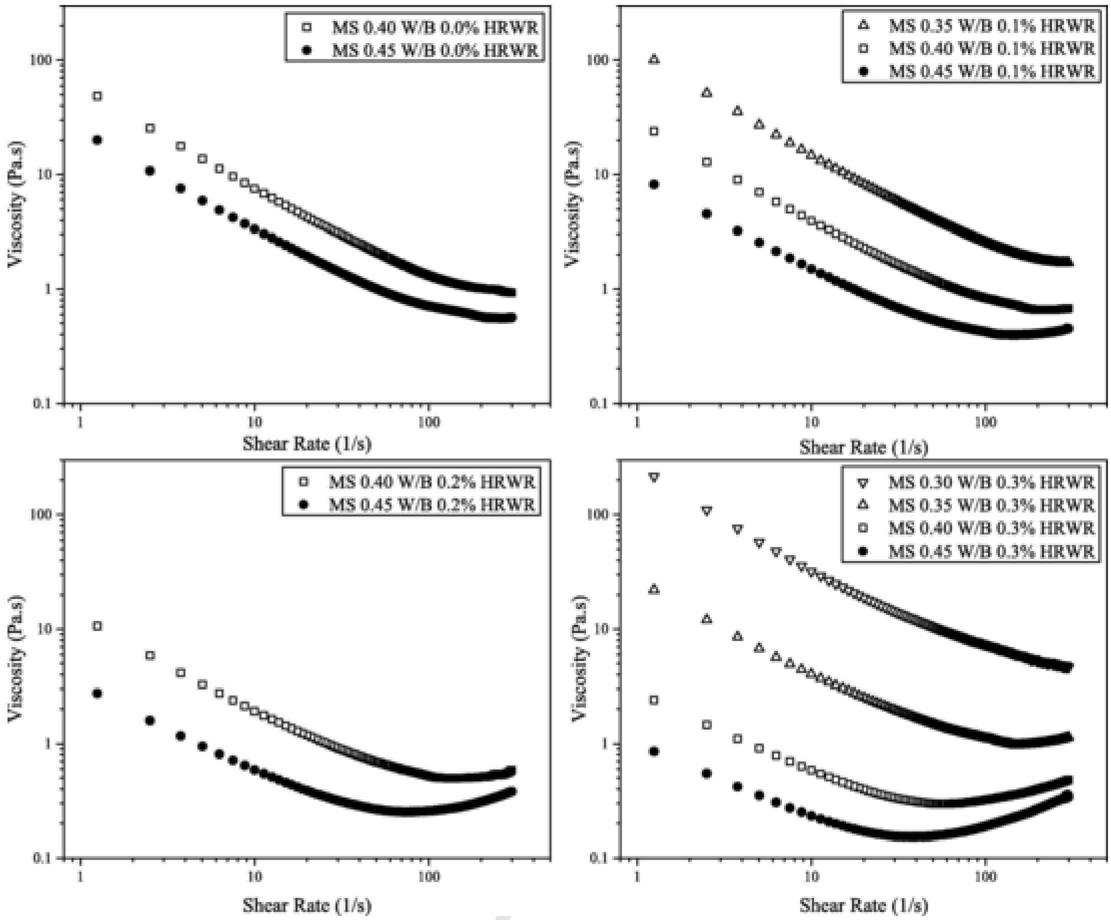

Fig. 13. Effect of w/b ratio & different dosage of HRWR on shear thickening of suspension with 8% MS.

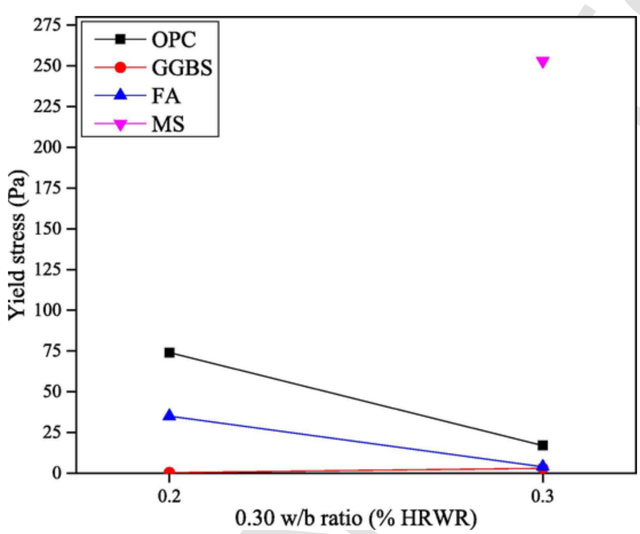

Fig. 14. Yield stress of different suspensions at 0.30 w/b ratio for different HRWR dosage.

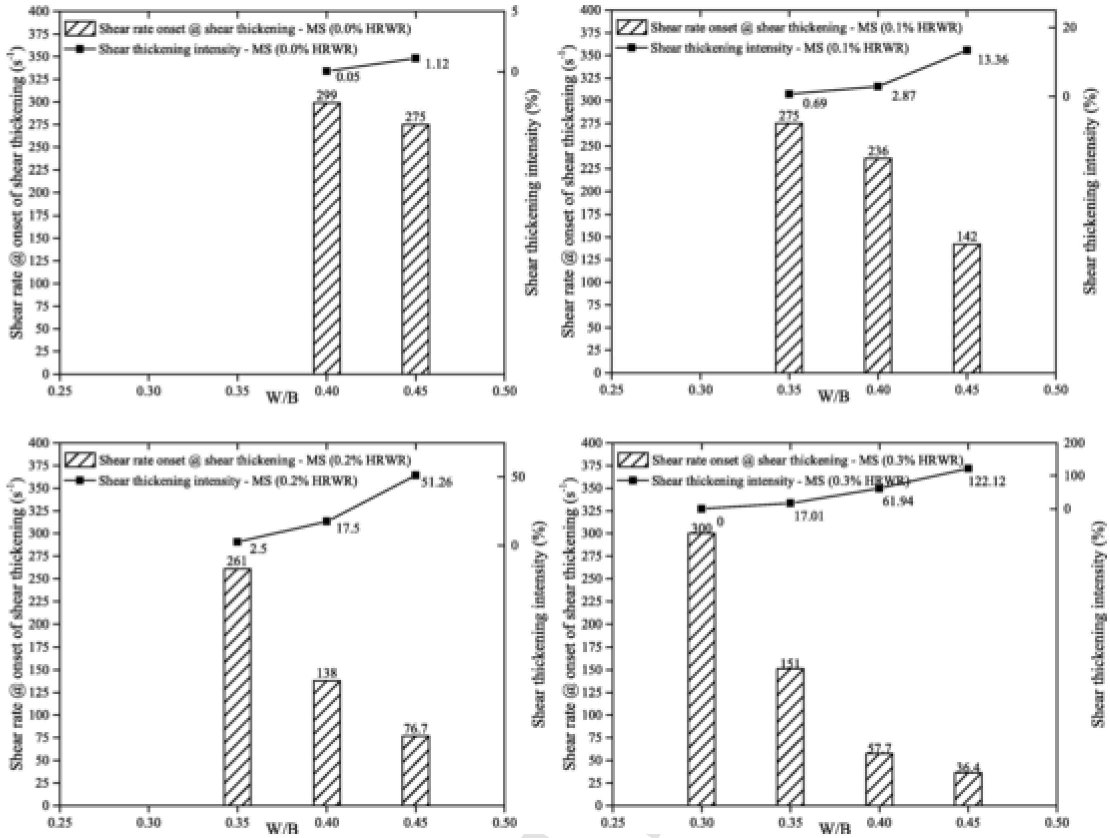

Fig. 15. Shear rate @ onset of shear thickening & shear thickening intensity of suspension with 8% MS.

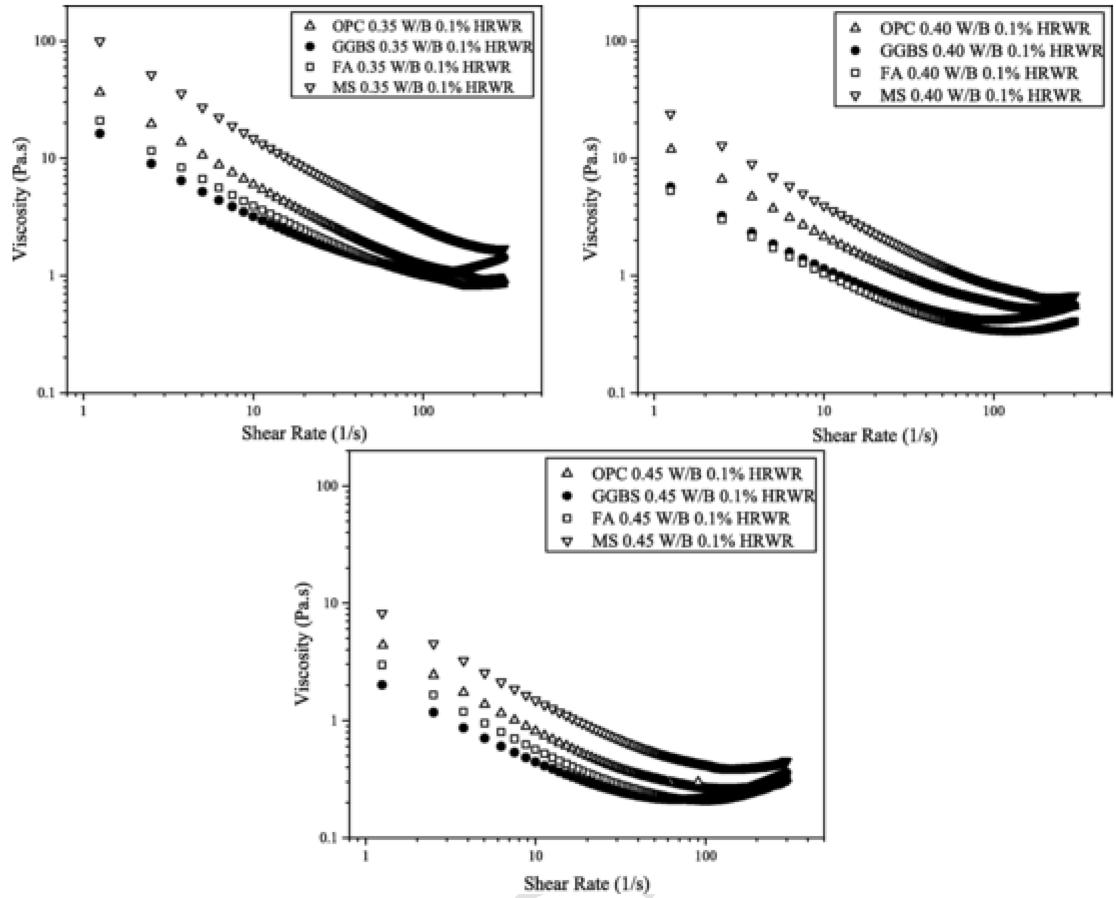

Fig. 16. Effect of w/b ratio on shear thickening of suspension with different mineral admixtures at 0.1% dosage of HRWR.

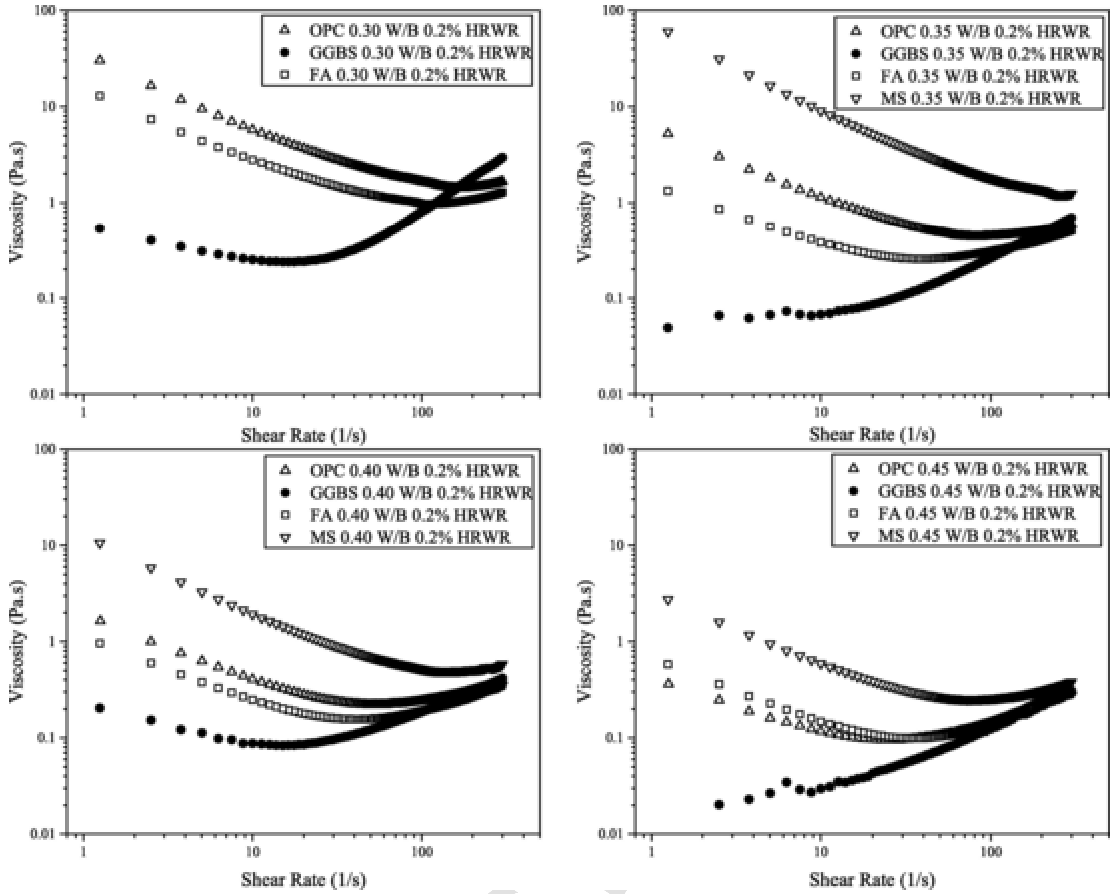

Fig. 17. Effect of w/b ratio on shear thickening of suspension with different mineral admixtures at 0.2% dosage of HRWR.

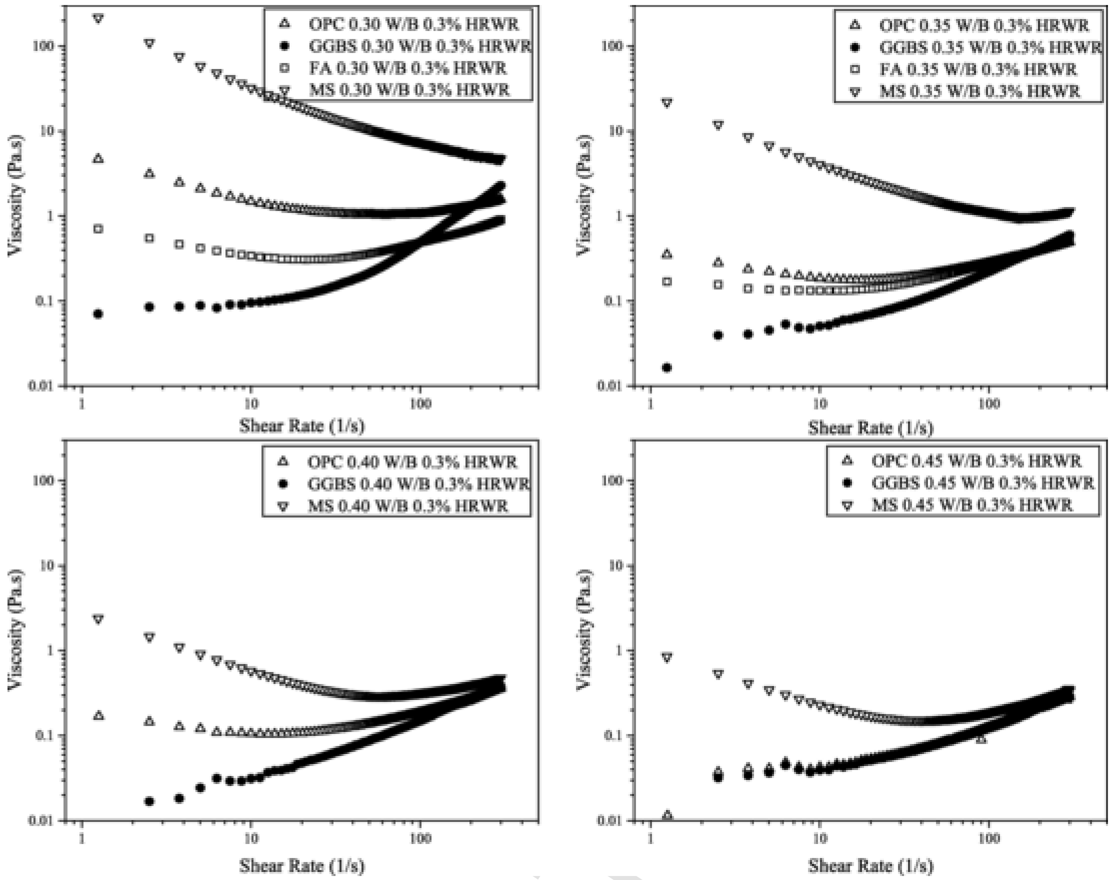

Fig. 18. Effect of w/b ratio on shear thickening of suspension with different mineral admixtures at 0.3% dosage of HRWR.

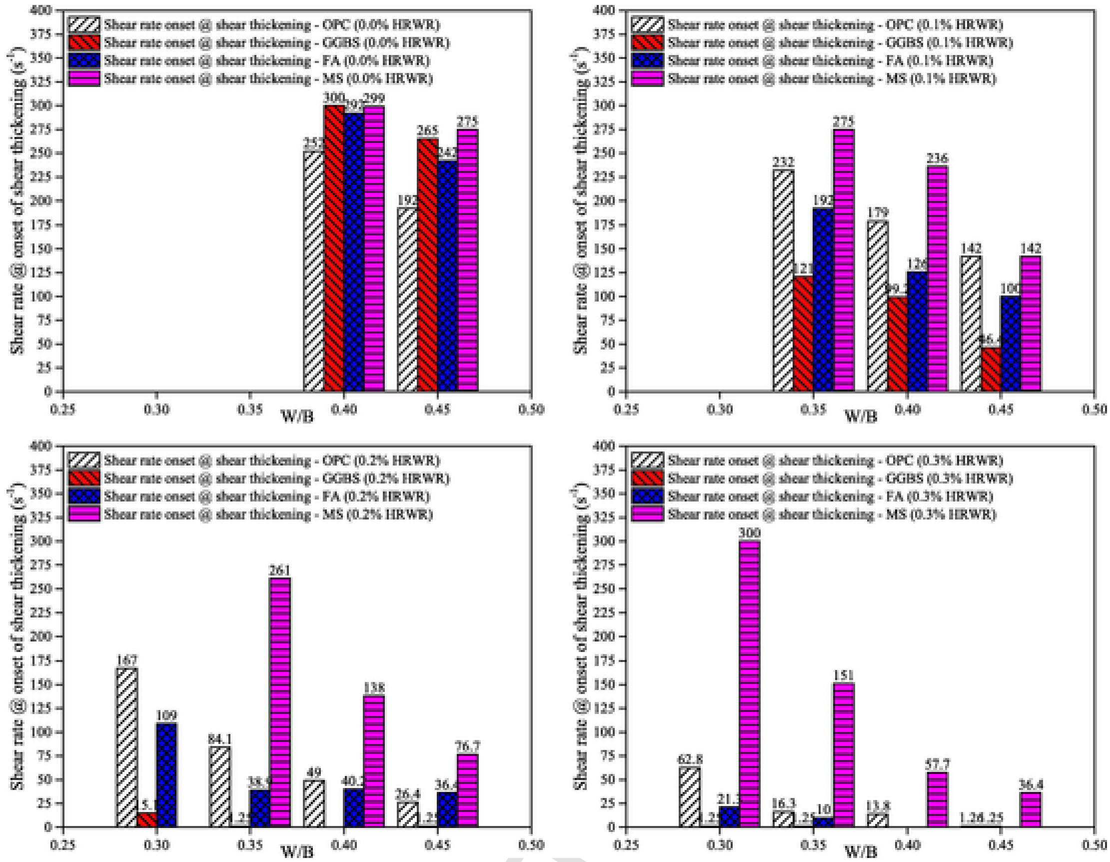

Fig. 19. Shear rate @ onset of shear thickening for different suspensions.

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