- Technical Paper –

EVALUATING CONCRETE RHEOLOGY USING AN INTENSIVE CONCRETE MIXER WITH HELICAL IMPELLER RHEOMETRY

Chandra Kiran VINUKONDA*1, Siddharth ROY CHOWDHURY*2, Masanobu SHIMADA*3 and
Toshimi MATSUMOTO*4

ABSTRACT

Acknowledging the limitations of slump test to measure concrete workability, this paper advocates for a shift towards evaluating workability using scientific principles of concrete rheology. This study introduces a newly developed intensive concrete mixer with a helical impeller rotor tool, that could serve as a rheometer. Preliminary assessment confirms the capability of the helical impeller rheometer to evaluate concrete rheology similar to that of coaxial cylindrical rheometer, which is the foundational principle of concrete rheology measurement. The study also lays the groundwork for exploring additional functions like measuring optimum mixing time and thixotropy.

Keywords: *Concrete rheology, helical impeller rheometer, coaxial cylinder rheometer, yield stress, plastic viscosity.*

1. INTRODUCTION

Understanding concrete workability and its assessment is essential for optimizing the construction process and ensuring that the desired properties are achieved upon hardening. The mechanical and durability properties of concrete in its hardened state are heavily influenced by the quality in its fresh state – the phase from the moment all of its constituents are combined to the point of placement and finishing.

The slump test is an empirical method widely used to measure concrete workability, even today. When it was developed in the early 1900s, improving concrete flowability commonly involved increasing water content. The slump test was quickly adopted because of its simplicity and its effectiveness as an indicator of water content in concrete mixes, thereby serving as a reliable measure of workability. However, the use of modern chemical admixtures, such as water reducers, has allowed concrete to maintain flowability with low water-to-cement content. This presents a challenge as two concrete mixes with different water-to-cement ratios (W/C) could have the same slump value but behave differently in reality [1]. Moreover, tests like these are operator-sensitive, and thus, the properties for same mix of concrete made under same conditions will vary depending upon the workmanship. To improve quality control and performance of concrete, workability measurements based on fundamental principles instead of empirical tests are pertinent.

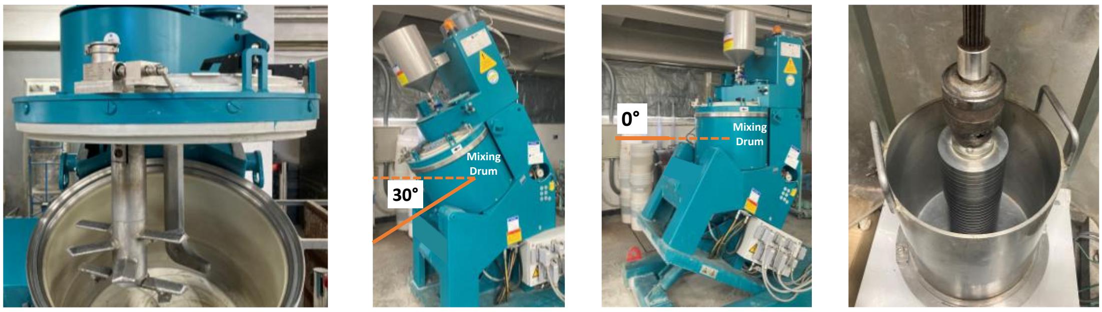
Rheology is the science that seeks to characterize the flow and deformation of materials using fundamental principles of stresses and shear rates, which can also be applied to cement-based systems [2]. The devices attempting to use fluid rheology methods to measure the flow of concrete, i.e., measuring shear stress at varying shear rates, are called rheometers [3].

The first practical rotational rheometer, developed by Couette, features two concentric cylinders with fluid placed in the annulus between rotating cylinders, which are in relative rotation about their common axis. It is common for the outer cylinder to rotate, and the torque required to keep the inner cylinder (bob) stationary is measured. Most commercial instruments utilize similar design concepts [4]. However, the large size of the inner cylinder disturbs the fluid system, so the gap between the cylinders should not be too narrow [5]. One of the primary issues with rotational rheometers is wall slip, typically caused by large velocity gradients in the gap between the cylinders. When slip occurs, the measured viscosity can be significantly lower than the actual viscosity of the sample. To prevent slippage of the concrete on both the bob and the container, the bob consists of a series of vertical blades (vane). The vane causes less disturbance in the fluid compared to a cylinder, is less susceptible to artifacts arising from large particle sizes and is particularly effective in reducing the impact of the wall-slip effect [5, 6].

The general principle of rheometers converges on determining the relationship between a parameter related to shear stress (mostly torque) and a parameter related to shear rate (mostly rotational speed), which is the T-v curve where T is the torque and v is the rotational speed. After this basic step, the method used to "*translate*" this relationship to a shear stress-shear rate relationship ($\tau - \dot{\gamma}$ curve) (where τ is the shear stress and $\dot{\gamma}$ is the shear rate) starts to diverge a lot from one rheometer to another based on the complex geometry of the impellers (vanes) [7].

---

*1 Technical Development Center, Pozzolith Solutions Ltd., Masters (Engineering), JCI Member
*2 Technical Development Center, Pozzolith Solutions Ltd., Masters (Engineering)
*3 Technical Development Center, Pozzolith Solutions Ltd., Bachelors (Engineering)
*4 Technical Development Center, Pozzolith Solutions Ltd., Doctor (Engineering)



(a) *(b)* *(c)* *(d)*

Fig. 1 Rheometers used this study.

(a) Intensive mixer with the helical impeller rotor tool. ***(b)*** Intensive mixer in its usual configuration (30° drum inclination) ***(c)*** Intensive mixer as a rheometer (0° drum inclination) ***(d)*** Co-axial cylindrical rheometer

The aim of this study is to check if the intensive mixer with a helical impeller rotor tool, that can serve as a rheometer can measure rheological characteristics of concrete similar to that of a coaxial cylindrical rheometer. The two rheometers used in this study are an intensive concrete mixer with sequence automation and process data control that can be used for the calculation of rheological properties through precise control of the speed of the mixing helical rotor tool, and a conventional coaxial cylinder rheometer.

2. MEASURING RHEOLOGY OF CONCRETE

2.1 Rheological Behavior of Concrete

For fresh concrete, being a more complex fluid due to the presence of fine and coarse aggregates in the cement paste suspension, a single factor like viscosity is not sufficient to describe rheology. The rheology of fresh concrete can be described using at least two parameters: Yield stress τ_0 and plastic viscosity μ. Those parameters are usually obtained from the linear relationship between shear stress τ and shear rate $\dot{\gamma}$ is modeled by Bingham fluid law, showed by Eq. 1 [8].

$$\tau = \tau_o + \mu\dot{\gamma} \qquad (1)$$

However, recent research has shown nonlinear rheological behavior of fresh concrete modelled by the Hershel- Bulkley equation, showed by Eq. 2, could also be a better fit.

$$\tau = \tau_o + k\dot{\gamma}^n \qquad (2)$$

where, k is the consistency index and n is the power index. Absolute values of rheological characteristics can be determined from the $\tau - \dot{\gamma}$ curve, otherwise known as a rheological profile [7]. The plastic viscosity represents the slope, and yield stress corresponds to the y-intercept in a rheological profile. However, the slope and y-intercept from the T-v curve could also provide a relative measure of plastic viscosity and yield stress, respectively and the same understanding is used in this paper.

2.2 Concrete rheometers used in this study.

As stated earlier, two rheometers have been used in this study – helical impeller rheometer and coaxial cylindrical rheometer, denoted by R_HI, R_CC respectively (Fig. 1).

The geometrical configuration of the coaxial cylindrical rheometer (as shown in the figure 1*d*) is based on the principle of coaxial cylinders. The outer cylinder rotates, while the inner cylinder measures the resistant torque. The coaxial cylindrical rheometer used in this study has an outer cylinder radius of 12.5 cm and an inner cylinder radius of 5.0 cm. The height of the inner cylinder submerged in concrete is 20.0 cm, leaving a clearance gap of 50 mm. in the vertical direction, which is more than twice the maximum aggregate dimension of the mixed concrete (20 mm). The volume of concrete needed in this rheometer is around 12 – 15 liters.

The intensive concrete mixer was developed by implementing new rheology interface. When mixing concrete, it can record critical parameters such as power consumption of the mixing pan and the rotor tool. By monitoring the characteristic power curve, it is possible to keep track visually of when the concrete is '*ready*' i.e., the optimum mixing time for concrete. When used as a rheometer, it operates on the Searle principle – the torque-measuring rotor tool rotates in a stationary container (drum). The rotor tool is a helical impeller, with each protrusion measuring 14.0 cm from the center. The clearance gap between the tool and the bottom of the drum, i.e., in the vertical direction, is 50 mm, similar to R_CC. The inclination of the drum can be changed from 30° (in its usual configuration – Fig. 1*b*) to 0° (Fig. 1*c*) from the horizontal level.

While both the inner and outer cylinders in the coaxial rheometer have simple shapes, the complex geometry of the rotor tool of the helical impeller rheometer makes it challenging to determine shear stress and, consequently, the absolute values of rheological characteristics – plastic viscosity and yield stress. Therefore, relative measures of these parameters were obtained from the T-v curves.

Concrete rheology was assessed using the Hysteresis method, involving both increasing and decreasing shear rates, forming a hysteresis loop (Fig. 2) [9]. The T-v curve points during increasing shear were fitted using the Herschel–Bulkley power equation (blue data points in the figure), while those during decreasing shear were fitted using the Bingham linear model (orange data points in the figure). Beyond obtaining relative measures of yield stress and plastic viscosity from the intercept and slope of the Bingham

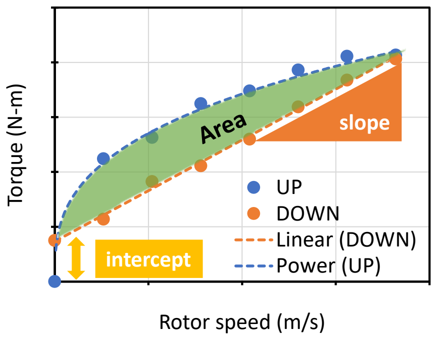


Fig. 2 Determining rheological characteristics from rheological profile.

down line, respectively, a relative measure of a third parameter called thixotropy could also be obtained by determining the area between the Herschel–Bulkley up and Bingham down curves, which is an indication of the ease with which the concrete flows (lower the thixotropy, easier the concrete flows).

3. EXPERIMENTAL PROGRAM

3.1 Raw Materials and Apparatus

Tables 1 and 2 describe the raw materials and concrete mix designs used in this study respectively. Fresh properties of concrete – slump and air content were measured as per JIS A 1101 and JIS A 1128.

Table 1 Physical properties of Raw materials

Raw material	Symbol	Physical properties
Water	W	Tap water
Cement	C	Ordinary Portland Cement Density = 3.16 g/cm^3, Specific surface area = 3,240 cm^2/g
Fine aggregate (Sand)	S	Sand from Oi River system Surface dry density = 2.59 g/cm^3, Surface moisture content = 1.94 %
Coarse aggregate (Gravel)	G	Crushed hard stone from Ome Surface dry density = 2.65 g/cm^3, Surface moisture content = 0.63 % Maximum dimension = 20 mm
Admixtures	WR	High range AE Water Reducer
	VMA	Viscosity Modifying agent
	AE	AE agent

Table 2 Concrete Mix design

Target Slump (cm)	Target Air (%)	W/C (%)	s/a (%)	Unit content (kg/m^3)			
				W	C	S	G
18 ± 1.0	4.5 ± 0.5	45.0	47.0	170	378	810	935
		55.0	47.0	170	309	837	965
		31.0	43.0	170	548	681	924

The concrete mix designs provided in table 2 are regularly utilized at the institute. Since the current study is a preliminary assessment of the effectiveness of the rheometers, the authors opted to use familiar mix designs without making any changes.

When using the helical impeller rheometer (R_HI), 30 litres of concrete is mixed for 180 s after the addition of superplasticizer at its usual configuration i.e., drum inclination is 30°. Upon confirming that the slump and air content of concrete are as per our requirements, mixer is lifted so that drum inclination is 0° and is then subjected to hysteresis.

For rheological measurements with the coaxial cylindrical rheometer (R_CC), 30 litres of concrete is mixed with a 55L twin shaft mixer for 90s after the addition of superplasticizer. Upon confirming that the slump and air content of concrete are as per our requirements, 15 litres of concrete is placed in coaxial rheometer and is subjected to hysteresis.

Once concrete is in the rheometer, it is subjected to pre-shear of 1.0 m/s for 20 s., and then is let to rest for 60 s., before starting the hysteresis program. During hysteresis shearing, the frequency of rotating tools of both rheometers (outer cylinder in coaxial rheometer, inner helical tool in impeller rheometer in rpm) have been adjusted so that the rotating speed (in m/s) is same for both the rheometers (eq. 3).

$$v = \frac{2\pi}{60} \times r \times N \qquad (3)$$

where v is the rotational speed in m/s, r is the radius of the rotating tool in m., and N is the angular velocity in rpm. Given the radii of rotating parts of coaxial cylindrical rheometer and helical impeller rheometer are 12.5 cm., and 14.0 cm., respectively, shear rates applied in R_CC are 0 – 70 rpm in steps of 10 rpm, while in R_HI are 0 – 63 rpm in steps of 9 rpm, both resulting in rotational speeds from 0 – 0.92 m/s in steps of 0.13 m/s. At the end of increasing shear rate, the rotating tool is maintained at top speed of 0.92 m/s for 10 s. before starting to decrease shear rate (Fig. 3).

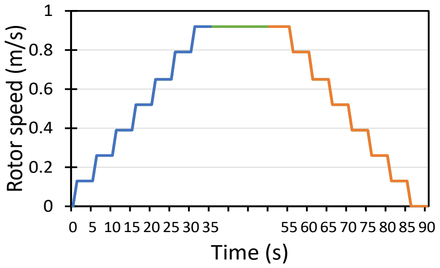


Fig. 3 Hysteresis program

Of the parameters that can be measured using the intensive mixer – optimum mixing time for concrete (while mixing), relative measures of dynamic yield stress, plastic viscosity, thixotropy (when using it as a rheometer); the focus of this paper is only yield stress and plastic viscosity. While the authors realize the merit of being able to measure optimum mixing time and thixotropy, they deemed it best fit for a future study.

3.2 Outline of this Study

The aim of this study is to assess the reproducibility of data obtained from R_HI, and upon establishing its confidence in the data i.e., rheological characteristics, is to then investigate how rheological profiles and, subsequently, rheological parameters vary in response to changes in the concrete mix design.

(1) Reproducibility of Rheometers

Concrete with W/C = 45%, fresh properties of 18 cm. slump and 4.5% air content is used as reference.

To assess reproducibility, three concrete batches with the exact same composition as the reference were mixed in the intensive mixer. Rheology profiles of all three batches (*n*1, *n*2, *n*3) were acquired by subjecting each mix to hysteresis shear in R_HI. Additionally, rheology profiles of three batches mixed in a twin-shaft mixer were obtained from R_CC (*n*1, *n*2, *n*3) for comparison. Repeatability was determined by the Co-efficient of variation (CV) which is the ratio of standard deviation to the mean. Higher reproducibility is indicated by a lower CV. Data with a CV less than 10% is considered highly reproducible.

(2) Rheological Variations in Concretes with Similar Slump

As explained in the introduction, a good example of two concrete mixes with similar fresh properties showing contrasting workability can be observed in concretes with varying W/C. Concretes with different W/C with identical slump and air content tend to show similar values of yield stress but have contrasting viscosity reflective of W/C. A simple demonstration of above phenomena is conducted in mixes with W/C = 55%, 45%, 31% to see if these trends can be seen from both rheometers – R_HI, R_CC.

(3) Changes in Rheological Profiles with Concrete Mix Design

In this study, the influence of seven factors that strongly affect the fresh properties of concrete with the same composition as reference i.e., W/C = 45% on the yield stress and viscosity of concrete, measured using the R_HI have also been assessed. These factors include passage of time (T), increase in air content (Air), increase in water content (W), addition of water reducer (WR) alone, addition of viscosity-modifying agent (VMA) alone, and levels of combined (WR + VMA). Each factor is tested at three levels ("–, 0, +" or "0, +, ++"), where 0 represents the base, – signifies reducing the corresponding factor, and + and ++ denote an increase in the corresponding factor, used when reducing the amount is not feasible (eg.: passage of time). For each case, it is ensured that at least one measure of fresh concrete (slump or air content) falls within the target range, and whenever possible, both values are within the specified range (Table 3).

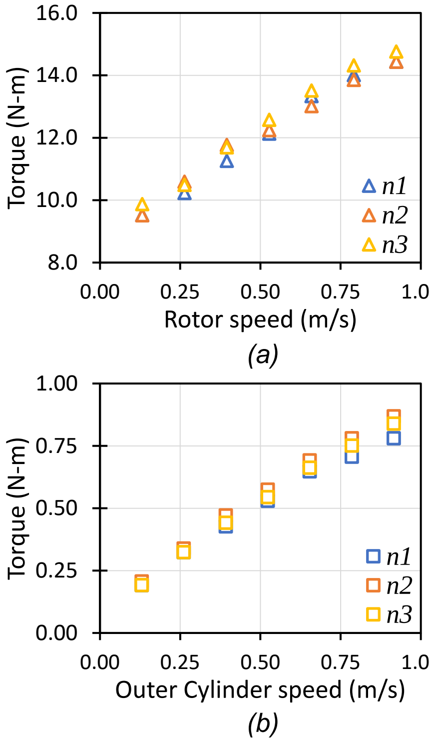
Table 3 Level settings of each factor

Factor	Change in mix design	Level			
		–	0	+	++
T	Time passed after mixing (min.)		0	15	30
Air	Desired air content in concrete (%)	3.0	4.5	6.0	
W	Water content in concrete (kg/m^3)	160	170	180	
WR	Dosage of WR (C × %)	0.75	0.90	1.05	
VMA	Dosage of VMA (C × 0.001%)		0.00	0.25	0.75
WR + VMA	Same as the above two		0.90 + 0.00	1.00 + 0.25	1.15 + 0.75

4. RESULTS AND DISCUSSION

4.1 Reproducibility of Rheometers

The results of reproducibility test are shown in Fig. 4 and Table 4. Both rheometers demonstrated strong levels of reproducibility based on rheological profiles.



(a)

(b)

Fig. 4 Results of Reproducibility test.
(a) Helical Impeller rheometer: R_HI
(***b***) Coaxial cylindrical rheometer: R_CC

Table 4 Quantified Reproducibility of rheometers

Rheometer	Parameter	*n*1	*n*2	*n*3	CV
R_HI	Plastic Viscosity	6.60	6.10	6.59	3.64
	Yield Stress	8.65	8.99	9.01	1.85
R_CC	Plastic Viscosity	0.75	0.82	0.84	4.92
	Yield Stress	0.12	0.11	0.12	6.47
	*Plastic Viscosity**	13.73	14.92	15.38	4.74
	*Yield Stress**	28.39	23.99	27.19	7.00

**Absolute values of Plastic Viscosity (in Pa·s), Yield stress (in* N/m^2 *or* Pa)

Looking at quantitative measure of reproducibility, the coefficient of variation (CV), yield stress and plastic viscosity values for both rheometers had CV less than 10%. This low CV indicates consistent and reliable measurements from both instruments.

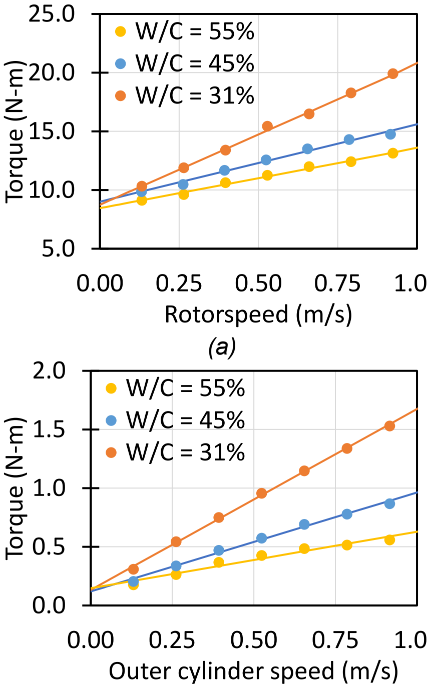
Notably, the helical impeller rheometer showed better reproducibility, with lower CV values for yield stress and plastic viscosity. These results confirm the reliability of the measurements and highlight the superior capacity of the helical impeller rheometer in capturing key rheological parameters.

4.2 Rheological Variations in Concretes with Similar Slump

The similarity in fresh properties of W/C = 55%, 45%, 31% concretes achieved by adjusting the dosage of superplasticizer are shown in Table 5, along with corresponding rheological profiles obtained from R_HI, R_CC. Fig. 5 shows the rheology profiles.

Table 5 Rheological properties of concretes with varying W/Cs but same slump

Rheometer	W/C (%)	WR (C × %)	Slump (cm.)	Air (%)	Plastic Viscosity (slope)	Yield Stress (y-intercept)
R_HI	55.0	0.75	18.0	4.6	5.15	8.46
	45.0	0.90	19.0	4.2	6.59	9.01
	31.0	1.10	19.0	4.1	12.04	8.77
R_CC	55.0	0.60	18.5	4.0	0.48	0.15
	45.0	0.70	19.0	4.2	0.84	0.12
	31.0	0.90	18.0	4.3	1.54	0.13



(a)

(b)

Fig. 5 Demonstration of concretes with varying W/Cs with similar slump (same yield stress) exhibiting different plastic viscosities.
(***a***) Helical Impeller rheometer: R_HI
(***b***) Coaxial cylindrical rheometer: R_CC

The similarity in slump of three batches is clear from the fact that all three profiles have same y-intercept i.e., yield stress. A key observation is that the viscosity of each mix which couldn't be distinguished through slump, is evident from the rheology profiles i.e., slopes or plastic viscosity for each W/C is different. As one would expect, plastic viscosity increases as W/C decreases. Both rheometers show similar trends of change in rheology profiles with W/C.

It's important to note that at a velocity of 100 rpm (equivalent to 1.31 m/s) of the outer cylinder in R_CC, concrete inside experiences high centrifugal force – the aggregates move towards outer cylinder and mortar moves towards inner cylinder and segregation is observed, a phenomenon known as wall slip. To prevent torque readings from being influenced by wall slip, the maximum velocity of the rotating outer cylinder during the hysteresis program is restricted to 0.92 m/s or 70 rpm in both R_CC, R_HI.

4.3 Changes in Rheological Profiles with Concrete Mix Design

Fresh properties of concrete with changes in concrete mix design and rheological characteristics are shown in Table 5. Changes in rheological profiles can be viewed in Fig. 6.

There have been many studies that evaluated the effect of changes in concrete mix design on the rheological parameters. Some of the key trends pointed out in [10] are as follows.

- **Air:** Increasing air content doesn't affect yield stress but reduces the plastic viscosity.
- **WR:** Increasing dosage of water reducer doesn't affect plastic viscosity but reduces yield stress.
- **T:** With the passage of time, both the yield stress and plastic viscosity increases.
- **W:** Increasing water content reduces both yield stress and plastic viscosity.
- **VMA:** Similar effect as that of the passage of time,
- **WR + VMA:** Similar to an addition of individual effects – yield stress reduces (like when increasing WR), but plastic viscosity increases (like when increasing VMA)

As evident from fig. 6, the trends of changes in rheological profiles with changes in each of the six factors – Time (T), Air, Water reducer (WR), viscosity modifying agent (VMA), WR + VMA, Water content (W) obtained from the helical rheometer align consistently with findings in previous literature [10].

The effects of various material properties of concrete, time, additives, etc., on concrete rheology can be systematically revealed on a graph with plastic viscosity (μ) as the x-axis and yield stress (τ_0) as the y-axis. The plot illustrating the changes in the relation

Table 6 Changes in fresh properties and rheological characteristics with concrete mix design

Rheometer	Mix	WR (C × %)	AE (C × 0.01%)	VMA (C × 0.001%)	W (kg/m^3)	Slump (cm.)	Air (%)	Plastic Viscosity (slope)	Yield Stress (y-intercept)
R_HI	Ref. (0)	0.90	0.5	-	170	19.0	4.2	6.59	9.01
	T (+)				170	14.0	4.5	8.20	13.18
	T (++)				170	8.5	4.0	8.70	16.79
	Air (–)	0.95	0.0	-	170	19.0	3.2	8.60	8.50
	Air (+)	0.80	1.0	-	170	19.0	6.0	5.82	8.88
	WR (–)	0.75	0.5	-	170	15.5	5.0	7.07	10.16
	WR (+)	1.05	1.0	-	170	21.0	4.5	7.17	6.79
	VMA (+)	0.90	0.5	0.25	170	16.0	4.5	7.53	9.83
	VMA (++)	0.90	0.5	0.75	170	13.5	4.2	8.09	12.14
	WR + VMA (+)	1.00	0.5	0.25	170	18.0	4.0	7.79	7.55
	WR + VMA (++)	1.15	1.0	0.75	170	19.0	4.4	7.89	6.83
	W (–)	1.10	0.3	-	160	18.0	4.3	7.32	10.45
	W (+)	0.55	1.0	-	180	19.0	4.3	7.17	6.69

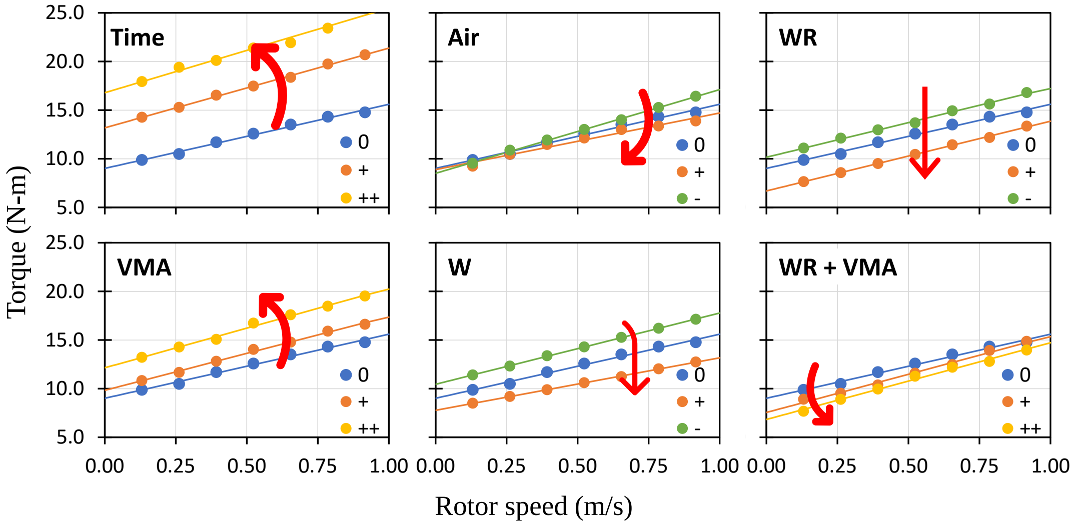


Fig. 6 Change in rheological profiles as obtained from E_HI with each factor of concrete mix design (*red arrow indicates the direction of increase of each factor*)

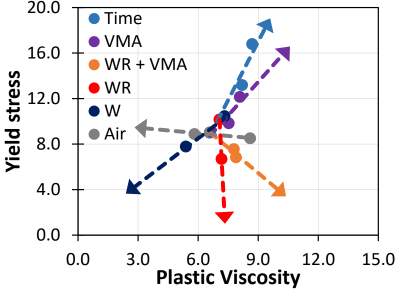


Fig. 7 *Rheograph* with relative measures of plastic viscosity and yield stress obtained from helical impeller rheometer.

between yield stress (τ_0) and plastic viscosity (μ) as a function of various alterations in concrete characteristics is defined as a *rheograph* by O.H. Wallevik [10]. However, a similar *rheograph* could be constructed using relative measures of plastic viscosity and yield stress from T-v curve. When we plot results of table 6 and fig. 6 to produce a *rheograph* (Fig. 7), the result is quite similar to the one presented in [2, 10].

Although differences in concrete rheology can be seen through changes in rheological profiles and its characteristics, the significance of the variation needs to be established through more tests. For *e.g.*, when tested for reproducibility of rheological characteristics from R_HI in W/C = 45% concrete, a change of 0.50 in plastic viscosity (plastic viscosity values of $n1$ and $n2$ are 6.60 and 6.10) is considered to be within tolerable range. The minimum change in plastic viscosity that could imply a corresponding significant change in concrete rheology and the factors that it depends on, and if the helical rheometer can be used to distinguish between mixes with considerably different rheology would be an interesting case study to pursue.

5. CONCLUSIONS

The authors conducted experiments to quantify concrete rheology using an automated intensive mixer equipped with a helical impeller rotor tool, which also functions as a rheometer and compared the result to that from a coaxial cylindrical rheometer, leading to the following observations.

(1) The helical impeller rheometer and coaxial cylindrical rheometer could differentiate between concrete mixes with the same slump.
(2) Both rheometers showed good reproducibility in generating rheological profiles; the helical impeller rheometer exhibited higher reproducibility.
(3) Rheological profiles obtained from the helical impeller rheometer align well with trends observed in prior literature.

REFERENCES

[1] Subramanian, N., “Rheological properties of Concrete,” *STRUCTURE,* pp. 8 - 11, Jan 2021.

[2] Ferraris, C. F., “Role of Rheology in Achieving Successful Concrete Performance,” *Concrete International,* vol. 39, no. 6, pp. 43 - 51, Jan 2017.

[3] Hackley, V. & Ferraris, C. F., “Guide to Rheological Nomenclature: Measurement in Ceramic Particulate Systems,” Special Publication (NIST SP) 946, Jan 2001.

[4] Macosko, C. W., “Shear rheometry,” in *RHEOLOGY Principles, Measurements and Applications*, Wiley-VCH, Inc., 1994, p. 188.

[5] Barnes, H. A., Carnali, J. O., “The vane-in-cup as a novel rheometer geometry for shear thinning and thixotropic materials,” *Journal of Rheology,* vol. 34, no. 6, pp. 841 - 866, Aug 1990.

[6] Barnes, H. A., “A review of the slip of polymer solutions, emulsions and particle suspensions in viscometers: its cause, character, and cure,” *Journal of Non-Newtonian Fluid Mechanics,* vol. 56, no. 3, pp. 221-251, Mar 1995.

[7] Le, H.D. & De Schutter, et. al., “Computational fluid dynamics calibration of Tattersall MK-II type rheometer for concrete,” *Applied Rheology,* vol. 23, no. 3, pp. 34741 1-12, Jun 2013.

[8] Ferraris, C. F., “Measurement of the Rheological Properties of High Performance Concrete: State of the Art Report,” *Journal of Research of the National Institute of Standards and Technology,* vol. 104, no. 5, pp. 461-478, Sep-Oct 1999.

[9] Roussel N., “A thixotropy model for fresh fluid concretes: Theory, validation and applications,” *Cement and Concrete Research,* vol. 36, no. 10, pp. 1797-1906, Oct 2006.

[10] Wallevik, O. H., and Wallevik, J. E., “Rheology as a tool in concrete science: The use of rheographs and workability boxes,” *Cement and Concrete Research,* vol. 41, no. 12, pp. 1279-1288, Dec 2011.