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Role of Rheology in Achieving Successful Concrete Performance

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Abstract

Workability is one of the most important properties of concrete as it determines how easily the material can be placed. Workability affects many aspects of a concrete construction, including productivity (e.g. casting rate), processing (e.g. finishing), fresh state properties and hardened state performance of the concrete. For example, the structural properties of concrete will depend highly on how well the material is consolidated, while the aesthetics will depend on the quality of finishing. Workability is often measured using empirical tests, such as slump, slump flow, V-funnel, and J-ring. But it is rheology - the science of flow - that lays the foundation to understanding, controlling and predicting concrete workability. This paper provides a basic introduction to rheology. It will provide examples of how the basic fundamental principles of rheology can be applied to concrete technology to achieve suitable concrete performance as it pertains to segregation susceptibility, pumpability, surface finishability and formwork pressure. It will also provide a summary of test methods and equipment typically used to measure rheological properties.

Keywords: Bingham, formwork pressure, pumpability, rheology, segregation, surface finish, viscosity, workability, yield stress.

Introduction

This article provides a basic introduction to concrete rheology, as well as some insight into how rheology can be applicable to concrete construction. The fresh state performance of concrete is not only important for proper concrete placement and finishing, but also for its hardened state properties. Yet, the most commonly used workability test methods are based on empirical methodologies, such as slump, or slump flow, and to a lesser extent: V-funnel, L-box and J-ring tests. Even self-consolidating concrete (SCC), which is governed by the property of flowing under its own weight [1], is typically classified based on the results of empirical tests such as slump flow, V-funnel and J-ring. 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. Similar to how the hardened state mechanical properties of concrete are characterized by stresses and strains, rheology provides the user a way to objectively and quantitatively assess the fresh state properties of concrete by relating the shear stresses and shear rates [2]. Furthermore, it is a science that can be applied to various cement-based systems,

including but not limited to grouts, SCC, fiber-reinforced concrete, and traditionally vibrated concrete.

In this paper, basic rheology terminology is introduced, followed by typical measuring instruments and testing procedures. The concepts of rheology are then further applied to five different practical applications: mixture design and quality control, segregation, pumping, formwork pressure and surface finish.

Terminology (all grey area to be placed in a box – separate from the text)

Rheology: Rheology is the science of flow and deformation of matter [2]. For fluids, relationships can be described by plotting the shear stress versus the shear rate.

The Bingham model is a linear approximation of the shear stress-shear rate relationship of a material or fluid (see Figure 1), and it is described by two material parameters: yield stress and plastic viscosity. Most cement-based materials can be described as Bingham materials that follow this model. The Bingham yield stress, or dynamic yield stress, of cement-based materials is related to the slump [3, 4] or slump flow [5].

Yield stress: is the stress required to initiate material flow. Typically, two types of yield stresses are considered:

Static yield stress: The static yield stress represents the stress required to transition from a solid-like to a liquid-like behavior (going from rest to flow). That is, starting from a static state and going to a dynamic state. As most cementitious materials exhibit thixotropy, the static yield stress increases over time. [6, 7].

Dynamic yield stress: The dynamic yield stress is typically taken as the apparent stress where the material transitions from a liquid-like behavior to a solid-like behavior (going from flow to rest). The dynamic yield stress is an extrapolated value based on the flow curve (shear stress vs. shear rate) and is often based on measurements performed on the ”down” flow curve (the shear stress-shear rate curve obtained from measurements in which the shear rate is decreased from a high shear rate to a low shear rate (see Fig. 1)).

Viscosity: is a measure of a material’s resistance to flow after flow is initiated. The higher the viscosity, the higher the material’s resistance to flow. This term is generally used to describe materials that show liquid-like behavior and it provides a way to fundamentally quantify the **“**measure of the resistance of a fluid to deform under shear stress” [8].

Plastic viscosity is the slope of the shear stress-shear rate relationship as described by the Bingham model. (see Fig. 1).

Thixotropy: Cement-based materials are more complicated than model Bingham materials, since the rheological properties of cement-based materials will also vary with time. Thixotropy is the reversible material stiffening with time of the material at rest, and its ability to re-fluidize when sheared [9, 10]. Per definition, thixotropy has a physical nature due to particle agglomeration [11, 12] and it is not the same as stiffening due to hydration, which is chemical in nature.

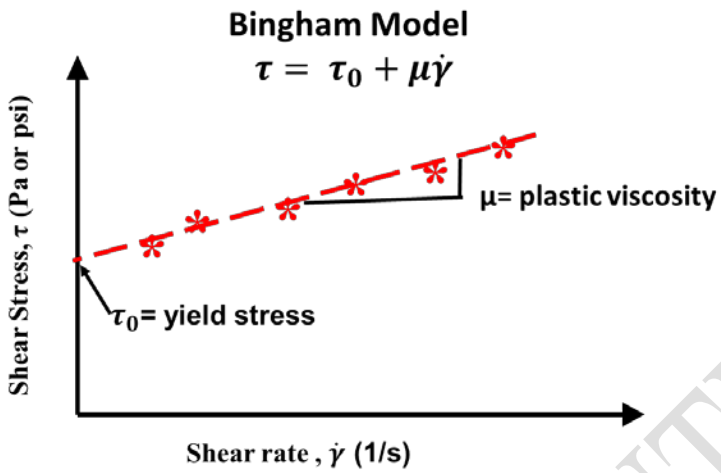

Figure 1. Representation of Bingham fluid. The stars represent experimental points that are approximated by the straight line.

Measurements tools and procedures

Tools/devices

Standard equipment used to characterize the rheological properties of fluids are rotational shear rheometers. Such equipment is commonly used in asphalt binder testing laboratories (state, federal agencies and producers, see for example ASTM D7175 [13], AASHTO T315 [14]). These devices apply continuous shear to the sample through rotational movement at controlled torque or speed. Rheometers for concrete must be specifically designed due to the large particle size of the aggregates. Most geometrical configurations for concrete rheometers are based on coaxial cylinders shown in Figure 2. The coaxial cylinder geometry consists of an inner cylinder (i.e., a bob) inserted into an outer cylinder (i.e. a cup). Various geometries can be used for the bob, including but not limited to a solid cylinder [15], vane [16], and a double spiral [17]. The vane and double spiral geometries can be used in place of the inner cylinder of a coaxial cylinder rheometer to prevent slippage [20]. Another commonly used rheometer geometry for concrete is the parallel plate [18, 19]. The surfaces of the coaxial cylinder and parallel plate should be textured or roughened to prevent slippage between the concrete and rheometer surface [20]. Concrete rheometers have been used on various types of concrete classes (e.g., self-consolidating concrete, and fiber-reinforced concrete), but are not well-suited for stiff concretes (e.g., zero-inch slump concrete).

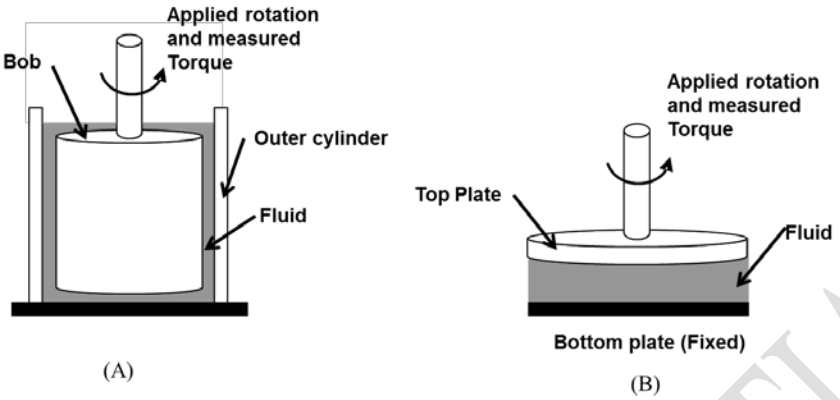

Figure 2. Typical Rheometer Configurations: Coaxial Cylinders, Parallel Plates [21]

Although rotational concrete rheometers have been successfully used to measure concrete rheology, a series of tests has shown that results from different rheometers do not agree with each other in absolute terms, caused by differences in experimental techniques and instruments [22, 23, 24]. Nevertheless, these results have been shown to rank different mixtures in a similar fashion. Another way to compare results from different rheometers would be to calculate relative plastic viscosity as described in Ferraris and Martys [25]. In order to enable more meaningful comparisons among laboratories and their rheometer, efforts are underway at the National Institute of Standards and Technology (NIST) to develop a standard reference material (SRM) that would be used to calibrate the rheometers [26, 27]. A RILEM Technical committee, TC-266: Measuring Rheological Properties of Cement-based Materials (MRP) [28] is in the process of developing guidelines for the use of rheometers in characterizing cementitious materials. Also, ASTM C1749 [29] provides guidelines to use rheometers to measure paste.

Procedures

There are two major types of measurements for concrete rheology: the flow curve test and the stress growth test. The choice of test depends on the rheological property required to be measured.

Flow Curve Test

The dynamic yield stress and plastic viscosity are calculated from the down curve of the flow curve. A flow curve test is performed by shearing concrete at different shear rates and measuring the resistance to flow, resulting in a flow curve such as the one plotted in Figure 1. In most cases, a constant high-shear rate is applied to bring the sample to a reference state in order to normalize the effects of thixotropy [30, 31, 32]; then, the shear rate is decreased in increments (also referred to as down-curve). As shown in Figure 1, if the flow curve is fitted with a linear function, the intercept is the Bingham yield stress (dynamic yield stress) and the slope is the plastic viscosity.

Stress Growth Test

The stress growth test is used to determine static yield stress (going from rest to flow), and how this property increases with resting time. The static yield stress at rest is the consequence of workability-loss, which includes thixotropy, hydration and other factors. The test is performed with a rheometer by applying very low shear rate to concrete initially at rest, increasing the strain

until the concrete begins to flow (yield). The maximum shear stress from the shear stress versus shear strain (or time) plot is equal to the static yield stress, as shown in Figure 3. The static yield stress is dependent on the shear rate or strain applied. These parameters need to be selected carefully to minimize the effect of the material setting evolution on the measurement of the static yield stress [33].

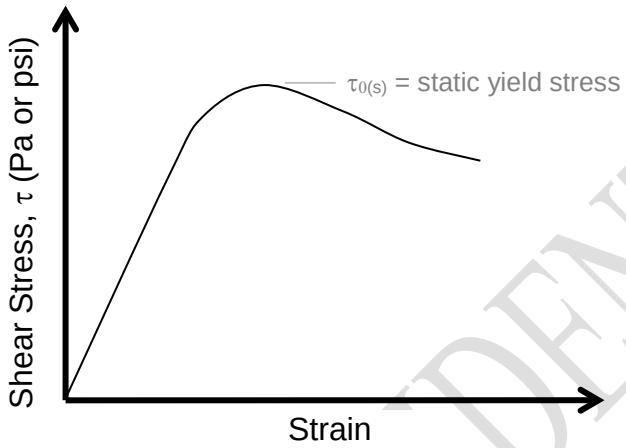

Figure 3. Stress Growth Test

Implications of inappropriate rheological properties

In the applications discussed below, rheology is tailored through the mixture design process. Nearly all aspects of the mixture proportions, including powder content, water-to-cementitious material ratio (w/cm), supplementary cementitious materials (SCMs) content, aggregate properties and content, and admixtures play an important role in concrete rheology. Yield stress and plastic viscosity of the paste increase as the w/cm decreases and as the cement gets finer [34, 35]. These properties are further modified (up or down) by the incorporation of SCMs. Due to the incorporation of aggregate, the yield stress of concrete is higher than that of the paste alone. Aggregate angularity, surface texture, maximum particle size, gradation, packing and content, all can have a significant effect on the viscosity and yield stress of concrete. Rheology controlling admixtures such as viscosity modifying agents (VMAs) and water reducing admixtures (WRAs) (normal, mid and high-range), can also enhance placement, consolidation and finishability of concrete and even increase thixotropy without the need to adjust the water content. Figure 4 summarizes some of the general effects that different components can have on rheology of concrete. For example, increasing the water content can decrease both the yield stress and plastic viscosity. On the other hand, the use of a low dosage of silica fume can decrease viscosity, while higher dosages can lead to increase in both yield stress and viscosity. It should be noted that, except for the WRA+VMA behavior, Figure 4 shows the effect of individual components only and does not consider the interactions between multiple components added. The synergistic effect of adding WRA and VMA to a mixture will depend on the dosage and type of the admixtures employed, thus

the line shown in Figure 4 is for illustrative purposes and should not be interpreted as WRA having more of an effect on rheology than VMA.

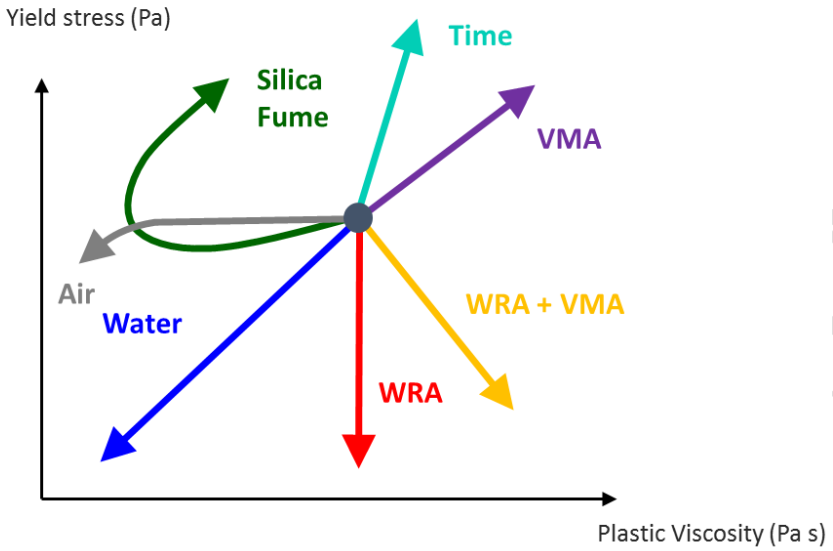

Figure 4. The effect of an increase in specific constituent materials on concrete rheology [adapted from 36]

Limiting variations in concrete properties for a job requiring high volumes of concrete can present a difficult challenge. Thus, once a mixture proportion has been approved for a project, implementing a continual quality control process is crucial. Rheometers that are more rugged and designed for field use are available to accurately quantify and monitor the concrete performance during processing (e.g., mixing, pumping, casting, finishing, etc...). Frequent monitoring of the rheological properties not only serves to ensure that the proper concrete is being placed, but also acts to inform the batch plant if changes are necessary and in what direction the changes need to be made. However, in situations where one does not have access to a field rheometer, effort should be made to characterize the rheological properties of the mixture in the lab and then correlate the rheological properties with the field friendly-workability test method(s) that will be used on the jobsite. In the following sections, specific applications will be highlighted to show the influence of rheology on the performance.

Segregation

In many concrete applications, increased flowability facilitates placing and finishing, but increasing the flowability beyond the capabilities of a particular mixture design can result in segregation. Segregation leads to a concrete that is not homogenous and may hinder mechanical properties and reduce the service life of concrete. Segregation can be observed in different forms whether it is the aggregate migrating within the paste or mortar phase, or excessive amount of the water phase of the cement paste migrating to the surface of the concrete (i.e., bleeding).

The yield stress of the suspending matrix (typically that of the paste or mortar phase) [37] is a key rheological parameter to ensure that a concrete mixture would have adequate segregation resistance. The magnitude of the desired yield stress will depend on the application; however, the yield stress alone of the suspending liquid (paste or mortar) may not be sufficient to keep the fine and coarse

aggregate particles suspended in the paste or mortar, respectively. An elevated plastic viscosity of the suspending liquid can slow down the segregation. Additionally, if the concrete is at rest, the yield stress increases due to thixotropy limiting further migration of the aggregates. In this way, if a low yield stress concrete is designed, a relatively high viscosity and thixotropy is necessary to minimize segregation effects [37].

Common approaches to modify yield stress and viscosity include varying dosages or types of fines (such as limestone powder), supplementary cementitious materials (SCMs) [38, 39, 40], and use of chemical admixtures [41, 42, 43]. Additionally, decreasing the maximum aggregate size helps decrease segregation [**Error! Bookmark not defined.**], and having a well-graded aggregate packing creates an enhanced particle lattice effect (smaller particles holding larger ones in position) that can help keep aggregates suspended [44, 45].

Pumpability

Two major problems can occur during concrete pumping. The first problem is blockage during start-up, which is mostly the consequence of a non-pumpable mixture design (usually a result of a high coarse aggregate fraction) or inappropriate selection or preparation of the pumpline (lack of, or inadequate priming) [46]. The second problem is excessive pressure during pumping, which can be caused by high flow rates, small pipes, or inappropriate rheological properties of the concrete.

Although the velocity profile in concrete during pumping is complex, as particles move to form the lubrication layer near the pipe wall [47], relatively simple correlations between pumping pressure and plastic viscosity have been proposed [48]. The lower the viscosity of the concrete, the lower the pressure needed to pump (Figure 5). If the viscosity is low, pumping pressure can increase when the yield stress increases (slump or slump flow decreases) [49]. It was shown [49] that in most cases, viscosity is more dominant than yield stress to determine pumpability.

The most significant way to reduce pressure during pumping is by enlarging the pipe diameter. Increasing the pipe diameter from 4” to 5” (100 mm to 125 mm) can roughly decrease pumping pressure by a factor of two [50]. Decreasing the flow rate and/or viscosity of the concrete are other alternatives to reduce pumping pressure. For conventional concrete, decreasing the yield stress (increasing the slump) can also reduce pressure [46].

It should, however, be noted that the actual flow behavior in pipes is more complex. For instance, extensive studies on the characterization of the lubrication layer have been undertaken. The reader is referred to the recent, detailed literature for more information [51, 52].

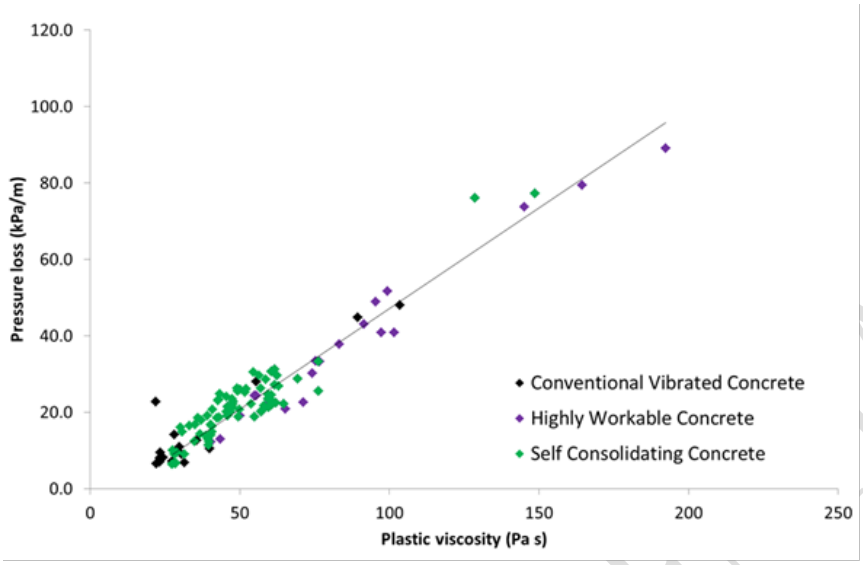

Figure 5: The pressure loss (expressed per meter of straight pipe, 100 mm in diameter at a flow rate of 8 l/s) is well correlated to the plastic viscosity of concrete, as shown above for three concrete mixes with widely varying workabilities. The three types of concretes in the figure have a widely different workability range. Figure adapted from Feys et al., [49]

Formwork Pressure

In placing conventional concrete within formwork (and in general), vibration is required to achieve proper consolidation. As the vibration is applied, yield stress is lowered, allowing consolidation to occur. When the vibration is removed, the high-thixotropic nature of normal concrete restores the high yield stress. Although the high yield stress of conventional concrete is responsible for requiring vibration, the high yield stress combined with high thixotropy is advantageous since it also results in low formwork pressure [12].

SCC is a highly-flowable concrete. However, a SCC mixture must be capable of handling high flow while providing adequate segregation resistance. Because of its high flowability, SCC does not require any external vibration to consolidate it; thus, faster casting rates can be achieved during construction. However, its low yield stress can result in high formwork pressure [12]. Therefore, for SCC applications, SCC formwork is an important consideration. Underestimating the pressure can lead to deformed formwork with malformed structures or, in the worst case, a formwork collapse. Overestimating the pressure is an economical issue due to the high share of formwork cost [53]. Besides the balance between formwork strength and cost, SCC used in areas where formwork pressure is a concern requires careful attention to thixotropy. In other words, as the SCC rests in the form, yield stress and viscosity increase, reducing the amount of vertical pressure that is translated horizontally to the formwork. The faster this rate of increase in rheological properties occurs, the lower the formwork pressure.

Increasing thixotropy from a mixture design perspective has been the focus of much recent research. Some ways to enhance thixotropy include the use of chemical admixtures (such as VMAs), SCMs (such as silica fume) and reducing w/cm [11, 12, 54, 55].

Quality of Surface Finish

The quality of the surface finish of concrete is linked to its aesthetics and is characterized by the homogeneity of the gray scale (or tint), roughness, or presence of bug holes. Several specifications/standards define the surface finish of concrete or mortar (NF P18-503, HUS AMA 98 or BS 8110, CIB N^{o} 24, etc.).

Surface finish is affected by a variety of parameters including mixture proportions, setting time, rheology, formwork surfaces, type of release agent, casting technique, placement speed and temperature [56]. Figure 6 shows three different zones in a rheology diagram in which surface finish of SCC is affected in a different way. If the plastic viscosity of the mixture is too low (**Zone I**), the risk for segregation during casting can be elevated, especially in the case of large free fall height if direction of concrete flow changes during casting. This segregation, in turn can affect the surface finish. In **Zone II**, concrete has adequate viscosity, but high yield stress. In this case, the yield stress can stabilize large entrapped air bubbles, thus preventing them from leaving the system and resulting in bugholes. On the other hand, consolidation lowers the yield stress, thus enabling unwanted air bubbles to rise. The consolidation energy necessary to avoid bugholes is dependent on the yield stress and plastic viscosity of the mixture. In **Zone III**, mixtures have a low yield stress, enabling the large entrapped air bubbles to rise out of the concrete and resulting in good surface quality. It should be noted that when the viscosity of the mixture is very high, the bubbles will rise slowly. Slow air ascension can also occur as a consequence of an increase in static yield stress that results from the thixotropy when the concrete is at rest.

Ways to achieve a low yield stress with a balanced viscosity include the use of SCMs, chemical admixtures (e.g., water reducers), reducing the w/cm, and increasing the paste volume [57].

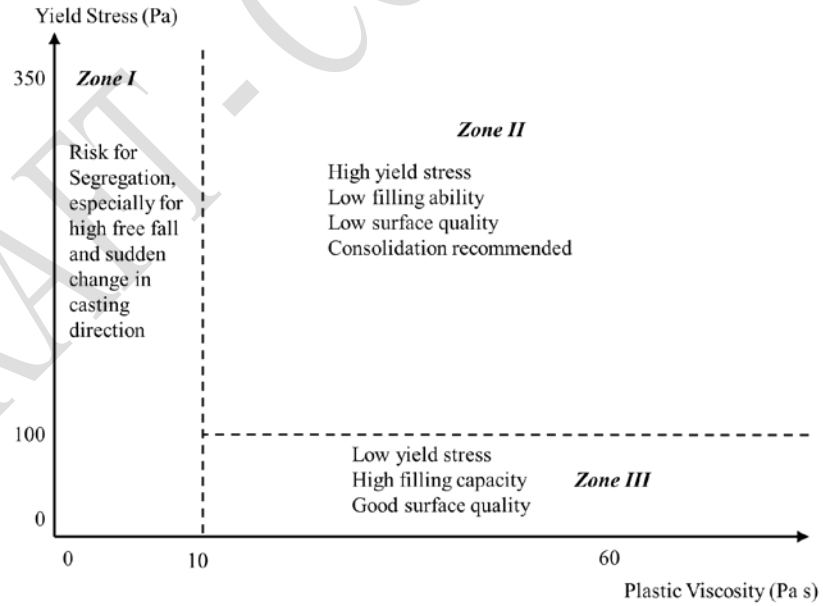

Figure 6. Influence of rheology on surface finish of self-consolidating concrete L-shaped elements. Figure adapted from Abd El Megid [58]

Conclusions

Rheology provides a fundamental understanding of concrete workability. The rheological properties of concrete need to be balanced to achieve good quality for each of the properties that are considered. For example, reducing yield stress and plastic viscosity to reduce pumping pressure will result in an increased risk for segregation. On the other hand, increasing yield stress to reduce formwork pressure may require additional consolidation to guarantee adequate surface finish. Rheology can be an effective tool for specifying, designing, and managing concrete workability, revealing concrete characteristics that are not indicated by slump alone. Results from different rheometers can be correlated and can be used to describe multiple aspects of workability. In contrast, empirical tests, such as the slump test and other empirical tests, measure a value, such as a distance or time that is specific to the test method. This value may not be sufficient to ensure proper performance for the multitude of processing steps (e.g., pumping, surface finish, formwork pressure, etc.) that a concrete mixture must endure during its life. As a consequence, it is difficult to compare results from one type of empirical test to another and results in the need for multiple tests to describe different aspects of workability. Using rheometers to determine rheological properties would provide more relevant information on the quality of the concrete.

Figure 7 summarizes the key points of the paper:

- Segregation can be controlled by increasing the yield stress or the plastic viscosity, but it should be noted that increasing both parameters too much will lead to very stiff concrete.
- Formwork pressure can be reduced by using a high yield stress concrete, or using a highly thixotropic concrete in slow filling conditions.
- Pumping pressure mainly decreases with a decrease in viscosity. Decreasing the yield stress also decreases pumping pressure, but to a lesser extent.
- Good surface finish can be achieved by having adequate viscosity: not too low, as the risk for segregation increases, but not extremely high as the air bubbles will not be able to escape. If the yield stress is elevated, consolidation is recommended to remove air.

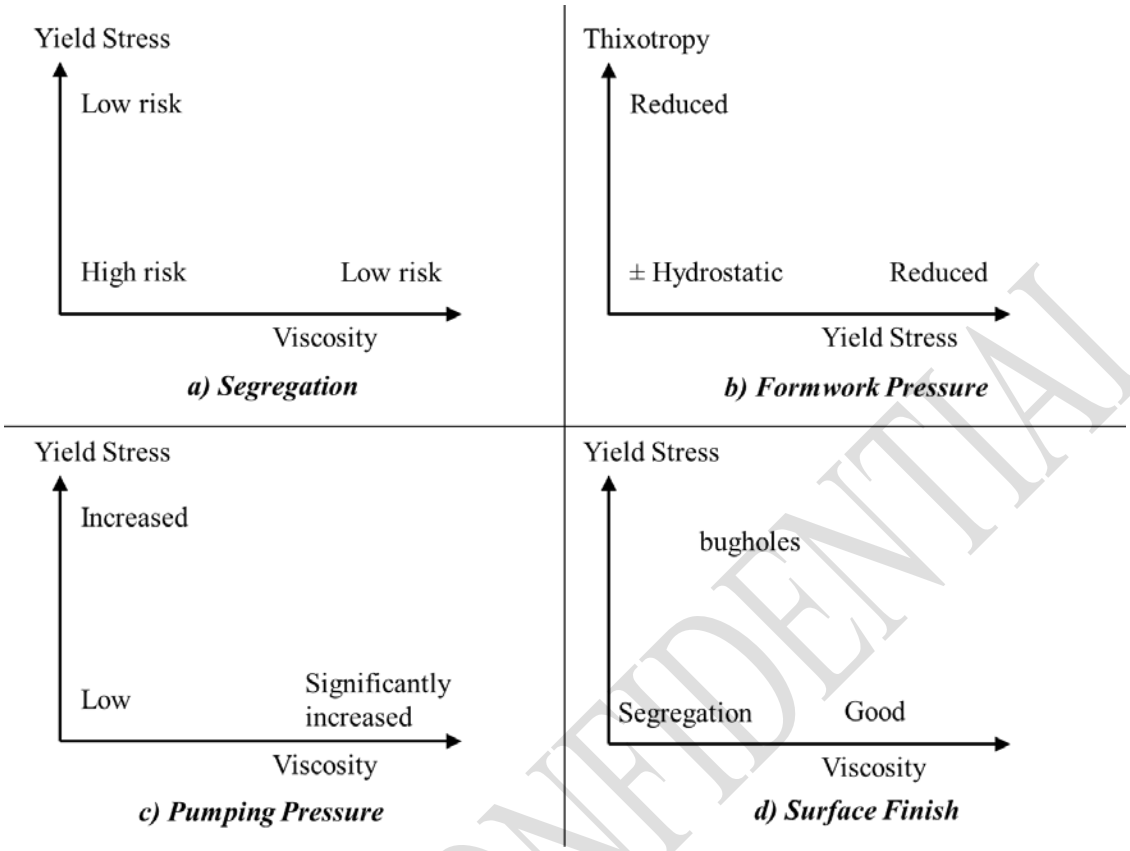

Figure 7. Summary of the impact of rheological parameters on concrete performance: (a) segregation, (b) formwork pressure, (c) pumping pressure and (d) surface finish

References

1 ACI Committee 237 (2007). ACI 237R-07 "Self-Consolidating Concrete." American Concrete Institute: Farmington Hills, MI, USA.

2 Bingham, E. C. (1922). *Fluidity and plasticity* (Vol. 2). McGraw-Hill Book Company, Incorporated.

3 Ferraris, C. F., & de Larrard, F. (1998). *Testing and modelling of fresh concrete rheology*. Gaithersburg, MD, USA: National Institute of Standards and Technology. (http://ciks.cbt.nist.gov/~garbocz/rheologyNISTIR/)

4 Wallevik, J. E. (2006). Relationship between the Bingham parameters and slump. *Cement and Concrete Research*, *36*(7), 1214-1221.

5 Roussel, N., & Coussot, P. (2005). "Fifty-cent rheometer" for yield stress measurements: from slump to spreading flow. *Journal of Rheology (1978-present)*, *49*(3), 705-718.

6 Mahaut, F., Chateau, X., Coussot, P., & Ovarlez, G. (2008). Yield stress and elastic modulus of suspensions of noncolloidal particles in yield stress fluids. *Journal of Rheology (1978-present)*, *52*(1), 287-313.

7 Billberg, P., & Österberg, T. (2001). Thixotropy of self-compacting concrete. In *Proceedings of the Second International Symposium on Self-Compacting Concrete* (pp. 99-108).

8 ACI CT-13 (2013). ACI Concrete Terminology. American Concrete Institute, Farmington Hills, MI, USA.

9 Barnes, H. A. (1997). Thixotropy—a review. *Journal of Non-Newtonian fluid mechanics*, *70*(1), 1-33.

10 Barnes, H. A., Hutton, J. F., & Walters, K. (1989). *An introduction to rheology* (Vol. 3). Elsevier.

11 Ferron, R. D., Shah, S., Fuente, E., & Negro, C. (2013). Aggregation and breakage kinetics of fresh cement paste. *Cement and Concrete Research*, *50*, 1-10.

12 Billberg, P. (2006). *Formwork pressure generated by self-compacting concrete – Influence of thixotropy and structural behavior at rest* (Doctoral dissertation). Retrieved from TRB. (Accession No. 01083377).

13 ASTM D7175 (2015). Standard Test Method for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer. ASTM International, West Conshohocken, PA, USA.

14 AASHTO T 315 (2012). Standard Method of Test for Determining the Rheological Properties of Asphalt Binder Using a Dynamic Shear Rheometer (DSR). http://www.techstreet.com/products/1841452

15 Dontula, P., Macosko, C. W., & Scriven, L. E. (2005). Origins of concentric cylinders viscometry. *Journal of Rheology (1978-present)*, *49*(4), 807-818.

16 Barnes, H. A., & Nguyen, Q. D. (2001). Rotating vane rheometry—a review. *Journal of Non-Newtonian Fluid Mechanics*, *98*(1), 1-14.

17 Ferraris, C. F.; Martys, N.; George, W. L.; Garboczi, E. J.; Olivas, A. (2016). Calibration of rheometers for cementitious materials. In *6th North American conference eon the design and use of self-consolidating concrete*. Washington, D.C.

18 Ferraris, C. F., Obla, K. H., & Hill, R. (2001). The influence of mineral admixtures on the rheology of cement paste and concrete. *Cement and Concrete Research*, *31*(2), 245-255.

19 Ferraris, C. F., & de Larrard, F. (1998). *Testing and modelling of fresh concrete rheology*. NISTIR 6094, Gaithersburg, MD, USA: National Institute of Standards and Technology.

20 Dzuy, N. Q., & Boger, D. V. (1985). Direct yield stress measurement with the vane method. *Journal of Rheology (1978-present)*, *29*(3), 335-347.

21 Hackley, V. A., & Ferraris, C. F. (2001). *The use of nomenclature in dispersion science and technology* (Vol. 960, No. 3). National Institute of Standards and Technology. (http://fire.nist.gov/bfrlpubs/build01/art108.html)

22 Feys, D., & Khayat, K. H. (2013). Comparing rheological properties of SCC obtained with the ConTec and ICAR rheometers. In *5th North American conference on the design and use of self-consolidating concrete. Chicago*.

23 Ferraris, C. F., & Brower, L. E. (2001). *Comparison of Concrete Rheometers: International Test at LCPC (Nantes, France) in October, 2000*. NISTIR 6819, Gaithersburg, MD, USA: National Institute of Standards and Technology. (http://fire.nist.gov/bfrlpubs/build01/PDF/b01074.pdf)

24 Ferraris, C.F., & Brower, L.E. editors (2004). *Comparison of concrete rheometers: International tests at MB (Cleveland OH, USA) in May 2003*. NISTIR 7154, Gaithersburg, MD, USA: National Institute of Standards and Technology. (http://ciks.cbt.nist.gov/~ferraris/PDF/DraftRheo2003V11.4.pdf)

25 Ferraris, C. F., & Martys, N. S. (2003). Relating fresh concrete viscosity measurements from different rheometers. *Journal of Research-National Institute of Standards and Technology*, *108*(3), 229-234.

26 Ferraris, C. F., Martys, N. S., & George, W. L. (2014). Development of standard reference materials for rheological measurements of cement-based materials. *Cement and Concrete Composites*, *54*, 29-33.

27 Olivas, A., Ferraris, C. F., Guthrie, W., & Toman, B. (2015). Re-Certification of SRM 2492: Bingham Paste Mixture for Rheological Measurements. *NIST Special Publication*, *260*, 182.

28 RILEM technical committee MRP (2015). Measuring Rheological Properties of Cement-based Materials. (http://www.rilem.org/gene/main.php?base=8750&gp_id=333)

29 ASTM C1749 (2012). Standard Guide for Measurement of the Rheological Properties of Hydraulic Cementious Paste Using a Rotational Rheometer. ASTM International, West Conshohocken, PA, USA.

30 Lapasin, R., Papo, A., & Rajgelj, S. (1983). Flow behavior of fresh cement pastes. A comparison of different rheological instruments and techniques. *Cement and Concrete Research*, *13*(3), 349-356.

31 Shaughnessy, R., & Clark, P. E. (1988). The rheological behavior of fresh cement pastes. *Cement and Concrete Research*, 18(3), 327-341.

32 *Ferron, R., Gregori, A., Sun, Z. and S. Shah.* "Rheological method to evaluate structural buildup in self-consolidating concrete cement pastes," *ACI Materials Journal, v104(3),* May/June 2007, pp. 242–250

33 Saak, A. W., Jennings, H. M., & Shah, S. P. (2001). New methodology for designing self-compacting concrete. *ACI Materials Journal*, *98*(6), 429-439.

34 Bentz, D. P., Ferraris, C. F., Galler, M. A., Hansen, A. S., & Guynn, J. M. (2012). Influence of particle size distributions on yield stress and viscosity of cement–fly ash pastes. *Cement and Concrete Research*, *42*(2), 404-409.

35 Lee, S. H., Kim, H. J., Sakai, E., & Daimon, M. (2003). Effect of particle size distribution of fly ash–cement system on the fluidity of cement pastes. *Cement and Concrete Research*, *33*(5), 763-768.

36 Wallevik, O. H., & Wallevik, J. E. (2011). Rheology as a tool in concrete science: The use of rheographs and workability boxes. *Cement and Concrete Research*, *41*(12), 1279-1288.

37 Roussel, N. (2006). A theoretical frame to study stability of fresh concrete. *Materials and structures*, *39*(1), 81-91.

38 Esmaeilkhanian, B., Khayat, K. H., Yahia, A., & Feys, D. (2014). Effects of mix design parameters and rheological properties on dynamic stability of self-consolidating concrete. *Cement and Concrete Composites*, *54*, 21-28.

39 Khayat, K. H., Assaad, J., & Daczko, J. (2004). Comparison of field-oriented test methods to assess dynamic stability of self-consolidating concrete. *ACI Materials Journal*, *101*(2), 168-176.

40 Assaad, J., Khayat, K. H., & Daczko, J. (2004). Evaluation of static stability of self-consolidating concrete. *ACI Materials Journal*, *101*(3), 207-215.

41 El-Chabib, H., & Nehdi, M. (2006). Effect of mixture design parameters on segregation of self-consolidating concrete. *ACI materials journal*, *103*(5), 374-383.

42 Chia, K. S., & Zhang, M. H. (2004). Effect of chemical admixtures on rheological parameters and stability of fresh lightweight aggregate concrete. *Magazine of Concrete Research*, *56*(8), 465-473.

43 Tregger, N., Gregori, A., Ferrara, L., & Shah, S. (2012). Correlating dynamic segregation of self-consolidating concrete to the slump-flow test. *Construction and Building Materials*, *28*(1), 499-505.

44 Shen, L., Struble, L., & Lange, D. (2009). Modeling dynamic segregation of self-consolidating concrete. *ACI materials journal*, *106*(4), 375-380.

45 Wang, X., Wang, K., Taylor, P., & Morcous, G. (2014). Assessing particle packing based self-consolidating concrete mix design method. *Construction and Building Materials*, *70*, 439-452.

46 Kaplan, D., de Larrard, F., & Sedran, T. (2005). Design of concrete pumping circuit. *ACI materials journal*, *102*(2), 110-117.

47 Choi, M., Roussel, N., Kim, Y., & Kim, J. (2013). Lubrication layer properties during concrete pumping. *Cement and Concrete Research*, *45*, 69-78.

48 Choi, M., Ferraris, C. F., Martys, N. S., Lootens, D., Bui, V. K., & Hamilton, H. T. (2015). Metrology Needs for Predicting Concrete Pumpability. *Advances in Materials Science and Engineering*, *2015*. (http://www.hindawi.com/journals/amse/2015/456238/)

49 Feys, D., Khayat, K. H., Perez-Schell, A., & Khatib, R. (2015). Prediction of pumping pressure by means of new tribometer for highly-workable concrete. *Cement and Concrete Composites*, *57*, 102-115.

50 Feys, D., Khayat, K. H., Perez-Schell, A., & Khatib, R. (2014). Development of a tribometer to characterize lubrication layer properties of self-consolidating concrete. *Cement and Concrete Composites*, *54*, 40-52.

51 Chapdelaine, F. (2007). *Fundamental and Practical Study on Pumping of Concrete* (Doctoral dissertation). Retrieved from Laval, Université Laval.

52 Feys, D. (2016). How do concrete rheology, tribology, flow rate and pipe radius influence pumping pressure? *Cement and Concrete Composites*. 66(2), 38-46.

53 ACI Committee 347 (2001). Guide to Formwork for Concrete. American Concrete Institute, Farmington Hills, Michigan, USA.

54 Assaad, J., Khayat, K. H., & Mesbah, H. (2003). Variation of formwork pressure with thixotropy of self-consolidating concrete. *ACI Materials Journal*, 100(1), 29-37.

55 Khayat, K. H., & Omran, A. F. (2009). State-of-the-art review of form pressure exerted by self-consolidating concrete. *Final Report Ready-Mix Concrete (RMC) Research and Education Foundation, American Concrete Institute (ACI), and Strategic Development Council (SDC)*.

56 Dieryck, V., Desmyter, J., Michel, F., & Courard, L. (2005). Surface quality of Self-Compacting Concrete and Raw Materials Properties. *Self-Consolidating Concrete*, 287-295.

57 Kwasny, J., Sonebi, M., Plasse, J., & Amziane, S. (2015). Influence of rheology on the quality of surface finish of cement-based mortars. *Construction and Building Materials*, *89*, 102-109.

58 Abd El Megid, W. (2012). *Effect of Rheology on Surface Quality and Performance of SCC* (Doctoral dissertation, Supervisor Khayat, K.H.). Retrieved from Université de Sherbrooke.