UNDERSTANDING THE PUMPABILITY OF CONCRETE

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ABSTRACT

With the increasing need for underground opening's support and the increasing knowledge available today in concrete technology, shotcreting, and particularly the wet-mix process, is in great demand. Successful pumping operations however usually require a certain amount of experience. On the one hand, engineers design a mixture with high workability for ease of transport through the hose system, and on the other hand, they strive for a mixture that is relatively stiff, adhesive, and cohesive to achieve good adhesion and build-up on vertical or overhead shooting surfaces. This article presents some of the most recent research on the understanding of the key parameters affecting concrete mobility and stability under pressure, i.e. pumpability. Taking into account the mechanics of full size pumping equipment, the concept of *Real Paste Content* is introduced as a minimal quantity of effective paste under pressure available for mobility through a hose system. Experimental results used to validate the concept allow explanation of behavioral variations between the different concrete mixtures.

INTRODUCTION

Several important innovations were introduced in the shotcrete industry over the last decades, mainly through equipment and chemical admixture improvements. These innovations combined with the quality of the concrete produced, the inherent flexibility of the methods and the new applications now possible are at the origin of the on-going success of shotcrete. However, all these activities generated growing demands and expectations that often represent critical technical challenges to the engineers. The research work presented here is aimed at better understanding the fundamentals behind the wet-mix shotcrete process and help the engineers with some of the associated challenges.

Background Information

For many years, dry-mix shotcrete process has been the preferred choice in the mining and civil repair industries. However, the fact that the nozzle operator controls the amount of water added to the mixture is often seen as a drawback for dry-mix shotcrete because it controls to a significant extent the quality of the final in-place product (mechanical properties, durability and reinforcing bars encasement). The advantages of the wet-mix process over the dry-mix process are, from an engineering point of view, significant: not only does wet-mix shotcrete produce much less rebound, but the composition of the mixture is also better controlled since all the water is added before the material is pumped. Due to these two important advantages, the in-place composition and the hardened properties of wet-mix shotcrete are generally more consistent and predictable, which explains a shift in the industry toward this shooting process.

The use of high strength wet-mix shotcrete in the underground world is more and more popular. Not only does it allow higher production rates, it is also particularly well suited for thick applications of fiber reinforced shotcrete shells. The placement of wet-mix shotcrete is however sometimes complicated due to the compromise required between the pumpability and the shootability imperatives. At the pump, a relatively fluid concrete that will be easy to pump is required; at the nozzle, a stiff material is wanted so it does not sag or slough off the wall. In this situation, a question that often arises on the job site is whether or not the concrete delivered will be pumpable. The economical impact, as well as the dispiriting effect on the crew, of a major pump/line blockage can be very significant. It is the role of the engineer to design better concrete mixtures that will be easier to pump or pump over longer distances. The difficulty however, lies in defining what is a pumpable mixture or what are the mechanisms behind the transport of concrete under pressure in a tube.

This paper presents some of the most fundamental research conducted on the pumping of concrete as well as on the characterization of the fresh concrete in its fluid state. Different aspects related to the characterization of fresh concrete and the effect of mixture design on pumpability are presented in the paper. The concept of *Real Paste Content* is brought forward as a tool to help engineers clearly understand the mechanisms taking place during the transport of concrete under pressure.

CONCRETE PUMPING

The pumpability of concrete is not an easy concept to define and requires the introduction of notions such as stability and mobility under pressure to do so. In general, concrete pumpability is defined as the capacity of a concrete under pressure to be mobilized while maintaining its initial properties (Gray ([1]), Beaupré, ([2])). The research efforts reported over the last decade on the pumpability of concrete usually focus on either the *stability* of concrete under pressure, or on its *mobility* under pressure.

Stability Under Pressure

One of the main concerns about fresh concrete under pressure is the possibility of segregation, i.e. the separation of the paste from the aggregate phase, which usually

leads to hose blockage. In the hose, this phenomenon occurs when the pressure applied to the concrete pushes the paste through the aggregate skeleton (Browne & Bamforth, (3)). This segregation, or forced bleeding, is often associated with mixtures having deficient particle size distribution or with excessive water/cement ratio. Some studies propose testing procedures to verify the stability of the fresh concrete under pressure. In Browne & Bamforth (3), the amount of water forced out of a fresh concrete sample plotted against the slump of the mixture allows these authors to establish a zone of pumpability. Kaplan (4) and later Chouinard (5) use a similar test, with a reduced pressure, to measure bleeding rates: higher bleeding rates identify mixtures that will create blockage upon pump start-up.

A second problem associated with pumping, albeit not usually critical in mining but often critical in civil applications, is the modification of the air void system. Indeed, the use of pumps to transport concrete generally results in a loss of air ranging anywhere from one to three percent (Hover, (6), Boulet, (7), Chouinard, (5), Du and Folliard, (8)). It has also been shown that the resulting air-void system possesses no or very few bubbles with diameters below 50 µm (Pigeon et al., (9)). Several authors have observed this air loss and have proposed mechanisms that could account for this diminished air content (Hover, (6), Boulet, (7), Chouinard, (5), Chapdelaine, (10)). These mechanisms are *suction* and *dissolution* during the pumping or placing process.

The *suction* mechanism occurs when the concrete is subjected to negative pressures. In a piston-actuated pump, the piston-chamber fills up with concrete not only by gravity alone but also by a suction effect caused by the retracting piston. This movement causes a decrease in pressure, which can cause the air to expand to larger bubbles and (later) escape from the concrete. This phenomenon can also be observed in a vertical section of hose where the concrete is in free fall. According to Chapdelaine (10), the volume of air can double if the surrounding pressure decreases by half.

The *dissolution* mechanism is explained by Dyer (11). His hypothesis (Figure 1) is that while the concrete is pressurized, the smaller air bubbles dissolve in the surrounding water. When the concrete depressurizes upon exiting the hose, thermodynamic rules show the air returns, but within the larger bubbles that did not previously completely dissolve instead of forming new small air bubbles.
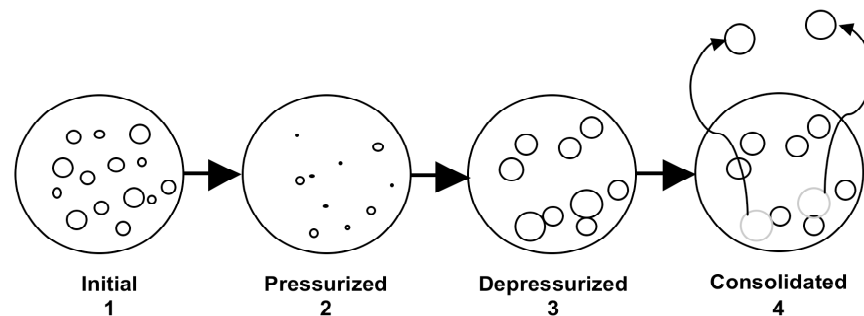

Figure 1: Air loss during and after pumping, according to Dyer (11)

Boulet (7) has shown that in addition to Dyer's (11) dissolution mechanism, the pressurization time and maximum pressure reached are also important parameters in the air loss effect. It is important to emphasize that this mechanism does not alter the air content significantly. The final air volume remains practically the same but alters the spacing factor. However, the stability of the larger air bubbles formed is such that these bubbles will escape more easily upon handling and consolidation of the concrete, hence the reported air losses.

Mobility and Friction

One of the early studies on the pumping of concrete is the paper published by Ede (12). The interesting observations of his study are that hydraulic conditions are present during concrete pumping and that the amount of friction is not related to the pressure applied, which in turns means that the energy loss in a straight length of pipe is linear.

Many researchers have worked at identifying a relationship between the velocity of concrete and the friction of the concrete against the pipe walls (Ede, (12); Browne & Bamforth, (3); Tattersall & Banfill, (13); Kaplan,(4)). The variability of the results could be explained by the lack of some approaches to introduce a "dynamic" term in their models, which would take into account the behavior of concrete while it is in movement. A solution is to integrate in these modeling approaches a characterization of the *rheological* and *tribological* properties of the fresh concrete since *rheology is the science that studies the flow of matter* and *tribology is the science that studies the interaction of surfaces in relative motion*. We usually talk about rheology and tribology of concrete in its fresh state.

Rheology of fresh concrete has received a lot of attention from researchers over the last two decades (Tattersall & Banfill, (13); Tattersall, (14); Bartos, (15); Beaupré, (2); Ferraris & de Larrard, (16)). It is widely accepted today that fresh concrete obeys a rheological model known as the Bingham model. In this model, two properties are required to describe completely fresh concrete behavior: the yield value (τ_0) and the plastic viscosity (μ) (see Figure 2). The physical interpretation of this model is that to put a Bingham fluid into motion, a minimum effort must first be supplied to initiate flow or to overcome the yield value (τ_0). Once motion or flow is initiated, the required force increment to deform concrete is proportional to the shear rate increment applied and is attributed to the plastic viscosity term.
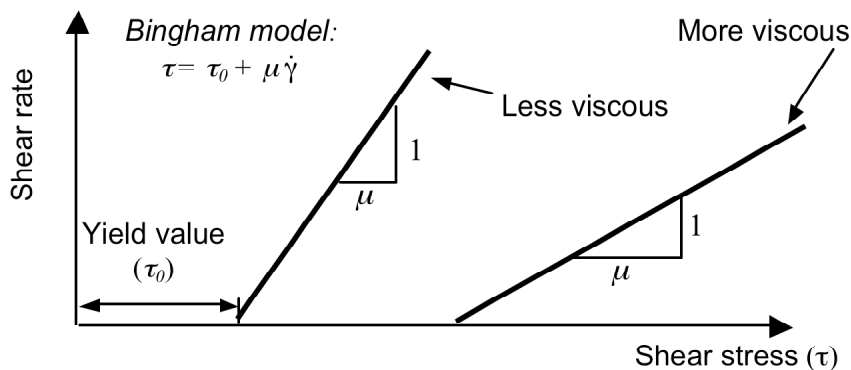

Figure 2: Graphical representation of the Bingham model.

The use of a two parameter flow model for fresh concrete has important practical implications. Indeed, instead of using a single parameter test, which relates to the yield value, such as the slump value to characterize the fresh concrete, the Bingham flow model allows to capture the viscous behavior of the fresh concrete. This is of prime importance to understand, and discriminate, the flow behavior of modern concretes such as self-leveling concrete and other highly plasticized concrete mixtures such as low water/cement ratio high performance wet-mix shotcretes. There are a number of laboratory rheometers available on the market with various configurations; in all cases, they yield results similar to those found in Figure 2.

Tribology of fresh concrete has, on the other hand, received very little attention from the concrete research community probably because it bears interest, for the moment, only to fresh concretes being pumped. What one wants to measure in a tribology test is the friction of fresh concrete against a given surface type (Morinaga, (17); Kaplan, (4)). It is only recently (Kaplan, (4); Chapdelaine, (10)) that a tribometer was used in conjunction with a rheometer to completely characterize fresh concrete mixtures intended for pumping. Figure 3 presents a schematic of the tribometer used by Chapdelaine (10) and an example of an on-going test. The relationship found with a tribometer is similar to the one found with the rheometer:

$$\tau_{surface} = \tau_{0i} + \eta_i \, \omega$$

where $\tau_{surface}$ is the surface friction, τ_{0i} is the yield strength of the *interface*, η_i is the viscosity of the interface and ω is the angular velocity of the rotating surface.
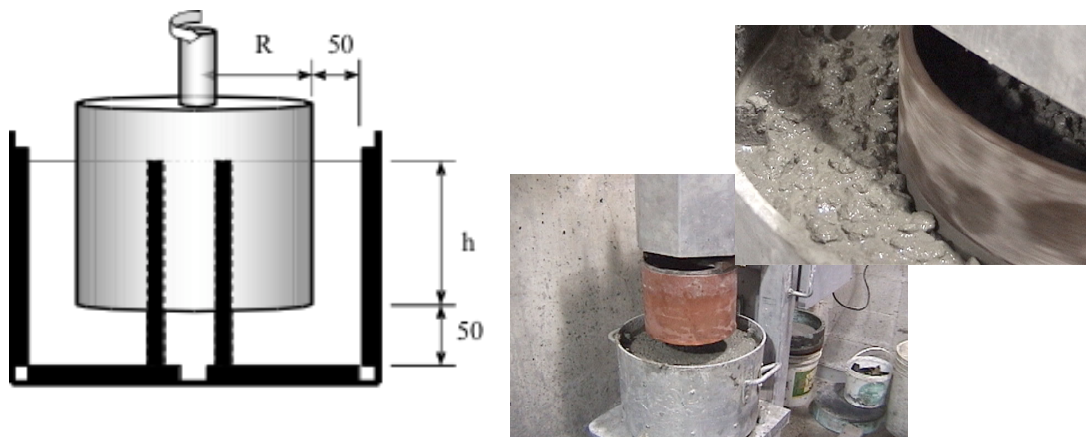

Figure 3: Schematic of the tribometer and on-going test (from Chapdelaine, (10)).

Pulling together the rheological and tribological properties of his fresh concretes, Kaplan (4) was able to propose a bi-linear model relating the required pumping pressure with the actual flow of concrete. The first portion of his model (lower concrete velocities) is entirely described by the interface properties (tribology) while the second portion of his model requires both the interface properties and the flow properties of the concrete to predict pumping pressure (see Figure 4). By proposing

such a model, Kaplan is suggesting that at low velocities, the concrete moves as a block in the pipe, with only a small thickness of paste lubricating the walls (often identified as friction flow or «plug flow»). As the velocity increases, the pressure imposed on the central portion of the block is sufficient to initiate flow in that portion (the applied shear stress is greater than the yield value, τ_0) therefore generating a viscous flow in the concrete. Details on the equations and other parameters behind the model can be found in Kaplan (4) and Jolin et al. (18).
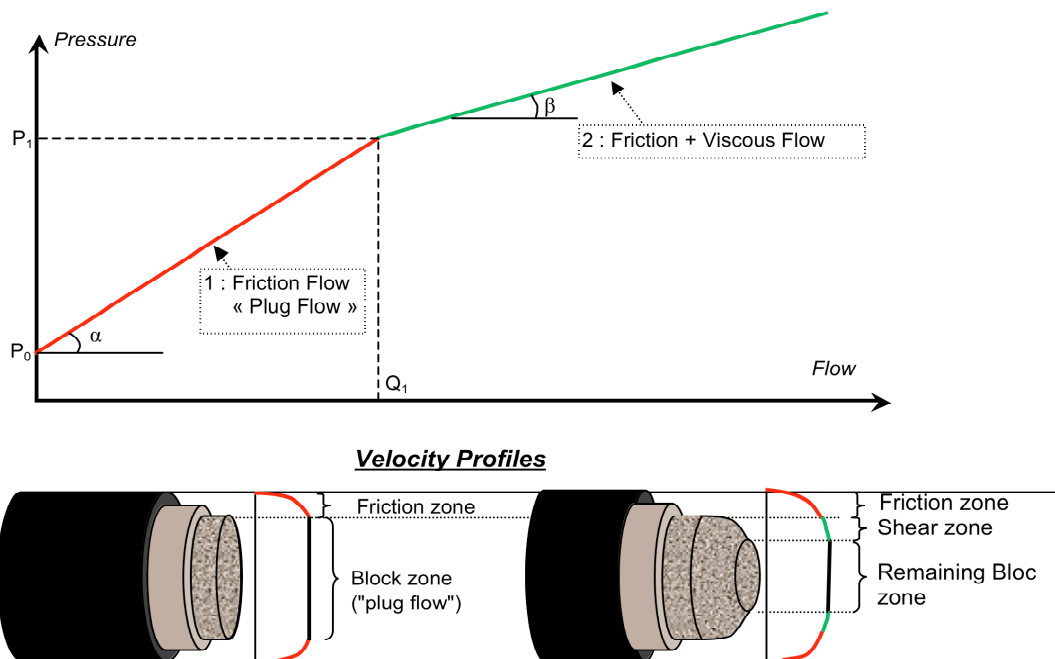

Figure 4: Kaplan's model (4) along with a representation of the flow in the pipe for both portion of the model.

RESEARCH PROJECT

The M.Sc. research project undertaken in 2006 by a young and highly motivated engineer (Dennis BURNS) was aimed at improving our understanding and control of wet-mix shotcrete used in small line pumping (hose diameter of 38.1 mm – 1½ in) for civil engineering work where the use of set accelerators is limited due to long term durability concerns. Among others, a specific objective was to extend the work done by Kaplan (4) and Chapdelaine (10) to small line pumping and derive mixture design rules that would allow optimal pumpability. As the reader will see, the difficulties and challenges encountered with small-line pumping are surprisingly close to those found when pumping over long distances or over long periods of time.

Experimental Program

The experimental program covered several mixture design parameters such as particle size distribution, binder content and air content. In all cases, the mixtures were pre-blended and pre-bagged by King Packaged Materials (Blainville, Qc, Canada). These pre- blended mixtures were the basis of several different mixtures.

The pre-blended materials follow two distinct particle size distributions. The first type is based on the Dinger-Funk (19) optimal particle size distribution curve. The second mixture is based on the ACI gradation curve # 2 (ACI506R-05, (20)). The bags contained all the dry materials, while the liquid components such as the water, the superplasticizers and the air-entraining admixture were added during the mixing. Table 1 lists the different basic mixtures used for the entire project as well as the proportions of the mixture designs.

Table 1: Basic mixture compositions used in the project.

Mixture*	OPC	Silica Fume	Sand (< 5mm)	Stone (2.5-10)	SP	AEA
	kg/m^3	kg/m^3	kg/m^3	kg/m^3	ml/m^3	ml/m^3
DF-10SF-13	361	31	829	761	3634	1321
DF-10SF-7	374	32	834	766	3658	665
DF-10SF-3	403	35	926	850	3690	-
DF-10-13	371	-	821	755	3628	1319
ACI-10SF-13	368	32	1024	544	3606	1311

* All water/binder ratios are of 0.41 – Slump for all mixtures is 7.5 to 10 cm

Mixture identification is self explanatory: the first set of letters stands for the particle size distribution used (see paragraph above), the second set indicates the type of binder used (10SF for ordinary Portland cement with 8% silica fume, or 10 for ordinary Portland cement alone) and finally, the last digits represent the *target* air content of the fresh concrete before pumping. As it can be seen, high air content are sought in some cases in order to make use of the *High Initial Air Content Concept* proposed by Beaupré to facilitate pumping and placement (Beaupré, (2); Jolin & Beaupré, (21)). This concept, used in many areas in North-America, consist in entraining a large number of small bubbles in the fresh concrete, which increases workability and facilitates pumping, which will be expelled upon impact on the receiving surface, providing a instantaneous "slump killing effect", allowing to achieve large build-up thicknesses without the use of set accelerators.

Finally, each of the mixtures presented in Table 1 were batched, pumped and shot. A number of parameters were controlled and tests on the fresh and hardened concrete performed. The following section reports some of the key results and observations of this phase.

Results and Observations

All five mixtures presented in Table 1 had already been used in the laboratory for other R&D activities and were known to pump and shoot very well using our *Allentown Equipment PowerCreter 10* with a 50 mm (2 in) internal diameter hose. The challenge in this particular project was to verify the feasibility with a 38.1 mm (1½ in) internal diameter hose. Unfortunately, as can be seen from Table 2 below, none of the *initial* mixtures of Table 1 made it through the hose. With that being said, the initial mixtures were then modified to simply increase the *paste content* of the

mixtures (hence the suffix *–mod* following mixture identification). Considering that the aggregates relative proportion remained constant and that the water/binder ratio were also maintained constant, it is difficult, looking at Table 2, to understand the key parameters that made a mixture pumpable or not.

Table 2: Experimental results of pumpability test.

Mixture[*]	Binder content	Air content (before pumping)	Volume of paste	Pumpability
	kg/m^3	%	%	
DF-10SF-13	392	13	41.9	NO
DF-10SF-13-*mod1*	405	13	42.8	*Blocked*
DF-10SF13-*mod*	415	13	43.5	Pumpable
DF-10SF-7	406	7	41.5	NO
DF-10SF-7-*mod*	445	7	39.6	Pumpable
DF-10SF-3	438	3	35.1	NO
DF-10SF-3-*mod*	465	3	37.0	Pumpable
DF-10-13	403	13	42.4	NO
DF-10SF-13-*mod*	420	13	43.6	Pumpable
ACI-10SF-13	400	13	42.2	NO
ACI-10SF-13-*mod*	415	13	43.5	Pumpable

[*] All water/binder ratios are of 0.41 – Slump for all mixtures 7.5 to 10 cm

Indeed, often times to explain pumpability, the cement contents are assessed. From Table 2, it strikes as odd that certain mixtures pumped at lower binder content than others. For example mixture *DF-10SF-3* did not pump with 438 kg/m^3 of *binder* materials, but *DF-10SF-13-mod* pumped with only 415 kg/m^3 of binder materials. The answer most probably does not only lie in the binder content to assess pumpability.

The next lead was to consider paste, which is a factor often cited when pumpability problems are encountered (McAskill, ([22]); Chapdelaine & Beaupré, ([23]), Powers, ([24])). The *paste content* is expressed as the cumulative percentage of the volume of air, water and cement. Again from Table 2, it can be seen that mixtures with lower paste contents pumped, whereas others with higher paste contents did not. For example, *DF-10SF-3-mod* pumped with 37.0 % of paste whereas *ACI-10SF-13* did not pump with 42.4 % of paste. Again paste may not be the only parameter to fully assess the pumpability of a mixture.

A careful examination of the results reported in Table 2 as well as a comprehensive analysis of the laboratory observation and available literature led the authors to derive what is herein called the *Real Paste Concept*.

The *Real Paste Concept* is defined as the *amount of paste (%) present in the concrete while under pressure in the hose,* which represents the amount of paste required to create the lubricating layer against the pipe wall and to fill the inter-granular voids. Therefore, it is a *volumetric interpretation* of the paste content as the material is under pressure. It is interesting to note that the actual paste volume changes as pressure is applied to the concrete since the air volume diminishes to negligible values. Therefore, as pressure increases, the paste content becomes equivalent to the volume of binder material and water.

To clearly understand the effect of pressure on mixture design, a mixture used in this project is analyzed in Table 3 for two situations: under atmospheric pressure and under high pressure. The important result in this Table is in the lower-right cell: the *Real Paste Content* for this mix is 35.1%.

Table 3: Proportions at atmospheric pressure and under high pressure.

| *DF-10SF-7-mod* | COMPOSITION | | |
| | Atmospheric pressure | | Under high pressure* |
	kg/m³	% by volume	% by volume
Binder content	445	14.5	**15.6**
Water	178	17.8	**19.1**
Sand 0-5 mm	861	32.1	**34.5**
Gravel 2.5-10 mm	791	28.3	**30.4**
Air content	-	7.0	**0**
Admixtures	7.2	0.3	**0.4**
PASTE CONTENT** (%)	_	39.6	*35.1*

* The pressure is such that all the air volume is dissolved in the water; hence the air content is equal to zero.

** The PASTE CONTENT is the sum of binder, water, and admixtures.

The approach is relatively simple. The initial mix design (in kg/m³) is transformed into percentage of the total volume, in this case 1 m³ or 1000 liters (both columns under *atmospheric pressure*). Now to find the numbers in the last column, one must realize that under pressure (or in the hose), all of the air bubbles are dissolved in the water: in this case 7% of air volume basically disappears under pressure. This *volume reduction* of the initial 1000 liters of concrete means that we are left, under pressure, with 930 liters of concrete, made of *exactly the same quantity of solid constituents*. Therefore, when put under pressure, even if the initial volume of paste is reduced by the amount of air (39.6 % minus the air content), the total volume occupied by the constituents is reduced, which brings the effective paste content under pressure or the *Real Paste Content,* to 35.1%. Using Tables 1 and 2, it is possible, with the air content before pumping, to assess the *Real Paste Content* of each mixture and

check it against the pumpability obtained. Table 4 was constructed using this approach.

Table 4: *Real Paste Content* and pumpability results.

| Mixture	Volume of paste (atmospheric pressure) %	*Real Paste Content**	Pumpability
DF-10SF-13	41.9	33.2	NO
DF-10SF-13-*mod1*	42.8	34.2	*Blocked*
DF-10SF13-*mod*	43.5	35.1	Pumpable
DF-10SF-7	41.5	31.8	NO
DF-10SF-7-*mod*	39.6	35.1	Pumpable
DF-10SF-3	35.1	33.1	NO
DF-10SF-3-*mod*	37.0	35.1	Pumpable
DF-10-13	42.4	33.8	NO
DF-10SF-13-*mod*	43.6	35.2	Pumpable
ACI-10SF-13	42.2	33.8	NO
ACI-10SF-13-*mod*	43.5	35.1	Pumpable

* Amount of paste in the concrete under pressure

As it can be seen from Table 4, it appears that a value of *Real Paste Content* of 35.1% is somewhat a minimum value below which a mixture is not pumpable (with the particular aggregates used and a 38.1 mm - 1½ in internal diameter hose). Indeed, when the first mixture is analyzed, it is shown that it did not go through the pump with 33.2% of *Real Paste Content* (which, incidentally, pumped perfectly through a 50 mm – 2 in hose). In the laboratory, it was then decided to increase the paste content by re-batching the mix with an increased binder and water content (the w/b was maintained as well as the aggregates relative proportions). This modified mixture, *DF-10SF-13-mod1*, would cause blockage, i.e. the material pumped for a few strokes but clogged a few moments later. After unclogging the hose, the material pumped again for a few piston strokes and clogged again. This is very interesting because it appears that 34.2 % is right on the threshold of pumping. Slight variations in the homogeneity of the mixture or in the thickness of the lubricating layer for example are enough to have the mixture pump or clog. When brought to a value of 35.1%, the mixture *DF-10SF-13-mod* went through the pump without incident. Based on this initial observation, all other mixtures were brought up to 35.1 % of *Real Paste Content*: all modified mixtures pumped without clogging.

DISCUSSION

The observations reported in the section above are, after all, not very surprising. It has long been understood in the concrete and shotcrete industry that a proper mix design for adequate pumpability required high cement content or, more precisely, high paste content. Comprehensive research work on concrete pumping (Kaplan, (4); Chapdelaine, (10)) and on wet-mix shotcrete (Beaupré, (2)) has also used this approach with success. However, it is, to our knowledge, the first time a quantitative value, here the *Real Paste Content*, is derived to support this minimum paste content approach.

The obvious question now facing us is: can we predict this *minimum Real Paste Content* in order to avoid the labor-intensive task of blocking a pump to find out about it? To answer that question, work from Chapdelaine (10) had to be revisited and extended to the case of 38.1 mm - 1½ in internal hose diameter. Indeed, Chapdelaine observed that the *thickness* of the lubricating layer in a pipe filled with concrete in movement is constant regardless of the pipe diameter and is approximately 1 mm in thickness. This observation involves that the *relative amount* of paste required to lubricate the hose increases with smaller diameter hoses, as can be seen from Figure 5.
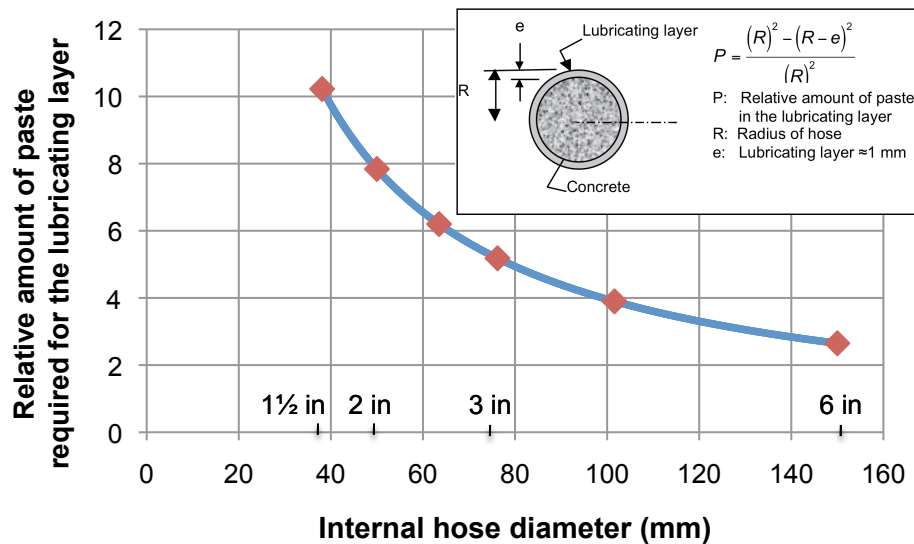
Figure 5: Relative amount of paste required for a 1 mm thick lubricating layer in the hose (adapted from Chapdelaine, (10))

From the figure, it can be seen that a relative amount of 10.2% of paste is required just to form that lubricating layer. Using the representation of the "plug flow" movement in Figure 4, one can assume the rest of paste required is that to fill the voids between the aggregates. Using this approach, measurements of the porosity of the *aggregate phase* were conducted: the *DF* and *ACI* particle size distributions both yielded a porosity value of 24.0% (Burns, (25)). This 24% porosity of the aggregate phase combined with the 10.2% paste requirement to form the 1 mm lubricating layer in the 38.1 mm (1½ in) hose yield a *minimum* theoretical paste content of 34.2%. This is extremely interesting as this is the exact value of *Real Paste Content* at which

the *DF-10SF-13mod1* could pump but only for a few strokes before clogging, indicating that the threshold value for paste content had been reached. There is therefore an original relationship between the theoretical paste requirement and the *Real Paste Content*, making this last concept a unique and novel tool for optimizing mixture designs of concrete intended for pumping.

A note of caution, the approach presented does not guarantee pumpability, good aggregates properly distributed in size and stable rheological properties are only a few of the other requirements for pumpable concrete. Nonetheless, it is the belief of the authors that this *Real Paste Content* concept represents a step forward in our understanding of the pumpability of concrete, and that it can be used to improve the reliability of the efforts put into mixture design and construction quality control.

CONCLUSIONS

Concrete pumping is more and more popular and is in constant evolution around the world. Over the last decade, the increasing use of wet mix shotcretes and the more stringent requirements with regards to shotcrete performance have raised the importance of concrete pumping in the industry. Many aspects of concrete pumping still require the attention of the scientific community. It is the wish of the authors that the research work conducted in the shotcrete laboratory of the Research Center on Concrete Infrastructures (*Centre de recherche sur les infrastructures en béton)* will contribute to improving the tools and knowledge available to the concrete and shotcrete industry.

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