International Journal of Engineering and Technical Research (IJETR)
ISSN: 2321-0869, Volume-1, Issue-8, October 2013

Correlation between the pumping and the rheological properties of self-compacting concrete: a practical study

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***Abstract*— For self-compacting concrete, the arrival of new admixtures, but also of the colloidal agent and of various cementitious additions have remarkably changed rheology compared with standard concrete.**

In order to exploit the potentials of concretes characterized by a superior performance in the fresh state, such as Self-Compacting Concrete (SCC), procedures for predicting its flow behavior are needed in order to properly design casting, in particular pumping.

This paper presents a study based on pumping parameters proposed in the literature to quantify the plastic viscosity and yield stress of fresh concrete. The experimental data reported in this article were used to evaluate the possibility of predicting these parameters in order to choose the most appropriate formulation for any particular site and subsequently to develop pumping pressure prediction equations suitable for any given pumping circuit geometry and any given concrete from our experimental results.

***Index Terms*—plastic viscosity, pumping, rheology, self-compacting concrete, yield stress.**

I. INTRODUCTION

Rheology is the science that studies the deformation and flow of matter. It is generally accepted (Tattersall and Banfill, 1983) [1] that fresh concrete has a binghamian behavior. The behavior law of a binghamian fluid writes: $\tau = \tau_0 + \mu \dot{\gamma}$

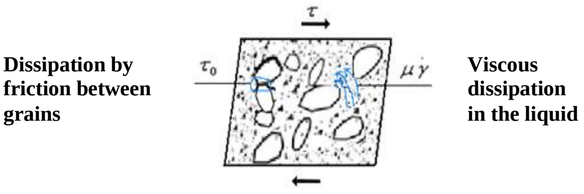

Fig. 1: Physical interpretation of the Bingham model.

From a physical point of view, the two parameters of Bingham, yield stress τ_0 and plastic viscosity μ was interpreted [2] as follows (fig.1): the shear threshold is explained as the macroscopic sum of all solid grain internal frictioning it depends directly on the number and the nature of contacts between the grains and therefore on the compactness of the granular skeleton. Beyond the threshold, the stress applied to the mixture causes the flow which translates into relative motions between solid grains (friction), and the circulation of the liquid phase between the grains, due to inter-grain porosity.

It the latter that would cause the viscous dissipation in the fluid flow and explain the second term $\mu \dot{\gamma}$ in the law of Bingham. The more circulation is difficult, the more the parameter μ is important.

Viscosity characterizes a fluid's resistance to sliding or deformation. It is due to the fact that the layers of a fluid in motion cannot slide freely and independently from one another, giving rise to frictional forces that directly oppose the flow. Viscosity is thus the inverse property of fluidity.

The most adopted approach to quantify the rheological properties of fresh concrete is to experimentally measure the shear stress relatively to the shear rate using a rheometer. Other researchers have attempted to quantify the plastic viscosity of fresh concrete from its composition, in particular the works of Roshavelov [3], Ferrari and deLarrard [4] and Kasami [5].

Initially, we decided not to take into account this correlation between viscosity and rheological parameters, and to concentrate on understanding the influence of a concrete's composition on its pumping and later predict the required pumping pressure depending on the characteristics of the building site-essentially the geometry of the pumping circuit. These results were eventually to be compared with the rheological parameters, for validation.

II. SETTING THE CONTEXT

The flow of fresh concrete in a formwork is a three-dimensional free surface flow generated by the gravity of a threshold fluid within a network of obstacles consisting of steel bars. An implementation flaw may have many causes. It can be caused by the coarsest aggregates blocking the flow along the frames or by behavior of the concrete itself when the gravity- generated stress is not sufficient to keep the concrete flowing and filling the formwork completely. In

Manuscript received October 14, 2013

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order to exploit the potentials of concretes characterized by a superior performance in the fresh state, such as Self-Compacting Concrete (SCC), procedures for predicting its flow behavior are needed in order to properly design casting, in particular pumping.

For several years, pumping has been the most used technique to cast fresh concrete [6, 7]. The concrete is placed in a pump that delivers it to the desired location through flexible or rigid hoses, made of rubber or steel.

But this technique requires a so-called "pumpable" concrete, i.e. a concrete that can more under pressure in a confined space while keeping its initial properties (Beaupré, 1994 [8], Gray, 1962 [9]). To try and avoid blocking problems, new admixtures, colloidal agent and various cementitious products have been thus added that have remarkably changed the rheology of fresh concrete.

More recently, Kaplan, 2000 [10] has shown that it is necessary, in addition to rheological measurement, to use the tribological measure to establish a prediction model of the pumping pressure.

Tribology is the science that studies the phenomena that may occur between two material systems in contact be they immobile or animated by relative movements. In the case of fresh concrete and more specifically in the case of fresh concrete pumping, tribology is the study of the interface between the fresh concrete and the wall of the hose (or one other mobile used to make a tribological test [11]). See figure 2.

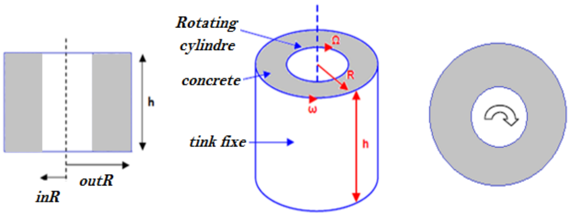


Fig. 2: Schematic of the tribometer test

III. INFLUENCE OF COMPOSITION ON PUMPING

All factors in the composition of concrete affect its pumpability [12]. All the authors having published on the subject deal with this issue, but in different ways. Concrete is a granular mixture having a voids volume of about 7 to 10% at the mixer's output (before vibration). The shape and size of the particles must therefore be taken into consideration since these factors greatly influence the volume of inter-grains voids (Kempster, 1969 [13]).

The friction between the particles, or between the coarse grains and the walls of circuit pumping, increases pressure up to sometimes create a blockage [14, 15]. Neville 1995 [16], shows that a certain volume of cement is necessary to fill the space between the grains otherwise the pumping is difficult or impossible. Also, segregation problems may occur if the amount of fine particles in the mixture is insufficient or if the compactness of the granular skeleton is low (Browne & Bamforth [17]). In these cases, a separation of the coarse aggregates and the cement paste can occur and cause a blockage. On the other hand, the problem of excessive friction may occur in the case of concrete mixtures having a very compact granular skeleton and a high content of binder. In this situation, it appears that the available paste is absorbed by the fine particles to fluidify the mixture, which causes solid friction contacts between the grains and sometimes blocks the concrete's flow. Therefore, the role of cement paste is to fill the gaps left between the grains of sand and gravel. An reduction in volume of the cement paste is possible only by reducing the volume of the voids between the granular particles (Goltermann et al. 1997 [18]).

The amount of water added to the concrete mix greatly influences its rheology (decrease in plastic viscosity and yield stress [1]) but also causes a risk of segregation. It is thus the most important factor to control. Ede, 1957 [19] studied the pumpability of concrete mixtures with different W / C ratios but constant cement content. He observed that the concrete mix should contain just enough water to saturate the voids between the aggregates otherwise the pressure required to pumping increased significantly [20].

Figure 3 shows the three identified areas. When the concrete does not contain enough water and the voids between the aggregates are not filled, there is a flow by solid friction. The concrete behaves as a granular material and consequently, its mobility of concrete is greatly reduced [21, 22]. Indeed, Ede (1957) explains that the flow resistance appears to be function of pumping pressure (figure 4. b). This corresponds to the first area on the figure 3, after which an abrupt change in mobility occurs, referred to as the "transition zone" where the amount of water is sufficient to fill the voids. Finally, when the amount of water exceeds a certain ration, we enter a third zone where the flow is of hydraulic type. In this case, the pumping pressure is transmitted to all constituents by water that fills all voids of the granular skeleton. Moreover, there appears to be formation of a lubrication layer at the periphery of the flow, which promotes the mobility by preventing friction of solid particles against the pipe's wall [23](figure 4. a).

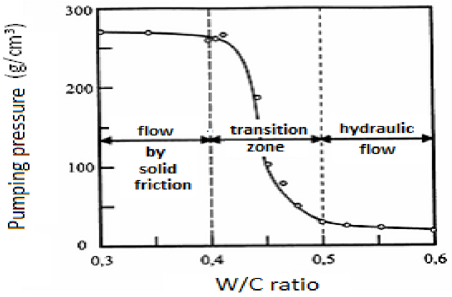
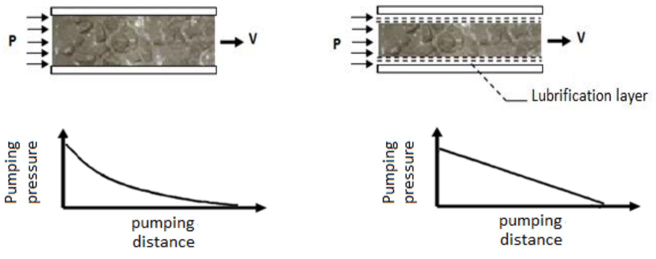


Fig. 3: Effect of W / C ratio on the mobility of concrete when pumping (Ede, 1957)



a) Flow by solid friction   b) Hydraulic flow

Fig.4: Representation of the two types of flow (Loadwick, 1970) [24].

IV. Application: Pumping

Generally, SCC is significantly less constraining to use than vibration-implemented concrete, thanks to its ease of casting over long distances and large heights.

The flow properties of SCC have given rise to the establishment of new procedures to fill the formworks, as the characteristics of SCC allow for important horizontal paths.

On a site with difficult access, it is thus now possible to implement the concrete by pumping- with mobility as an essential condition: the concrete must indeed oppose the least possible resistance to its displacement in the pumping pipes so as to develop the lowest possible pumping pressure.

P (in Pa) is the pressure applied at the level of the pump. The concrete then flows in bulk by sliding. Its flow is slowed by friction constraints $\tau_f(x)$ exerted at the interface between the concrete and the pipe, as shown in figure 5.

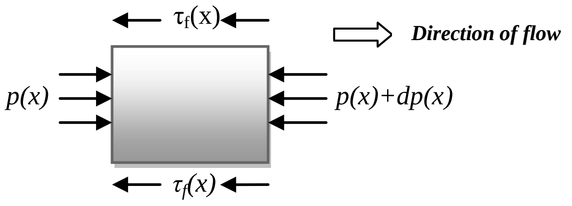


Fig. 5: Equilibrium of a concrete element in the pipe

By writing the equilibrium of a section unit of concrete, the derivative of the pressure dp(x)/dx (in Pa / m) as a function of τ_f (x) and R is written (2):

$$\text{p(x).R} = [\text{p(x)} + \text{dp(x)}].\text{R} + 2.\tau_f\ \text{(x).dx} \qquad (1)$$

$$\text{dp(x)/dx} = -2\,\tau_f\,\text{(x)/R} \qquad (2)$$

For a given flow, dp(x)/dx is constant, therefore the frictional stress τf does not depend on the pressure. On the other hand dp(x)/dx evolves when the flow rate of concrete increases, therefore τ_f depends on the sliding velocity

☞ τ_f (x) = τ_f, constant for a given flow rate.

Moreover, the boundary conditions are written (see figure 6) : p(L)=0 et p(0)=P

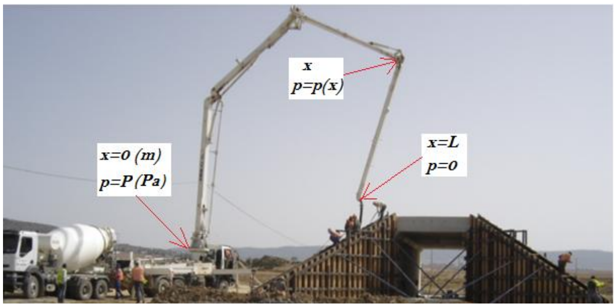


Fig. 6. Pumping circuit

Pumping pressure becomes: $\text{P} = 2\text{L}\,\tau_f/\text{R}$ (3)

There is a way to evaluate in the laboratory the friction of concrete with a pipe using a tribometer with coaxial cylinders. The behavior of the concrete-steel interface is described by the following model: $\tau = \tau_{0i} + \eta V_g$, where τ is the stress of the interface (in Pa), τ_{0i} the threshold of the interface (in Pa), η the interface viscous constant (in Pa.s/m) and V_g the relative velocity of sliding (in m/s).

Assuming that the concrete remains motionless in the tank during the test, the pressure at the pump P (in Pa) for a given flow, depending on the stress of friction τ_f and the geometry of the circuit is (4):

$$\text{P} = 2\text{L/R}\ (\tau_{0\text{i}} + \eta\text{Vg}\ ) = 2\text{L/R}\ (\tau_{0\text{i}} + \eta\text{Q}/\pi\text{R}^2) \qquad (4)$$

where Q is the pumping flow rate (in m^3/s)

$$\text{Q} = \text{S.Vg} = \pi\text{R}^2.\text{Vg}$$

Knowing that the average concrete has a density ρ, if the pipe is no longer horizontal but its output is at a height H (in m) above the pump, the expression of the pressure becomes (5):

$$\text{P} = 2\text{L/R}\ (\tau_{0\text{i}} + \eta\text{Q}/\pi\text{R}^2) + \rho.\text{g.H} \qquad (5)$$

where g is the gravity (in m/s²) and ρ is the density of concrete.

During pumping, and when the velocity of sliding between the pipe and the concrete becomes important, the frictional stress τ_f becomes large enough that a shear spreads in concrete.

Beyond this velocity, the total flow rate (described by the Buckingam-Reiner equation) is the sum of a flow rate by sliding and a flow rate by shear:

$$Q = \frac{V_g}{\pi R^2} - \frac{\pi R^4}{8\mu}\frac{dp(x)}{dx}\left(1 - \frac{4}{3}\left(-\frac{dx}{dp(x)}\frac{2\tau_0}{R}\right)\right) \qquad (6)$$

where

τ_0 yield stress (in Pa)

μ plastic viscosity (in Pa.s)

dp/dx pressure gradient (Pa/m)

From (3) we have :

$$V_g = \frac{Q - \dfrac{\pi R^3}{4\mu}\tau_{0i} + \dfrac{\pi R^3}{3\mu}\tau_0}{\pi R^2 + \dfrac{\pi R^3}{4\mu}\eta}$$

The pressure at the pump for a given flow becomes (7):

$$P = 2\frac{L}{R}\left(\tau_{0i} + \eta\frac{Q - \frac{\pi R^3}{4\mu}\tau_{0i} + \frac{\pi R^3}{3\mu}\tau_0}{\pi R^2 + \frac{\pi R^3}{4\mu}\eta}\right)$$

V. EXPERIMENTAL STUDY

We created a building site for which the implementation of concrete was done by pumping. The pumping circuit was as following: pipe diameter 130 mm, height of pumping 200 m, horizontal distance 100 m.

Our laboratory has in its catalogue four formulations of self-compacting concrete. Table 1 presents the figures concerning the rheological properties for all mixtures manufactured during this research project.

Table 1: Properties of self-compacting concretes available

Formulations	SCC 1	SCC 2	SCC3	SCC 4
Constituents (Kg/m^3)				
Cement	30.5.5	350	350	283.8
Total water	167.4	177.4	179.7	192.2
Superplasticizer	5.88	6.5	6.38	5.00
Limestone filler	164.5	170	100	116.1
Gravel 5/10	900	830	790	900
Sand 0/2	870	830	990	900
Mechanical and rheological characteristics				
Mass density (Kg/m^3)	2446	2440	2428	2429
Compressive strength (MPa) at 28d	49.8	56.0	53.0	49.5
Air content (%)	1.2	2.8	2.4	1.8
Slump flow (mm)	650	720	725	670
Flow threshold (Pa)	24.8	19.4	12.4	30.5
Plastic viscosity (Pa.s)	290.3	92.6	109.5	115.3
Tribology data				
Threshold of the interface τ_{0i} (Pa)	50	60	70	50
Viscous interface constant η(Pa.s/m)	900	1400	1700	980

This table indicates that the most fluid mixtures (high slump flow) have the lostest shear thresholds. The air content is another parameter that influences the plastic viscosity of concrete. The more a mixture contains a large air volume, the less it is viscous because the volume of available paste to fluidify a mixture is also a function of the air content [6].

For example, the concrete SCC2 that contains 2.8% of air is very viscous compared to other mixtures.

Finally, the concrete selected for our building site was SCC2, because of its lower plastic viscosity that allowed it to rub less and thus require a lower pumping pressure. Regarding the mechanical characteristics, the SCC2 has a compressive strength of about 56 MPa.

After a few days of casting without problem, the concrete suddenly become more difficult to pump. To understand what was happening, the pump operator then made measurements of pressure for two pumping rates. These are given in table 2. The pump used on the building site was a piston pump with a volume of 60 litres.

Figure 7 below shows an example with two pistons working by filling one while emptying the other via a valve shifting opening towards the feeder and shutting towards the pipe.

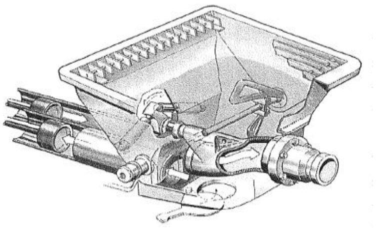


Fig. 7: Piston pump with valve letting concrete in from hopper to one piston and out to tube from the other piston alternating with the strokes of the two pistons (Putzmeister make)

A pump operator can follow the pumping rate by counting the number of piston strokes per minute. He can also read the pressure on a pressure gauge in the hydraulic circuit of the pump. This hydraulic pressure is equal to 1.8 times the pressure on concrete at the outlet of the pump.

Table 2: pumping data

Measure N°	1	2
Pumping rate (Strock /min)	6.0	8
Hydraulic pressure-Pressure gauge(bars)	225	270

From (5) we have:

$$P_1 = 2L/R\ (\tau_{0i} + \eta Q_1/\pi R^2) + \rho.g.H$$

$$P_2 = 2L/R\ (\tau_{0i} + \eta Q_2/\pi R^2) + \rho.g.H$$

Therefore $$\eta = \frac{(P_2 - P_1)}{2L(Q_2 - Q_1)}\pi R^3$$

$$\tau_{0i} = \frac{R}{2L}(P_1 - \rho.g.H) - \eta\frac{Q_1}{\pi R^2}$$

Numerical applications:

R=0.065 m
P_1=225/1,8 105= 125.105 Pa
P_2=270/1,8 105= 150.105 Pa
Q_1=6*60/60/1000=0.006 m^3/s
Q_2=8*60/60/1000=0.008 m^3/s

We find: η = 1796 Pa.s/m and τ_{0i} = 74.29 Pa

The cheking of formulation by tribometer tests provides an estimate of the value of the interface viscous constant (η) and threshold (τ_{0i}). These results are similar to the formula SCC3, so we can say that there was a problem during transport of the material. Otherwise there was probably confusion in formulation at the concrete plant.

VI. CONCLUSION

This article is a practical example to confirm the choice of a formulation based on the calculation of pumping rate and the hydraulic pressure as the well as rheological characteristics of the mixture.

The pumpability of concrete is basically connected to its mixer output rheology. In addition, the stability of the rheology must be guaranteed throughout implementation, knowing that, in a real life situation of on-site construction, technical and mechanical constraints related to the choice of equipment are not 100% controllable. Therefore, the pumpability is a feature that should depend only on the properties of the fresh concrete and remain independent of equipment or pumping conditions. It can be claimed that the factors that determine the pumpability of concrete remain linked to its composition.

It during pumping a decrease in the workability of the concrete often occurs. It is therefore important to ensure that the rheology after pumping is sufficient for the final implementation.

One of the issues raised in this work was the identification of the most appropriate parameter to validate the formulation proposed by the laboratory. It appears that the pumping pressure and viscous constant of the interface are best parameters to validate the choice of this formulation.

The relationships obtained from studied analytical methods allow to establish the degree of pumpability of concrete mixes. Therefore, it is possible by knowing the characteristics of a pumping circuit (length and diameter) to calculate the maximum pressure required to achieve the concrete pumping.

For each application, the required characteristics are different. Finishing needs, implementation, pumpability, segregation resistance etc.. define if a concrete has good properties when fresh. In the light of the results obtained during this project, it appears that the optimum rheology for pumping is the one where the shear threshold of concrete is low so as to obtain a minimum resistance to flow.

REFERENCES

[1] Tattersall, G.H. & Banfill, P.F.G. (1983) The Rheology of Fresh Concrete , London, Pitman, 1983, 356 p.
[2] de Larrard F., 2000, « Structures granulaires et formulation des bétons », Etudes et Recherches des Laboratoires des Ponts et Chaussées, OA34, Paris.
[3] ROSHAVELOV T.T. “Concrete mixture proportioning with optimal dry packing”. In Proceeding of the First International RILEM Symposium of Self-Compacting Concrete. RILEM, 19.
[4] Ferraris, C., De Larrard, F. (1998), Testing and modelling of fresh concrete rheology , National Institute of Standards and Technology, NISTR 6094, Gaithersburg, MD, February, 61 p.
[5] Kasami H., Ikeda T. and Yamane S (1979) On Workability and pumpability of superplasticized concrete, Proc. 1st CANMET/ACI Conf on Superplasticizers in Concrete, Ottawa, V.M.Malhotra Ed., ACI SP62, 67-86.
[6] Johansson, A., Tuutti, K. (1976), Pumped concrete and pumping concrete, CBI Research Reports, 10:76 (Swedish Cement and Concrete Inst.).
[7] Sakuta, M., Yamane, S., Kasami, H., Sakamoto, A (1979) Pumpability and Rheological Properties of Fresh Concrete, Proceedings of Conference on Quality Control of Concrete Structures, vol.2, Swedish Cement and Concrete Research Institute, Stockholm, june 17-19, pp.125-132.
[8] Beaupré, D. (1994) Rheology of High Performance Shotcrete , Ph.D. Thesis of the University of British Columbia, Canada, 249 p.
[9] Gray, J. (1962) Laboratory procedure for comparing pumpability of concrete mixtures , presented at the sixty-fifth annual meeting of the society, National Crushed Stone Assn., Washington, D.C., June 24-29, pp. 964-971
[10] Kaplan, D. (2000) Pompage des bétons , Thèse de doctorat de l’École Nationale des Ponts et Chaussées, 225 p.
[11] Chapdelaine, F. (2006). Étude fondamentale et pratique sur le pompage du béton. Département de génie civil, Université Laval, Canada. Thèse, 200 pages.
[12] CHOPIN D., DE LARRARD F., CAZACLIU B., « Why do HPC and SCC require a longer mixing time? », Cement and Concrete Research, vol. 34, n°12, p. 2237-2243, 2004
[13] Kempster, E. (1969), Pumpable Concrete , Current Paper No. 29/69, Building Research Station, Garston, aug. 1969.
[14] Murata, J. (1984) Flow and deformation of fresh concrete, Materials and Structures, vol.17, no.98, march-apr, pp. 117-129.
[15] Kaplan D, deLarrard, F., Sedran T.(2005) Avoidance of Blockages in Concrete Pumping Process, ACI Materials Journal, 102 (3) 183-191
[16] Neville, A.M. (1995) Properties of Concrete, Fourth Edition, Longman Group Limited, London, 844 p.
[17] Morinaga, M. (1973), Pumpability of concrete and pumping pressure in pipelines, Fresh. Concrete : Important Properties and heir Measurement, Proceeding of a RILEM Seminar Held March, Leeds, vol. 7, pp.7.3-1 à 7.3-39.
[18] Goltermann, Packing of aggregates: an alternative tool to determine the optimal aggregate mix. ACI Materials Journal. V94, No 5, Sept/Oct 1997, pp 435–43.
[19] Ede, A.N. (1957), The resistance of concrete pumped through pipelines , Magazine of Concrete research, vol 9, no. 27, nov, 1957, pp. 129-140
[20] Tattersall, G.H. (1973) Lubrification Layer in Concrete Pumping – A Written Contribution to Discussion Topic Number 7, Fresh Concrete: Important Properties and Their Measurement – Proceedings of a RILEM Seminar Held on 22nd – 24th March 1973 in Leeds England, vol.3, University of Leeds, Leeds, England, pp. 7.D1-1 – 7.D1-5
[21] BROWNE, R.D., BAMFORTH, P.B. (1977). Tests to Establish Concrete Pumpability, ACI Journal, Vol. 74, No. 5, May, pp. 193-207.
[22] Weber, R. (1963) The transport of concrete by pipeline, Cement and Concrete Association Library Translation No. 129, Cement and Concrete Association, Londres, 1963, 85 p.
[23] Yingling, J, Mullings, G.M., Gaynor, R.D. (1992) Loss of air in Pumped Concrete, Concrete International, vol.11, no.10, oct., pp. 57-61.
[24] Loadwick, F. (1970) Some Factors Affecting the Flow of Concrete Through Pipelines , Proceeding of the First International Conference on Hydraulic Transport of Solids in Pipes, British Hydromechanics Association, Bedford, pp. D1-1 – D1-31.

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