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Testing pumpability of concrete using Sliding Pipe Rheometer

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HIGHLIGHTS

- Need for new and reliable device to test pumpability of concrete is emphasized.
- Sliding Pipe Rheometer (Sliper) is introduced and its operating procedure elaborated.
- Influence of concrete composition on pumpability is investigated.
- Advantages of Sliper are demonstrated through comparison with other test methods.
- Sliper estimations are validated using full-scale pumping measurements.

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ABSTRACT

The pumping of concrete is an important part of modern construction processes. Irrespective of the immense practical significance of this process, pumping pressure is still being estimated using conventional methods such as the slump test, which has proved inadequate. The Sliding Pipe Rheometer (Sliper) is a new device developed to resolve this problem and provide reliable estimations of pumping pressures. Using this device, a series of laboratory tests to investigate the pumpability of concretes with various compositions was performed. The results obtained provide a solid basis to demonstrate the links between mixture parameters, e.g., water-to-binder ratio, aggregate shape, admixtures, and consistency class, and the pumpability of concrete. For the sake of comparison, all the concretes were tested using a concrete viscometer and the flow table test as well. This comparison emphasized the advantages of using Sliper to determine the rheological behavior of concrete during pumping, while a good correlation between the results obtained in the test series with Sliper and the concrete viscometer was found. Finally, the predicting capability of Sliper was validated under field conditions by measuring full-scale pumping pressure.

1. Introduction

The global construction industry is currently witnessing enormous growth and change in terms of construction technology and methodology. Reducing construction time is a major change separating modern and conventional modes of construction. Concrete pumping is one of the key reasons for this tremendous change. It has made feasible the construction of very large structures, i.e., bridges and skyscrapers, within very short times. Thus, concrete pumping is a significant, very important activity in modern construction. The pumping of concrete not only reduces significantly the total time of construction, but it also reduces the total cost of construction by reducing labor requirements. Concrete pumping also helps ensure the designed workability of the fresh concrete by accelerating its transport and placement, thereby reducing time-dependent effects.

Fresh concrete is a heterogeneous suspension with various constituents of different shapes, sizes, and material properties. The workability of concrete depends very much on its composition [1]. Since even a slight variation in the mix design can have a pronounced impact on the behavior of concrete in fresh state [2,3] and since compositions of modern concretes are complex and vary considerably from case to case, it is difficult to establish the quantitative links between the mixtures' compositions and their rheological properties. This makes it very challenging to predict and optimize the rheological characteristics of fresh concrete in order to meet specific requirements resulting from particular technological processes [2].

Concrete pumping is done by pushing concrete at high pressure into pipes made of either flexible, abrasion-resistant material or steel [3]. The pressure applied provides the necessary thrust to move the concrete forward, i.e., it causes the concrete material to

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deform in the direction of the applied force and, hence, to transmit the force further. Since coarse aggregates cannot be deformed easily, fresh mortar plays the major role in the deformation behavior of concrete. For most of the concretes it is evident from previous studies that concrete flows as a plug in the pumping pipelines [4–9], as illustrated in Fig. 1; coarse aggregates move towards the center of pipe forming a core (plug), while an easily deformable, lubricating layer is formed at the internal walls of the pipelines, leading to a considerable reduction in the required pumping pressure. The lubricating mortar layer consists of cement paste (cement, water, mineral admixtures and chemical additives) and fine aggregates.

The fine mortar content in concrete has a significant influence on the pressure required to move fresh concrete forward at a particular flow rate. Accordingly, the mix composition should be predetermined in such a way that the fresh concrete has sufficient mortar content and can flow without stagnation over the distances required, particularly through pipe bends and narrow sections. At the same time, a pronounced segregation of mix constituents must be avoided in order to prevent losses of homogeneity and blockages in the pipes. In achieving all these aims, the concrete mixture must, in addition to having sufficient mortar content, have a high packing density of the solid components as well as good cohesion [3].

Obviously the rheological properties of concrete are crucial to its flow characteristics, and they define to a great extent the pumping pressure required. The rheology of concrete influences the pumping process in two ways: (1) by affecting the force transmission inside the core (plug), and (2) by influencing the shearing behavior of lubricating layer at the walls of the pipe. The rheological behavior of fresh concrete can be satisfactorily described by the Bingham model, with its two parameters: yield stress τ_0 and plastic viscosity μ [10]. Both these parameters are sensitive to variations in the mix composition, and both parameters affect the pumping behavior of fresh concrete, although to different extents.

Conventionally, the pumpability and workability of fresh concrete have been determined using the standard slump test [11,12] or flow table test [13,14]. General quantitative estimation of required pumping pressure using, for example, nomographs based on slump or spread values have been proposed and discussed in a number of previous publications [15,16]. However, these methods have many limitations, as nomographs do not include the complete range of certain parameters, e.g., very high spreads and pipe lengths. More importantly, some crucial parameters, as examples aggregate shape, grading, paste volume, etc., cannot be taken into consideration while estimating pumping pressures using nomographs. Even in the case of the allowed range of nomographs, estimated pumping pressures based on slump or spread are not necessarily reliable for modern concretes like SCC and HPC [4,7]. One powerful explanation of this is that the slump, slump flow, or spread values correlate well with only one of the Bingham parameters, namely the yield stress τ_0, i.e., the stress needed to begin the deformation process starting at the zero shear rate [17–20]. The correlation of slump with the second Bingham parameter – plastic viscosity μ – is very poor.

However, plastic viscosity is very important [5,21,22] to the estimation of the resistance of concrete to pressure in the pipe since this parameter is a measure of the increase in shear stress with increasing shear rate. Higher concrete flow rates Q (with their higher shear rates!) can be achieved at a constant pressure P (shear stress!) if the plastic viscosity μ is reduced. In other words, for a given value of Q the required pumping pressure P increases with increasing plastic viscosity.

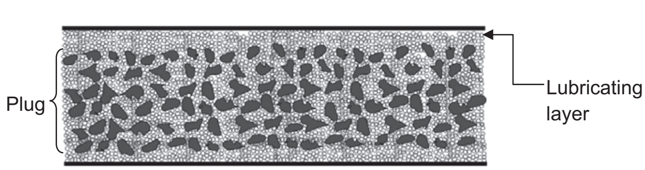

Fig. 1. Schematic view of plug flow of concrete during pumping.

Another significant point of note is the difference in flow conditions during the slump (flow) test or table flow test and during concrete pumping. The slump (flow) test, the deformation of the concrete "cake" for softer consistencies in conjunction with some radial, surface flow with low deformation rate, cannot reproduce the flow conditions of fresh concrete inside a pumping hose line, i.e., plug flow with a lubricating layer and high deformation rate. The influence of the lubricating layer on the pumpability of concrete is enormous, as has been emphasized in previous research [4,7,9]. Therefore, the absence of the lubricating layer in the slump flow test makes an estimation of pumping pressure based on such a test even less reliable.

More advanced concrete testing devices such as rheometers and viscometers can be used to estimate both parameters of the Bingham model and are, therefore, more suitable for estimating the pumpability of fresh concrete. However, portability and ease of operating of the testing equipment play considerable role in the selection of testing equipment for use on site, especially if the location is remote or nomadic, such as in the construction of roads, canal beds, etc. The inadequacy of current equipment and the scarcity of sound methodologies give birth to the demand for dedicated, portable, yet reliable testing equipment for the quantitative estimation of pumping pressure and the determination of concrete's pumpability. A new concrete testing equipment, Sliding Pipe Rheometer (Sliper) has been developed [7] by Putzmeister to solve the above-mentioned problems.

While Sliper seems to meet all the above-mentioned demands of portability, reliability, and a methodology optimized with respect to concrete pumping, no systematic scientific parameter studies have been performed with this device as yet as it relates to various concrete compositions. Furthermore, it is not known how well the results obtained with Sliper would correlate with the results of measurements performed using a concrete viscometer or conventional empirical methods, indeed such as the slump test or the flow table test.

In the article at hand the new, specialized device for testing concrete pumpability – the Sliding Pipe Rheometer – is introduced and its working procedure briefly explained. Furthermore, a parameter study on the effects of mixture composition on the pumpability of fresh concrete performed with Sliper is presented. These results are discussed and compared with those obtained using both the concrete viscometer and the flow table test. Finally, the predictive capacity of the approach based on Sliper measurements for estimation of pumping pressure is demonstrated.

2. Sliding Pipe Rheometer (Sliper)

The crucial difference Sliper has in comparison with regular rheometers is its very close adaption to real pumping processes as well as its relatively simple and robust setup. By using as its central element a piece of pipe with the actual geometry of the pipe in operation and by applying a testing procedure which mimics pumping at various speeds, the physical conditions in the concrete pumping process can be efficiently reproduced, see Fig. 2. The pumpability is tested by filling the pipe placed in the topmost position with fresh concrete and eventually letting the pipe slide downwards under the force of the weights attached to the pipe. While the pipe moves, the concrete body remains in the initial position, pressing against a pressure sensor positioned at the head of the metal piston along which the pipe slides down. Various speeds