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Cement and Concrete Research 34 (2004) 821–828

CEMENT AND CONCRETE RESEARCH

Tribological behaviour of self compacting concrete

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Received 24 January 2003; accepted 17 September 2003

Abstract

The use of superplasticizers to obtain concretes that are highly workable, easy to place in formwork and require no vibration has spread throughout Europe in the last few years. The placing process for fresh, so-called self-compacting concrete (SCC) depends on the friction that occurs at the concrete/wall interface.

A rectilinear movement tribometer was developed to characterize SCC. The effect of several parameters affecting the concrete/metal plate friction coefficient is examined. These parameters include the roughness of the plate, the sliding velocity against the plate, the pressure or normal stress and the nature of the demoulding agent at the concrete/wall interface. Physical mechanisms are proposed.

Keywords: Demoulding agent; Friction coefficient; Concrete wall interface; Self-compacting concrete; Tribometer

1. Introduction

Concrete friction plays a fundamental role at various stages of construction and public works operations, including pumping, formwork filling, construction of facings, etc. As an example, fresh concrete may be pumped through long circular pipes. At certain hard to reach sites, these pipes may be up to 2000 m long. The problems that may arise in such cases include the formation of blockages and head loss in the pipes [1]. These problems, which may lead to complete stoppage of the works, are usually caused by concrete friction against the pipe walls.

Form design is the main concern of formwork manufacturers, as customers and owners are becoming increasingly demanding in this area since the advent of highly fluid, so-called self-compacting concretes (SCCs). The use of these concretes has become widespread in recent years, as they provide savings in labour, reduce noise due to vibration and shorten completion times. These concretes may be placed in 10- to 12-m forms in a single pour. When constructing very high diaphragm walls, it is essential to determine the thrust exerted by the concrete against the forms. At present, for the sake of safety, the relevant French Standard [2] recommends taking into account the hydrostatic thrust of the material when designing forms.

At the end of 1999, tests concerning diaphragm filling operations were performed using formwork fitted with various instruments [3,4]. The results of these tests showed that there was a decrease of about 20% in comparison with the hydrostatic thrust at the base of the form. The difference appears to be due to concrete/wall friction and the thixotropic nature of the concrete [5]. The forms were therefore oversized, thus increasing construction costs.

The workability and quality of cast concrete elements are a major economic challenge. Concrete surfaces and facings may vary in quality or colour, or be pitted. The factors that are likely to affect the occurrence of this type of defect include the actual placing in the formwork, the specific features of the form walls and the use of a demoulding agent between the concrete and formwork. Demoulding oils or release agents are used on formwork in the form of a thin film, which prevents the concrete from adhering to the wall.

Earlier studies [6,7] were conducted to determine the pressure of the concrete as it is placed in the forms. This work was based on knowledge of the intrinsic parameters of the material such as internal angle of friction and cohesion

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0008-8846/$ – see front matter
doi:10.1016/j.cemconres.2003.09.013

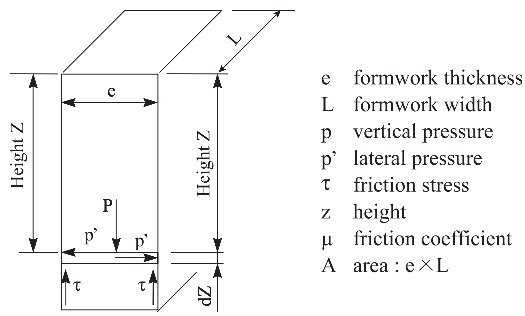

Fig. 1. Stress schematic representation in a formwork.

[8]. When these parameters are known, it seems logical to use the theory of ensiled granular media to determine pressures on the forms. The case of silos is adopted for this study as the weight of grains in silos is borne mainly by the sidewalls: a description of this effect is given by Janssen [9]. This theory was applied to formwork [10]. In the case of SCCs (Fig. 1), the pressure P may be estimated by the following equation:

$$P = \frac{\rho geL - \tau_0(2e+2L)}{f\mu(2e+2L)(1-\sin\varphi)} \times \left(1 - \exp - \frac{f\mu(2e+2L)(1-\sin\varphi)}{eL} z\right)$$

where ρ is the concrete density, τ_0 the yield stress, g the gravitational acceleration, e distance between the formwork faces, L the formwork width, z the height of the formwork, φ the internal friction angle determined experimentally with the tribometer modified [10] and μ the friction coefficient between the formwork and the concrete. A coefficient f is placed in front of the parameters describing particle–particle and concrete–wall friction. Contrary to Janssen approach, the inequality of the Amontons–Coulomb law is considered in this equation and expressed by the coefficient f [11]. The value of this coefficient is calibrated on the basis of site measurements.

However, this approach involves a parameter that is still difficult to estimate now, namely, the coefficient of friction between the material and form wall. Indeed, while the friction of solid materials is now well understood, this is not true of fresh concrete, which is not a continuous medium. It is a dense suspension, containing water and particles covering an extremely wide grain size distribution varying from submicron scale to around a centimetre.

The behaviour of concrete at the concrete/wall interface is not yet well understood, so it is important to consider this approach within the framework of the criteria normally used in tribology. The tribometers used to study friction are not designed for studying pasty materials but in the related field of clay pastes, Djelal [12] designed a tribometer to study clay paste friction during extrusion shaping. This instrument was adapted at the Artois Laboratory of Mechanics and Housing to study the case of fresh concrete friction against a metal surface [10]. The particular focus of attention was the friction involved when SCCs are introduced into forms and the parameters that will affect thrusts.

The first part of this article describes the tribometer. The effect of several parameters affecting the concrete/metal plate friction coefficient is then examined. These parameters include roughness, the sliding velocity against the plate, the pressure or normal stress and the nature of the demoulding agent at the concrete/wall interface. Lastly, analysis of the results has provided a better understanding of the mechanisms involved at the concrete/steel interface.

2. Experimental methods

2.1. Measurement principle

The principle adopted is identical to that used by Djelal [12] to study kaolin pastes. This involves sliding a metal plate between two samples of concrete (Fig. 2). The interchangeable plate is moved at a velocity V while the tractive strength $2F$ is measured thanks to a sensor. The friction stress τ_f is calculated by dividing the force obtained by the area of the sample in contact with the plate Sc.

The normal force sensor placed between the jack rod and the piston gives the force exerted by the former on the latter. This value, denoted N, divided by the contact surface gives the contact pressure P or normal stress. The friction coefficient μ can be obtained from the ratio between friction force and normal force.

2.2. Description of the tribometer

The material is placed in the 120-mm-diameter cylindrical sample holders, into which a piston is inserted. This dimension was chosen to take into account the size of the biggest aggregates. It has to be at least five times larger than the largest gravel [13] for the measurements to be independent of the size of the sample holder.

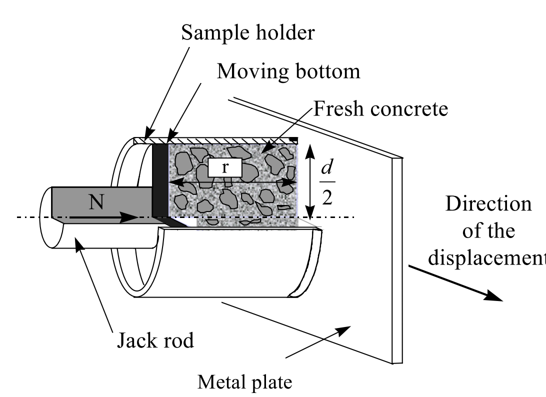

Fig. 2. Details of sample holder.

The purpose of the piston is to transmit the pressure exerted by a pneumatic jack rod (Fig. 3) to the concrete samples and apply them against the plate. A gasket system is installed on the sample holder to avoid all leakage of water. The stiffness of the gaskets is adjusted so that the material's liquid phase cannot pass between the plate and the gaskets.

The plate is moved by an engine connected to an endless screw. The rotating movement of the screw is transmitted via a nut and transformed into a translatory movement in the tie. The tie transmits its motion to a plate guided by a slide. There is a rail on which bearings are fixed, guiding the two parts in motion.

In order to reduce gravity forces, the plate is displaced horizontally. Furthermore, all the elements forming the tribometer are aligned, in order to minimize interference forces. A frame mounted on a slide balances the pressures on either side of the plate through action and reaction effects. A single jack rod is used to bring the sample into contact with the metal plate. The plate is moved 800 mm. Contact pressure can reach 1700 kPa. Sliding velocity varies from 0 to 300 mm/s.

2.3. Rating and measurement

For each test, the tangential force (or friction force) F_{mes} is measured according to the time. This force corresponds to the combination of the two friction forces:

– The resultant of the interference friction force (F_{par}) produced by the gasket system against the metal plate and the tie against the slide.
– The resultant of the tangential friction force produced by both material samples against the plate.

Thus:

$$F = (F_{mes} - F_{par})/2$$

An example of a recording is shown on Fig. 4. Curve 1 corresponds to variations in the measured interference force (F_{par}) without fresh concrete. Curve 2 shows the change in tangential force (F_{mes}) on a concrete with no

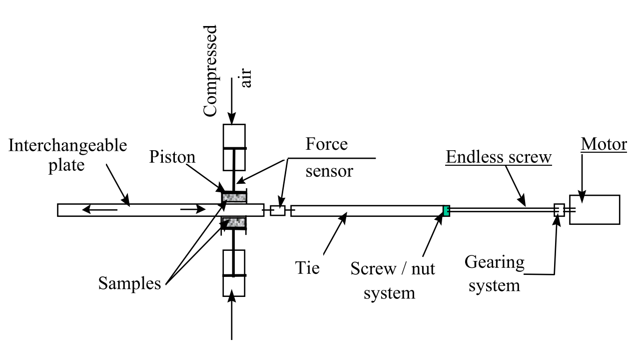

Fig. 3. Principle of tribometer.

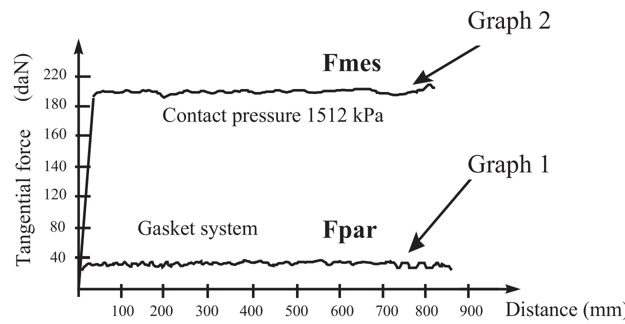

Fig. 4. Growth in tangential force according to the distance for fresh concrete without demoulding agent.

additives under a normal pressure of 1512 kPa and velocity of 100 mm/s. This curve can be split into two parts:

– A strong increase leading to a value that corresponds to the static friction force F_{stat}.
– A steady regime where the dynamic friction force value F_{dyn} is chosen.

No difference is observed between static and dynamic friction when the concrete is directly in contact with the metal surface, which is not the case when a demoulding agent is applied to the plate.

The friction force is obtained by averaging the four values measured on the recording curve. For each measurement point, an average of three tests is carried out.

3. Materials

This study deals with the friction behaviour of an SCC which is used on a building site against XC38 steel surfaces for formwork.

3.1. Self-compacting concrete

SCCs are extremely workable concretes that can be placed without requiring vibration. The high fluidity of these concretes is obtained by adding a superplasticiser. Calcareous filler can be introduced into the concrete mix to reduce bleeding and segregation, and improve the quality of concrete surface in terms of colour. The composition of the concrete tested is given in Table 1. All particles of sand, cement and filler with a diameter of less than 63 μm are referred to as fine particles or fines [14]. The angular shape of these grains can play an important role in the friction stress occurring at the concrete/wall interface.

To characterize the consistency of the prepared concrete, a workability test (slump flow test) was performed on site. This was in the form of a slump test using the Abrams cone method. However, the average diameter (a mean of two orthogonal diameters) of the spread concrete is measured a minute later. A spread of 70 cm was seen for this concrete. The density of the concrete is 2300 kg/m^3. It is characterized by a shear threshold of the order of 100 to 200 Pa [7].

3.2. Metal plate

Studies concerning clay paste friction [12] have shown that roughness has a significant influence on friction stress. It has been established that this stress increases if the roughness departs from the average size of the clay particles. Some formwork roughness measurements were performed on site with the help of a portable roughness meter (Ra = 0.3 μm and Rt = 2.3 μm). For this study, a plate was made of XC38 steel with the same characteristics as the formwork walls.

To understand the friction mechanisms at the concrete/wall interface, a plate of greater roughness was also studied (Ra = 1.6 μm and Rt = 13.6 μm). The ridges due to manufacturing are oriented in the direction of plate movement.

3.3. Demoulding oils

Two demoulding agents were tested for this study: Oil 31E and Oil 31S. They are vegetable-based products (soya oil and rapeseed oil). The suitability of vegetable oils for demoulding can be explained by the very nature of the vegetable ester molecules [15]. Due to the polarity of the molecules, these oils spread evenly and adhere preferentially to the metal wall surface.

Oil 31E is a water/oil emulsion with surface-active agents. This emulsion ensures a homogeneous oil layer, but the presence of active material is reduced and dampness at the concrete/steel interface is increased. Oil 30S is a mixture of oil and solvent that contains a surface-active agent. This type of formulation leads to the formation of a thin, homogeneous layer of oil after the solvent has evaporated.

Table 1
Self compacting concrete composition

Components	Quantity
Cement CPA-CEM I 52,5 R	350 kg/m^3
Calcareous filler	100 kg/m^3
Sand 0/3,15	473 kg/m^3
Sand 0/4	315 kg/m^3
Gravel 4/10	452 kg/m^3
Gravel 10/14	363 kg/m^3
Total water	200 ± 5 l
Water reducer	1.8 l
Superplasticizer	4.05 l
Viscosity modifying agent	1.28 l
Density	2300 kg/m^3
Water/(cement + filler) ratio	0.44
Slump flow	70 ± 2 cm

Table 2
Demoulding oil characteristics

Characteristics	Oil 31E	Oil 30S
Type	Water + oil	Solvent + oil
Density at 20 °C (kg/m^3)	1000	800
Viscosity at 25 °C (mPa s)	5	4.5
Contact angle (degree)	39.4	4
Tensioactivity (%)	2 to 2.2	2.5
Fatty acid	0	1
Active material (%)	15	35

Table 2 sums up the characteristics of the oils. Viscosity and surface-active properties are two important parameters that will condition the efficiency of the demoulding agent. It should be noted that a small drop contact angle indicates a high wetting power, which will avoid any absence or total disappearance of oil from the form walls. The way these oils are applied to the mould is particularly important since it conditions the quality of the formwork surface. Surplus oil can affect the quality of demoulding and can produce defects (airholes, stains, tears, etc.) on the formwork surfaces.

4. Results and discussion

The rate of concrete placing in formwork varies from 0.5 to 1 m^3/h on a site. This corresponds to velocities of concrete rising in the formwork that vary from 2 to 20 mm/s. Tests performed in situ by CEBTP [3] showed that the pressure exerted by SCC 12 m deep is nearly 19 t/m^2, i.e., 190 kPa.

In order to characterize SCC friction against a metal surface, rising speeds and pressures were studied in the ranges 0.5 to 50 mm/s and 40 to 500 kPa, respectively. The effect of pressure and velocity were studied first of all for a concrete in direct contact with the plate, without using any demoulding agent. Friction tests were also done with different demoulding oils in the same conditions as the tests without demoulding agents. The study deals mainly with dynamic friction. Measurements made during the different tests displayed significant differences.

4.1. Effect of pressure on friction coefficient

The change in friction coefficient according to concrete pressure against the plate is shown in Fig. 5 for a velocity of 2.5 mm/s and for the two surfaces tested (Ra = 0.3 and 1.6 μm). The variation in friction coefficient is not constant for the two roughness values tested. Similar results were found by Kendall [16] for friction with a wet sand and by Djelal with kaolin pastes [12].

Coulomb's law, which applies to the friction between a wall and granular materials, such as powders, dry sand or solids, does not seem to apply to concrete. The curves

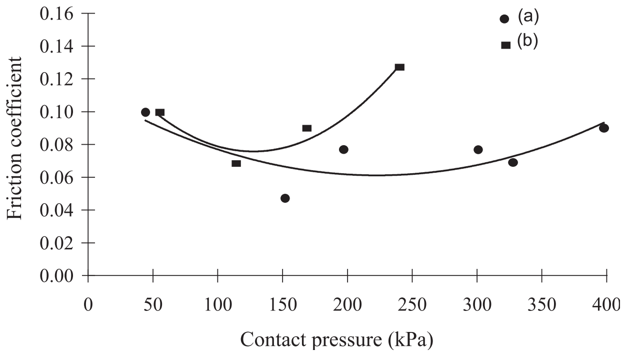

Fig. 5. Evolution of the friction coefficient according to the contact pressure without demoulding agent for a 2.5 mm/s sliding velocity: (a) Ra = 0.3 μm; (b) Ra = 1.6 μm.

in Fig. 5 display a minimum that appears above about 140 kPa.

Fluid concrete, contrary to its appearance, is not a continuous medium. The different elements of the concrete will play very specific roles during friction. The pressure stress applied to the material is transmitted to the granular phase and to the paste formed by the binder (cement + filler). This stress will cause part of the liquid phase and fines to migrate towards the interface. A lubricating surface (or boundary) layer (water + fines) is therefore formed at the interface (Fig. 6a). A plate of only slight roughness (0.3 μm) has ridges that are not deep enough for the surface layer to seep out. It remains at the concrete/plate interface. The surface layer is therefore under pressure and recaptures part of the normal stress.

When pressures are higher than 140 kPa, it is assumed that the liquid phase, which was at first confined to the interface, will move into the sample under the effect of pressure (Fig. 6b). The material in contact with the surface will adopt a granular behaviour during shearing, which explains the increase in friction coefficient.

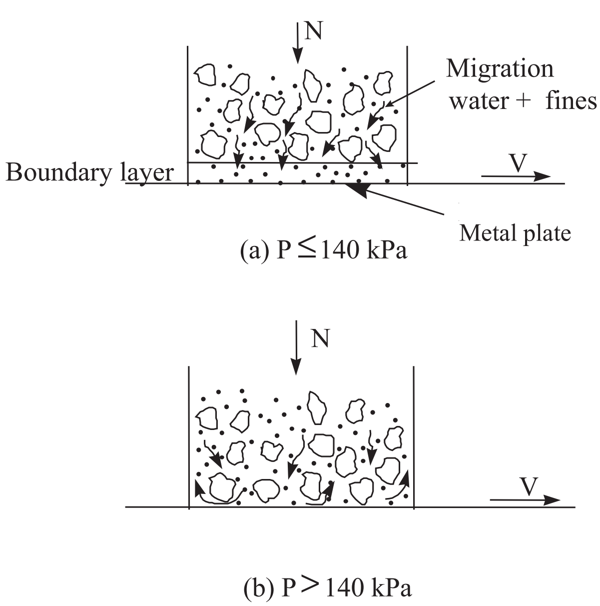

Fig. 6. Schematic representation of a concrete/metal plate interface (Ra = 0.3 μm).

When the plate roughness value is about 1.6 μm, the friction coefficient is more or less equal to that in the previous case, for pressures below 110 kPa. The roughness Rt is 13.6 μm, which allows some of the particles in the boundary layer to become lodged in the ridges. Shear occurs mainly in this layer (Fig. 7a).

In the case of pressures above 110 kPa, part of the boundary layer will migrate towards areas under less stress (Fig. 7b). The grains of sand or gravel will be directly in contact with the tips of the ridges. The force exerted by these tips as the plate is displaced will cause them to rotate and thus produce considerable energy dissipation. As a result, there will be a more rapid increase in the friction coefficient and the metal surface will be worn. Indeed, after a series of tests corresponding to about 70 passages of the concrete against the plate, the grains have both widened and deepened the ridges. Values of Ra = 2 μm and Rt = 26.8 μm were found.

4.2. Effect of velocity on friction coefficient

Fig. 8 gives the variations in friction coefficient as a function of velocity for three pressures (50, 132 and 240 kPa) for a roughness value of 0.3 μm. The friction coefficient does not appear to vary with the velocity. The average depth of scoring (Rt = 2.3 μm) prevents fines in the paste from lodging between the roughness cracks. Shear will occur in the boundary layer.

The curves shown in Fig. 9 show the friction coefficient as a function of the velocity for a roughness value of 1.6 μm. With a pressure below the critical value (110 kPa), the friction coefficient does not vary with the slip velocity. Shear occurs in the boundary layer. In the case of pressures above the critical value, the friction coefficient is sensitive to the

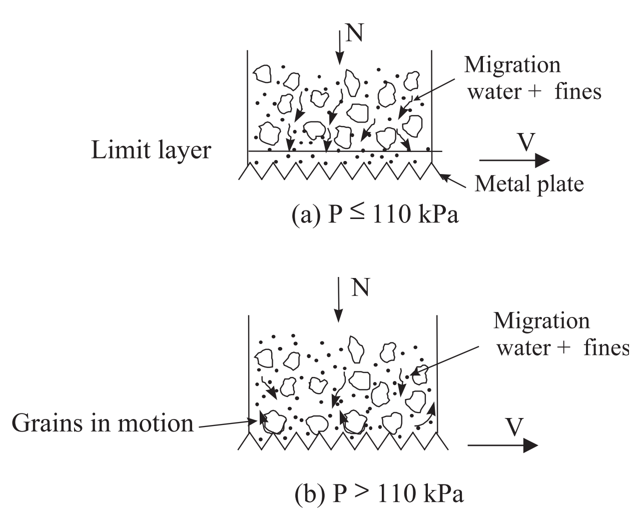

Fig. 7. Schematic representation of a concrete/metal plate interface (Ra = 1.6 μm).

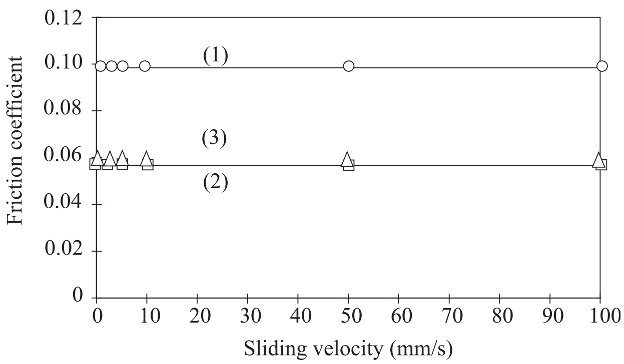

Fig. 8. Evolution of the friction coefficient according to the sliding velocity (Ra = 0.3 μm): (1) P = 50 kPa, (2) P = 132 kPa, (3) P = 240 kPa.

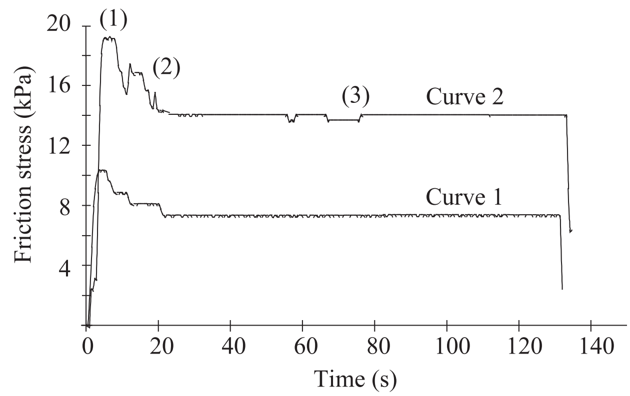

Fig. 10. Evolution of the friction stress according to the time: (Curve 1) Oil 30S, (Curve 2) Oil 31E, v = 2.5 mm/s, P = 192 kPa.

velocity. It decreases with the velocity, stabilising above 25 mm/s. In the case of low velocities, high values were recorded. The curves are very similar in appearance to Stribeck's curve. In the present case, the boundary layer could act as a lubricant.

When $0.5 < V < 25$ mm/s, under the effect of pressure, part of the boundary layer will become lodged in the plate ridges and flow in the grooves under the effect of plate movement. The grains trapped in the gaps will then cause grains of concrete in contact with the wall and close to it to rotate, producing major dissipation of energy. This dissipation, which gives rise to an increase in the friction coefficient, decreases as the velocities increase (V>25 mm/s). In this case, the grains have less and less time to move and thus to resist shear. Moreover, shear will occur in the boundary layer, which has no time to flow. The friction coefficient values are then very close to that found for a plate with a lower roughness value. These results were also found with other pressures.

4.3. Effect of demoulding agents

Fig. 10 shows the recording of friction stress as a function of time for a 0.3 μm interface to which a demoulding oil had been applied previously. The same shaped curve is found for two oils studied. These recordings are different from those obtained for a concrete/wall interface. The curve can be broken down into three parts:

- static friction (1),
- a decrease linked with the properties of the demoulding agent (2),
- dynamic friction (3).

The comparative study concerns the case of dynamic friction. The change in dynamic friction coefficient as a function of contact pressure (Fig. 11) shows a decrease in the coefficient for both oils tested. Interface effects introduced by the demoulding agents will be superimposed on the phenomena described above. For a pressure of less than 140 kPa, shearing takes place in the surface layer (water + fines + demoulding agent). When pressures exceed this critical value, the change in friction stress depends on the characteristics of the interface agent used.

The percentage of active material content in Oil 30S (35%) is higher than that in Oil 31E (15%), which explains

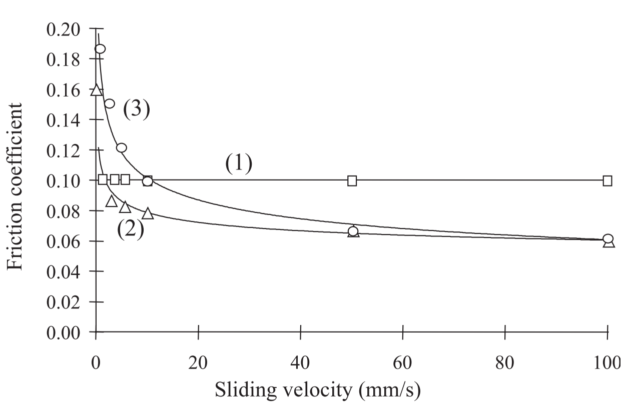

Fig. 9. Evolution of the friction coefficient according to the sliding velocity (Ra = 1.6 μm): (1) P = 50 kPa, (2) P = 132 kPa, (3) P = 240 kPa.

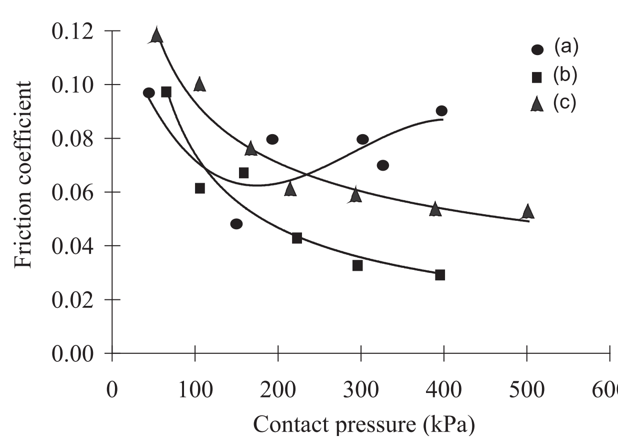

Fig. 11. Evolution of the friction coefficient according to a contact pressure for a 2.5 mm/s velocity: (a) concrete, (b) Oil 30 S, (c) Oil 31 E.

the fact that the increase in friction coefficient increase is less than for the first oil.

With surface-active agents on the metal wall, a quantity of water remains at the interface (Fig. 12). Thus, a boundary layer remains at the interface in the case of pressures above 140 kPa. This phenomenon can be observed as long as the attraction force of the surface-active agent is greater than that producing the dispersal of the pressure-generated boundary layer.

In the case of Oil 31E, the friction coefficient is less important than in the case of concrete without a demoulding agent. The boundary layer progressively disappears and delays the occurrence of granular behaviour.

The change in friction coefficient as a function of velocity (Fig. 13) shows a variation in the curves. For $0 < V \leq 30$ mm/s, the friction stress decreases significantly with the velocity. When the velocity tends towards 0, it seems that the stresses will tend towards a value that corresponds to concrete friction without any interface agent (Fig. 7). When the velocity is above 30 mm/s, a hydrodynamic phase is almost reached.

In the case of high pressures, the effect of the demoulding agents is not negligible, and the appearance of the curves is maintained. Nevertheless, when the velocity tends towards 0, there is a significant decrease in friction stress compared to the situation without any demoulding agent. For $0 < V \leq 30$ mm/s, there may be a mixed phase, where it is assumed that the load-bearing capacity can be partly absorbed by the grains (sand and gravel).

4.4. Interaction between concrete and demoulding agents

The curves shown in Fig. 11 help to correlate the efficiency of the demoulding agents to their physicochemical characteristics.

Two criteria prove to be particularly influential as regards friction stress:

- The quantity of active material deposited in the case of Oil 30S is sufficient for the esters, which are in contact with calcium hydroxide, to be converted into insoluble carboxylate (soaps) and form a hydrophobic film, thus preventing the concrete from adhering.
- The presence of surface-active agents in the Oil 31E and 30S is essential for the concrete to be hydrophobic. The water at the surface of the concrete is thus emulsified. In the case of the Oil 31E, all the esters are used in the emulsion, a less favourable situation than that occurring with Oil 30S.

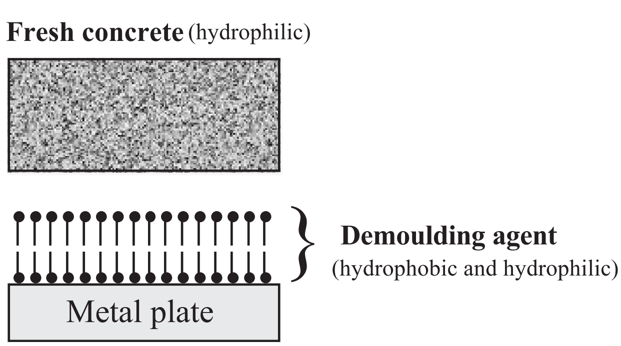

Fig. 12. Schematic representation of a plate/demoulding agent/concrete interface.

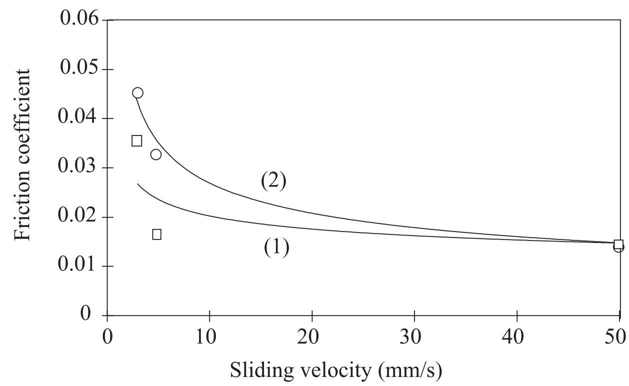

Fig. 13. Evolution of the friction coefficient according to the sliding velocity (Ra = 0.3 μm, P = 338 kPa): (1) Oil 30S, (2) Oil 31E.

Thus, Oil 30S formula is the one that best minimises friction stresses. In this case, the "solvent" matrix helps to deposit a uniform quantity of active material, enabling the concrete to become hydrophobic. The surface-active agent completes this process.

The wetting power of the demoulding agents (e.g., the contact angle) seems to act directly on the friction coefficient. Indeed, Oil 30S has the lowest friction coefficient and highest wetting power, while the viscosities are similar.

5. Conclusion

Friction exerted by concrete on metal surfaces plays an important role during placing operations. The tribometer developed for these tests enabled this friction to be measured.

The tests and observations made reveal a set of mechanisms that depend on the properties of the interface (roughness, velocity, nature of the demoulding agent, etc.). At this stage of the study, the local mechanisms proposed are still partly hypotheses, and must be supported by physical investigation techniques. Subsequently, the migration of fines and water in the concrete and the characteristics of the interface film (composition, thickness) could be studied by a technique involving radioelements.

The radioelement technique involves placing gamma radiation emitters that can be detected through the walls on the concrete constituents. This plotting technique can be used to characterize the segregation occurring in the concrete without disturbing the tribological measurements in progress.

Lastly, the choice of demoulding agent is a crucial issue. It is of major concern for the building trade, as it affects the quality of facings and the thrust exerted on formwork. The properties of these agents enable them to work at the concrete/wall interfaces to reduce adhesion and friction. Their performance varies widely depending on their composition.

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