SHOTCRETE PERFORMANCE OF REFRACTORY CASTABLES

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INTRODUCTION

Sprayed concretes were originally developed for civil construction in the early 20th century [1, 2]. The high installation rates, low cost and good final mechanical properties of the applied material are responsible for today's widespread use of this placing process [1, 2].

The application method consists of pumping either the dry powder (Gunning) or the fluid concrete (Shotcrete) directly from the mixer into the pipeline nozzle, where a spray flow is formed by the injection of high-pressure compressed air (both techniques) and water (only Gunning). Immediately after it reaches and covers the target surface, the concrete sudden loses its fluidity due to the action of cement-setting accelerators and coagulant additives also injected into the nozzle [1-7].

Rebound losses and dust released into the air are the major problems associated with gunning [1-2]. These difficulties are greatly reduced when the concrete is pumped in the fluid state, which justifies the growth of shotcrete applications [6].

The advantages of this method are well known, but it has only recently become common practice to use refractory castable shotcrete for lining large areas or repairing damaged surfaces [6, 7].

Despite the continuous technological advances in shotcrete machines [1, 2], sprayable compositions are still developed based on empirical and semi-empirical methods [6]. This discrepancy reveals the lack of characterization techniques to simulate shearing conditions during the application of shotcrete [6] and the need for further research on the subject.

The main objective of the present study was to reduce this technological gap. To this end, a set of experiments based on castable rheometry was developed to evaluate the shotcrete performance of refractory castables. In addition, commercial shotcrete compositions were evaluated based on this new testing procedure.

1. SHOTCRETE APPLICATION PROCESS

Refractory castable shotcrete is a multistage application process comprising four consecutive steps, i.e., mixing, pumping, spraying and consolidation. The efficiency of this application method is usually quantified by the rebound loss, which is defined as the percentage of material that fails to stick to the covered surface [1-5].

It is a generally accepted assumption that only self-flowing castables (free-flow between 80 and 110 %) [8] are qualified for shotcrete applications because of their pumpability and lower rebound, which result from the absence of large round agglomerates (golf balls) [7] when sprayed. However, this assumption is questionable, since contradictory rheological behaviors such as dilatancy and pseudoplasticity can also afford high-flow compositions, which, however, are not necessarily pumpable or sprayable [8].

Pileggi and Pandolfelli [8, 9] demonstrated that the mixing and pumping performance of castables is strongly affected by the rheological behavior of these materials. Dilatant compositions, for instance, are difficult to mix and unsuitable for pumping. On the other hand, pseudoplastic castables with excessive water content may segregate during pumping due to their very low matrix viscosity. Nevertheless, both behaviors might be verified in self-flow castables.

In addition to the rheological behavior, the action of cement-setting accelerators and coagulant additives is strongly influenced by the chemical compositions of castables [1-7].

The capability to shotcrete and the material's effective hardening on the covered surface are therefore the outcome of the four consecutive steps (mixing, pumping, spraying and consolidation) involved in the shotcreting technique.

2. NOVEL MULTISTAGE CHARACTERIZATION TECHNIQUES

Based on the successive steps of the shotcrete application process, a multistage experimental setup, comprising mixing, pumping, spray shooting and consolidation characterization, was employed to simulate and evaluate the performance of three distinct commercial shotcrete compositions (A, B and C).

Details concerning the castables, such as their chemical composition, polymeric fiber content, shotcrete additive (sodium silicate) and amount of water required for mixing, were supplied by Saint-Gobain, Brazil (Table I).

2.1 Mixing

A rheometer [8, 9] developed specifically to evaluate the rheological behavior of castables was used to mix the compositions. The torque profile and the time elapsed to mix 4 kg of each castable were recorded online. Castable mixing was carried out at 33 rpm, according to the following experimental setup: (a) dry-powder homogenization (time: 180 s); (b) water addition and mixing up to the turning point; and (c) castable homogenization after the turning point (time: 120 s).

In view of the successive steps involved in the shotcrete process, it is reasonable to consider low mixing energy as a basic requirement for sprayable castables. This characteristic offers economical and technical benefits, such as the production of highly homo-

Table 1. Castables chemical composition, polymeric fiber content, shotcrete additive (sodium silicate) and amount of water required for mixing.

Composition (wt. %)	A	B	C
SiC + C	19.0	86.0	0.0
Al_2O_3	70.0	9.1	83.0
SiO_2	7.0	2.6	13.0
CaO	0.7	0.3	1.7
Others	3.3	2.0	2.3
polymeric fiber (wt. %)	0.0	0.1	0.1
shotcrete additive (wt. %)	1.0	1.0	1.0
water content (wt. %)	7.0	6.5	6.0

Note: The compositions were supplied by Saint-Gobain/Brazil. 6 mm long polypropylene fibers were used in the compositions B and C.

geneous materials without the need for powerful and expensive mixers [9], and without promoting undesirable castable heating [8, 9] and degradation of the polymeric fibers usually employed in sprayable compositions [1, 2, 10].

The results reported on herein (Figure 1) proved that the fiber-free composition (comp A) required the lowest mixing energy (M_E) and the lowest torque at the turning point (T_{TP}), whereas the two fiber-containing systems (comp B and C) showed higher values for these two parameters. A similar trend was reported by Salomão et al. [10], who demonstrated that the mixing energy and torque at the turning point scaled with the size and content of the polymeric fibers within the castable.

Comparing these results to others described in the literature [8-10], compositions A and C can be classified as easy mixing systems. The large amount of highly irregular and coarse abrasive silicon carbide grains in composition B probably explains its high mixing energy.

2.2 Pumping

The pumping of refractory castables is a demanding step in which the material flows over long distances inside pipelines and is subjected to high shear rates and volume-restricted conditions [8].

In the present work, the free-flow value of each composition was measured (ASTM C-860 adapted for self-flowing castables) immediately after mixing. Four kilograms of each composition was then subjected to two successive shearing cycles (between 2 and 75 rpm) in a rheometer, in which the castable was subjected to both unrestricted and volume-restricted conditions [8]. The rheological results are displayed on Figure 2.

Self-flowability was achieved only for the fiber-free composition A mixed with 7.0 wt.% of water. Compositions B and C displayed a similar low fluidity suitable for castables applied under vibration [8, 9].

Based on the traditional cone flow selection criteria, only composition A was suitable for pumping and shotcrete applications [7, 8]. However, both compositions A and C were pumpable due to their pseudoplastic behavior, which matched the ideal torque range for pumping [8] under both shearing conditions (unrestricted and restricted volume).

Regardless of its pseudoplastic characteristics, composition B greatly surpassed the

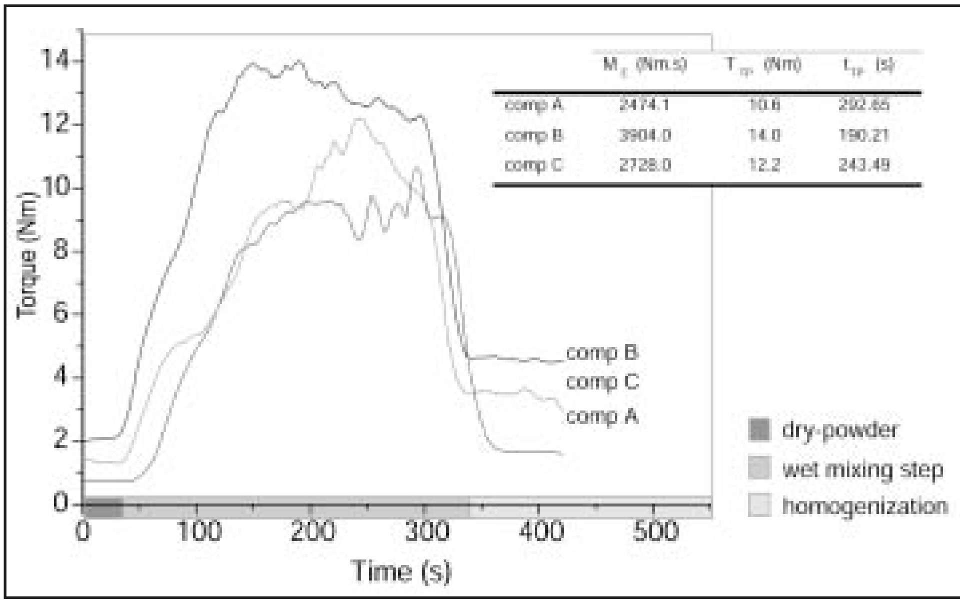

Figure 1 – Mixing behavior of the compositions A, B and C. Note: the inset in the graph shows the mixing energy required and the maximum torque at the turning point.

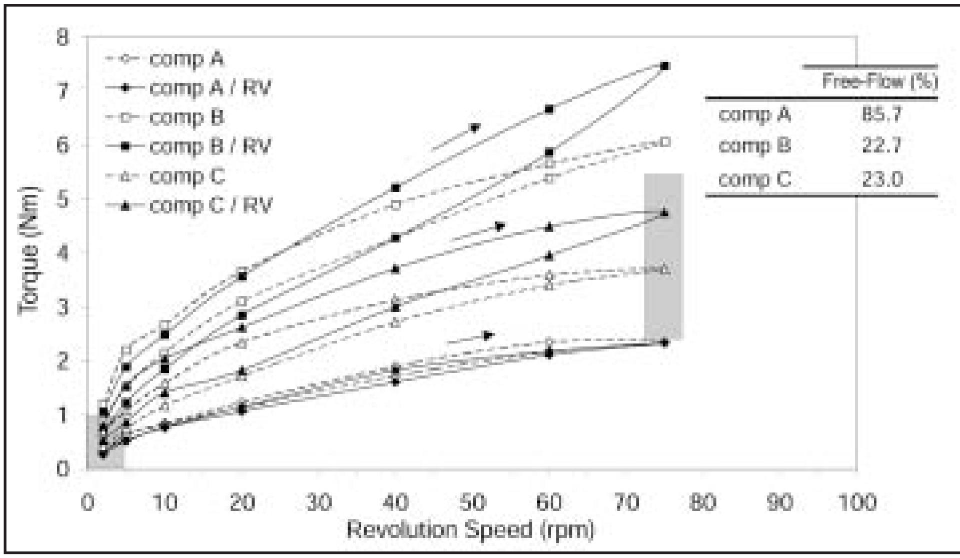

Figure 2 – Rheological behavior of the compositions A, B and C measured through shearing cycles (between 2 and 75 rpm) carried out without and with volume restriction (RV). Note: gray area highlights the torque range suitable for pumping [8].

ideal pumping range at high shear. Such rheological behavior does not, in effect, inhibit the flow inside pipelines, but high energy would be required to achieve this purpose. That being the case, the shotcrete's performance would be negatively affected by the undesirable outcome resulting from excessive shearing energy, such as excessive heating, irregular flow (plug-flow), segregation and structural damage (fiber rupture, particle fracturing) [6, 8].

2.3 Spray Shooting

The essence of the shotcrete application process consists of generating a compact castable layer by spray shooting the material onto the surface to be covered. In practice, the nozzle's conical geometry and the injection of high-pressure compressed air and additives into the pumped material cause a high-speed spray flow against the surface, which adheres to and consolidates on the surface (Figure 3).

Ideally, the castable spray flow is composed of individual high-speed granules (coarse aggregate covered with a matrix layer). It is reasonable to assume that, in order to ensure the granules' adhesion, the damping behavior of the matrix layer must

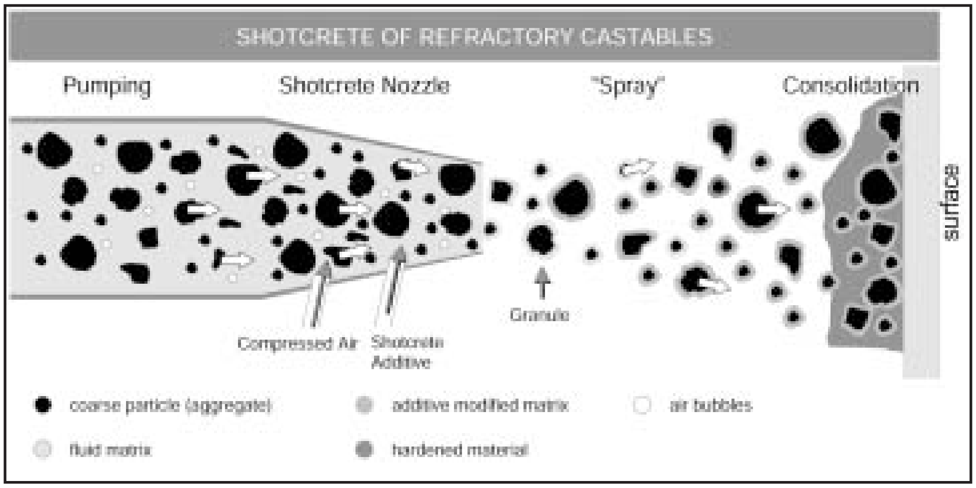

Figure 3 – Schematic drawing of castable spray shooting and the material's consolidation onto the surface.

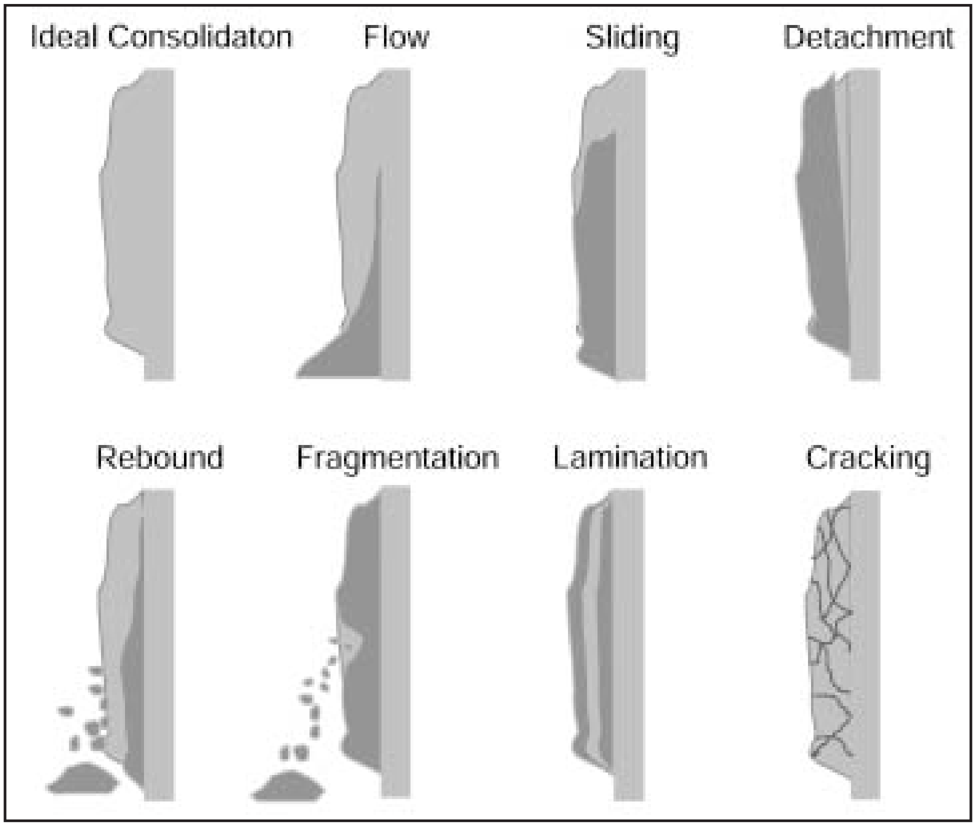

Figure 4 – Schematic drawing of the different problems that may occur during the shotcreting of refractory castables. Note: light gray represents the ideally consolidated castable; the dark gray, the distinct consolidation problems.

be able to dissipate all the kinetic energy associated with the granules when they strike the surface.

The dissipation of energy is aided by reducing the granule size or increasing the matrix/aggregate ratio. It is worth mentioning that the characteristics of the matrix layer also control the adhesion of granules to the surface, as well as its homogenizing capacity and its consolidating nature.

In addition to its high application rate, the shotcrete process often involves undesirable material losses (> 15 wt. %) caused by rebounding or fragmentation of the first deposited layer when successive applications are required [1-7]. Problems associated with the consolidated material, such as creep strain, sliding, detachment and lamination / cracking of the applied layer, are also common [1-7] (Figure 4).

These flaws have generally been attributed to the inadequacy of the pumped material to be sprayed [7] or to some of the multiple parameters involved in generating the spray [5]. However, the techniques conventionally applied to characterize the shotcrete performance of refractory castables do not provide accurate information about the phenomena involved in the spray shooting process, since they are based only on post-application analyses or on rheological evaluations of the matrix [6].

A laboratory test developed specifically to characterize the shooting performance of castables was recently proposed by Pileggi and Pandolfelli [6]. This method involves the use of a rheometer to simulate the shear conditions during the castable's application. The method allows for easy quantification of the impact of any specific factor (additives, water content, rheological nature, etc.), on the shotcrete's performance. However, this novel technique does not allow for analyses of the sticking tendency of shot-sprayed materials or of strength increases in the consolidated layer. For this reason, two alternative tests are proposed herein to improve the rheometer-based characterization method.

2.4. Sticking Test

After mixing, a conical device was introduced into the mixing bowl in order to provide a surface target. Additionally, the planetary mixing paddle was replaced by another specifically designed for shooting the castable at a high velocity against the conical target (Figure 5 (A)).

For the sticking test, the prepared castable (2 kg) was also homogenized at 33 rpm for 30 s. The shotcrete additive (1 wt. % of an aqueous solution composed of 0.4 wt. % sodium silicate and 0.6 wt. % of water) was injected at the end of the homogenization step and the revolution speed was suddenly escalated to 75 rpm, held there for 10 s, and then reduced to zero (Figure 5 (B)). The rebound loss was defined as the weight percentage of non-adhered material.

Large rebound losses were recorded for the self-flowing pumpable composition A, both with and without added fiber, whereas compositions B and C actually displayed good sticking features (Figure 6). These results confirmed the hypothesis that high fluidity is not directly related to shotcrete performance. However, the addition of fiber unexpectedly increased the rebound loss in composition A.

Considering that the same shotcrete additive (sodium silicate) was used in each composition, it can be concluded that the chemical composition and physical characteristics of the tested materials strongly influenced the material's adhesion onto the surface.

2.5 Consolidation Test

In order to evaluate the reaction profile during the shotcrete application process, the sodium silicate solution was injected into the castables (2 kg) at the end of the mixing homogenization step. Immediately following this addition, the revolution speed was abruptly escalated to 75 rpm, held for 10 s, then reduced to 20 rpm and held there for 120 s to evaluate the torque increase under low shear conditions (Figure 5 (B)).

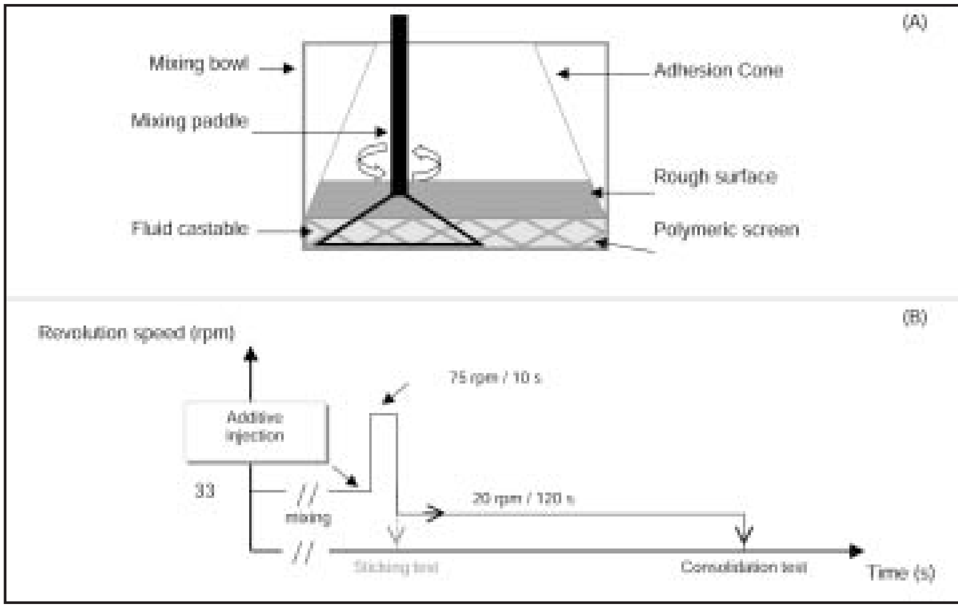

Figure 5 – (A) Schematic Drawing for the conical device employed in the sticking test; (B) revolution speed set-up employed in the sticking (only until the 75 rpm / 10 s step) and in the consolidation tests (75 rpm for 10 s + 20 rpm for 120 s). Note: the polymeric screen prevents the castable from sliding over the internal surface of the cylindrical bowl.

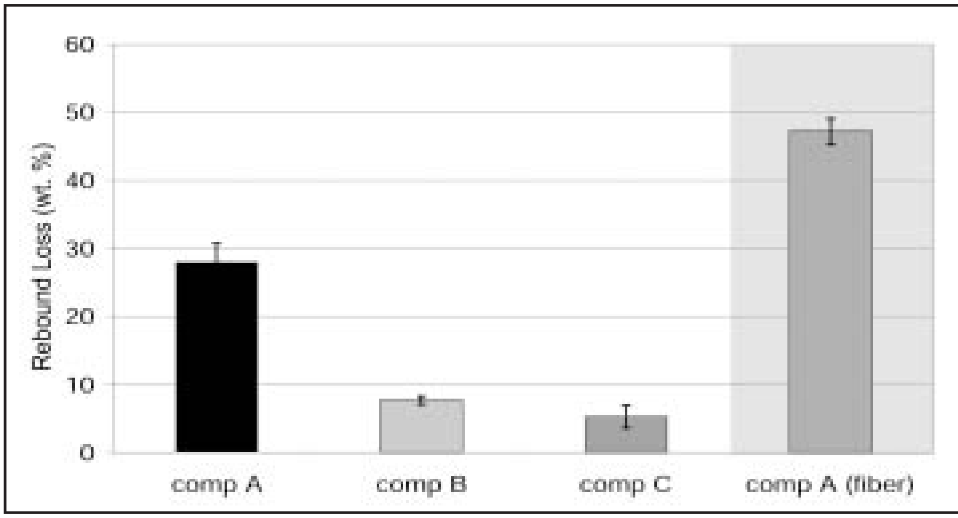

Figure 6 – Rebound loss measured in the sticking test for the compositions A, B and C. The shotcrete additive was sodium silicate (0.4 wt %). Polypropylene fibers were also added in equal amounts to compositions A, B and C.

In theory, the first 10 s at 75 rpm simulates the high-speed spray-shooting process. Only composition A (fiber) reacted instantaneously (Figure 7), resulting in a positive initial reaction rate (estimated through the angular coefficient calculated from the best linear fitting between torque and time actually held at 75 rpm in the high speed step), as demonstrated on Table II. The other systems remained almost unchanged in the first 10 s, probably due to a balance between the effects promoted by the additional liquid and the coagulating action of the shotcrete additive.

The addition of fiber accelerated the coagulating action promoted by the sodium silicate in composition A, possibly due to the friction promoted by the fibers [10]. This behavior is the main reason for the highest rebound loss reached by this system; in fact, the literature reports that rebound losses are minimized when the additives react more slowly in this initial stage [4].

High initial reaction rates harden the material inside the nozzle, hindering the formation of spray and leading to the formation of large agglomerates [7]. Moreover, hardened matrixes cannot dampen the collision impact between the granules and the surface.

In order to produce a dense coating on the surface, there must also be a lapse of time before the individual granules begin their setting reactions [4]. This condition ensures proper binding and homogenization between successively applied layers, preventing the material from sliding and reducing rebound losses.

This lapse of time was measured indirectly through the resting time, defined here as the time elapsed before restarting the torque increase at this stage (due to the action of the additive) and after reducing the revolution speed from 75 to 20 rpm in the rheometer.

According to this parameter, composition A (fiber) showed the shortest resting time, followed by the fiber-free composition (comp A), thus further reinforcing their high rebound loss. Both low-rebound compositions B and C displayed a similar resting time.

High initial reaction rates associated with short resting times may be assumed to be the driving force that increases rebound losses in refractory castable shotcrete.

Regardless of the rebound, the consolidated material must also be strengthened over the surface to avoid the creep strain resulting from its own weight, which allows thick layers of coating to form. In the experimental setup proposed herein, the maximum torque in the final step (20 rpm / 120 s) describes the material's consistency after its application.

Composition A, with or without added fiber, resulted in high maximum torque val-

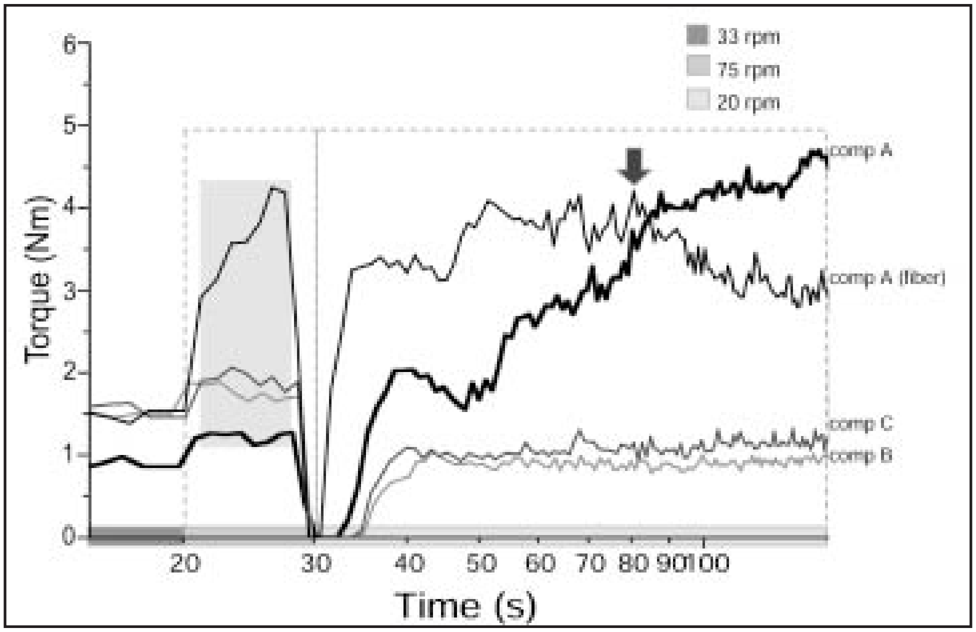

Figure 7 – Reaction profile measured through the consolidation test for the compositions A, B and C. Note: sodium silicate (0.4 wt %) was used as the shotcrete additive. The dark gray arrow indicates the rupture that occurred in composition A (fiber) under shearing. The reaction rate was estimated through the angular coefficient calculated from the best linear fitting between torque and the real time at 75 rpm (gray area) in the high speed step.

Table 2. Parameters calculated during the consolidation test: reaction rate; resting time; maximum torque at low speed step (20 rpm).

	(75 rpm)	(20 rpm)	
	reaction rate (Nm/s)	resting time (s)	maximum torque (Nm)
comp A	0.00	2.09	4.69
comp B	-0.04	4.17	1.01
comp C	-0.02	4.18	1.30
comp A (fiber)	0.22	0.65	4.15

Note: the reaction rate was estimated through the angular coefficient calculated from the best linear fitting between torque and time in the 75 rpm step.

ues during this step. Conversely, compositions B and C did not afford significant maximum torque values, which may have inhibited the formation of thick layers of coating.

The fiber-containing composition A developed excessive rigidity, evidenced by the rupture of its structure by shearing during the test (20 rpm). In practice, such a lack of plasticity may result in lamination or in the rupture of the consolidated layer from the impact caused by spraying on successive layers of material.

In fact, a suitable behavior would have been achieved with a composition/additive combination that provided a resting time similar to that of compositions B and C, and a final torque such as that of composition A.

3. FINAL REMARKS

The new testing procedure proposed here demonstrated that high fluidity is not the most important feature for good shotcrete performance. Instead, low mixing energy and low torque values at high shearing rates under volume-restricted conditions were found to be better requirements for shotcrete of materials.

According to the sticking and consolidation test results, rebound losses are reduced when the shotcrete additive does not cause a high initial reaction rate or a too brief resting time. High maximum torque after consolidation is also required for placing thick layers.

In view of all these factors, composition C displayed good shotcrete performance, though only for thin coating layers. Composition A resulted in large rebound loss due to its high reaction rate, which was further increased with the addition of fiber. On the other hand, composition B required a lot of energy for mixing and proved unsuitable for pumping.

The multistage characterization technique developed to evaluate the shotcrete performance of refractory castables was a further step used for analyzing the mixing, pumping and shooting behavior of these materials.

ACKNOWLEDGEMENTS

The authors are greatly indebted to the Brazilian research funding institutions FAPESP and CNPq, and to Saint Gobain / Brazil, for their support of this research work.

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ries preparation laboratory), two large-volume air furnaces for processing and characterization of refractories.

The main research project is "Refractories for Non-Ferrous Metals Smelting" sponsored by NSERC and five industrial partners. The partnership in this project has an equilibrated structure for improving the existent processes and creating new technologies for non-ferrous metallurgy. The industrial partners are TeckCominco Metals Ltd. and Inco Ltd., two of the largest producers of Zinc-Lead and respectively Nickel in the world, Hatch Associates Ltd., one of the largest metallurgical design companies in the world, and two refractory manufacturers, RHI, the largest refractory manufacturer in the world and the main supplier of refractories for non-ferrous furnaces, and Clayburn Industries, the only 100% Canadian owned refractory producer in Canada, also having manufacturing plants in China and USA.

The main objective of this Consortium is to address specific issues regarding manufacturing and use of refractories for zinc-lead and nickel-copper smelting. Our research is concentrated on three directions: i) establish the mechanisms of failure for refractories used in industrial furnaces and develop solutions for increasing the life in service for the commercially available refractories; ii) establish the mechanisms of hydration for refractories used in combination with water cooling jackets and develop solutions for increasing their life in service; iii) develop new refractories with improved corrosion and hydration resistance. We are also developing new reactive oxide powders used in refractory technologies to allow the formation of a ceramic matrix in refractory castables at the operating temperatures of industrial furnaces, much lower than in steel technologies. The new developed refractories are tested against traditional bricks in the corrosive gases and metal fumes, similar to those from the industrial smelting furnaces, before being selected for pilot and industrial scale experiments.

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UBCeram maintains close working relationship with a number of BC industries, as well as research and industrial organizations throughout Canada and the US. The majority of the research programs are of a collaborative nature, including cash and in-kind contribution from industry. Additionally, UBCeram is involved in a number contract services in the areas of expertise, obviously related to characterization of ceramics and refractories but also delivery of trial samples of the novel materials and techniques developed through UBCeram research programs.

THE FUTURE

By virtue of changing times and also because of the geographical location of Vancouver, we are encouraged to "work locally and think globally". The vision of UBCeram is that it will become a major ceramics laboratory, servicing primarily Western Canada and Northwest US, but also active on a world scale, in particular within the Pacific Rim countries. Our research collaborations with Asian countries increased rapidly in the recent 2-3 years. We will continue to build on our expertise in structural ceramics, ceramic coatings, ceramic composites and refractories. In the short term, UBCeram will link together professionals from British Columbia and the other provinces of Canada to form a pool of expertise capable of addressing most of the local and worldwide needs of users and manufacturers of ceramics and refractories. Our web site will serve as a focal communication and information tool for the UBCeram related research, teaching and service.

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