EFFECT OF SHOTCRETE CONSISTENCY AND NOZZLEMAN EXPERIENCE ON REINFORCEMENT ENCASEMENT QUALITY

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1. INTRODUCTION

The proper encasement of reinforcement in shotcrete is a critical issue with respect to the quality and the durability of a shotcrete application. One simply has to refer to the Shotcrete Nozzleman Training Course offered by the ASA (see *Shotcrete* Magazine, Vol. 1, No. 4) or the recently available Nozzleman Certification Program of ACI to confirm this statement. Although many concerns have been raised, mostly by owners, regarding the presence of voids around reinforcement and their potential effects on structural performance, there is, unfortunately, little technical data available to back up the shotcrete industry on this problem.

Several years of experience with a certification program for shotcrete nozzlemen, as well as early research (Studebaker, 1939) suggest that the best approach is to apply dry-mix shotcrete[1] at its *wettest stable consistency,* which is defined as *"the consistency at which the moisture content is the maximum, the maximum being determined by the stability of the fresh gunite* (shotcrete)." However, observations on many job sites and training of nozzlemen show that many apply shotcrete with a relatively dry (stiff) shooting consistency, which may adversely affect rebar encapsulation as well as increase rebound.

The Industrial Chair on Shotcrete and Concrete Repairs of Laval University (City of Quebec, Canada) has initiated a thorough investigation into the *Evaluation of reinforcement encasement quality and its effect on shotcrete quality*. This research program is financed by the partners of the Industrial Chair, the Concrete Research Council of ACI, as well as by the American Shotcrete Association (ASA). It has several objectives, including:

1. Development of a test method to quantitatively evaluate reinforcement encasement;
2. Identification of the most significant mixture design and shotcreting technique parameters with respect to proper rebar encasement;
3. Evaluation of the effect of reinforcement encasement quality on structural behavior; and
4. Evaluation of the effect of reinforcement encasement quality on durability, particularly with respect to reinforcement corrosion.

This paper presents the preliminary results dealing with the second objective. First, the experimental program prepared to evaluate the effect of consistency, as measured by a penetration test (Armelin et al., 1997 and Jolin, 1999), and nozzleman experience on the quality of reinforcement encasement.

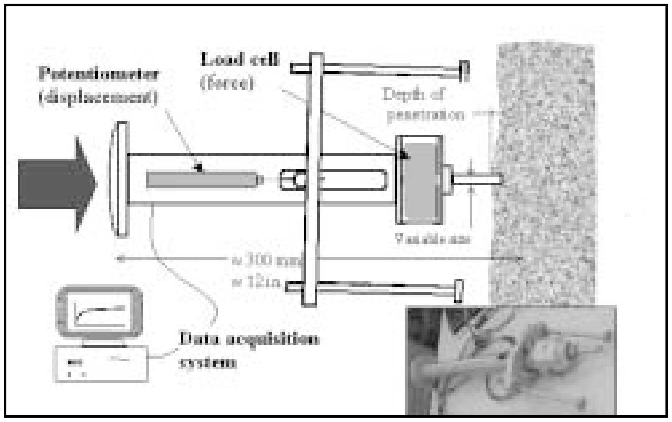

Figure 1: Schematic of the electronic penetrometer.

2. EXPERIMENTAL PROGRAM

This section includes a description of the penetration test used to evaluate shooting consistency. Then, the results of the investigation, along with some descriptive pictures, are presented. Since the first objective listed above is not yet completed, the ACI core grading system, adapted for sawed panels, has been used to evaluate the quality of the encasement. Only the dry-mix shotcrete process was considered in this study.

A total of 16 certification panels were shot with the same standard dry-mix shotcrete mixture (mixture design is given in Table 1). The variables of the study were: nozzleman experience and the consistency of the freshly applied shotcrete. The experience of the nozzlemen was quite variable: first, an experienced nozzleman, second, a shotcrete researcher (Ph. D. in shotcrete technology) with limited experience as a nozzleman (less than 500 hours), and a last person with no shotcreting experience at all. Each was asked to shoot several certification panels at different shotcrete consistencies (Figure 2). For the non-experienced nozzleman, the spraying consistency was adjusted by the experienced nozzelman prior to the application.

The method to evaluate shooting consistency is described in the next section.

2.1 Evaluation of consistency

Dry process shotcrete consistency or workability has usually been

[1] Although reinforcement encasement problems can be encountered in both processes, the presence of void around reinforcement is usually more important in the dry process than in the wet process.

defined only qualitatively. Powers (1968) defines the consistency as the resistance of a material to deformation, often referred to as "dry" or "wet" consistency. This definition of consistency is well-suited to the shotcrete industry. Anyone who has worked with shotcrete has heard of a mixture being shot "too stiff," or of a mixture sloughing because it was shot "too wet." The first thing a nozzleman does after stopping a shooting operation is to poke the fresh shotcrete surface with his finger, probably the simplest way to assess consistency.

In this project, consistency was determined using a penetration test. The measurement is carried out by pushing a flat head cylindrical needle into the fresh concrete; the penetration resistance is regarded as being a measurement of the consistency. This method has been used in many research projects (Prudêcio et al. 1996; Figueiro and Helene 1996; Armelin et al. 1997; and Jolin 1999) and has been found to be a reliable method to assess the workability of the fresh material. The apparatus used is shown in Figure 1. The typical results and interpretation is outside the scope of this paper. In short, the reader should remember that following a short initial penetration, the material deforms and flows around the needle under a constant pressure; this pressure is defined as the consistency.

Table 1: Standard Quebec's D.O.T. dry-mix shotcrete used in this study.

Material	Proportion
Cement (10SF)*	450 kg/m^3 (760 lbs/cu.yd)
Fine aggregate	1510 kg/m^3 (2545 lbs/cu.yd)
Coarse aggregate 10-2,5 mm	235 kg/m^3 (400 lbs/cu.yd)
Polypropylene fibers	1.0 kg/m^3 (1.7 lbs/cu. yd)
Air-entraining admixture	As required for adequate air void system

*The type 10SF is an ordinary portland cement which contains about 8% silica fume.

3. RESULTS

Three days after shooting, the 16 reinforced test panels were saw-cut perpendicular to the reinforcement to analyze the encapsulation quality. Visual examination of the sawed panels, based on the ACI core grade system (ACI 506.2-95), was performed by two ASA-approved examiners. Figure 2 shows the test panel used and an example of the reinforcement encasement evaluation specimens (each panel yields 16 "core grading locations"). Although the results of the core grade should not be averaged for training and certification purposes, the authors did so in Figure 3 for the sake of simplicity and clarity, since each panel received sixteen grades per examiner.

The unreinforced panels were properly cured, and cored in order to perform compressive strength tests and evaluate absorption values. Also, setting times were evaluated on some of the mixtures produced. These results will, however, be presented in a future paper.

Figure 2: Certification panel used in the province of Quebec with typical sawed specimens.

Panel is 600 x 600 mm^2 (24 x 24 in^2) at the back and 125 mm (5 in.) thick. Clear spacing behind reinforcement is 25 mm (1 in). The equally spaced bars are, top to bottom: #25M (#8), #20M (#6), #15M (#4), and 2 adjacent #15M (#4).

3.1 Encapsulation quality

Figure 3 offers a conclusion that everyone would expect: the experience of the nozzleman is of prime importance in the production of good quality reinforcement encapsulation. The second conclusion taken from Figure 3 is that, along with nozzleman experience, the shooting consistency is also of prime importance. There are therefore two important requirements[2] for obtaining good quality rebar encapsulation: adequate shooting technique (reflected here by the nozzleman experience) and sufficiently plastic fresh shotcrete (reflected here by a low shooting consistency). Figure 3 clearly shows that a beginning nozzleman will have a very hard time embedding reinforcement even if the shooting consistency is adequate, and that an experienced nozzleman may also have a hard time embedding reinforcement if the shooting consistency is not adequately adjusted.

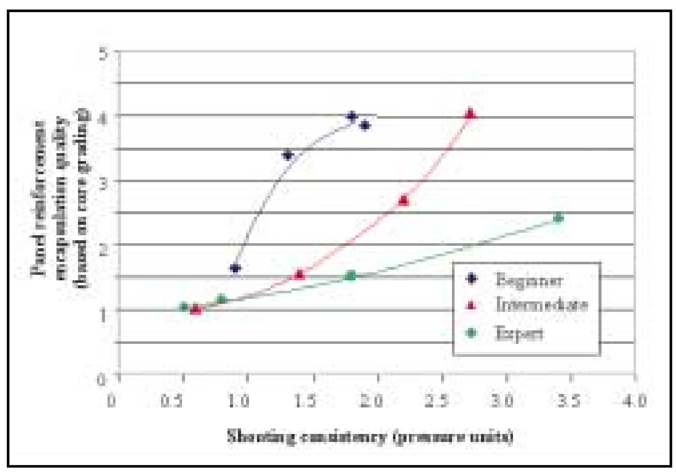

Figure 3: Overall encapsulation quality as a function of the shooting consistency and the experience of the nozzleman.

Now, having in mind these two conditions for good rebar encapsulation—shooting consistency **and** nozzleman experience—further observations of the encapsulation test panels were made to verify whether the type of defects found were related to these

[2] Given the right equipment is used, and that it is set and operated by an experienced crew.

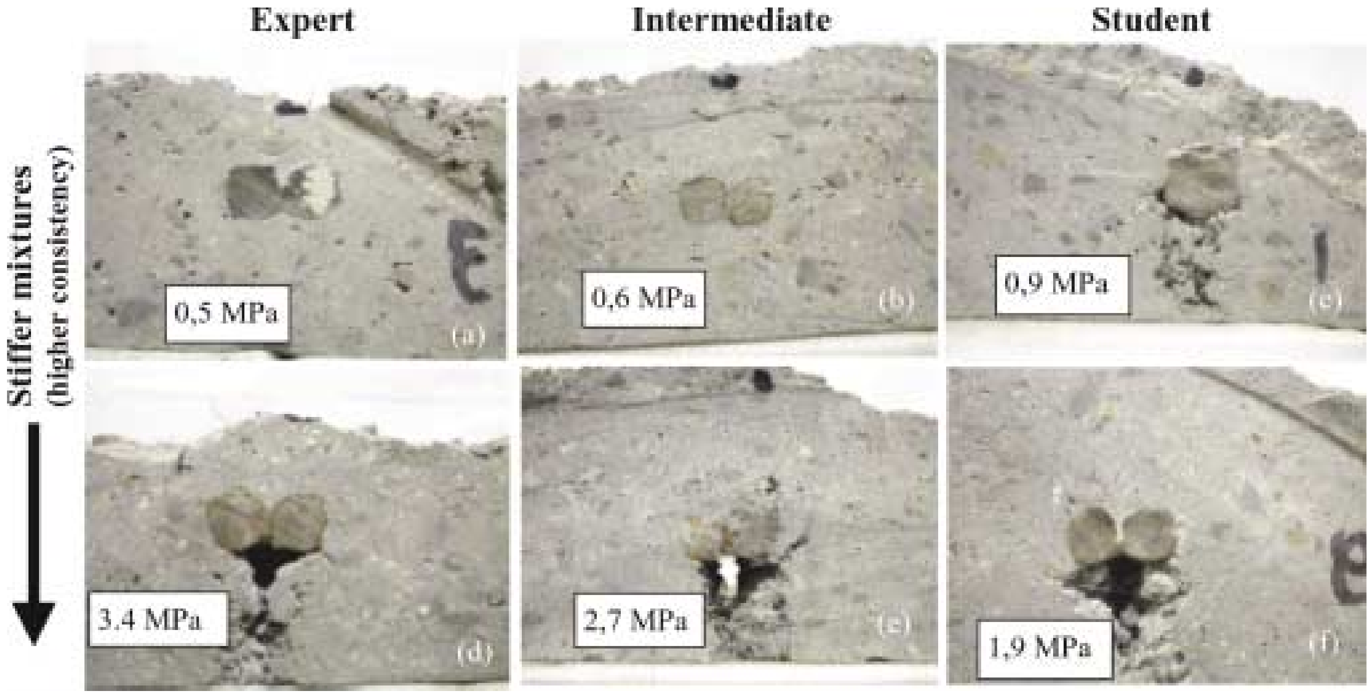

Figure 4: Six examples of reinforcement encasement quality as a function of the shooting consistency and nozzleman experience.

conditions. Even though this was a visual examination, an interesting observation was made, as presented in the following section.

3.2 Types of defects in reinforcement encapsulation

Although many types of defects can be identified on a specimen used for evaluation of reinforcement encasement quality, the visual examination performed in this study was focused on the quality immediately behind the reinforcement, and highlighted two categories of major defects: voids behind the reinforcement (Figure 4(d), (e), (f)), and entrapped rebound behind the reinforcement (Figure 4(c), (e), (f)).

The assumptions made early in this project were, first, that a poor nozzling technique alone (given an adequate consistency) would probably result in a majority of bars with rebound entrapped behind; and second, that a high shooting consistency ("too stiff"), given proper nozzling technique, would result in a majority of bars with an empty void behind, due to the lack of plasticity in the mixture. The overall observations made on the 16 panels confirmed these assumptions. Obviously, other types of defects were also observed, but the general trend is clear. Figure 4 shows examples taken from 4 different panels. The nozzleman experience and the shooting consistency are reported on each picture. The reader should go back to Figure 3 to develop an appreciation of the shooting consistency.

4. DISCUSSION & CONCLUSIONS

The initial findings of this research project on reinforcement encasement quality are presented in this paper and are extremely interesting. Although the results confirm common knowledge concerning the effect of nozzleman experience and shooting consistency on the quality of reinforcement encapsulation, it is now possible to relate it to laboratory data. It is shown that, no matter how good the shotcreted material is, the inexperienced nozzleman will most probably not be able to properly encase the reinforcement. Also, it is shown that experience alone is not sufficient to guarantee a good reinforcement encasement everywhere. A sufficiently low shooting consistency must be met.

The last statement of the previous paragraph has significant consequences. Indeed, the question now is how to verify whether all dry-mix shotcrete mixture is shot at a sufficiently low consistency to allow proper encasement of the reinforcement. Although a complete answer cannot be given, it should be noted that the shotcrete mix design is extremely important when it comes to reinforcement encapsulation, by way of the wettest stable consistency attainable for a given mixture. In Jolin et al. (2001), it is reported that a shotcrete made with silica fume and 10 mm (3/8 in) coarse aggregate yields the mixture with the *lowest stable consistency*, and is thus the mixture with the best chances of realizing good reinforcement encapsulation.

5. ACKNOWLEDGMENTS

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