Pergamon

CEMENT AND CONCRETE RESEARCH

Cement and Concrete Research 29 (1999) 753–760

Tests to characterise properties of fresh dry-mix shotcrete

Marc Jolin [a,*], Denis Beaupré [b], Sidney Mindess [a]

[a]Department of Civil Engineering, University of British Columbia, Vancouver V6T 1Z4, Canada

[b]Department of Civil Engineering, Laval University, Ste-Foy, Québec G1K 7P4, Canada

Manuscript received 13 July 1998; accepted manuscript 8 March 1999

Abstract

The intent of this project is to study the fundamental characteristic properties of dry-mix shotcrete. Although several factors are known empirically to influence the shooting properties of the dry process shotcrete, it is generally not clear how and why these variables are important, particularly with regard to the maximum buildup thickness. With this in mind, different dry-mix shotcrete mixtures were shot, and rebound and maximum buildup thickness were evaluated for each. In particular each mixture was shot at a different consistency, which was evaluated from the force required to push a needle into the fresh shotcrete. Relationships were found between the penetration resistance of a fresh mixture and its fresh tensile strength or maximum buildup thickness (cohesiveness). However, distinct relationships were obtained for the different mixtures tested, which implies that consistency (penetration stress) is not sufficient by itself to characterise fresh dry-mix shotcrete. The addition of silica fume or air-entraining admixture allowed one to shoot better quality shotcretes. However, these additions had an opposite effect on the fresh tensile strength.

Keywords: Fresh concrete; Rheology; Workability; Silica fume; Shotcrete

Shotcrete is a pneumatically applied, self-compacting material. Its mode of application makes it appropriate for placing concrete for tunnelling, repairs, slope stabilisation, and other activities for which conventional placing methods would be less economical or efficient. The two main questions regarding fresh properties that arise with this method of placing concrete are: (1) What is the amount of rebound going to be? and (2) What maximum thickness can safely be placed? The mechanisms behind the rebound of particles are now better understood [1,2], but the maximum buildup thickness is a property that needs further study. Although some factors are known empirically to influence the buildup thickness (for example, accelerating admixtures, silica fume, amount of water added to the mix), it is not clear how, why, and to what extent these variables are important. Accurate prediction of the maximum buildup thickness has many important advantages: safety and confidence of the construction crew, quality of the in-place shotcrete, and economy if the number of successive application is reduced. Therefore, the main objective of this research project was to identify the mechanisms involved in the placement of a sound layer of dry sprayed concrete. Also, because of the uniqueness of the dry-process shotcrete, special tools were used to measure the fresh properties of the in-place shotcrete.

* Corresponding author. Tel.: 418-656-3163; Fax: 418-656-3355; E-mail: mjolin@gci.ulaval.ca.

0008-8846/99/$–see front matter
PII: S0008-8846(99)00071-X

1. Research program

The preliminary research program consisted of identifying tests to assess the properties of fresh dry-mix shotcrete. The UBC Penetrometer [1,2] and the fresh tensile strength apparatus were used. In addition, various shooting parameters, such as the amount of water added at the nozzle and the mass of the in-place shotcrete, were monitored during a shooting session. This study was entirely carried out in the shotcrete laboratory of Laval University.

Several mix parameters were investigated to compare their effects on the fresh concrete properties. These were: the presence of coarse aggregates, silica fume, and air-entraining admixture. The first mixture was a regular mortar with a cement to sand ratio of 1:4. For the second mixture, 10% of the cement was replaced with silica fume. The third mixture was similar to the first one, but was shot with an air-entraining admixture added to the shooting water (15 ml/liter of water). Finally, the last mixture was a regular shotcrete mixture with dry proportions by mass of 18% cement, 2% silica fume, 62% sand, and 18% coarse aggregates. The first and third mixtures were made with Type III cement, while the second and last were made with Type I cement and silica fume. In every case, mixtures were produce using dry prebagged material.

Shotcrete was sprayed using a rotating barrel ALIVA 246 (Aliva AG, Postfach, Switzerland) with a 32-mm diameter hose. Shooting operations took place in a rebound chamber. Normal gunning techniques were observed unless otherwise specified [3,4].

2. Fresh dry-mix shotcrete

2.1. Water flow

When dealing with dry-mix shotcrete, it is generally agreed that the most important factor influencing the quality of the material are the skills and experience of the nozzleman, who is the one controlling the consistency of the fresh shotcrete through a metering water valve mounted on the nozzle. As demonstrated later, the consistency is a critical property of the fresh shotcrete since it affects the amount of rebound, the maximum buildup thickness, and the workability [5], which in turn controls reinforcement encasement and finishing operations. Hence, the water flow at the nozzle was the first parameter monitored and controlled in this project. Water flow records obtained during two shooting sessions are shown in Fig. 1. The dotted line represents an uneven water flow at the nozzle during shooting; this implies that the mix will not be homogeneous (laboratory notes confirm that observation). For example, a mixture that tends to stick to the delivery hose, or one that exhibits irregular flow of dry material, would change the pressure equilibrium at the water ring, thereby introducing significant variations in the water flow. Such mixtures were discarded and reshot. In Fig. 1 the solid line shows an acceptable shooting session; the water flow at the nozzle is relatively constant, which allows for a homogenous in-place shotcrete. Thus, water flow measurements can provide a good indication of the quality and regularity of a particular shooting session.

2.2. Consistency

Powers [6] defined consistency as the resistance of a material to deformation; materials are often referred to as having "dry" or "wet" consistency or as being "stiff" or "soft." This definition is well suited to shotcrete technology. To ensure comparability among mixtures of various compositions, a consistency criterion may be set, for which the nozzleman is allowed to adjust the water flow to achieve the desired consistency (as opposed to equal water/cement ratio in conventional concrete). A quantitative way to assess consistency was presented by Prudêncio et al. [7] by using the Proctor apparatus (cylindrical needle of 9-mm diameter [8]). A correlation was found where the higher the water content of the in-place shotcrete, the lower the penetration resistance. Using an instrumented version of the Proctor needle, Armelin and colleagues [1,2,5] obtained similar relationships between penetration resistance and rebound as well as in-place water/cement ratio.

The instrumented version of the Proctor apparatus was also used in this project; thus, a consistency test consists of pushing a 9-mm cylindrical needle into fresh shotcrete and recording the penetration stress as a function of the depth of penetration (minimum of four similar curves per test). Fig. 2 shows typical results obtained on a 450- × 450-mm fresh shotcrete panel; the four curves represent tests made on four different areas of the panel, hence demonstrating excellent repeatability. The value of the plateau found is then referred to as the consistency or the penetration stress.

Fig. 3 shows the relationships obtained for different mixtures between the penetration stress and the water flow at the nozzle. In view of the relationships cited above and the excellent correlation shown in Fig. 3, the penetration resistance is considered to be a general test to evaluate fresh dry-mix shotcrete consistency or workability. The consistency value obtained is *not* a compressive strength; rather, it is much more closely related to the shear strength of the material [9–11].

2.3. Rebound

The amount of rebound obtained on vertical surfaces typically falls between 15 and 35% for the laboratory setup used and is comparable with values reported in the literature

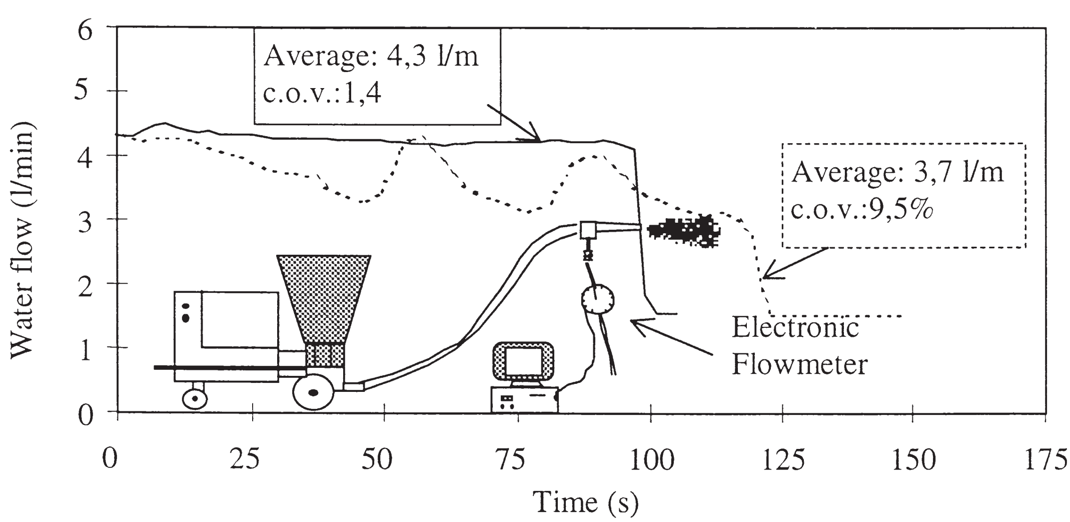

Fig. 1. Water flow at the nozzle during two shooting sessions; dotted line represent a rejected sample because of inhomogeneity, c.o.v. represents the coefficient of variation.

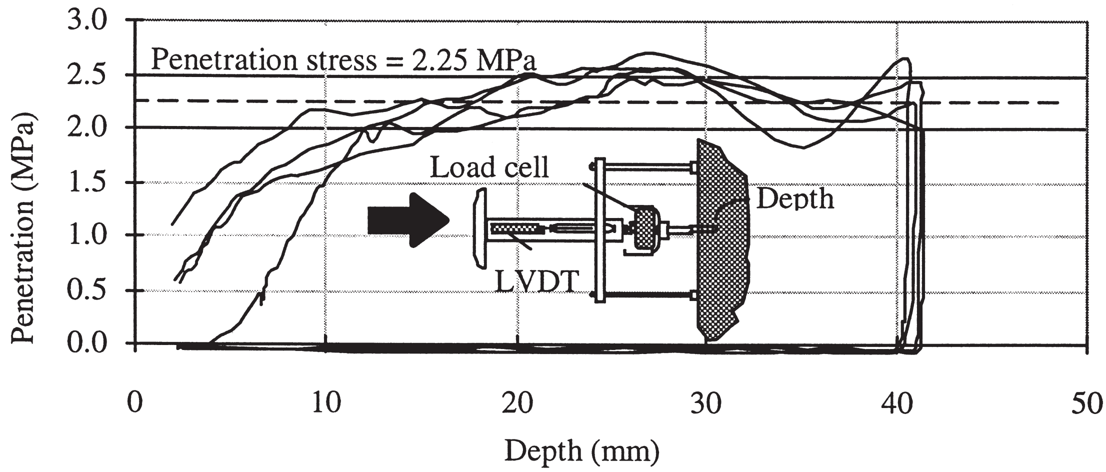

Fig. 2. Penetration load as a function of the depth of needle penetration for one mixture.

[5,12–14]. Fig. 4 shows the amount of rebound obtained for the different mixtures shot at various water flows at the nozzle. Note the excessive amount of rebound obtained for the plain mortar mix. Consistencies encountered for rebound values greater than 35% are not of practical interest; however, such mixtures were shot to verify successfully the general shape of one curve. If Fig. 3 and Fig. 4 are combined (see Fig. 5), an almost linear relationship between the shooting consistency and the amount of rebound is obtained for each mixture, as was also reported previously [5]. Assuming the consistency to be related to the shear strength of the fresh shotcrete, this proportional relationship is expected, since rebound mechanisms involve the yield strength of the material. This highlights the importance and the validity of the consistency measurement as a general comparator for fresh shotcretes. A complete treatment of rebound mechanisms are reported elsewhere [1,2].

2.4. Buildup thickness

Maximum buildup thickness measurements were made using the frame shown in Fig. 6. The maximum buildup thickness value is the maximum thickness of shotcrete that can successfully be applied in a single overhead pass (measured from the mesh to the bottom, as in Fig. 6). A poor correlation was obtained between the maximum buildup thick-

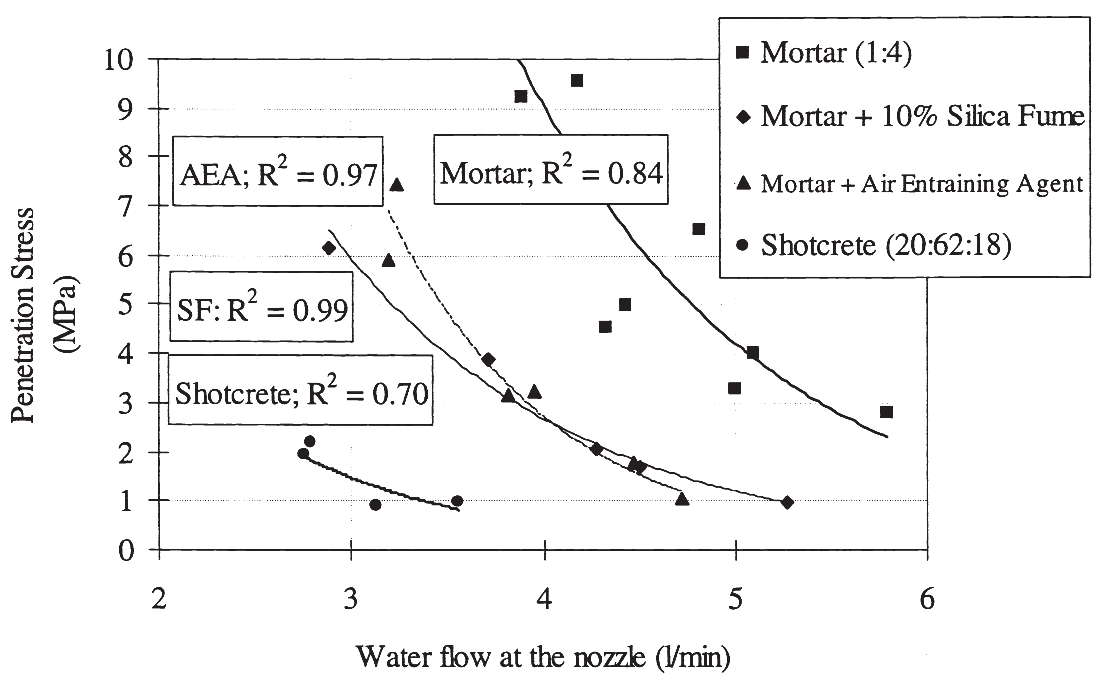

Fig. 3. Consistency (penetration stress) of different mixtures shot with different water flows at the nozzle.

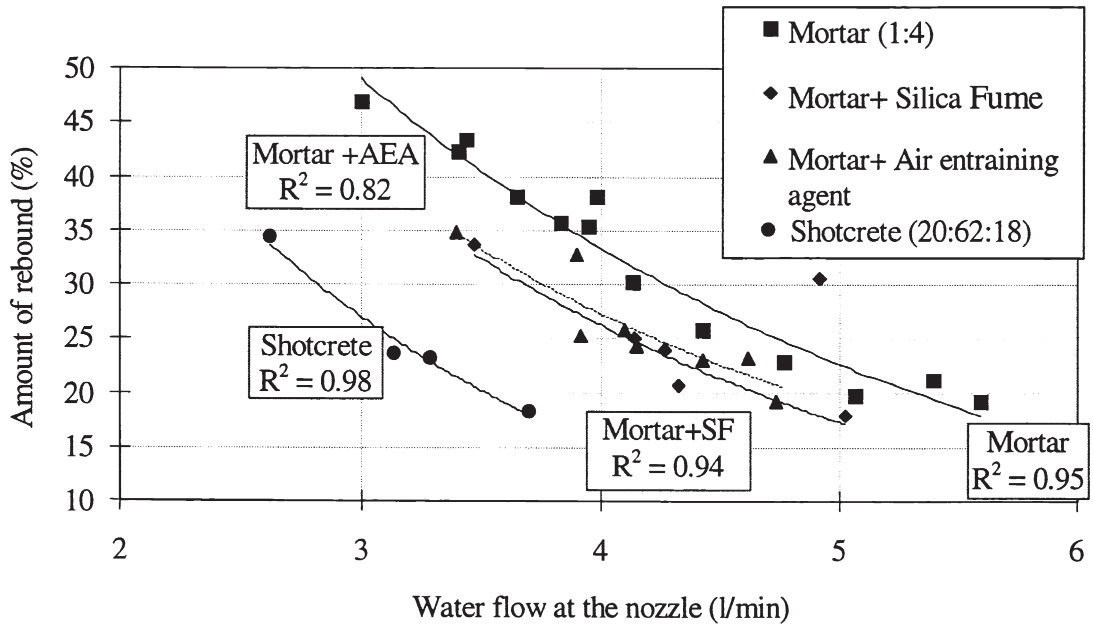

Fig. 4. Rebound values for various mixtures shot with different water flows at the nozzle.

ness and the penetration stress, as shown in Fig. 7. This can be explained by the relatively large test panels (600-mm sides) that were used. Their size made it difficult to fill them evenly without creating a "bump" in the centre that led to poor test repeatability. Moreover, it was difficult for the operator to assess the thickness with the required precision. For these reasons, another quantity, the cohesiveness, was measured. The cohesiveness, defined as the average tensile strength over the ruptured area, was calculated as the weight of the overhead panel (mounted on load cells) divided by the area of the ruptured surface in the shotcrete after fallout. The values of cohesiveness obtained in this manner are shown as a function of the consistency in Fig. 8. It is assumed that the cohesiveness is related to the maximum buildup thickness and that similar relationships would appear in Fig. 7 if the maximum buildup thickness test setup was modified and enhanced.

The curves presented in Fig. 8 show, first, that for a given mixture, there is a direct relationship between the cohesiveness and the consistency. This is expected since, in failure terms, tension and shear are related [10,11]. (A failure criterion is a mathematical expression that relates the shear stress on the failure plane at failure to the stress state of the element at failure [9–11].) Second, there is a distinct curve for each type of mixture; thus, for a given consistency, two different mixtures may not achieve the same maximum

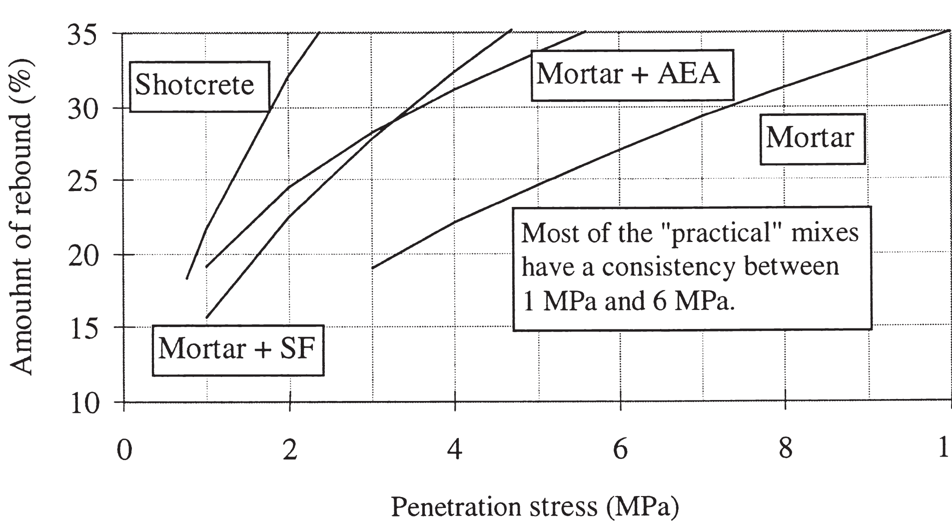

Fig. 5. Predicted relationships between the amount of rebound and the penetration stress (consistency).

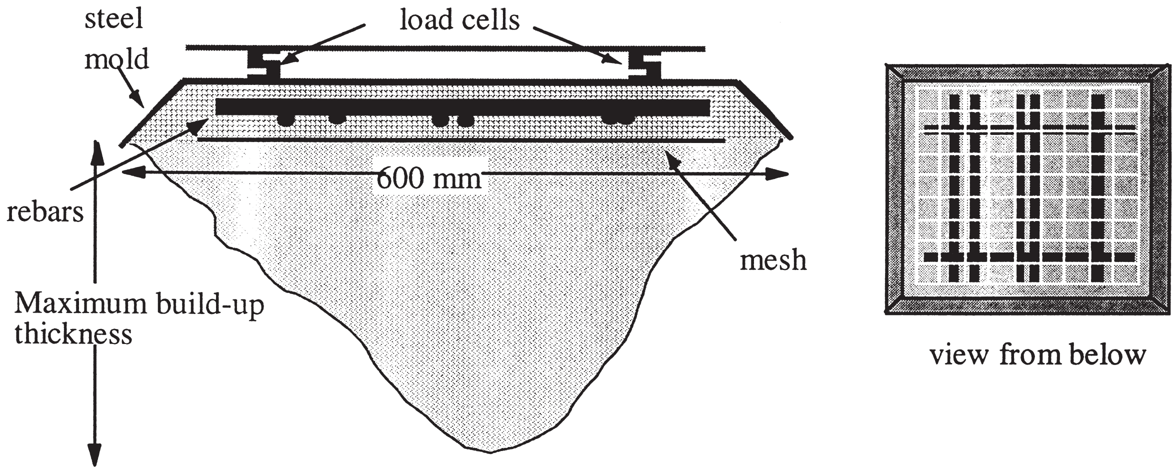

Fig. 6. Typical buildup patterns when a large testing panel is used.

buildup thickness. Therefore, the consistency measurement is not sufficient by itself to completely characterise the properties of fresh dry-mix shotcrete.

Although Fig. 8 suggests that almost any cohesiveness (and buildup thickness) can be attained with any of the tested mixtures, one must remember that the higher the consistency, the larger the fraction of material rebounding will be, as shown in Fig. 5 for a vertical rebound situation. Also, the quality of the in-place shotcrete can also be impaired if a mixture is shot excessively dry (high penetration resistance).

2.5. Fresh tensile strength

The fresh tensile strength test was also performed on the various mixtures. The test procedure is relatively simple. First, shotcrete is shot directly into a special mould mounted vertically in the rebound chamber. After finishing operations, the mould is moved to a special frame equipped with a load cell and a displacement transducer. Fasteners are then removed to permit free movement of the half panel on the rails. An electrical motor applies a slow deformation rate to the movable part of the apparatus. The load and the displacement are recorded as the fresh shotcrete is loaded in tension. A schematic drawing of the apparatus and the typical results obtained for one test are presented in Fig. 9. Fresh tensile strengths are plotted against penetration stress values in Fig. 10 for a few mixtures. The same conclusions presented in the two preceding paragraphs for the cohesiveness apply equally to fresh tensile strength, since both properties describe the same phenomenon (i.e., tension failure).

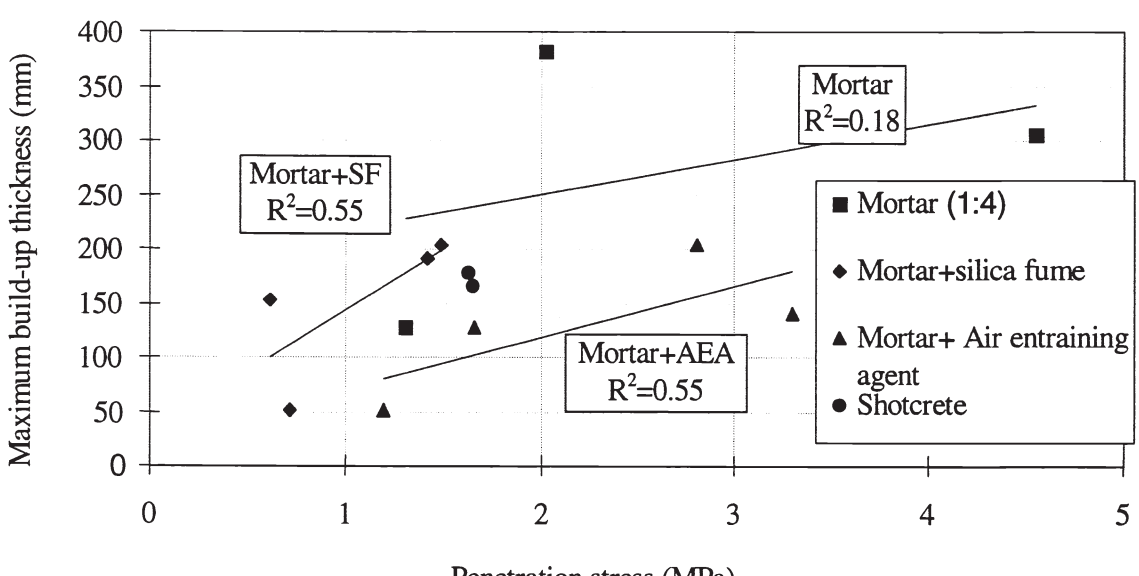

Fig. 7. Maximum buildup thickness values for various mixtures shot with different water flows at the nozzle.

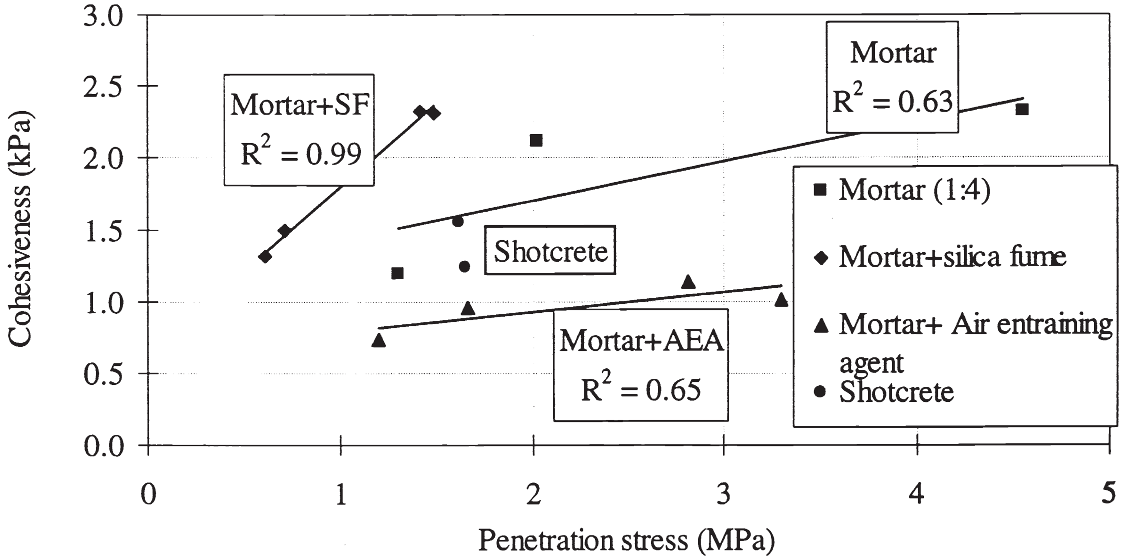

Fig. 8. Cohesiveness (maximum buildup thickness) for various mixtures as a function of the penetration stress (consistency).

3. Discussion

The equipment and the test setup used allowed the shooting of homogeneous and well-controlled mixtures. The use of the UBC Penetrometer provided a quantitative measure of a well-known quality of shotcrete: its fresh consistency. This consistency, which is related to the shear strength of the fresh material, was therefore used as a common comparator among mixtures. The relationships found between the consistency and the amount of rebound as well as the water flow at the nozzle confirmed the usefulness of the consistency test as a comparison criterion. However, it was shown that this test is not by itself sufficient to completely characterise fresh dry-mix shotcrete since, for an equal consistency, different mixtures behaved differently under tensile stress.

Although the maximum buildup thickness measurements were not satisfactory, an equivalent quantity, the cohesiveness, exhibited good correlation with the consistency measurements and, moreover, provided distinct curves for each of the mixtures studied. The same remarks apply to the fresh tensile strength test, since the stiffer the mixture, the more difficult it was to separate. Though if both relationships were expected from a failure theory point of view, the fact

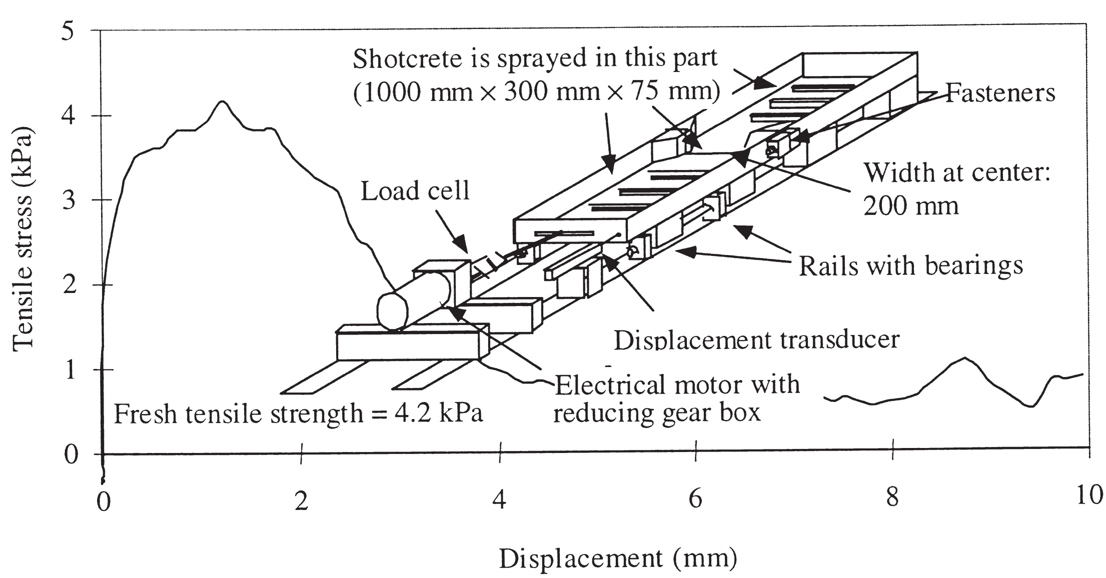

Fig. 9. Tensile stress in shotcrete as a function of the relative displacement of the two halves of the mould.

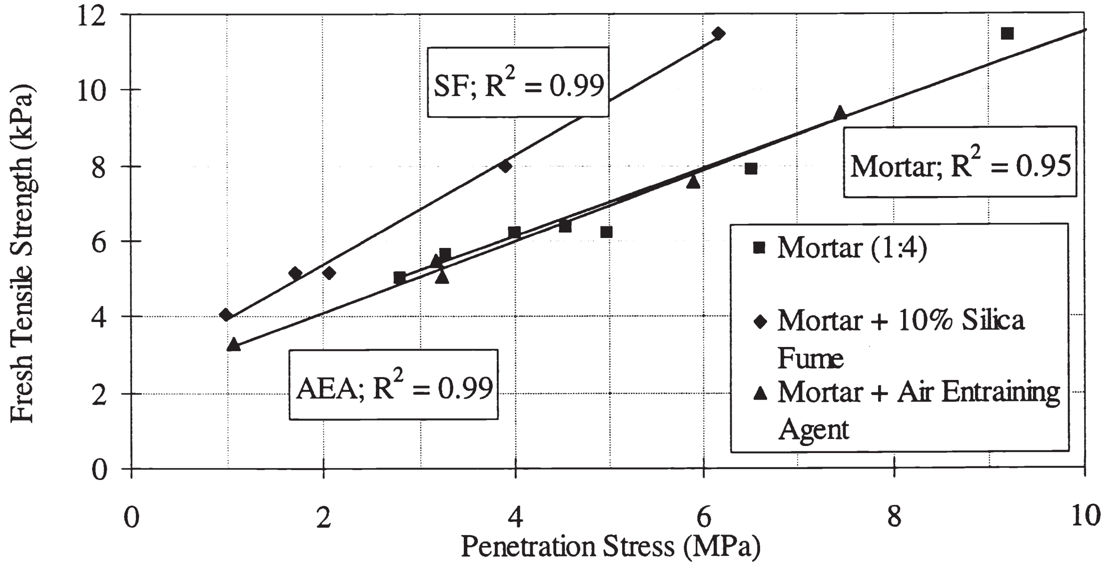

Fig. 10. Fresh tensile strength for various mixtures as a function of the penetration stress (consistency).

of retrieving them and working with industrial scale equipment was an important goal of this project.

One point, however, is not clear: the difference in order of magnitude between the cohesiveness values found (0,5–2,5 kPa) and the fresh tensile strength values obtained (3–12 kPa). A tentative explanation may be found by comparing the stress states of the two failure situations. The fresh tensile strength test is closer to a slowly applied "pure tension" test (0,36 mm/s) as opposed to the maximum buildup thickness test in which the initial movement or cracking of the mass propagates practically instantaneously under a constant load.

The discussion of the different behaviours of the various mixtures was left at this point to permit some general comments. Consider first the shooting consistency of the various mixtures. In general, a nozzleman will try to place shotcrete at its wettest stable consistency in order to attain the lowest possible rebound rate, good substrate bond, good reinforcement encasement, and good finishability (known as the good shootability requirement previously reported [15]). Based on this principle, the addition of an air-entraining admixture or coarse aggregates and the replacement of a pure cement binder by a silica fume cement binder is beneficial, because it allows one to shoot at lower consistencies. The mechanisms of action of these three factors cannot be strictly identified, because of the complex interrelation between the consistency, the amount of rebound, and the in-place composition of the mix. However, the effect of silica fume on the *mortar + silica fume* mixture, and the effect of the silica fume and coarse aggregate on the *shotcrete* mixture, are certainly related to the better particle grading of the material: (1) silica fume is known to increase workability for an identical water content, and (2) the lower surface area of the larger aggregates also increases workability for the same amount of paste [16,17]. Similarly, air-entraining admixtures allow mortar to be placed at lower consistencies, probably due to the so-called "ball-bearing" effect of the bubbles [16,18].

A note of caution: although Fig. 5 suggests the lowest rebound rates for the plain mortar mixture at a constant consistency, laboratory notes report that this mix is not suitable for construction site use due to its excessively stiff consistency, which would not allow for adequate finishing or rebar encasement. According to the nozzleman, it was nearly impossible to place this mix at a sufficiently low consistency.

As pointed out previously [4,5,13,14], silica fume increases the cohesion of fresh shotcrete, as confirmed in both Figs. 8 and 10. This effect is somehow expected since silica fume is known to increase the yield value of concrete mixtures at the replacement rate used [15,18,19]. On the other hand, the expected reduction of fresh strength brought about by the use of an air-entraining admixture, by decreasing the yield value of fresh concrete [17,18], is shown clearly in Fig. 8, but is totally absent from Fig. 10. This can again be explained by the different testing condition (see last paragraph of preceding section).

4. Conclusions

The major conclusions that can be drawn from this study are:

1. Regularity of the water flow at the nozzle is of prime importance in order to obtain a homogenous mixture.
2. The penetration test is a good test to assess the fresh material consistency and may be used as the common comparator between mixtures.

3. The fresh tensile strength test and the cohesiveness test correlate closely with the consistency of the material, as would be predicted from a failure theory approach.
4. The distinct curves obtained for the various mixtures in Fig. 8 show that for the same consistency, the behaviour under tensile stress of different mixtures will vary. Thus, the relationship between the shear strength (as assessed by the penetration test) and the tensile strength cannot be completely characterised by a single test.
5. Although silica fume and air-entraining admixtures have the same beneficial effect on consistency, it is clear from the results presented that their mechanisms of action differ since their effect on cohesion is opposite.

In the light of these conclusions, further research should include:

1. Increased control over shooting parameters, such as air flow and pressure, to allow even better comparison between results.
2. A reliable procedure to determine the maximum buildup thickness needs to be developed, probably involving a smaller sample with reduced nozzle motion.
3. Additional mix design variables need to be evaluated in order to target the specific effect of each variable and eventually produce mixtures with the required fresh qualities.

Acknowledgments

The authors are grateful to the Natural Sciences and Engineering Research Council (NSERC) of Canada for its financial support of this project through the “Chaire industrielle sur le béton projeté et les réparations en béton” (Industrial Chair on Shotcrete and Concrete Repairs). The members of this Chair are: Ministère des transports du Québec (Quebec’s Department of Transportation), Ville de Québec (City of Quebec), Master Builders Technologies Ltd, Sika Canada Inc., Béton mobile du Québec Inc., King Package Materials and Co., Ciment St-Laurent Inc., and Lafarge Canada Inc.

References

[1] H.S. Armelin, N. Banthia, Mechanics of aggregate rebound in shotcrete (I), Materials and Structures, RILEM 31 (206) (1998) 91–120.
[2] H.S. Armelin, N. Banthia, Mechanics of aggregate rebound in shotcrete (II), Materials and Structures, RILEM 31 (207) (1998) 195–202.
[3] T.R. Crom, Dry-mix shotcrete nozzling, Concrete International 3 (1) (1981) 80–93.
[4] American Concrete Institute, ACI 506R-90, Guide to shotcrete, 1990.
[5] H.S. Armelin, N. Banthia, D.R. Morgan, C. Steeves, Rebound in dry-mix shotcrete, Concrete International 19 (9) (1997) 54–60.
[6] T.C. Powers, The Properties of Fresh Concrete, John Wiley & Sons, New York, 1967.
[7] L.R. Prudêncio, H.S. Armelin, P. Helene, Interaction between accelerating admixtures and portland cement for shotcrete, ACI Materials J 93 (6) (1995) 619–628.
[8] ASTM C1117-89, Standard Test Method for Time of Setting of Shotcrete Mixtures by Penetration Resistance, ASTM Book of Standards, 04.02, USA, 1992.
[9] R.D. Holtz, W.D. Kovacs, An Introduction to Geotechnical Engineering, Prentice Hall, Englewood Cliffs, New Jersey, 1981.
[10] K.L. Johnson, Contact Mechanics, Cambridge University Press, Cambridge, U.K., 1985.
[11] W. Johnson, P.B. Mellor, Engineering Plasticity, John Wiley & Sons, New York, 1983.
[12] M. Jolin, D. Beaupré, M. Pigeon, A. Lamontagne, Use of set accelerating admixtures in shotcrete, Jour Mat Civil Eng, ASCE 9 (4) (1997) 180–184.
[13] D.R. Morgan, Dry-mix silica fume shotcrete in western Canada, Concrete International 10 (1) (1988) 24–32.
[14] D.R. Morgan, Advance in shotcrete technology for support of underground openings in Canada, in: Shotcrete for Underground Support V Conference Report, J.C. Sharp, T. Franzen (eds.), Engineering Foundation, New York, 1990, pp. 358–382.
[15] D. Beaupré, Shootability of fresh shotcrete, in: Production Methods and Workability of Concrete, P.J.M. Bartos, D.L. Mars, D.J. Cleland (eds.), E & FN Spon, London, UK, 1996, pp. 95–108.
[16] A.M. Neville, J.J. Brooks, Concrete Technology, Longman Group Ltd., New York, NY, USA, 1991.
[17] G.H. Tattersall, P.F.G. Banfill, The Rheology of Fresh Concrete, Pitman, London, 1983.
[18] D. Beaupré, Rheology of high performance shotcrete, Ph.D. Thesis, Dept. of Civil Eng., Univ. of British Columbia, Canada, 1994.
[19] O.E. Gjørv, Report MSL 92-6 (R), Energy, Mines and Resources, Canada, 1992.