MECHANISMS OF PLACEMENT AND
STABILITY OF DRY PROCESS SHOTCRETE

by

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ABSTRACT

The knowledge available today in shotcrete technology usually permits the production of strong and durable shotcretes. Unfortunately, very few research projects have focused on the development of the shotcrete process itself. Consequently, the fundamental knowledge on the properties and behaviour of fresh dry-mix shotcrete is very limited. The objective of this research project is thus to develop methods to evaluate the properties of fresh dry-mix shotcrete in order to better understand its behaviour, or its shootability. Shootability is defined by the ease and efficiency with which a shotcrete mix can be placed; the main parameters which characterise shootability are rebound, maximum build-up thickness and reinforcement encasement. To understand and control these characteristics requires an understanding of the mechanisms involved in the placement and the stability of a shotcrete layer. These mechanisms involve both rheological and mechanical concepts: the dynamic placement of the material, without external vibration, implies high shear rates, whereas the in-place stability of the fresh material is more closely related to plasticity in terms of shear resistance.

The consistency of fresh dry-mix shotcrete is considerably stiffer than that of conventional concrete, and therefore special apparatus and new testing procedures had to be created or adapted to evaluate the fresh properties of this unique material. The tests included the penetration test, fresh tensile strength test and fresh shear strength test. These tests along with detailed analysis of the in-place proportions of the mixtures helped to provide an understanding of the mechanisms needed to optimise the shootability of dry-mix shotcrete. Apart from the properties related to shootability, fundamental properties such as the yield value, the cohesion and the angle of friction were also determined. Additional information has also been gathered on the fresh dynamic properties of shotcrete, which are especially important in understanding the factors affecting the sound placement of a layer of shotcrete. Finally, a set of clear recommendations is proposed in view of the knowledge and information gathered concerning future avenues of research and development.
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CHAPTER 1
INTRODUCTION

1.1 - ORGANISATION

In order to facilitate the understanding of the work presented, this thesis is divided into 9 chapters. Chapters 1 and 2 are dedicated to the introduction and to an overview of the shotcrete process, including most common shotcrete properties. Chapter 3 is used to underline the problems or unknowns in dry process shotcrete through a literature survey. Chapter 4 covers the development phase of the tools needed to characterise fresh dry-mix shotcrete, while Chapter 5 presents the preliminary results obtained during that phase. Chapters 6 and 7 offer a complete characterisation of different fresh dry process shotcrete mixtures; both conventional and fundamental properties are investigated using the tools described in Chapter 4. In particular, Chapter 7 focuses on the fundamental properties of fresh dry-mix shotcrete in the light of the discussion presented in Chapter 3. The question of flowability of fresh dry-mix shotcrete around reinforcing bars in structures is addressed in Chapter 8; both theoretical aspects and experimental results are presented. Finally, Chapter 9 offers a summary of the findings of this research program along with general conclusions and recommendations.

1.2 - DEFINITION OF SHOTCRETE

The American Concrete Institute, Committee 506, defines shotcrete as a mortar or concrete that is pneumatically projected at high velocity onto a surface. In this definition, the words high velocity imply that the process produces a self-compacting material. Its mode of application makes it an appropriate material for tunnelling, repairs, slope
stabilisation and other application where conventional form work and normal concrete placing techniques would be inadequate.

There are basically two processes used to apply shotcrete: the wet process and the dry process. These are most often referred to as wet-mix shotcrete and dry-mix shotcrete, respectively. The basic difference between the two processes is whether or not the mixing water is present in the concrete mix before its entry into the spraying equipment. All of the mixing water is present in the concrete before its introduction into the pump for the wet-mix shotcrete; for the dry-mix shotcrete, the majority of the water is introduced near the end of the delivery hose. It is common practice in the dry process to introduce the material into the shotcrete delivery equipment either in the oven dry state or containing only a small part of the mixing water.

This basic difference in how the water is introduced greatly influences the fresh properties of the shotcrete that is produced. Since the wet-mix shotcrete needs to be pumped, the material entering the pump is required to exhibit sufficient workability for pumping purposes, and at the same time to possess sufficient stiffness to prevent sloughing once in place. These apparently contradictory requirements often require the use of concrete admixtures such as plasticizers and set accelerators. The advantages of the wet-mix process are the high capacity output, the relatively low material losses due to rebound and, because of its lower stiffness, easier finishing operations. The drawbacks are, however, the relatively complicated set-up requirements, the high cost of the equipment, and the difficulty in achieving satisfactory overhead applications. Thus, the wet mix process is better suited for large volume applications such as tunnel linings or large surface repairs.

On the other hand, the dry-mix process usually yields a stiffer in-place mix, since it is not required to flow as a continuous material in the delivery hose, because the particles are transported by the air stream. This leads to a material which can achieve a higher build-up thickness, but which also has higher material rebound losses. The equipment available generates smaller output rates, but its relatively smaller size and cost, along with the possibility of spraying small volumes economically make this process attractive for mine opening and structural repairs.
1.3 – PROBLEM DESCRIPTION

As mentioned earlier, particular to the dry-mix shotcrete process is the way in which most or all of the required water is introduced at the end of the transport process, i.e. just before the exit of the material at the nozzle. This unique feature produces a concrete subjected to a very short mixing period (typically from $\frac{1}{20}$ to $\frac{1}{2}$ second, depending on the nozzle configuration) and considered, in traditional concrete technology terms, as having a low workability. This low workability is at the origin of two important phenomena in dry-mix shotcrete: (1) some of the particles exiting the nozzle and travelling toward the receiving surface will not adhere to it, but will rebound; and (2) a relatively high build-up thickness can be achieved on vertical surfaces as well as on overhead surfaces. Clearly, these two phenomena, rebound and maximum build-up thickness, are the most important parameters used to characterise fresh dry-mix shotcrete. The mechanisms behind rebound in dry-mix shotcrete have been presented in detail by Armelin (1997) in his Ph.D. thesis. However, the mechanisms responsible for the build-up of a thickness of shotcrete and its early stability are still unclear and need further study.

The literature provides many references in which dry-mix shotcrete studies were undertaken to identify the effects of different parameters on shotcrete properties: accelerating admixtures, air-entraining admixtures, silica fume, etc. (for instance, Schutz, 1981 & 1982; Morgan et al., 1988; Morgan, 1991; Lamontagne et al., 1995; Jolin et al., 1997; and Beaupré et al., 1999). The work reported in these papers mainly concerns the effects, as opposed to the causes, of these parameters on the properties of shotcrete. These can provide quick answers to specific mix design or job site problems. However, in order to further improve and promote shotcrete, the more fundamental mechanisms of the process need to be investigated and better understood.

Many other properties of fresh dry-mix shotcrete, besides rebound and maximum build-up thickness, are also important. There is a growing amount of work being carried out in the field of quality control of shotcrete projects where adequate encasement of the reinforcing steel and sufficient substrate bond are the main concerns. Other concerns come from extreme environments, where early cracking due to wind and heat, or delayed
hydration and fall-outs due to cold conditions need to be addressed. Most of the time, the properties underlying these phenomena are not even identified, and very limited information is available concerning the effects of mix design and shooting parameters on these problems.

1.4 – RESEARCH OBJECTIVES

The main objective of this research project is to investigate the fundamental mechanisms involved in the placement and the stability of a sound layer of dry-mix shotcrete. More precisely, the goal is to design tools to characterise the fresh shotcrete, and then to use them to generate a data base of basic properties for mixtures with various mix design parameters. This is accomplished using industrial scale shotcrete equipment in a laboratory environment. It is expected that the information gathered at this point will provide the basis for a rational explanation of different fresh shotcrete rheological behaviours.

Ultimately, from a fresh shotcrete point of view, the knowledge acquired will permit us to establish the basis for designing better mixes, possessing acceptable rebound proportions, perfect reinforcement encasement properties, and adequate maximum build-up thicknesses.
CHAPTER 2
SHOTCRETE TECHNOLOGY

2.1 - INTRODUCTION

In this chapter, various aspects of shotcrete are described to provide a general overview of the technology. First, a brief description and comparison of both shotcrete processes are presented. Second, the dry process is emphasised, by discussing and briefly reviewing the equipment utilised by the industry. Finally, an overview of the most significant properties of fresh dry-mix shotcrete is presented, along with comments on the hardened properties.

2.2 - SHOTCRETE PRODUCTION

2.2.1 - DRY-MIX PROCESS

The inventor of the dry-mix process, Carl E. Akeley, obtained a patent for the equipment and the method in 1911. Surprisingly, the principle of the method itself has not changed much over the years: a dry aggregate-cement mixture is pneumatically conveyed to a nozzle where water is added before exiting. Over the years, however, major improvements have been made in the equipment and in the mixture design. Figure 2.1 presents the typical layout for dry-mix shotcrete production.

The most important aspect of this process is the fact that the nozzleman controls the amount of water added to the mix by way of a metering valve placed on the nozzle. This has the important advantage of allowing the nozzleman to instantly adjust the consistency of the mix: water infiltration on a rock face requires a "stiffer" mixture while reinforcement encasement requires a flowing mixture. The downside, however, is that
the final product properties are strongly affected by the experience of the nozzleman, with sand pockets and layering often attributed to poor nozzleman workmanship.

Along with the shooting water, it is common to introduce admixtures such as set accelerators, air-entraining agents, or latex to the mixture being shot. The solid materials are usually either prepared on site using batch or continuous mixers, or pre-bagged. The latter technique is of great practical interest since it permits the inclusion of any or all of the ingredients in the same bag: aggregate, cement, silica fume, fly ash, fibres, powdered set accelerator and/or powdered air-entraining admixture.

Figure 2.1: Typical job site layout for dry-mix shotcrete operations.
2.2.2—Wet Process

This process consists of pumping conventional fresh concrete all the way to the nozzle. Before exiting the hose, the material is accelerated and sprayed onto the receiving surface by the introduction of compressed air through the nozzle. Figure 2.2 presents the typical equipment layout of a wet-mix production site. The pumpability requirement favours the use of special admixtures such as water reducers and superplasticizers. Set accelerators sometimes need to be added at the nozzle to increase the thickness of shotcrete applied in a single pass. The quality control of wet process shotcrete is made easier since the composition of the mixture (including the water/cement ratio) is known a priori. The wet-mix shotcrete process is not discussed in any detail in this research project. The reader can refer to Wolsiefer & Morgan (1993), Beaupré (1994), ACI 506 (1995), and Austin & Robins (1995) for further information.

Figure 2.2: Typical job site layout for wet-mix shotcrete operations.
2.2.3 – COMPARISON BETWEEN WET AND DRY PROCESS SHOTCRETES

The main differences between the two processes are summarised in Table 2.1, reproduced from “Guide to Shotcrete” of ACI Committee 506R90. The choice of process should be made with respect to site specific conditions. As general information, Table 2.2 shows typical mix design proportions for both processes.

Table 2.1: Comparison of wet and dry-mix processes

<table>
<thead>
<tr>
<th>Dry-mix shotcrete</th>
<th>Wet-mix shotcrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Instantaneous control over mixing water and consistency of mix at the nozzle to meet variable field conditions.</td>
<td>1. Mixing water is controlled at the delivery equipment and can be accurately measured.</td>
</tr>
<tr>
<td>2. Better suited for placing mixes containing lightweight aggregates, refractory materials and shotcrete requiring early strength properties.</td>
<td>2. Better assurance that the mixing water thoroughly mixed with other ingredients.</td>
</tr>
<tr>
<td>3. Capable of being transported longer distances.</td>
<td>3. Less dusting and cement loss accompanies the gunning operation.</td>
</tr>
<tr>
<td>4. Start and stop placement characteristics are better with minimal waste and greater placement flexibility.</td>
<td>4. Normally has lower rebound resulting in less material loss.</td>
</tr>
<tr>
<td>5. Capable of higher strength(^1).</td>
<td>5. Capable of greater production.</td>
</tr>
</tbody>
</table>

\(^1\) The importance of this advantage of dry-mix shotcrete has been diminishing with the appearance of superplasticizers in the 1980's. There are reports of high performance wet-mix shotcrete with compressive strength greater than 90 MPa (Beaupré, 1994).
Table 2.2: Typical mix compositions for wet and dry shotcrete processes.

<table>
<thead>
<tr>
<th>Constituents</th>
<th>Wet-Mix Shotcrete</th>
<th>Dry-Mix Shotcrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>170 kg/m³</td>
<td>180 kg/m³ (1)</td>
</tr>
<tr>
<td>Cement</td>
<td>360 kg/m³</td>
<td>405 kg/m³</td>
</tr>
<tr>
<td>Silica Fume</td>
<td>40 kg/m³</td>
<td>45 kg/m³</td>
</tr>
<tr>
<td>Sand</td>
<td>1250 kg/m³</td>
<td>1510 kg/m³</td>
</tr>
<tr>
<td>Coarse Aggregate (Max 10 mm)</td>
<td>500 kg/m³</td>
<td>235 kg/m³</td>
</tr>
<tr>
<td>Air-Entraining Admixture</td>
<td>0.3 l/m³</td>
<td>20 ml/l of shooting water</td>
</tr>
<tr>
<td>Water-Reducing Admixture</td>
<td>1.5 l/m³</td>
<td>-</td>
</tr>
<tr>
<td>Superplasticizer</td>
<td>1.5 l/m³</td>
<td>-</td>
</tr>
</tbody>
</table>

(1) The amount of water added to the mix varies according to the placing conditions. The value of 180 kg/m³ of water is based on an assumed water/binder ratio of 0.4. The real in-place proportion is not known a priori in dry-mix shotcrete; it has to be experimentally evaluated.

(2) It is more common to report dry-mix shotcrete proportions as percentage of dry material.

2.3 – DRY-MIX SHOTCRETE EQUIPMENT

2.3.1 – DELIVERY EQUIPMENT

The equipment needed to produce dry-mix shotcrete generally includes a shotcreting machine, often called a dry-mix gun, a length of hose with a nozzle, a source of compressed air (usually an industrial air compressor), a source of clean water and sometimes a predampener in which a small portion of the total mix water may be introduced. The capacity of the air compressor is a function of the length and the diameter of the hose used for shotcreting; recommendations and typical equipment sizes can be found in ACI 506R90 “Guide to Shotcrete”.
The dry-mix gun is typically one of the three following types: double chamber gun, barrel
gun or feed bowl gun. Although the principle of action may vary, the intent is always to
obtain as homogenous and uniform a flow of dry material as possible. The double
chamber gun uses the principle of the airlock to bring material continuously to a feed
wheel located at the bottom of the machine. Figure 2.3 shows this piece of equipment
along with the operating sequence. The barrel and the feed bowl guns both function on
the same principle: a rotating section with cavities is gravity charged from a hopper. As

![Double Chamber Gun and Operating Sequence](image)

**Figure 2.3: Double chamber gun and operating sequence (from ACI 506R90, 1995).**

the section rotates, it becomes sealed and compressed air discharges the cavities into the
delivery hose. The barrel gun is made with straight vertical cavities, while the feed bowl
gun contains U-shaped cavities. Figure 2.4 shows schematic drawings of both of these
guns.
If all three types of machine are well maintained and properly operated, they should all be equivalent as far as in-place material properties are concerned. However, serious discrepancies can arise when the equipment is not maintained or operated by properly trained people. For these reasons, the equipment used in laboratory evaluations should always be kept in perfect condition.

2.3.2 - NOZZLES

It may seem surprising to find a section dedicated to dry-mix shotcrete nozzles alone. However, the discussions presented in later chapters require the reader to understand in detail the differences between the various methods used to mix the water with the dry material. When dry-mix shotcrete is produced, a number of options regarding the wetting of the material are available. First, a predampener can be used to introduce part of the
water into the mix prior to its entry into the gun. Second, the water ring\(^2\) can be located at various positions in the nozzle body, from approximately 300 mm before the exit of the nozzle to some distance upstream, usually up to 3 m from the exit. The latter position represents what is called a “prewetting” nozzle or “long” nozzle. Thus, the craftsmen need to choose between a “long” or “short” nozzle with or without predampening. Figure 2.5 shows the different concepts of location of the water ring.

![Diagram of nozzle with water ring](image)

**Figure 2.5:** Typical dry-mix nozzle with (a) the water ring in the nozzle body and (b) the water ring upstream ("prewetting" nozzle).

There are today two different ways in the industry of considering the choice of nozzle and predampener. Some consider that the use of a prewetting or “long” nozzle efficiently replaces predampening with respect to dust emission, rebound and homogeneity of the in-place concrete. Others believe that the predampening phase is a mandatory procedure of the dry-mix shotcrete process, no matter what type of nozzle is used down the line. There is, however, agreement on one point: a standard or “short” nozzle should *always* be used in conjunction with predampening when pre-bagged oven dry materials are used, to prevent poor homogeneity of the in-place concrete and excessive dust emission.

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2 A water ring is the device in the nozzle body through which the water is added to the material.
2.4 – PROPERTIES OF FRESH DRY PROCESS SHOTCRETE

This section presents first an overview of the most common fresh properties of dry-mix shotcrete, namely setting time, rebound, maximum build-up thickness and consistency. The second part of this section introduces some of the important hardened properties of shotcrete. This last portion will be limited in length, since a review of all of the available information would represent an entire book by itself.

2.4.1–SETTING TIME

Setting time is an important property, since it greatly influences the production rate of dry-mix shotcrete. The standard procedure used to measure the initial and final setting times of shotcrete is to push a standard diameter needle into its surface to a given depth and recording the required pressure. ASTM C 1117, Standard Test Method for Time of Setting of Shotcrete Mixture by Penetration Resistance describes the procedure in detail.

The usual way of shortening the setting time of shotcrete is by introducing a set accelerator into the mix. Initial setting times of less than one minute have been reported (Jolin et al. 1997). When considering set accelerators, it is important to be clear about the type of effect sought. Some accelerators will only reduce the initial set, thus rapidly stiffening the shotcrete. Other accelerators will reduce not only the initial setting time, but also the final setting time, thus rapidly stiffening the shotcrete and also increasing its early compressive strength. The drawback is that these latter admixtures, although efficient in the short term, generally reduce to some extent the long term mechanical properties and durability (Schutz, 1981 & 1982; Lukas & Kusterle, 1990; Gebler et al., 1992; Prudêncio et al., 1996; Jolin et al. 1997). Indeed, the effect of these admixtures on the cement paste microstructure can reduce its quality by solidifying it too quickly, thus interfering with normal cement hydration. Other means of reducing initial and/or final setting time of shotcrete exist, including rheology modifiers, consistency control systems, and other special proprietary systems.
2.4.2 - REBOUND

The rebound phenomenon with shotcrete is well known to all practitioners. Many studies have been carried out on shotcrete rebound (e.g., Parker et al. 1976; Crom, 1981; Banthia et al., 1992). More recently, the fundamental principals underlying rebound mechanisms in dry process shotcrete have been investigated (Armelin, 1997).

Factors affecting rebound can be divided into two main categories: those related to the shooting parameters and those related to the mix design. In the first category, the shotcrete process itself is the most important parameter: the wet process usually yields lower rebound proportions than the dry process. This also involves the distance to the receiving surface, the orientation of the surface, the angle of the nozzle to the surface, the air pressure, etc. The second category includes, in addition, the amount of cement and silica fume present in the mixture as well as its consistency.

An extensive research project conducted by Parker (1976) offers an interesting approach for understanding rebound phenomena. The average rebound, also called the percentage rebound or overall rebound, is the most commonly used parameter in the industry and is given by:

\[
R_{AVE} = \frac{\text{Total weight rebounded (kg)}}{\text{Total weight shot (kg)}} \times 100 \%
\]  

Parker, however, defined the Rebound Rate Ratio \((R_{RR})\), which is given by:

\[
R_{RR} = \frac{\text{Rebound rate (kg/s)}}{\text{Material delivery rate (kg/s)}}
\]

The rebound rate is the instantaneous rate of rebound bouncing off the receiving surface, and therefore has units of mass divided by time. The material delivery rate has similar units and is defined as the weight rate of all of the material leaving the nozzle. These definitions imply that the rebound rate ratio is "the ratio of the amount of material falling to the ground to the amount of material shot at the wall at any given precise instant or any convenient period of time" (Parker et al., 1976). Since rebound rate ratio is based on instantaneous rates, it is different from and should not be confused with, the universally used term of average rebound or percentage rebound.
Because the rebounding of particles is much more important in the first few millimetres of a shotcrete application, the rebound rate ratio is a more appropriate measurement to report rebound, although it is much more difficult to measure. The important differences between the RRR in the first moments of shooting and subsequently involves the influence of the thickness of shotcrete applied on the average rebound value. Thus, a rebound rate ratio value must be given along with the precise moment at which it was measured.

The thickness effect on the average rebound burdens this parameter with a serious limitation: average rebound values of two mixtures are comparable only if the thicknesses applied are the same, or at least very large (> 150 mm). As shown in Figure 2.6, the rebound rate ratio decreases rapidly and stabilises, correctly reflecting the initial layer effect; however, the average rebound curve decreases less rapidly, demonstrating the strong influence of the shotcrete thickness on the average rebound value. According to Parker, "no other parameter exerted as great an influence on the rebound than the thickness of shotcrete applied".

Figure 2.6: Variation of rebound with time and thickness (Parker et al., 1976).
It is also interesting to note that the shooting consistency has an influence on rebound which is certainly as important as the applied thickness. Armelin et al. (1997) showed that the same dry process shotcrete mixture shot at different water addition rates could produce shotcretes with overall rebound varying by a factor of 2. This observation finds a very nice explanation in Zynda (1965), who stated that a low water content causes internal forces which are responsible for bulking, which in turn must increase the rebound since these same forces resist compaction. Further discussion on consistency is presented below, in Section 2.4.4.

Further discussions of the factors affecting rebound in shotcrete can be found in Kobler (1965) and Crom (1981). These two papers offer interesting guidelines concerning the shooting parameters affecting rebound (e.g. distance of nozzle from surface and angle of nozzle to the surface); recommended good practice is presented along with expected rebound increases if it is not respected. Studies of rebound in dry process shotcrete containing a set accelerator have been conducted by Schutz (1981 & 1982); Jolin et al. (1997); and Armelin, (1997). Conclusions on the effect of set accelerators on rebound are often contradictory. Lukas et al. (1995) indirectly explains these different conclusions by highlighting the important relation between the very early strength development (0–30 seconds) and rebound; the in-place layer should initially not harden too quickly to allow the incorporation of the incoming aggregates, but at the same time should not keep its plastic consistency too long to attain the desired application thickness. Therefore, testing various accelerator types or even slightly changing their dosages can play an important role on the amount of rebound measured. Finally, Morgan (1988 & 1990) reports studies undertaken to investigate the effect of silica fume on the rebound of both shotcrete processes; reductions of as much as 10% of the overall rebound are commonly encountered.

Unfortunately, comparisons amongst the different studies is sometimes difficult because of the variable tests procedure which include, apart from the consistency and the thickness applied, the air flow and pressure, the water pressure, the material delivery rate, the type of equipment used and the general shooting technique.
2.4.3 - Maximum Build-up Thickness

Along with rebound, the maximum build-up thickness is the other important and obvious characteristic of fresh dry-mix shotcrete. It is usually defined as the maximum thickness of shotcrete that can be applied in a single pass *in a stable manner*. This definition is intentionally general, since there are no accepted standards available to evaluate the maximum build-up thickness of a shotcrete mixture.

This property is especially important since it involves serious safety and economic issues: fall-outs are both dangerous to the craftsmen and costly to repair. In order to evaluate build-up thickness, different set-ups have been used. Morgan (1991) has proposed a test in which the sample is shot onto a vertical surface until either loss of adhesion or cohesion occurs (Figure 2.7). The maximum thickness shot is then recorded as the thickness-to-sloughing value. Either of the two failure mechanisms, loss of adhesion or loss of cohesion, is responsible for the unstable behaviour of the sample. From a practical point of view, this test provides a simple and relatively easy procedure with which to compare mixes. The results are difficult to interpret from a fundamental point of view, since the test is purely empirical. However, Beaupré (1994) found an excellent correlation between the maximum build-up thickness obtained with this test and the yield value of the mixture shot using the wet-mix process (Figure 2.8).

![Figure 2.7: Thickness-to-sloughing test set-up (from Beaupré, 1994)](image-url)
Figure 2.8: Relationship between the maximum build-up thickness obtained with the thickness-to-sloughing test set-up and the in-place yield value (adapted from Beaupré, 1994).

A second test set-up presented by Beaupré (1996) requires one to shoot an overhead sample; the maximum thickness applied is called the maximum build-up thickness. As with the previous procedure, this test does not directly give information on the fundamental properties of the sprayed material, although a good correlation between the overhead maximum build-up thickness and the consistency is reported by Armelin (1997). Figure 2.9 shows the typical set-up.

These two procedures are very different: the first uses a vertical panel without reinforcement, while the second uses an overhead panel with a complete reinforcement layout. This, however, represents different job site realities. In practice, a number of different build-up failures can happen: localised fall-outs, relatively large overhead decohesion, and vertical sloughing on a wall. These failures represent different stress states. They can cover small or large areas, they can occur in the mass of the shotcrete itself or along the wire mesh, and they can even be delayed in time. Consequently, both test procedures are valid; they simply don’t refer to the same failure problem. Figure 2.10
Figure 2.9: Typical build-up test set-up (from Beaupré, 1996).

illustrates different stress states for maximum build-up thickness failures. Note that in this figure, failure does not necessarily means fall-out if reinforcement is present, since simple decohesion will lead to poor in-place quality shotcrete.

Figure 2.10: Failure mechanisms involved in maximum build-up thickness situations.
2.4.4 - CONSISTENCY

The consistency or the workability of dry-mix shotcrete is normally only assessed qualitatively. Powers (1968) defines consistency as the resistance of a material to deformation, often referred to as a "dry" or "wet" consistency or "stiff" or "soft" material. This definition of consistency is well suited to the shotcrete industry. Anyone who has worked with shotcrete has heard of a mixture shot "too stiff", or 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 the consistency.

As a general rule, a nozzleman will try to spray dry-mix shotcrete at its wettest stable consistency. The nozzleman does so in order to minimise rebound losses, facilitate the required finishing operations and, most important, allow proper encasement of the reinforcing steel, while providing sufficient stiffness to insure the stability of the shotcrete until it sets. The first reference to this concept is found in Studebaker (1939), where he defines the stable wettest consistency as "the consistency at which the moisture content is the maximum, the maximum being determined by the stability of the fresh gunite (shotcrete)". The description of an apparatus and the method used to evaluate dry-mix shotcrete consistency quantitatively is presented in Section 4.3.

2.5 - PROPERTIES OF HARDENED DRY PROCESS SHOTCRETE

From a general point of view, the mechanical characteristics of good quality shotcrete are the same as those of a conventional concrete of the same composition and characteristics. An assumption generally accepted is that the optimisation of the fresh shotcrete properties will enhance hardened shotcrete properties by producing a more homogeneous material. However, care must be taken to follow proper gunning technique and use adequate combinations of equipment (Crom, 1981; ACI 506, 1995; Austin & Robins, 1995). Unfortunately, even with a good mixture composition and the right equipment, there is no guarantee that the in-place material will perform as expected. The operation of the equipment is one of the crucial parts of the process; indeed, parameters such as air velocity, operating pressure and material delivery rate have been known to play major role.
roles in the quality and properties of the in-place shotcrete. An example of poor equipment operation is reported by Ward and Hills (1978), who had problems with the uniformity of the in-place mixture which were attributed to the cyclic arrival of material at the nozzle and an eccentric segregated discharge pattern at the nozzle. They also reported severe pulsation and "choking" of the system during shooting. These symptoms are not acceptable and do not represent a correct shooting session. Correct adjustment of the air flow and/or material delivery rate could have produced an acceptable shooting session; otherwise, a different equipment combination should have been selected.

A well-known relationship first presented by Stewart (1933) and later thoroughly analysed by Glassgold (1989), correlates the compressive strength of the shotcrete to the velocity at the nozzle (Figure 2.11). It is apparent that there is an optimum velocity for a given hose diameter; note that in this case, velocities are obtained by dividing the unrestricted air flow by the cross section of the hose. Results obtained by Armelin (1997) are also reproduced in Figure 2.11. However, no direct comparison is possible between the two studies since other parameters are not constant, especially the mixture composition.

![Figure 2.11: Unrestricted air flow velocity versus compressive strength for different hose diameters (Stewart, 1933 and Armelin, 1997).](image)

There is no direct comparison possible between Armelin's and Stewart's results since the mixtures used are different.
In the same vein, Zynda (1965) stated that shotcrete compressive strength is affected by both the material velocity at the nozzle and by the water-cement ratio. He also entertained the concept of shooting at the *wettest stable consistency* with high velocities. His arguments are that a low water/cement ratio, combined with low velocities, will produce low strengths due to insufficient compaction. Even if high velocities together with a low water/cement ratio can produce good strength, this is accompanied by excessive rebound, which results in a greater in-place cement content, and is therefore uneconomical.

Personal experience of the author suggests that the important parameters for hardened shotcrete quality, apart from proper initial mixture composition and perfect gunning technique, are the combination of air flow, material delivery rate and water flow in the hose. An incorrect adjustment of any of these three quantities will lead to a reduction of the shotcrete quality; unfortunately, this is not always detectable during the shooting process, but only through testing of the hardened material. Therefore, it is our belief that recommending a shooting distance or water pressure alone is not sufficient; it is the entire combination of shooting parameters that needs to be specified. Note that for a given equipment layout and mixture, there can be more than one correct combination of air-water-material delivery rate and speed.

The last item worth mentioning is the quality of the air voids system\(^3\). It has been established that a good quality air voids system in dry process shotcrete mixtures offers an adequate protection against freezing and thawing cycles, especially in the presence of deicer salts (Beaupré et al., 1994; Lamontagne et al., 1995; Jolin et al. 1997).

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\(^3\) An air void is defined by ACI as a space in cement paste, mortar or concrete filled with air; an entrapped air void is characteristically 1 mm or more in size and irregular in shape; an entrained air void is typically between 10 \(\mu\text{m}\) and 1000 \(\mu\text{m}\) in diameter and spherical or nearly so.
3.1 - INTRODUCTION

Following the basic review in Chapter 2, this chapter covers the more fundamental aspects of concrete and shotcrete technology. The first section deals with the rheology of fresh concrete; these principles can be applied to both dry and wet-mix shotcretes. The second section presents topics related particularly to the dry-mix process, namely the rheology and rebound mechanisms of dry-mix shotcrete. Finally, the research objectives of the present study are laid out in detail.

3.2 – RHEOLOGY OF FRESH CONCRETE

3.2.1 – PRINCIPLES OF RHEOLOGY

The rheology of fresh concrete has received a lot of attention from researchers over the last two decades (Tattersall & Banfill, 1983; Tattersall, 1991; Bartos, 1992; Beaupré, 1994; Ferraris & de Larrard, 1998). Rheology is generally defined as the science of deformation and flow of matter. Thus, the main use of rheology in the field of concrete technology is to permit the complete characterisation of the flow behaviour of fresh concrete. The economical and technological advantages ensuing from such information allow for better quality control and new concrete applications such as self-levelling concrete and high performance wet-mix shotcrete (Tattersall, 1991; Beaupré, 1994; and Lacombe, 1998).
It is widely accepted today that fresh concrete obeys the rheological model known as the Bingham model. In this model, two properties are required to describe completely fresh concrete behaviour: the yield value ($\tau_0$) and the plastic viscosity ($\mu$). Both of these parameters have a physical meaning. On the other hand, the single parameter most commonly used, the slump value (ASTM C143), is purely empirical. Equation 3.1 shows the mathematical formulation of the Bingham model.

$$\tau = \tau_0 + \mu \cdot \dot{\gamma}$$

(3.1)

The other terms of this equation are the applied shear rate ($\dot{\gamma}$) and the resulting shear stress ($\tau$). This is not a stress-strain relationship as for solids, but a stress-strain rate relationship, used to represent the behaviour of flowing matter. The physical interpretation of this model is that to put a Bingham fluid into motion, a minimum effort must first be supplied to initiate flow or to overcome the yield value ($\tau_0$). Once motion or flow is initiated, the required force increment to continue the concrete deformation is proportional to the shear rate increment applied and is attributed to the plastic viscosity term. Figure 3.1 presents a graphical representation of the Bingham model for concrete.

![Graphical representation of the Bingham model.](image)

**Figure 3.1: Graphical representation of the Bingham model.**

The use of a two parameter flow model for fresh concrete has important practical implications. In shotcrete, probably the best example is to be found in the doctoral work of Denis Beaupré (1994). His research objectives concerned the production of high performance wet-mix shotcrete. Recognising on one hand the unreliability of a single
parameter test such as the slump value to characterise the fresh concrete, and on the other hand the conflict between the pumpability requirements (low yield value and viscosity) and the shootability requirement (high yield value), he constructed a rheometer\(^1\) that allowed him to measure, using a simple procedure, the flow characteristics of fresh concrete over a wide range of workabilities. His efforts opened the door to fundamental research on pumpability problems and also to the concept of high initial air content. This concept involves fluidifying the concrete by means of a high air content to obtain the desired pumpability properties; then, upon impact of the material on the receiving surface, a large number of air bubbles are driven out which acts to reduce the slump and hence leads to a high yield value, which permits a higher build-up thickness.

Another important aspect of fresh concrete rheology is the structure of fresh cement pastes. The electrostatic properties of cement particles make cement pastes different in behaviour from similar suspensions of inert particles. One of the differences is obvious from the phenomenon called structural breakdown illustrated in Figure 3.2 (Tattersall & Banfill, 1983). After a cement particle comes in contact with water, the particle becomes covered by a gelatinous membrane which provides a link between particles that needs to be broken in order to continue mixing. However, the breaking of this membrane requires additional work so, as the particles separate, the mixing effort will decrease, thus displaying a shear thinning behaviour. Obviously, the mixing method used to prepare a sample for testing in a rheometer will strongly influence the degree of structural breakdown measured. For this reason, Tattersall (1991) suggested the use only of samples that have been thoroughly mixed in order to go through all of the structural breakdown of cement particles prior to testing.

A second important difference between cement pastes and inert suspensions is the time dependence. As we all know, water and cement combine to form a solid material. As this reaction proceeds, the ion concentration and the amount of water change, thus influencing the rheological properties of the paste/concrete. Thus, the age of a paste is important when determining its rheological properties.

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\(^1\) The description of the IBB Rheometer can be found in Beaupré and Mindess (1996).
The last important phenomenon associated with cement paste is known as thixotropy. Thixotropy is defined as the property of a gel to become fluid when disturbed and then to return to its gel state when left undisturbed. For concrete, this means that a mix will be said to exhibit thixotropic behaviour if the structural breakdown phenomenon described earlier is reversible. The amount of time needed to reverse the effect of structural breakdown will vary from one mix to another. Thus, not only is the age of a paste or concrete important when determining the rheological properties, but also its complete time history.

### 3.2.2 – Rheology and Mix Composition

Many concrete additives and admixtures are used to modify the rheological properties of fresh concrete. The references cited in the previous section provide a more complete treatment of the various effect and mechanisms involved with many products. Table 3.1 is presented to show the effects of various additives and admixtures used in concrete technology.
Table 3.1: Effect of various concrete additives and admixtures on concrete rheology.

<table>
<thead>
<tr>
<th>Admixture or additive</th>
<th>Objective</th>
<th>Effect on rheology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silica Fume</td>
<td>In shotcrete, used to lower rebound and increase build-up thickness.</td>
<td>- Increased yield value (good for build-up thickness)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Lower plastic viscosity (pumping aid)</td>
</tr>
<tr>
<td>Set accelerators</td>
<td>Used to reduce setting time.</td>
<td>- Increase the rate of change with time, thus the yield value and plastic viscosity change rapidly.</td>
</tr>
<tr>
<td>Water reducers and superplasticizers</td>
<td>In concrete, used to increase workability.</td>
<td>- Significant decrease of the yield value.</td>
</tr>
<tr>
<td>Air-entraining agents</td>
<td>Used to increase freeze-thaw durability. Also, used to increase workability.</td>
<td>- Reduce both the plastic viscosity and the yield value.</td>
</tr>
</tbody>
</table>

3.3 – **FUNDAMENTAL PROPERTIES OF DRY-MIX SHOTCRETE**

This section presents an overview of the rebound mechanisms in dry-mix shotcrete as described by Armelin and Banthia (1998). This is followed by a discussion concerning the fundamental characterisation of fresh dry-mix shotcrete.

3.3.1 – **REBOUND MECHANISMS**

As discussed previously, the effects of various mixture compositions and shooting parameters on rebound are well documented. However, it is only recently that a rational theory of aggregate rebound mechanisms in fresh shotcrete was presented by Armelin (1997).

3.3.1.1 **Understanding rebound mechanisms**

The development of a theory of rebound in dry-mix shotcrete is made complicated by the difficulty of modelling the rheology of this material. This problem is easily understood
from a simple example: silica fume is known not only to lower drastically the rebound in shotcrete, but also to increase the yield value of concrete mixtures; both effects are, intuitively, incompatible. Is it possible to go from flow model properties, such as Bingham's yield value and plastic viscosity, in order to predict rebound? The link is not direct, since rheological flow models do not account for any elastic behaviour of the material, which is obviously present in rebound phenomena. To overcome this problem, Armelin considered fresh dry-mix shotcrete as a perfectly elasto-plastic material characterised by only one constant, its yield value (later called the contact stress). This assumption was incorrect, but since he was studying only a single stress combination, i.e. a hard particle hitting a soft surface, it produced impressively good results.

In addition, a good theory of rebound should be able to account for the following field observations:

- A stiffer consistency leads to a higher amount of rebound.
- Larger particles tend to rebound more than smaller ones.
- Higher amounts of silica fume and cement tend to reduce rebound.
- Shooting parameters such as air flow greatly influence the amount of rebound; excessively high or low air flow seems to create a large amount of rebound.

### 3.3.1.2 Rebound phases (after Armelin, 1997)

For simplicity, the rebound of a particle impinging a surface can be decomposed in two phases: the penetration phase and the reaction phase. From classical physics, the ratio of work done during the reaction phase to that done during the penetration phase can be related to the coefficient of restitution, (e):

\[ e = \sqrt{\frac{W_{\text{REAC}}}{W_{\text{PEN}}}} \]  \hspace{1cm} (3.2)

The penetration phase of an aggregate particle hitting a fresh shotcrete substrate is very similar to that of an indentation. The indentation of a plastic substrate by a rigid sphere is a classical problem of contact mechanics (Johnson, 1985). This interpretation leads to a
relationship between the work done in the penetration phase ($W_{\text{PEN}}$) and the volume displaced by the indenter ($V_{\text{PEN}}$):

$$W_{\text{PEN}} = \frac{1}{2} mv^2 = p_d V_{\text{PEN}}$$  \hspace{1cm} (3.3)

In this equation, $p_d$ represents the dynamic contact stress, and $m$ and $v$ are, respectively, the mass and the velocity of the indenter. The mass and the velocity are quantities known (or at least measurable) for a given particle. The dynamic contact stress, $p_d$, turns out to be a constant pressure applied to a spherical indenter during the penetration phase due to the plastic deformation of the substrate (for an ideal material). The penetration phase of an aggregate is recognised to be a dynamic event due to the high particle velocities measured (approximately 10 m/s to 60 m/s).

Once the penetration phase is over and the particle has reached its maximum depth in the substrate, the elastic energy stored in the latter is released and transferred back to the aggregate (indenter), eventually causing it to rebound. This step is called the reaction phase. It is important to understand that the energy released during this phase is somehow proportional to the volume displaced earlier, $V_{\text{PEN}}$, and to a quantity called the static contact stress, $p_s$ (as opposed to the dynamic contact stress, $p_d$).

$$W_{\text{REAC}} = kp_{s}^{2} V_{\text{PEN}}^{2}$$  \hspace{1cm} (3.4)

Substituting Eq. (3.3) and (3.4) into (3.2) leads to the key relationship:

$$e = K \cdot \frac{p_s}{p_d^{\frac{1}{3}} \cdot V^{\frac{1}{4}}}$$  \hspace{1cm} (3.5)

where $K$ is a constant related to the properties of the particle and the substrate.

Eq. (3.5) indicates that the coefficient of restitution is not only a material property characterised by $K$, $p_s$ and $p_d$, but that it is also influenced by the velocity of the indenter. This has an important repercussion, since high speed photography has shown that larger particles of a dry-mix stream exiting the nozzle travel at relatively lower speeds. Thus, the coefficient of restitution is closer to unity, hence increasing the energy restored to the particle and the probability of rebound for those larger particles.
The last quantity that needs to be included in this model is the work necessary to debond a particle, $W_D$, which is evaluated experimentally. This quantity plays its role during the reaction phase: if the energy transferred back to the particle ($W_{REAC}$) is larger than the debonding energy, then rebound of the particle will occur.

$$\frac{W_{REAC}}{W_D} \geq 1 \Rightarrow \text{REBOUND} \quad (3.6)$$

The path followed from Eq. (3.1) through Eq. (3.6) allows us to extract a few general concepts. First, the static contact stress, $p_s$, and the dynamic contact stress, $p_d$, can be related to the yield value and the plastic viscosity of a flow model. The static contact stress is similar to a yield value, which is also a “static” quantity. The dynamic contact stress includes a quantity related to the plastic viscosity, the “dynamic” parameter of the flow model. The difference of about one order of magnitude between $p_s$ and $p_d$ reported by Armelin supports this comparison ($p_d \approx 7$ to 10 times $p_s$).

Second, care must be taken when examining the equations, especially Eqs (3.5) and (3.6), regarding the relative weights of the various parameters. Even if the dynamic contact stress, $p_d$, decreases, thus leading to a coefficient of restitution closer to unity and leading to an increase of the reaction phase work ($W_{REAC}$), the amount of rebound will not necessarily increase. This is attributed to the fact that the debonding work ($W_D$) or pull-out work can increase more rapidly than $W_{REAC}$, hence reducing rebound\(^2\).

### 3.3.2— RHEOLOGY AND PLASTICITY OF DRY-MIX SHOTCRETE

The investigation of Armelin (1997) on rebound mechanisms does not help much when one tries to understand the stability of a layer of shotcrete already in-place or being placed. In other words, what are the properties of a fresh layer of shotcrete and how, or even to what extent, are those properties affected by shooting and mix design parameters? This section presents the reflections which led to the first part of this research project (presented in Chapters 4 and 5).

\(^2\) This phenomenon was encountered by Armelin when silica fume or cement content were increased in a mixture.
3.3.2.1 Bingham or not?

What are the properties of fresh dry-mix shotcrete? The fact that flow models such as the Bingham model do not account for the elastic component in the deformation of a material has already been emphasised. The question of whether fresh dry-mix shotcrete obeys the Bingham flow model still remains open. To find the answers, however, special steps need to be taken since the tools available today can barely measure the rheological properties of virtually no slump concretes, such as shotcrete. If one tries to measure the rheological properties on fresh dry shotcrete using conventional apparatus, the fresh shotcrete would probably be transformed into a loose aggregation of more or less clustered particles. This breakdown of the continuity\(^3\) forms new boundaries or new bodies, thus creating a different material. In other words, instead of testing the rheological properties of fresh shotcrete, the operator would be testing the rheology of clumps of fresh shotcrete.

Furthermore, one may question the usefulness of the information obtained from a complete flow characterisation of a mixture. In fact, Beaupré (1994) showed that viscosity is not important with regard to build-up thickness in wet process shotcrete. In Figure 2.8, the build-up thickness failure mechanisms all refer to quasi-static stress states. The dynamic properties are of interest only during the placement of the shotcrete, when high shear rates are encountered. Once in place, the relevant information concerns the mechanical properties of the material. Assuming that the mechanical properties are defined and measurable, a remaining part of the research is to compare the effect of various parameters on the mechanical properties. These parameters include all of the typical shooting technique and mix design parameters.

---

\(^3\) For a body to remain continuous, the compatibility equations must be satisfied everywhere. In the situation depicted here, the formation of new boundaries corresponds to the formation of new bodies (Timoshenko & Goodier, 1970; and Johnson & Mellor, 1983).
3.3.2.2 Modelling fresh dry-mix shotcrete

Armelin (1997) considered fresh dry-mix shotcrete to be a material obeying the Tresca yield criterion. A yield criterion is a hypothesis concerning the limit of elasticity of a material under any possible combination of stress\(^4\). It is usually represented as a surface in a three dimensional graph whose axes are the three principal stresses (\(\sigma_{ii}\)) or, more simply, as a curve in a Mohr diagram representation. The obvious advantage of this approach, when applicable, is the need to work only with the stresses at failure. Neither the stress to strain relationship or stress to strain rate relationship are required to apply a failure criterion. To be able to characterise fresh dry-mix shotcrete using a single failure criterion would thus provide the information required to investigate the mechanisms involved in the stability of a shotcrete layer.

However, the choice of a failure criterion needs to be addressed: the Tresca yield criterion is one generally used for metals, and does not account for the relatively weak tensile strength of certain materials such as ceramics, cohesive soils and concrete. Tresca's criterion states that yield is actually independent of the mean stress applied and can be written (Johnson & Mellor, 1983):

\[
\tau_f = \left| \frac{\sigma_{11} - \sigma_{33}}{2} \right|
\]  

and the mean or hydrostatic stress is equal to (in 2D):

\[
\sigma_m = \left| \frac{\sigma_{11} + \sigma_{33}}{2} \right|
\]  

Based on this assumption, the uniaxial compressive and tensile strengths of the material should be equal, which is certainly not true for fresh dry-mix shotcrete or any fresh or hardened concretes. To illustrate, according to Tresca's criterion, a shotcrete with only 0.1 MPa of compressive strength should reach an overhead build-up of more than 5 meters!! Thus, there is a definite need to find a yield criterion which reflects the behaviour of fresh dry-mix shotcrete more accurately.

\(^4\) Yield is used here as a synonym of failure since yielding of fresh dry-mix shotcrete is considered to be accompanied by large strains that lead to poor in-place shotcrete quality.
The consistency of fresh dry-mix shotcrete is extremely stiff when compared to conventional fresh concrete. It is actually much closer to that of compacted earth or consolidated clay and, as for clay and earth, cohesion is obvious in fresh dry-mix shotcrete since it is generally possible to achieve overhead applications. The most common failure criterion applied to soils is the Mohr-Coulomb failure criterion (Holtz & Kovacs, 1981 and Terzaghi et al., 1996). This criterion states that failure occurs when the shear stress on the failure plane reaches some unique function of the normal stress on that plane. The function used in this case is:

\[ \tau_f = \sigma_f \cdot \tan(\phi) + c \]  

(3.9)

where \( \tau_f \) and \( \sigma_f \) are respectively the shear and the normal stress on the failure plane at failure. The angle "\( \phi \)" and the constant "\( c \)" are two material properties: the first is the angle of internal friction, which represents the interlocking effect of the particles and the second is the intrinsic cohesion which represents the attraction exerted between the particles. This failure criterion was observed by L'Hermite and Tournon (Powers, 1968) during direct shear tests on fresh concrete. From a few different laboratory tests at different stress states, a family of Mohr circles is plotted, and it is then possible to construct the Mohr-Coulomb failure envelope, which is the actual relationship between \( \tau_f \) and \( \sigma_f \). Figure 3.3 shows a representation of a failure envelope for a “perfect” cohesive material.

Figure 3.3: Representation of the Mohr-Coulomb failure envelope.
This representation of the Mohr-Coulomb yield criterion clearly shows the strong dependence of the material on the hydrostatic component of the stress. Also, it shows the existence of a shear resistance (cohesion) even when there is no normal stress applied. This cohesion exists due to the very small particles present, for which interparticle attraction is a prominent attribute. These two aspects are essential in order to acknowledge the existence of an overhead build-up thickness in shotcrete.

Practically, the information that can be obtained from such a representation is twofold. First, it allows for a rational interpretation of the behaviour of fresh shotcrete in tension versus compression. Second, it is possible once the envelope is obtained to compare the relative effects of various parameters with two fundamental properties, “c” and “\( \theta \)”. It is believed that working with these fundamental properties will permit a rational explanation of otherwise empirical observations, e.g. the cohesive effect of silica fume.

### 3.3.2.3 Practical considerations

Anyone who has worked in concrete research, especially shotcrete research, knows that obtaining an envelope similar to that in Figure 3.3 is practically impossible for fresh concrete or shotcrete. Indeed, before a failure envelope can be drawn, we need to obtain a few Mohr circles corresponding to different stress states. To do so, special tools and test procedures need to be developed. Consequently, it is not to be expected that a linear failure envelope will necessarily be found since test conditions have a large influence on this type of characterisation. However, the goal is to show that fresh dry-mix shotcrete follows a failure criterion similar to the one presented, and thus to offer a rational explanation of the observed behaviour, making use of the information obtained for relative comparisons.

In the long run, such an understanding of fresh shotcrete will permit a more efficient mix design procedure and eventually allow for better quality control of the fresh material.
3.4 – CONCLUSION

The basic idea behind this research project when it was first considered in 1996 was to “put some science into the art of shotcreting”. The areas of possible research are numerous in shotcrete technology, but there is a particular lack of knowledge about the fundamental mechanisms underlying the behaviour of the material. The questions for which answers will be sought include:

- What are the relevant fresh properties of dry-mix shotcrete?
- Is there a (simple and easy) way to measure the fresh properties?
- How do silica fume or cement content affect the fresh properties of shotcrete?
- Which parameters most affect the fresh properties?
- Is there any way to carry out meaningful quality control on fresh shotcrete?
- Can we predict maximum build-up thickness?

It is not the goal of this thesis necessarily to answer all of these questions; but at least to prepare the tools with which to answer them.
CHAPTER 4
DEVELOPMENT OF CHARACTERISATION METHODS FOR FRESH DRY-MIX SHOTCRETE

4.1 - INTRODUCTION

As described in the previous chapter, it is not possible to use conventional rheometers to characterise fresh dry-mix shotcrete, due to its extremely low workability. This chapter presents the tools designed or adapted to evaluate the fresh properties of shotcrete: the U.B.C. Penetrometer, the fresh tensile strength apparatus, and the fresh shear strength apparatus. First, however, there is an overview of the shotcrete production equipment set-up.

4.2 – LABORATORY LAYOUT

4.2.1 – SHOTCRETING EQUIPMENT

To achieve the objective of this research program, industrial shotcreting equipment was used in a laboratory controlled environment. Throughout, shotcrete was produced using a dry-mix rotating barrel gun (model ALIVA 246, electric motor) with a barrel capacity of 3.6 litres. The material was conveyed to the nozzle either by a 32 mm (1¼ in.) inside diameter hose with the water ring placed in the body of the nozzle, or by a 38 mm (1½ in.) inside diameter hose with the water ring placed 2.5 meters upstream. Air supply was provided by an industrial air compressor with a rated capacity of 0.35 m³/s (750 cfm) and an operating pressure of 700 kPa (100 psi). The water pressure used was also 700 kPa (100 psi). In all cases, pre-bagged oven dry materials were used.
4.2.2 - Monitoring Equipment

When dealing with dry-mix shotcrete, it is generally agreed that one of the most important factors affecting the final product is the experience of the nozzlemen. His experience is of great importance since he is the one controlling the consistency of the fresh shotcrete by adjusting the amount of water added to the mix. The consistency is a critical property of shotcrete since it affects not only the hardened properties, but also the amount of rebound, the maximum build-up thickness and the workability, which in turn control reinforcement encasement and finishing operations.

Therefore, the first parameter monitored and controlled during the present research project was the water flow at the water ring. Water flow records obtained during two shooting sessions are shown in Figure 4.1. The dotted line represents an uneven water flow at the nozzle during shooting, which implies that the in-place mixture will not be homogeneous. Shooting sessions which generated such a graph had their mixture discarded and reshot. The solid line shows an acceptable shooting session: the water flow at the nozzle is relatively constant which suggests that the material exiting the nozzle is homogenous. It is assumed that water flow measurements provide a good indication of the quality and regularity of a particular shooting session. A mixture that tends to stick to

![Figure 4.1: 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.](image)
the delivery hose, or exhibits irregular flow of dry material, would change the pressure equilibrium at the water ring, hence introducing significant variations in the water flow.

To facilitate rebound measurements, the panels into which the material was shot were mounted on frames instrumented with load cells. A panel similar to the one presented in Figure 2.7 was thus suspended on three 225 kg capacity load cells. A vertical panel was similarly equipped as shown in Figure 4.2. The electronic signals of the water flowmeter and the load cells were all recorded by a data acquisition system linked to a computer. These recordings proved very practical since they allowed for later reference. Subsequently, the shotcreting machine itself was mounted on a scale in order to assess the delivery rate of the dry material.

Finally, a spring loaded, in-line, air flowmeter was attached to the air input of the shotcreting machine, which permitted the setting and monitoring of the air flow in the delivery hose.

4.3 – U.B.C. PENETROMETER

4.3.1 – Consistency

As presented in Section 2.4.4, consistency is an extremely important factor in the placement of a sound layer of shotcrete. Thus, a research program such as the one presented here must implement a way to assess quantitatively the shotcrete consistency.

A quantitative way of assessing the shooting consistency of fresh dry-mix shotcrete has been presented by Prudêncio et al. (1996). They measured the consistency using a Proctor
apparatus similar to the one described in ASTM C1117 (right side into Figure 4.3). The procedure consists of pushing a cylindrical needle into the concrete and recording the maximum pressure required to attain a given depth: this is referred to as a constant depth penetrometer. A similar apparatus had already been introduced by Sallstron (1969) and follows the same principle with a relatively smaller needle (left in Figure 4.3). In the same vein, a constant energy penetrometer, where the distance penetrated is recorded for a given energy of penetration, has also been used by Prudêncio et al. (1996) and Figueiredo and Helene (1996). The principal usage of these devices in the cited literature is to assess the fresh shotcrete compressive strength through empirical relationships, each apparatus being valid over a portion of the strength axis (typically from 0.2 MPa to 8 MPa).

Figure 4.3: Instruments used to assess shooting consistency.

In their paper, Prudêncio et al. (1996) assumed that: (i) the shooting stiffness measurement is a quantitative evaluation of the rheology of the applied shotcrete, (ii) it gives an indication of the ability of the shotcrete to hold to walls and overhead, and (iii) it is a measurement analogous to the yield value of Tattersall & Banfill (1983).
For this research program, an instrumented version of the Proctor apparatus (constant depth penetrometer) was developed\(^1\) to assess the fresh consistency of dry-mix shotcrete. The device is equipped with a compressive load cell and a potentiometer both linked to a data acquisition system and a computer (see Figure 4.4). The advantage of such an apparatus is to provide the complete pressure vs. depth of penetration curve. When used with a cylindrical needle, the resulting curve is characterised by an increasing pressure for the first millimetres of penetration followed by a plateau which is reached at a penetration depth of about a needle diameter. Figure 4.5 shows a typical test result, comprised of 5 measurements. The shapes of the curves presented show that the fresh dry-mix shotcrete behaved like an elastic perfectly plastic material. The presence of this plateau reinforces the idea that the consistency measurement is similar to the measurement of the yield stress value.

\(^1\) The first instrumented version, known as the U.B.C. Penetrometer, was constructed by Armelin, 1997.
The penetration stress at which the plateau appears is considered to be a quantitative measurement of the consistency of a fresh dry-mix shotcrete mixture. Therefore, whenever there is a numerical quantity attached to the word *consistency* in what follows, it corresponds to the value of the plastic plateau of a given mixture as measured only a few seconds after shooting the sample. The consistency value obtained *is not a compressive strength*; in fact, it is much more closely related to the shear strength of the material, as will be demonstrated later.

![Diagram](image.png)

**Figure 4.5: Typical result of a consistency measurement test; cylindrical needle, \( \phi = 9 \text{ mm} \).**

The consistency measurement is used extensively in the next chapter as a the basis for comparing mixtures. Thus, one is entitled to question the precision of the test, especially when relationships are drawn from its results. To illustrate the precision of the penetration test, Figure 4.6 presents the experimental data points obtained for rebound values vs. consistency. These experimental data points, each being the average of 5 actual consistency tests for each rebound value, are accompanied by error bars representing plus or minus one standard deviation. In all cases, the best fit line falls within the limits of precision of the tests. For reasons of clarity, these error bars will not be presented in the graphs which follow; however, the same degree of precision was generally observed throughout the research program with this test.
Figure 4.6: Experimental data points along with error bars of rebound versus penetration resistance for two shotcrete mixtures.

4.3.2 - INTERPRETATION

4.3.2.1 Previous relationships

Prudêncio (1993) found that the shooting stiffness was linearly related to the water to dry material ratio; the lower the water content, the higher the penetration resistance. Later, Prudêncio et al. (1996) also obtained a linear relationship between the early compressive strength (< 1 MPa) and the penetration resistance. Armelin (1997) obtained linear relationships between the shooting consistency and the amount of rebound produced for various mixtures.

To ensure comparability among mixtures of various compositions, one needs to set strict comparison criteria. In the case of dry-mix shotcrete, this comparison rule will be an equal consistency criterion (or an equal penetration resistance criterion) where the nozzleman adjusts the water flow to achieve the desired consistency. Throughout this
research project, the *equal consistency criterion* is therefore adopted, and refers to measurements made using the penetrometer shown in Figure 4.4.

### 4.3.2.2 Shape of the Indenter

In the early stages of this research project, three different needle configurations were tested. Their sizes and shapes are presented in Table 4.1. It appeared that the 3 mm diameter needle would be useful only for stiff to very stiff materials. Moreover, the plastic plateau did not appear when using this relatively small needle. Therefore, the use of this needle configuration was abandoned.

The second needle configuration used was basically an enlargement of the previous one: diameter of 9 mm with a cone angle of 60°. The results obtained were much better as the consistency plateau tended to appear more often and the relationships cited in the previous section were observed. However, the conical tip of this needle turned out to be a disadvantage when trying to interpret the test results: the effect of friction between the tip and the penetrated material is difficult to account for.

Following Armelin's (1997) example, a flat conical needle was selected for the major part of the project. There are two advantages in this case: the flat head needle test is easily compared to Prandtl's method of evaluation of foundation bearing capacity (Terzaghi et
al., 1996), and the friction between the needle and the material is practically negligible. Moreover, the plastic plateau is present in most of the tests carried out with this needle configuration.

4.3.3- MATHEMATICAL INTERPRETATION

The previous chapter concluded by stating that several tests were needed to characterise the Mohr-Coulomb failure envelope for a given material. Since this failure criterion contains two constants, the angle of friction, $\phi$, and the cohesion, $c$, at least two tests, or two Mohr circles at failure, are needed to characterise it. The main difficulty relies in relating the penetration stress (or consistency) obtained with the U.B.C. Penetrometer, to a complete Mohr circle. A direct solution for $\phi$ and $c$ cannot be directly obtained, but instead an equation of the form:

$$f(\phi, c) = 0$$

(4.1)

A second and different test is still required to find either $\phi$ or $c$, and then one can go back to equation 4.1 and solve for the remaining unknown.

4.3.3.1 Soil mechanics approach

Obtaining the penetration resistance from a penetration test into the fresh shotcrete can be compared to the case of the bearing resistance of a shallow circular footing resting on a granular soil. The empirical method of evaluation is well covered in Terzaghi et al. (1996). The key point is that the bearing capacity of such a footing is said to be a function of both the cohesion, $c$, and the angle of friction, $\phi$ of the foundation material.

The actual value of the bearing capacity is given by:

$$q = 1.2 N_c c$$

(4.2)

where $q$ is the bearing capacity per unit area,

1.2 is a coefficient accounting for the circular geometry of the footing,

$N_c$ is the bearing capacity factor, taken from Figure 4.7

---

2 At a cone angle of 60°, the mean penetration stress can increase by a factor of 3 when considering friction
Here, the bearing capacity is the actual penetration resistance, therefore Eq. (4.2) can be used as one of the required equations of the form of Equation (4.1).

\[
N_c = \cot \phi \left[ e^{\pi \tan \phi} \cdot \tan^2 \left( 45^\circ + \frac{\phi}{2} \right) - 1 \right]
\]

Figure 4.7: Relation between bearing capacity factor and angle of friction (from Terzaghi et al., 1996)

4.3.3.2 The plasticity approach

Classical plasticity references (e.g. Johnson & Mellor, 1983; Hill, 1983; Johnson, 1985) all contain models of perfectly plastic materials indented, extruded, rolled or formed, the simplest being the case of the infinitely rigid cylindrical flat indenter. The theory used to find a solution is the well known Slip-Line Field Theory. The principle of this theory is to construct a set of slip-lines for a given plastic deformation operation, and to use characteristic equations obtained from equilibrium considerations. These characteristic equations give the variation of the stresses along the slip-lines. The Hencky equations are

\[
\text{in the calculation; for the flat indenter, this increase is only of 6%, (Johnson, 1985).}
\]

3 The slip-lines are in fact the locations of the maximum shear stress; they form a set of orthogonal curves.
used with materials obeying the Tresca or von Mises failure criterion\(^4\) (Johnson, 1985).

To explain this method, an example is presented in Figure 4.8 for a Tresca material indented by an infinite flat wedge; \textit{this is not the solution that interests us}, but the development is somehow very similar and much simpler. Note that the solution found is the same as for Eq. (4.2) for a purely cohesive material \((c = k, \phi = 0)\).

\[\sigma_m = 2k\omega + \text{constant} \quad \text{along an } \alpha \text{-line}\]
\[\sigma_m = \text{constant} - 2k\omega \quad \text{along an } \beta \text{-line}\]

where \(\sigma_m\) is the mean stress on an element, \(k\) is the shear strength of the material and \(\omega\) the relative anticlockwise orientation of the principal directions.

In location "c", the stress normal to the surface is zero, thus allowing for the construction of the first Mohr circle "C". Using Hencky equation, we can write:

\[(\sigma_m)_c = -k \quad \text{and, since there is no rotation when travelling to location "d"},\]
\[(\sigma_m)_d = -k\]

A positive rotation of \(\pi/2\) is required along the \(\beta\)-line to get to "e" (and "f" at the same time).

Thus:

\[(\sigma_m)_r = (\sigma_m)_e = -k - 2k\frac{\pi}{2} = -k(1+\pi) \quad \text{and, to get the stress normal to the surface in "f" (Mohr circle F):}\]
\[\sigma_f = (\sigma_m)_f - k = -k(2+\pi)\]

So the compressive stress on the indenter is equal to 5.14 times the shear strength of the material (Johnson & Mellor, 1983).

\textbf{Figure 4.8: Example of solution of a flat wedge indenting a metal obeying the Tresca failure criterion.}

\(^4\) These two criteria are characterised by only one parameter, usually the shear strength of the material \((k)\).
As stated earlier in Chapter 3, fresh concrete obeys a failure criterion similar to the Mohr-Coulomb theory. So, instead of constructing consecutive Mohr circles enclosed between two parallel lines as in Figure 4.8 (b), we need to construct Mohr circles enclosed in two oblique straight lines, these two lines representing the linear Mohr-Coulomb failure envelope. Thus, instead of working with one simple constant (shear resistance $k$ in the case of Figure 4.8), we need to work with two constants, namely $\phi$ and $c$. The solution of this more complex problem is found in Hill (1985). He proposed a set of characteristic equations, similar to Hencky's equations, which allows one to “travel” along the slip-lines of a material obeying any failure criterion. His set of characteristic equations are:

\begin{align*}
\lambda - \omega &= C_1 \quad \text{along an } \alpha \text{-line} \\
\lambda + \omega &= C_2 \quad \text{along a } \beta \text{-line}
\end{align*} \tag{4.3}

where:

\begin{equation}
\lambda = \frac{1}{2} \left[ \int \frac{d\sigma}{\tau} - \phi \right] \tag{4.4}
\end{equation}

$\omega$ is the anticlockwise orientation of a principal stress direction, 

$\tau$ is the shear on the element, 

$\sigma$ is the normal stress to the $\alpha$- or $\beta$-line, and 

$\phi$ is the angle of friction of the material

Hill states that $\lambda$ is a known function of $\phi$ and so all that is needed is a relationship between $\tau$ and $\sigma$ to solve Eqs (4.3). At failure, this relationship is simply the expression of the failure criterion (in this case, Eq. (3.9)). Introducing it into Eq. (4.4) and (4.3), we obtain characteristic equations which are functions of the angle of friction, the cohesion and the stress state only. These equations will in turn allow us to obtain an equation relating $\phi$ and $c$, thus providing the first equation needed to construct the Mohr-Coulomb failure envelope of the material (see Eq. (4.1)). The complete development and the iterative steps needed to solve for $\phi$ and $c$ are given in Section 4.6. All the theoretical procedure described here will be applied to actual experimental results in Chapter 7.
4.4– **FRESH TENSILE STRENGTH TEST (FTS)**

4.4.1 – **THE FTS APPARATUS**

The principle of the fresh tensile strength test was proposed by Denis Beaupré in the early stages of this research project. The test procedure is divided into two general steps: first, shotcrete is shot directly into a special mould mounted vertically in the rebound chamber. Second, the mould is moved to a special frame equipped with a load cell and a displacement transducer. Fasteners are removed to permit free movement of the half panel on the rails and an electrical motor applies a slow velocity displacement (0.36 mm/s) to the movable part of the apparatus. The test is performed within a minute after the sample is shot. A schematic drawing of the apparatus is presented in Figure 4.9.

![Schematic drawing of the Fresh Tensile Strength Apparatus (FTS).](image)

**Figure 4.9:** Schematic representation of the Fresh Tensile Strength Apparatus (FTS).

Originally, the test was designed to simulate the stress state that occurs in an overhead maximum build-up thickness situation. As we will see later, it gradually replaced the maximum build-up thickness test, since it directly provides a fundamental property of the fresh dry-mix shotcrete, the tensile strength.
4.4.2 - RESULTS AND INTERPRETATION

The data acquisition system records the full force-displacement curve for each test. Figure 4.10 presents a typical curve obtained during a test. For normal consistency mixtures, the curve shows a rapid increase of the tensile stress followed by a more or less horizontal portion spanning usually less than 2 mm. The curve then goes down rapidly to an average value of 1 kPa, attributed partially to the friction of the rails\(^5\) and partially to the aggregates being pulled out of the paste matrix. Stiffer mixtures usually reach their maximum tensile strength at smaller displacements followed by a rapid reduction, without any apparent "horizontal" section.

![Graph of force-displacement curve for stiff and soft mixtures]

**Figure 4.10: Typical result of a Fresh Tensile Strength Test.**

The first question is whether the loading rate (pulling speed) has an influence on the measured value of the fresh tensile strength. To investigate this, the same mixture was shot at different consistencies\(^6\) and tested at variable pulling speeds. It was found that the

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\(^5\) A minimum friction is inevitable in this region of the rail. It is however much less important in the first few millimetres where the rails are better protected by the bearing casing itself.

\(^6\) It will be shown in Section 5.2.1 that consistency and water flow at the nozzle are directly related for a given mixture.
pulling speed had no significant influence on the measured value of fresh tensile strength over the range of speeds studied. Figure 4.11 shows the results obtained.

![Figure 4.11: Effect of the pulling speed on the value of fresh tensile strength.](image)

The advantage of the fresh tensile strength test is that the stress state at failure is easily modelled. Since the stresses are those of pure uniaxial tension, the corresponding Mohr circle will be tangent to the origin on the tension side of the normal stress axis. It can then be shown geometrically that the fresh tensile strength of the material, \( \sigma_{ut} \), is equal to (see Figure 4.12):

\[
\sigma_{ut} = 2c \cdot \frac{\cos \phi}{1 + \sin \phi} \quad (4.4)
\]

Equation (4.4) can be put in the form of \( f(\phi, c) = 0 \), and could therefore be used, along with the last equation presented in Section 4.6, to solve for the angle of friction, \( \phi \) and the cohesion, \( c \). Unfortunately, we will see in Chapter 7 that the fresh tensile strength results obtained cannot be put directly into a failure envelope diagram.

The reader should be aware that the value of fresh tensile strength found is an empirical measurement of the intrinsic tensile strength of the material. Size effects can play an important role in this measurement, which therefore should not be directly transferred to practice without prior validation.
4.5- *FRESH SHEAR STRENGTH APPARATUS (FSS)*

4.5.1 - *ORIGIN OF THE FSS APPARATUS*

The fresh shear strength apparatus was used later in the research project. This test, known as the vane test in soil mechanics (Holtz & Kovacs, 1981), was used in order to support the fresh tensile strength test. Some researchers had already used the vane paddles as a rheometer to determine the yield value of concentrated suspensions or greases (Dzuy & Boger, 1985; Collyer & Clegg, 1988). In this project, however, it was the soil mechanics approach that was favoured and the vane test was used to determine the shear resistance of fresh dry-mix shotcrete.

The vane paddles cannot be pushed into fresh shotcrete since this would disturb the sample to an unknown state. For this reason, a circular mould was built to support the vane while shooting around it in such a manner as to completely embed the vane. An increasing torque was then applied to the vane until failure occurred, using the IBB Rheometer of the Laval University laboratory. In every cases, the test was performed within a minute after the sample was shot. Figure 4.13 illustrates the procedure.

![Diagram of the Fresh Shear Strength Apparatus (FSS)](image)

**Figure 4.13:** Schematic representation of the Fresh Shear Strength Apparatus (FSS).
4.5.2 – RESULTS AND INTERPRETATION

It was observed during testing that the shear failure was sudden and seldom preceded by any rotation of the vane. These observation were confirmed by inspection of the curves generated by the data acquisition system; a typical test result is presented in Figure 4.14. This test has the advantage of correlating extremely well with the consistency measurement, as will be seen in Chapter 7.

![Figure 4.14: Typical result of a fresh shear strength test.](image)

**Figure 4.14**: Typical result of a fresh shear strength test.

It is possible to deduce from the maximum applied torque the value of the ultimate shear. Using the notation of Figure 4.13, and assuming that the maximum shear strength, $\tau_{sl}$, is reached at every point at failure, and that failure takes place on a cylindrical surface of height $L$ and diameter $2R$, we can write:

$$T_r = T_{base} + T_{side}$$  \hspace{1cm} (4.5)

where $T_r$ is the total torque applied,

$T_{base}$ is the portion of the total torque required to initiate rupture at the base of the sample, and
$T_{\text{side}}$ is the portion of the total torque required to initiate rupture on the side of the sample.

Knowing the surface area of the side of the cylinder, the required torque is then:

\[ T_{\text{side}} = 2\pi R^2 L \cdot \tau_u \]  
(4.6)

The base is a circular surface of radius “R”, therefore the required torque is:

\[ T_{\text{side}} = \int_0^R 2\pi R^2 \tau_u \, dR = \frac{2\pi R^3}{3} \cdot \tau_u \]  
(4.7)

There is no component for the torque on the top surface of the vane since there is no material above the vane. The dimensions of the vane used are such that every blade is square, that is $R = L = 50$ mm. Combining Eq. (4.6) and Eq. (4.7) into Eq. (4.5) and rearranging the terms to obtain the ultimate shear strength on the left hand side, we find:

\[ \tau_u = \frac{3T_i}{8\pi R^3} \]  
(4.8)

Which simplifies in this case to:

\[ \tau_u \text{ (kPa)} = 0.955 \cdot T_i \text{ (N-m)} \]  
(4.9)

Taking the example of Figure 4.13, the maximum torque applied is 53.3 N·m, and the ultimate shear strength of this mix is thus:

\[ \tau_u = 0.955 \cdot 53.3 = 50.9 \text{ kPa} \]

Going back to Figure 3.3, the stress state at failure associated to this test is one of pure shear and is thus represented by a vertical straight line from the origin to the failure envelope. In this particular case, the fresh shear strength found is therefore equal to the cohesion “c”.

The reader should understand that the value of ultimate shear strength obtained with this test is an empirical measurement of the intrinsic shear strength of the material. Parameters such as the size of the paddles and the size of the sample can play an important role in this measurement, which therefore should not be directly used in practice without prior validation.
4.6- INFINITE WEDGE INDENTER

This special section presents the development of the model of the infinite wedge indenter problem. The complete steps required to obtain a solution in the form of Eq. (4.1) are derived.

Before presenting the solution proposed by Hill (1983) for a general plastic material, a number of assumptions must be made. These are:

- The model is exact only for plain strain conditions.
- Elastic strains are neglected.
- Directions of principal strain rate and stress coincide.

Plain strain conditions means that a solution will be developed for the flat infinite wedge and then applied to the cylindrical needle, using the ratio found in Johnson (1985). Elastic strains can easily be neglected in this case since they are relatively small compared to the amount of plastic flow that takes place during a consistency measurement. The last assumption means that the loading rate parameter is not considered. Since it is intuitively obvious that loading rate is a factor, it will be important to insert the needle at a constant velocity for all tests.

As presented in Section 4.3.3, Hill (1985) proposed a set of characteristic equations for a general plastic material which are:

\[ \begin{align*}
\lambda - \omega &= C_1 & \text{along an } \alpha\text{-line} \\
\lambda + \omega &= C_2 & \text{along a } \beta\text{-line}
\end{align*} \tag{4.10 a, b} \]

where:

\[ \lambda = \frac{1}{2} \left[ \int \frac{dR}{Q} - \phi \right] \tag{4.11} \]

\( \omega \) is the anticlockwise orientation of a principal stress direction,
\( Q \) is the shear on the element,
\( R \) is the normal stress to the \( \alpha \)- or \( \beta \)-line, and
\( \phi \) is the angle of friction of equation 3.9.

Figure 4.15: Schematic of Hill’s equations.
The relationship needed to use Eq. (4.10) is the proposed failure criterion (note that here, tension is positive):

\[ |\tau| = c - \sigma \tan(\phi) \]

or, using Hill's notation

\[ |Q| = c - R \tan(\phi) \quad \text{(4.12)} \]

Replacing Eq. (4.12) in Eq. (4.11), and solving for \( \lambda \), we obtain Eq. (4.10) where the only unknowns are "\( \phi \)" and "\( c \)". The solution is easily obtained using the software MapleV™:

\[
\lambda = -\frac{1}{2} \left[ \frac{\ln(c - R \tan \phi)}{\tan \phi} + \phi \right] \quad \text{(4.13)}
\]

Then, similar to what was done in the example of Figure 4.8, the slip-line field can be constructed and we can follow a line all the way to the consistency or penetration stress value. We will "travel" along line a-b-d-e in Figure 4.16.

To start, point "a" has no stress normal to its horizontal surface; the corresponding Mohr circle must then be tangent to the origin of the axis. Thus, we can write (see Figure 4.17 for notation):

\[
R = R_a
\]

\[
R_a = \frac{\sigma_{uc}}{2} - \frac{\sigma_{uc}}{2} \sin(\phi)
\]

\[
= c \cdot \frac{\cos(\phi)}{1 - \sin(\phi)} - c \cdot \frac{\cos(\phi)}{1 - \sin(\phi)}
\]

\[
= -c \cdot \cos(\phi)
\]

and then, with Eq. (4.13)

\[
\lambda_a = -\frac{1}{2} \left[ \frac{\ln(c - R_a \tan \phi)}{\tan \phi} + \phi \right] = -\frac{1}{2} \left[ \frac{\ln(c(1 + \sin \phi))}{\tan \phi} + \phi \right] \quad \text{(4.14)}
\]
Since there is no rotation between point “a” and point “b”, we can directly write:

\[ \lambda_a = \lambda_b \]

The rotation between point “b” and point “d” is equal to 90° (counter clockwise, thus positive) and according to Eq. (4.10b), the constant \( C_1 \) is equal to \( \lambda_a \), therefore:

\[ \lambda_d = \lambda_a - \frac{\pi}{2} = -\frac{1}{2} \left[ \frac{\ln(c(1+\sin\phi))}{\tan\phi} + \phi + \pi \right] \quad \text{or,} \]

\[ -\frac{1}{2} \left[ \frac{\ln(c - R_d \cdot \tan\phi)}{\tan\phi} + \phi \right] = -\frac{1}{2} \left[ \frac{\ln(c(1 - \sin\phi))}{\tan\phi} + \phi + \pi \right], \]

Rearranging to extract \( R_d \) and considering that \( R_e = R_d \):

\[ R_e = R_d = \frac{1}{\tan\phi} \left[ c - c \left[ \ln(c \cdot (1 + \sin\phi)) + \pi \cdot \tan\phi \right] \right] \quad (4.15) \]

Note: \( R_e \) will be negative since compression is considered negative up to this point.

Let us now go back to Eq. (4.12), and rewrite it in terms of the principal stresses \( \sigma_1 \) and \( \sigma_3 \) (Holtz & Kovacs, 1981). Notice the signs; since soil mechanics notation is used here, compression is positive.

\[ \left| Q \right| = c - R \cdot \tan(\phi) \]

\[ \sigma_1 - \sigma_3 = (\sigma_1 + \sigma_3) \cdot \sin(\phi) + 2c \cdot \cos(\phi) \quad (4.12') \]

We can also write:

\[ R_e = \left( \frac{\sigma_1 + \sigma_3}{2} \right) - \left( \frac{\sigma_1 - \sigma_3}{2} \right) \cdot \sin \phi \quad (4.16) \]
Eq. (4.12') gives an expression for \(\sigma_3\):

\[
\sigma_3 = \sigma_1 \left( \frac{1 - \sin\phi}{1 + \sin\phi} \right) - 2c \cdot \left( \frac{\cos\phi}{1 + \sin\phi} \right)
\]  
(4.17)

Insert Eq. (4.17) into (4.16):

\[
R_e = \sigma_1 \cdot (1 - \sin\phi) - c \cdot \cos\phi
\]  
(4.18)

We obtain a second expression for \(R_e\) where \(\phi\) and \(c\) are unknown. Note that once we are at point "e", the maximum compressive stress (\(\sigma_1\)) is the actual penetration stress or consistency. Thus, in Eqs (4.12'), (4.16), (4.17) and (4.18), \(\sigma_1\) is related to the penetration stress measured with the U.B.C. Penetrometer. In fact, \(\sigma_1\) is taken as 88% of the penetration stress value, to take into account the circular shape of the indenter as proposed by Johnson (1985).

The next and last step is to combine Eqs (4.15) and (4.18) to obtain an equation of the form \(f(\phi, c, \sigma_i) = 0\). Bearing in mind the opposite sign conventions of these two equations, we finally have:

\[
\frac{1}{\tan \phi} \left[ c - e^{\ln(c \cdot (1 + \sin\phi)) + \pi \cdot \tan \phi} \right] + \sigma_1 \cdot (1 - \sin\phi) - c \cdot \cos\phi = 0
\]  
(4.19)

It is Eq. (4.19) that is used as the first equation of the two required to solve for the two unknowns of the Mohr-Coulomb failure criterion, namely the angle of internal friction, \(\phi\), and the intrinsic cohesion, \(c\).
CHAPTER 5
PRELIMINARY CHARACTERISATION

5.1- INTRODUCTION

This chapter presents the results obtained during the “tool development” phase of the research project. The key relationships which were obtained are presented. Basic properties such as rebound and maximum build-up thickness were evaluated, along with the fundamental properties of fresh tensile strength and penetration resistance.

5.2- RESEARCH PROGRAM

The “tool development” program consisted of identifying tests to assess the relevant properties of fresh dry-mix shotcrete. The UBC Penetrometer 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 shooting sessions.

Different mix parameters were investigated to compare their effects on the fresh concrete properties and, at the same time, validate the results obtained in the laboratory. The four mixtures investigated are presented in Table 5.1; they were chosen because they are known, by experience, to cover a wide range of behaviours.

Shotcrete was sprayed using a dry-mix ALIVA 246 equipped with a 3.2 litres rotating barrel and a 31.75 mm (1¼ in.) inside diameter hose. The water ring was positioned directly into the nozzle body, approximately 300 mm from the nozzle's end. Normal gunning techniques as described in Crom (1981) and Yoggy et al. (1995) were followed.
Table 5.1: Mixture composition.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Mortar*</th>
<th>Mortar +SF</th>
<th>Mortar +AEA</th>
<th>Shotcrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cement type (%)</td>
<td>30</td>
<td>10 + silica fume</td>
<td>30</td>
<td>10 + silica fume</td>
</tr>
<tr>
<td>Sand (%)</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>62</td>
</tr>
<tr>
<td>Coarse agg. (%) (10 mm max. size)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>18</td>
</tr>
<tr>
<td>Air entraining admixture</td>
<td>-</td>
<td>-</td>
<td>15 ml/l&quot;</td>
<td>-</td>
</tr>
</tbody>
</table>

* Proportions for dry-mix shotcrete are usually given in mass proportions of dry constituents.

** The air entraining admixture is mixed with the shooting water in a separate tank.

5.2.1- CONSISTENCY

To enable comparisons to be made amongst the mixtures of various compositions, a consistency criterion was set: the resistance to penetration. During this study, the nozzleman was allowed to adjust the water flow to achieve the desired consistency (as opposed to equal water cement ratio as in conventional concrete). The consistency was evaluated using the U.B.C. Penetrometer (Section 4.3). A 9 mm diameter conical needle (60° cone angle) was used for this part of the project. Because of the difficulties cited in Section 4.3.2.2, the penetration resistance reported for this needle corresponds to the penetration stress read at a penetration depth of 15 mm. This value then corresponds closely to the penetration resistance that would be obtained with a flat-end indenter, as was verified by parallel testing.

Figure 5.1 shows the relationships between the penetration stress and the water flow at the nozzle obtained for the different mixtures. In view of the relationships cited in Section 4.3.2.1 and the excellent correlation shown in this Figure, the penetration resistance is considered an appropriate test to evaluate fresh dry-mix shotcrete consistency or workability.

---

1 The requirement of Section 4.2.2 for homogeneous water flow at the nozzle is still valid.
Figure 5.1: Consistency (penetration stress) of different mixtures shot with different water flows at the nozzle.

Figure 5.2: Rebound values for mixtures shot with different water flows at the nozzle.
5.2.2- **REBOUND**

The amount of rebound obtained on vertical surfaces typically falls between 15 % and 35 % for the laboratory set-up used, and is comparable with the values reported in the literature (Morgan, 1988 and 1990; Armelin et al., 1997; and Jolin et al., 1997). Figure 5.2 shows the amount of rebound obtained for the different mixtures shot with various water flows at the nozzle. Note the excessive amount of rebound obtained for the plain mortar mix; the consistencies encountered for rebound values greater than 35 % were not of practical interest, however the mixtures were shot to verify, with success, the general shape of one curve.

Using the equation of the best fit curves in Figures 5.1 and 5.2, it is possible to plot the combined graph of the amount of rebound as a function of the consistency for each mixture, as shown in Figure 5.3. The proposed relationships are almost linear, as also reported by Armelin et al. (1997). Assuming the consistency to be related to the shear strength of the fresh shotcrete, this form of relationship is expected since the rebound mechanism involves the yield strength of the material (see Section 3.3.1). This confirms the importance and the validity of the consistency measurement as a general comparator for fresh shotcretes in this research project.

![Figure 5.3: Predicted relationships between the amount of rebound and the penetration stress (consistency).](image)

Figure 5.3: Predicted relationships between the amount of rebound and the penetration stress (consistency).
In general, a nozzleman will try to place shotcrete in the *stable wettest consistency*, in order to attain the lowest possible rebound rate, good substrate bond, good reinforcement encasement and good finishability (known as the *good shootability* requirements in Beauprè, 1996). 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 are beneficial, by allowing the shotcrete to be shot at lower consistencies (see Figure 5.3). The mechanisms of action of these improvements cannot be strictly identified, considering the complex interrelationships between the consistency, the amount of rebound and the in-place composition of the mixture. However, the effect of silica fume on the *Mortar+SF* mixture and silica fume + coarse aggregate on the *Shotcrete* mixture, is certainly related to the smaller particles in the material: (i) silica fume is known to increase workability for an identical water content, and (ii) the lower surface area of the larger aggregates also increases workability for the same amount of paste (Tattersall & Banfill, 1983; and Neville & Brooks, 1991). Similarly, an air-entraining admixture allows mortar to be placed at a lower consistency, probably due to the so-called “ball bearing” effect of the bubbles (Tattersall & Banfill, 1983).

Although Figure 5.3 shows that the lowest rebound rates are found for the plain mortar mixture for a given consistency, laboratory notes report that this mix is not suitable for construction site use due to its relatively stiff consistency, which would not allow for adequate finishing or reinforcing bar encasement. According to the nozzleman, it was nearly impossible to place this mix at a sufficiently low consistency for good reinforcement encasement.

### 5.2.3- BUILD-UP THICKNESS

Initially, maximum build-up thickness tests were performed in a panel similar to the one shown in Figure 2.9. Although this test panel has been found to give good results in the past for general testing, it was found to be very difficult to shoot mixtures into this panel that were not at a normal consistency. The panel size made it difficult to fill it evenly without creating a “hump” in the centre, which led to poor test reproducibility. Mixtures with high water content would not hold sufficiently well to allow for a real build-up test,
and failed instead by loss of adhesion or sloughing. On the other hand, the drier mixtures generated excessive amounts of rebound due to the "hump" and would sometimes fail at extremely large, and unsafe\(^2\), build-up thicknesses. Moreover, it was difficult for the operator to assess the thickness with the required precision. Also, from a practical point of view, repeated maximum build-up thickness tests resulted in a large volume of shotcrete to handle and dispose of.

By simply mounting a smaller panel into the one already present, it was possible to perform a different build-up thickness test on a much smaller surface, thus alleviating the problems previously encountered. Instead of mesh and reinforcing bars, the smaller panel had a number of steel studs on the bottom of the panel to prevent slippage of the shotcrete mass and to induce a horizontal plane of failure; the set-up is presented in Figure 5.4.

![Diagram of modified build-up test set-up with reduced area](image)

**Figure 5.4: Modified build-up test set-up with reduced area.**

At first glance, the results obtained with this set-up were better than those obtained with the original larger set-up. However, a poor correlation was obtained between the maximum build-up thickness obtained with the second set-up and the penetration stress, as shown in Figure 5.5. At this point, the monitoring equipment and the data acquisition system were used to evaluate another quantity, the *cohesiveness*. The *cohesiveness*,

\(^2\) One particular test led to a 120 kg piece of fresh shotcrete falling in the nozzleman area.
Figure 5.5: Maximum build-up thickness values for various mixtures shot with different water flows at the nozzle using a 400 mm square panel.

Figure 5.6: Cohesiveness for various mixtures as a function of the penetration stress (consistency) using a 400 mm square panel.
defined as the average tensile strength over the ruptured area, was calculated using the weight of the overhead panel (which was mounted on load cells) divided by the area of the ruptured surface in the shotcrete after fall-out. The values of cohesiveness so obtained are shown as a function of the consistency in Figure 5.6. It is assumed that the cohesiveness is proportional to the maximum build-up thickness, and that similar relationships would appear in Figure 5.5 if the maximum build-up thickness test were more precise.

The curves presented in Figure 5.6 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 (Section 3.3.2). Second, there is a distinct curve for each type of mixture so, for a given consistency, two different mixtures may not achieve the same maximum build-up thickness. Therefore, the consistency measurement is not sufficient by itself to completely characterise the properties of fresh dry-mix shotcrete.

Although Figure 5.6 suggests that almost any cohesiveness (and build-up thickness) can be attained with any of the tested mixtures, one must remember that the higher the consistency, the larger will be the fraction of material rebounding, as shown in Figure 5.3 for a vertical rebound situation. Moreover, the quality of the in-place shotcrete can be impaired if a mixture is shot excessively dry.

5.2.4- FRESH TENSILE STRENGTH

Another test performed on the various mixtures was the fresh tensile strength test. Fresh tensile strengths are plotted against penetration stress values in Figure 5.7 for a few mixtures (equipment problems unfortunately rendered impossible the evaluation of the shotcrete mixture). As for the cohesiveness test, a direct relationship is found between the penetration stress and the fresh tensile strength. Distinct curves are obtained for the different mixtures shot. This equivalence is expected since both tests induce the same phenomenon, tensile failure.
The relationships were such that the stiffer the mixture, the more difficult it was to separate the mobile part of the apparatus. Both sets of relationships (Figures 5.6 and 5.7) were expected from a failure theory point of view. To have obtained them by working with industrial scale equipment is an important achievement of this project.

![Diagram of Fresh tensile strength vs Penetration stress](image)

**Figure 5.7:** Fresh tensile strength for various mixtures as a function of the penetration stress (consistency).

### 5.3 - DISCUSSION

The equipment and the test set-up used permitted the shooting of homogeneous and well controlled mixtures. The use of the UBC Penetrometer provided a quantitative measure of an important property 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 amongst the different 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 build-up 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. Similar remarks concerning the distinct relationships apply to the fresh tensile strength test, since the stiffer the mixture, the more difficult it was to separate the halves of the specimen.

One point, however, is not clear: the difference in order of magnitude between the cohesiveness values found (0.5 to 2.5 kPa) and the fresh tensile strength values obtained (3 to 12 kPa). A tentative explanation for this is found when comparing the stress states of both failure situations: the fresh tensile strength test is a "constant displacement rate" (quasi-static) test at 0.36 mm/s, as opposed to the maximum build-up thickness test, in which the initial movement (or cracking) of the mass of shotcrete propagates practically instantaneously under a constant load, leading to catastrophic failure.

As pointed out by Morgan (1988 & 1990), Armelin et al. (1997) and many others, silica fume increases the cohesion of fresh shotcrete, as confirmed in both Figures 5.6 and 5.7. This effect is attributed to the increase of the yield value observed in concrete mixtures containing silica fume (Gjørv, 1992; Beaupré, 1996). On the other hand, the reduction of fresh strength due to the use of an air-entraining admixture, which decreases the yield value of fresh concrete (Tattersall & Banfill, 1983) is shown clearly in Figure 5.6. This effect is, however, less obvious in Figure 5.7, which can again be explained by the different testing conditions.

### 5.4 - CONCLUSIONS

The major conclusions which can be drawn from the laboratory work and the results presented are:

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

3. The fresh tensile strength and the cohesiveness 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 Figure 5.6 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 they have opposite effects on cohesion.

In the light of these conclusions, the next steps of this research were:

1. Increased control over shooting parameters, such as air flow and pressure, to allow an even better comparison between results.

2. New mix design variables and combinations of these needed to be evaluated in order to determine the specific effect of each and eventually produce mixtures with the required fresh qualities.

3. Water/binder ratio needed to be evaluated as well as the proportions of binder, sand and coarse aggregate for the in-place mixture, leading to a better understanding of the relative effects of silica fume and air-entraining admixtures, for example.
CHAPTER 6
BASIC MIXTURE PROPERTIES

6.1 - INTRODUCTION

The development phase of the various tools was presented in Chapters 4 & 5; the next step was to use them over a broad range of shotcrete mixtures. The collected data should then serve to better explain the behaviour of fresh dry-mix shotcrete. By the end of this chapter, the reader should be able to discern the links between the consistency and the in-place proportions of the mixture's ingredients.

This chapter presents, in its first part, all of the results obtained in evaluating the basic properties of fresh shotcrete: consistency, rebound, water/binder ratio, constituent proportions and maximum build-up thickness. The second part is a discussion concerning the parameters influencing the final composition of a fresh shotcrete layer. The consistency criterion previously set out is still valid; mixtures should always be compared based on their penetration resistance, as assessed here by the U.B.C. Penetrometer.

6.2 - INVESTIGATION PROGRAM

Seven different dry-mix shotcrete mixtures were shot in order to identify the effects of consistency\(^1\) on rebound, water/binder ratio and maximum build-up thickness. The various mixtures could also be compared amongst themselves to assess the consequence of varying the mixture composition. The mix design parameters considered were: the presence of silica fume, the type and proportion of binder, the proportion of coarse aggregates and the presence of an air-entraining admixture. Predampening was also included as a shooting technique parameter. The compositions of the different mixtures

\(^{1}\) From now on, consistency is evaluated using a cylindrical flat head needle with a 9 mm diameter.
are presented in Table 6.1. Shotcrete was sprayed using a dry-mix ALIVA 246 equipped with a 3.2 litre rotating barrel and a 38.1 mm (1½ in.) inside diameter hose. The water ring was positioned 2.5 meters upstream from the nozzle. Normal gunning techniques as described in Crom (1981) and Yoggy et al. (1995) were followed. Apart from the usual laboratory observations, the regular water flow criterion described in Section 4.2.2 was followed for all mixtures as a supplementary means of quality control of the in-place shotcrete homogeneity.

Table 6.1: Composition of the mixtures used.

<table>
<thead>
<tr>
<th>Binder</th>
<th>Type</th>
<th>(%)</th>
<th>(%)</th>
<th>(%)</th>
<th>Air entrain. Admixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10*</td>
<td>10</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>T10+SF</td>
<td>10SF</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>T30</td>
<td>30</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>T10@25%</td>
<td>10</td>
<td>25</td>
<td>60</td>
<td>15</td>
<td>-</td>
</tr>
<tr>
<td>T10+Agg</td>
<td>10</td>
<td>20</td>
<td>56</td>
<td>24</td>
<td>-</td>
</tr>
<tr>
<td>T10+AEA***</td>
<td>10</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>15 ml/l</td>
</tr>
<tr>
<td>T10+Predamp****</td>
<td>10</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
</tbody>
</table>

* Proportions for dry process shotcrete are usually given in mass proportions of dry constituents.
** The binder is made with normal Portland cement with 10% of its mass replaced by silica fume.
*** The air entraining admixture was mixed with the shooting water in a separate tank.
**** This mixture was the same as T10 but was predampened prior to its introduction in the dry-mix gun. A constant water content was obtained and controlled using the rapid drying technique (average of 3%).

The effect of a change in the aggregates gradation was studied only partially, by shooting a mixture containing an increased coarse aggregate content, T10+Agg. The aggregates used in this project consisted of a 10 mm maximum size coarse aggregate and a concrete sand (size distribution curves are presented in Appendix A). The combination originally chosen had a 85:15 sand to coarse aggregate ratio. This mixture did not contain enough large size particles for homogenous shooting. Indeed, the lack of large particles combined
with the use of a “long” nozzle allowed cement paste to stick to the last portion of the delivery hose. When sufficient paste had accumulated on the inside of the hose, the air pressure at the level of the water ring would increase, thus decreasing the water flow. Consequently, the mixture would become dry enough to act as an abrasive and clean the paste from the hose wall, leading to a large “clog” of paste exiting the nozzle. This led to an unacceptable pulsating effect at the nozzle, producing an uneven water flow recording (also see Section 4.2.2).

Consequently, it was decided to select a reference mix containing a sand to coarse aggregate ratio of 80:20, which allowed for acceptable shooting sessions (mixture $T10$). The coarse aggregate proportion was then increased for mixture $T10+Agg$ to a ratio of 70:30. Both of the combined aggregate distributions are presented in Figure 6.1, along with the ACI Committee 506 granular distribution #2 limits. The lack of fines and small sand particles (approximately 0.2 mm to 2 mm) in the mixes used here is obvious when compared to the ACI recommendation for dry-mix shotcrete. This was known at the beginning, but it was decided to go along with the available material.

![Figure 6.1: Gradation curves of combined aggregates for this project, and ACI Committee 506 limits for gradation #2.](image)

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6.3—DRY MATERIAL DELIVERY RATE

This section presents a rarely evaluated parameter, the dry material delivery rate. This is introduced, even though it is not strictly necessary, for a better understanding of the rest of this project; it is presented in its original form (Parker et al., 1976).

The dry material delivery rate was recorded during the shooting sessions for a given mixture of dry ingredients. It was measured by evaluating the slope of the dry-mix gun weight versus time and is an indicator of the ease with which the mixture flows through the dry-mix gun and the hose. It was calculated by taking the absolute value of the slope of the machine weight vs. time curve (Figure 6.2), in units of kilograms per minute. The slope is negative because the weight decreases with time. In the example shown in Figure 6.2, the dry mix delivery rate is given by:

\[ |-0.83| \text{ (kg/s)} \cdot 60 \text{ (s/min)} = 49.8 \text{ kg/min} \]

The average dry-mix delivery rates of the shooting sessions are given in Figure 6.3 for the various mixtures studied. It was decided to measure the delivery rates only after carrying out the investigation described in Chapter 5. The author (who was also the nozzleman), suspected that the dry material delivery rate varied significantly; variations in delivery rate are of importance when comparing mixtures on the basis of the water flow at the nozzle, as was done in Figures 5.2 and 5.3.

It is interesting to note that the addition of silica fume did not influence the dry material delivery rate, but instead increased the fluctuations between shooting sessions. Also, the

\[ Machine \ weight \ (kg) = -0.83 \cdot t \ (s) + 658.6 \]

Figure 6.2: Evolution of the shotcreting machine weights during a shooting session.

---

2 The air flow was maintained constant at 0.1 m³/s (225 cfm) throughout the entire phase, using the air flow meter described in section 4.2.2. The identical hose layout was also maintained throughout.
finer particles of Type 30 cement in mix T30, and the increased cement content in mix T10@25% slightly reduced the delivery rate, while predampening drastically reduced it by more than 25%. This major reduction was most probably caused by the cohesion of the prewetted grains and the bulking of the sand phase; indeed, the material was brought to such a moisture level as to produce an earth-like consistency. Looking at Figure 2.4(a), it is obvious that a more cohesive material would have increased difficulty in flowing into and out of the barrel chambers. Since mixtures T10 and T10+AEA are the same (the liquid air entraining admixture is mixed with the shooting water), their delivery rate were identical.

6.4 – INVESTIGATION OF REBOUND

6.4.1 - RESULTS

Rebound measurements were made using a vertical steel panel (Figure 4.2). The monitoring of both the panel and the shotcreting machine weights along with the water flow at the nozzle during a shooting session, permitted the evaluation of the rebound rate from the recorded data, instead of weighing the material on the floor. The great advantage of this method was to allow the nozzleman freely to adjust the mixture consistency in an
adjacent panel without having to worry about an artificial increase in the apparent rebound value. An example of a recording is presented in Figure 6.4. The calculation required to obtain the overall rebound rate is then:

\[
\text{Overall rebound} = 1 - \left[ \frac{y_2(60) - y_2(0)}{y_1(60) - y_1(0) + \text{amount of water in 60 sec}} \right]
\]

This calculation method considers rebound to be constant for the entire shooting session. This is untrue, since rebound is known to be much higher in the first millimetres (Parker et al., 1976; Armelin et al., 1997). However, on a comparative basis, the effect of this initial layer on the overall rebound rate is relatively small if the same thickness of shotcrete is applied for each test, as was done in this research project. Moreover, Figure 6.4 shows that this period of non-linearity is relatively short, which justifies it being neglected in the calculations.

Figure 6.4: Example of the evolution of the shotcreting machine and panel weights during a shooting session.
Using Eq.(6.1) for the example presented in Figure 6.4, the overall rebound value found was:

\[
\text{Overall rebound} = 1 - \frac{0.65 \times 60}{0.83 \times 60 + 3.17} = 26.4\% \quad (6.1a)
\]

As described above, the various mixtures were shot at different consistencies, and their overall rebound rate was evaluated. Figure 6.5 shows the results obtained along with the regression lines. Similar to the results of Armelin et al. (1997), the rebound rate of a given mixture increases linearly with its consistency. The complete list of results used to construct Figure 6.5 and the following ones is given in Appendices B.

During the present investigation, the objective was to shoot the same mixture at least five times at various consistencies. The target consistencies (i.e. penetration stresses) ranged between 1 MPa and 3 MPa. Figure 6.5 shows that for the majority of the mixtures, the

---

**Figure 6.5:** Experimental evaluation of rebound as a function of the consistency of the mixture.
lowest consistency investigated was 1.0 MPa. In fact, this represents a limit below which it was difficult to shoot without getting sloughing of the material. Table 6.2 shows the lowest consistency at which each mixtures was shot; this is identified as the *wettest stable consistency* (see definition in Section 2.4.4).

Table 6.2: Wettest stable consistency for each mixture shot.

<table>
<thead>
<tr>
<th>Wettest stable consistency</th>
<th>T10+Predamp</th>
<th>0.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10; T10+SF; T30; T10+AEA</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>T10+Agg; T10@25%</td>
<td>1.3</td>
<td></td>
</tr>
</tbody>
</table>

Based on this method, it can be seen that the increase in coarse aggregate content or cement content (mix T10+AGG and T10@25%, respectively) did not permit the attainment of a consistency as low as that for the reference mix T10. On the other hand, the predampening of the material prior to its entry in the dry-mix gun permitted the attainment of particularly low consistencies, as it was actually difficult to “stiffen” the mixture. The explanations of these observations will be presented later in this chapter.

Because it is well known that all of the ingredients of shotcrete do not rebound at the same rate, the in-place fresh shotcrete was sieved and the different portions weighed to determine the in-place material proportions. Figures 6.6 and 6.7 show the evaluated in-place binder and coarse aggregates contents (kg/m³), as a function of the consistency of all mixtures. In Figure 6.6, “C:A” is the ratio of the mass of cement to the overall mass of aggregates *in-place*; it relates closely to the cement content since a constant fresh shotcrete density was assumed in the calculations for all mixtures.

Laboratory procedure also included the evaluation of the water/binder ratio using the rapid drying technique. Figure 6.8 shows the evaluated in-place water/binder ratios, also as a function of the consistency for all mixtures.
Figure 6.6: Experimental evaluation of in-place cement content as a function of the mixture consistency.

Figure 6.7: Experimental evaluation of in-place coarse aggregate content as a function of the mixture consistency.
Figure 6.8: Experimental evaluation of the *in-place water/binder ratio* as a function of the mixture consistency.

6.4.2- ANALYSIS OF RESULTS

The overall rebound rates presented may seem high at first glance. However, the reader must understand that initially, no efforts were made to *optimise* the shotcrete mixtures, the point of the research being specifically to observe the effect of such optimising steps (e.g. silica fume, cement content, etc.). Figure 6.9 represents an overview of Figures 6.5 to 6.8, where only the main relationships have been highlighted. Observations both in the laboratory and on actual job sites suggest that a consistency of 2 MPa represents the upper limit for practical shotcrete applications. This limit is somewhat higher for an underground environment, where the usual absence of finishing operations and reinforcement encasement does not require a particularly workable fresh mixture. On the other hand, complete finishing operations or heavy reinforcement layouts such as in structural shotcrete requires an average consistency much closer to 1 MPa. These consistency limits consequently describe an acceptable range of rebound values in Figures 6.5 and 6.9 for modern shotcrete mixtures such as the silica fume shotcrete (rebound of 20% to 30%).
When compared to the reference mixture T10, the largest decrease in rebound rate came from the addition of silica fume or the increase in cement content. These reductions were of the order of 10% to 15% (mixture T10+SF and T10@25%). They were expected, and correlate well with previously published data (Morgan, 1988; Armelin et al., 1997) since silica fume is known to increase the cohesiveness of shotcrete and reduce rebound. The larger binder content increased the amount of paste available to “capture” the incoming aggregates, positively reducing the rebound rate; this is confirmed in Figures 6.6 and 6.8, where the in-place cement content is significantly higher for the T10@25% mixture and the water/binder ratio is similar to that of the reference mixture.

The reduction in rebound found with the use of a Type 30 cement can be explained by the increase in water/cement ratio obtained for a given consistency. The fineness of the cement is believed to require more water to wet all of the available surfaces and to provide the same consistency. Under a dynamic situation, e.g. an incoming aggregate, this extra water reduces the viscosity, thus facilitating the positive capture of a particle and
lowering rebound. This reduced viscosity for a given workability is reported in Tattersall & Banfill (1983) for cement pastes in which the fineness of the binder phase is increased.

The effect of an air-entraining admixture ($T10+AEA$) was somehow unexpected. While it decreased rebound for stiff consistencies, greater than approximately 2 MPa, it increased rebound for lower consistencies. These results are contrary to what was presented in Chapter 5, where the presence of an air-entraining admixture reduced the rebound for all consistencies. The reasons for this difference are not known, but the discussion presented below will, it is hoped, help to clarify these contradictory data.

The predampening of the reference mixture ($T10+Predamp$) permits one to attain lower consistencies and lower rebound values. This is of great importance, since the use of predampening is frequently left to the contractor's discretion and, as one can see, the effect of predampening can have serious consequences on the final product. A complete explanation of this phenomenon has yet to be found. However, a tentative explanation may be derived from particle packing theories. If the predampening procedure is considered to partially break down the cement particle clumps initially formed upon the contact of the cement grains and water, the result is a wider cement particle gradation. According to German (1989) and de Larrard & Sedran (1994), for an equal compacity or void ratio, the viscosity of the predampened mixture should then be lower than that of the reference mixture. The reduced viscosity allows incoming particles to penetrate the substrate more easily, thus reducing their possibility of rebounding. On the other hand, the lower consistencies obtained with the predampened mixture are due to the higher water/binder ratio; the relative increase in the stability of the plastic mixture, which permitted the attainment of the higher water/binder ratios, resulted from the increased surface area available to the water and closer particle spacing.

Figures 6.6 and 6.7 provide other interesting observations. First, shooting at too stiff a consistency has, in addition to the high rates of rebound, another important disadvantage for repair applications: the undesirable enrichment of the in-place mixture, which

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3 The shearing action of the predampener used can certainly accomplish this partial “structural breakdown”, described in Figure 3.2. For this reason, it is believed that the type of predampener used is of importance; the one used in this case consists of a 750 mm long endless gapped screw with a diameter of 100 mm.
increases shrinkage and cracking potential. Second, while the addition of cement (T10@25%) was beneficial to the rebound rate, the resulting in-place cement contents were the highest, thus limiting the attractiveness of this approach to achieve lower rebound.

The coarse aggregate content measurements show that mixture T10+Agg left much more coarse aggregates in place than did any of the other mixtures, which is of particular interest when considering the overall quality of the hardened material (further discussion on this particular mixture is presented in Section 6.7.1).

6.5—PRACTICAL CONSIDERATIONS

During the evaluation of the in-place cement content, the in-place water content also had to be evaluated. Thus, it was possible to determine the water/binder ratios. Figures 6.10 and 6.11 present the water/binder ratios of the seven mixtures tested as a function of the overall rate of rebound.

The water/binder ratios calculated are all surprisingly low, ranging from 0.22 to 0.40. Only the addition of silica fume and the predampening of the oven dry material led to “normal” water/binder ratios; the literature usually reports water/binder ratios in the range of 0.35 to 0.45 for dry process shotcrete (ACI 506R-95; Ward & Hills, 1977; Austin, 1995). The overall rebound rate measured varied linearly with the water/binder ratio.

Figure 6.10 reveals that for a constant amount of binder in the original mix, the relationships between the overall rebound rate and the water/binder ratio for all of the mixtures lie in a relatively narrow band. This is even more obvious if the rebound axis is stopped at a value of 40%, which would represent, in the opinion of the writer, the upper limit of practical mixtures (see Figure 6.11).

To examine this further, Figure 6.12 and 6.13 show the cement content as a function of the overall rebound rate. The relationships obtained indicate even more clearly that for a constant amount of any binder in the original mix, the in-place binder content is directly related to the overall rebound rate. Therefore, for a given initial binder content, the only
Figure 6.10: Experimental evaluation of the in-place water/binder ratio as a function of the overall rebound rate of the mixture.

Figure 6.11: Simplified version of Figure 6.10.
way to reduce the in-place cement content, which is important for crack control, is to reduce rebound. The addition of an air entraining agent, of silica fume or the change of binder type did not have an influence on the in-place cement content for a given overall rebound value.

An apparent solution would be to reduce the binder content of the original mixture so as to produce shotcrete with a lower in-place binder content. Unfortunately, there is a limit below which the reduction of initial binder content leads to excessive rebound, thus leading to a relatively high in-place cement content. This excessive rebound is generated because there needs to be a minimum amount of paste in-place to "capture" the incoming aggregates; it is as if the mixture was naturally adjusting itself on the wall.

Armelin (1997) reported that it is generally not effective to make dry process shotcrete with cementitious contents much below or above 400 kg/m$^3$, which corresponds to approximately a 19% binder content in the dry constituents. Indeed, two mixtures that he shot with initial cement contents of 350 kg/m$^3$ and 450 kg/m$^3$ ($\approx$ 16.5% and 21.5% dry proportions respectively) led to in-place cement contents, respectively, of 11% and 30% higher than the mixture shot with an initial cement content of 400 kg/m$^3$.

![Figure 6.12: Experimental evaluation of the in-place cement content as a function of the overall rebound rate of the mixture.](image)
The relative positions of the relationships on Figure 6.10 and 6.12 show indirectly that the in-place water content did not vary much with the overall rebound rate. For example, the water content of the reference mixture varied from 185 kg/m$^3$ to 174 kg/m$^3$ over the range of penetration resistance presented, a 5% variation only. The variation of in-place water content for all the mixture over the entire range of consistency fell between -5% to 15%, which is small when compared to the variations of in-place cement contents, which may vary by more than 50%.

This discussion would not be complete without looking at the relationship between the overall rebound rate and the coarse aggregate content presented in Figure 6.14. Contrary to what was shown in Figure 6.12, the type of binder or the addition of an air-entraining agent did have a strong influence on the in-place coarse aggregates content. Thus, even if the cement or paste contents of the in-place mix were the same for a given rebound value, the mix design parameters had a strong influence on the composition of the aggregate phase. This is probably due to a modification of the dynamic properties of the paste, because of the various changes or additions ($T30$, $T10+SF$, $T10+AEA$).
Figure 6.14: Experimental evaluation of the in-place cement content as a function of the overall rebound rate of the mixture.

Figure 6.15: Simplified version of Figure 6.14.
Although Figures 6.10 to 6.15 are interesting, one must keep in mind that they do not contain any information on the consistency of the mixtures shot. Thus, even if two mixtures give the same in-place cement content for a given rebound value, they do not necessarily correspond in the field. Indeed, when he operates the nozzle, the nozzlemaster intuitively adjusts the mixture to the desired consistency. As Figure 6.5 shows, different mixtures will yield different overall rebound values and in-place characteristics for a given consistency.

6.6 – VARIATION OF MAXIMUM BUILD-UP THICKNESS

This section presents the few results obtained with the maximum build-up thickness test. Only a few mixtures were tested for a number of reasons. First, laboratory observations led the author to seriously doubt the quality of this test when consistency is the varying parameter. The problems cited in Chapter 5 were again encountered and seemed, at this point, difficult to resolve. The problems referred to are those encountered when comparing the maximum build-up thicknesses of mixture shot at different consistencies, i.e. the stiffer one would create a bump, generating excessive rebound, while the wetter one would eventually become unstable under the air stream exiting the nozzle and would fall prematurely.

Second, a single maximum build-up thickness test required a lot of effort, which turned out to be excessively time consuming for this project where many tests needed to be performed to obtain the desired relationships. Finally, the harsh conditions of overhead shooting made the control and repetitiveness of the tests uncertain.

Nevertheless, the partial results obtained are presented for a unique value of consistency in Table 6.3. Indeed, the results seem to be quite acceptable for mixtures shot at wet to normal consistencies, i.e., for those with a penetration stress between 1.0 MPa and 2.0 MPa.

The results show a high maximum build-up thickness for the reference mixture, $T10$. They also show that for this range of consistencies, there was an increase in the maximum build-up thickness reached with the silica fume shotcrete mixture, $T10+SF$. 

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Table 6.3: Maximum build-up thickness and cohesiveness results obtained for a few mixtures shot at wet-to-normal consistencies.

<table>
<thead>
<tr>
<th>Mixtures with a consistency between 1 MPa and 2 MPa</th>
<th>Maximum build-up thickness (mm)</th>
<th>Cohesiveness (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10</td>
<td>270</td>
<td>2.6</td>
</tr>
<tr>
<td>T10+SF</td>
<td>320</td>
<td>3.4</td>
</tr>
<tr>
<td>T30</td>
<td>270</td>
<td>2.6</td>
</tr>
</tbody>
</table>

Similar results have already been reported by several others (Morgan, 1988; Wolsiefer & Morgan, 1993). The mixture T30 did not show any increase.

One must understand that the maximum build-up thickness test should not be discarded because it did not lead to satisfactory relationships versus consistency in this project. It remains a valid test for comparing shotcretes shot at normal consistencies. However, the repeatability is such that more than one test is required for valid comparison. Therefore, the maximum build-up thickness test was abandoned for the rest of this research project.

### 6.7 – DISCUSSION

Not all of the information presented in the previous sections of this chapter has been discussed in depth. This section brings a few additional elements to the discussion, and attempts to establish some general trends concerning the behaviour of fresh dry-mix shotcrete.

#### 6.7.1- CHANGE IN GRANULAR DISTRIBUTION

The effect of changing the aggregate gradation was partially studied through mixture T10+Agg, which contained the same amount of aggregate as T10, but in coarser proportions. The reduction in the overall rebound rate found compared to the reference mixture is contrary to some of the published data on dry-mix shotcrete technology.
(Armelin, 1997; Beaupré and Lamontagne, 1995). The in-place proportions evaluated are, however, consistent with the lower rebound values observed.

The challenge is, therefore, to determine why, because the sand gradation is coarser than that usually found in industry, the increase in coarse aggregate content might lead to a reduction in rebound instead of an increase, as previously reported for mixtures which follow the ACI Committee 506 #2 gradation. The use of a coarse sand is known to have a tendency to increase the overall rebound rate (Beaupré and Lamontagne, 1995; Studebaker, 1939), but this could not be detected in the current project, since all mixtures were shot using the same sand.

A tentative explanation of the phenomenon arises from comparison of the grain size distributions to an “ideal” distribution. In conventional concrete, an ideal aggregate size distribution is not easily obtained, though different methods are available (Fuller & Thompson, 1907; de Larrard & Sedran, 1994). There is, however, a simple way of comparing two distributions by using their geometric standard deviation assuming that they follow a log-normal distribution. A positive random variable \(X\) (in this case, the sieve size) is said to be lognormally distributed with two parameters \(\mu\) and \(\sigma^2\) if \(Y = \ln X\) is normally distributed with mean \(\mu\) and variance \(\sigma^2\). The associated distribution function yields the probability of a particle being smaller than a given sieve size; in soil mechanics terminology, it represents the cumulative percent passing.

Many aggregate size distributions follow a log-normal distribution (German, 1989; Shimizu & Crow, 1988; Harr, 1977). According to German (1989) and Cumberland & Crawford (1987), the larger the standard deviation, the higher the packing density obtained, notwithstanding the particle shapes. Thus, only the standard deviation of each aggregate distribution curve is needed for comparison.

Using \(Y = \ln (X) = \ln \text{(sieve size)}\), and knowing from the normal distribution law that the probability of a sample falling below one standard deviation over the mean is 84.5% \((\sigma = Y_{84.5} - Y_{50})\), the standard deviation of a given distribution is found directly by:

\[
\sigma = \ln(D_{84.5}) - \ln(D_{50}) = \ln \left( \frac{D_{84.5}}{D_{50}} \right)
\]  

(6.2)
Table 6.4 shows the standard deviations (i.e., the percent passing) calculated for the granular distributions used in this project and those of the limit of the ACI Committee 506. The gradation curves corresponding to the four cases are presented in Figure 6.1.

Table 6.4: Geometric standard deviations for various granular distribution.

<table>
<thead>
<tr>
<th>Granular distribution</th>
<th>$D_{50}$</th>
<th>$D_{84.5}$</th>
<th>$\sigma^* = \ln\left(\frac{D_{84.5}}{D_{50}}\right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>70:30 ($70\theta+Agg$)</td>
<td>2.9</td>
<td>6.5</td>
<td>0.81</td>
</tr>
<tr>
<td>80:20 ($70\theta$)</td>
<td>2.5</td>
<td>5.4</td>
<td>0.77</td>
</tr>
<tr>
<td><strong>ACI #2</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coarser limit</td>
<td>2.4</td>
<td>8.3</td>
<td>1.24</td>
</tr>
<tr>
<td>Average</td>
<td>1.4</td>
<td>5.7</td>
<td>1.40</td>
</tr>
<tr>
<td>Finer limit</td>
<td>1.1</td>
<td>4.8</td>
<td>1.47</td>
</tr>
</tbody>
</table>

* The larger the standard deviation calculated, the better the packing density obtained for this particle size distribution (German, 1989).

Table 6.4 shows that there was an increase in distribution quality (or standard deviation) when the initial mixture of aggregate of this project was coarsened, from 80:20 to 70:30. Conversely, the distribution quality also increases for a finer mixture of aggregate when the ACI limits are considered (i.e., going from the lower bound to the upper bound). From these observations, it seems that the quality of the distribution might be proportional to the overall rebound rate. Moreover, the results of Table 6.4 suggests that the #2 gradation of the ACI are considerably better than the one used in this project ($1.24-1.47 >> 0.77-0.81$).

The gradation utilised in this research program did not meet the ACI requirements which have generally been followed by other researchers. From the results and the discussion presented here, it is obvious that aggregate gradation plays an important, though not yet well understood, role in the behaviour of a shotcrete mix. It is the opinion of the author that aggregate particle size distribution should be included as an important research parameter in future dry process shotcrete investigations.
6.7.2–Rebound and Consistency

In the first part of this chapter, the effects on the rebound phenomenon associated with a high velocity placing process were studied. In general, the correlation coefficients (R²) presented in the Figures of this chapter are considered good for shotcrete technology, and thus attest to the quality of the different testing procedures. The overall rebound rate and the in-place mix composition evaluations lead to these first conclusions:

i. The shooting consistency is the key parameter affecting overall rebound rate. As might be expected intuitively, the stiffer the mixture shot (high consistency value), the higher the overall rebound rate.

ii. A direct consequence of rebound is the variation of the in-place mix proportions:
   - the stiffer the mixture, the higher the in-place cement content,
   - the stiffer the mixture, the lower the in-place coarse aggregate content,
   - the water/binder ratio decreases with a stiffer consistency.

iii. The mix design has a strong influence on the overall rebound rate for a given consistency. Differences of as much as 15% in overall rebound rate have been found when silica fume is used to replace a part of the cement.

iv. The aggregate distribution plays a dominant role in the placement of a shotcrete layer. In the case presented here, a coarse aggregate/sand mixture generated less rebound when the coarse aggregate proportion was increased (for an identical initial cement content).

v. The in-place cement content can be directly related to the overall rebound rate for all mixtures designed with the same binder content, independently of the type of binder. This is also true, with slightly larger variations, for the relationship between the water/binder ratio and the overall rebound rate.

vi. On the other hand, the coarse aggregates content varies significantly with initial mix design for a given overall rebound rate, which indicates the strong effect of the nature of the binder itself on the in-place proportions of the aggregate phase.
In order to more clearly delineate the various effects of the mix design parameters, Table 6.5 is presented. This Table indicates the tendency that each mixture showed compared to the reference mixture T10 for a given consistency.

The concept of the “binder granular distribution” was discussed in Section 6.4.2 to explain the lower rebound and lower consistencies attained for the mixture T10+Predamp. The principles of the concept are simple: the wider the particle size distribution of the binder phase (not to be mistaken with the aggregate distribution curves of the previous section), the lower the viscosity and the associated dynamic contact stress, and thus the lower the overall rebound for an equal in-place compaction. Also, this wider distribution of the binder particles probably binds more water, thus increasing the consistency for a given water/binder ratio, or, inversely, allowing a higher water/binder ratio for a given workability; the consequence is to lower the stable wettest consistency value. To verify the applicability of the concept, the effects of mixtures with different binder types are reviewed.

Table 6.5: Relative effects on mix behaviour of the various mixtures shot for a given consistency.

<table>
<thead>
<tr>
<th></th>
<th>Rebound (%)</th>
<th>Cement content (kg/m³) or C:A</th>
<th>Coarse agg. Content (kg/m³)</th>
<th>W/B</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>T10</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>T10+SF</strong></td>
<td>↓↓</td>
<td>↓↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td><strong>T30</strong></td>
<td>↓</td>
<td>↓</td>
<td>↑</td>
<td>↑</td>
</tr>
<tr>
<td><strong>T10@25%</strong></td>
<td>↓↓</td>
<td>↑</td>
<td>↑</td>
<td>—</td>
</tr>
<tr>
<td><strong>T10+AGG</strong></td>
<td>↓/2</td>
<td>(light tendency)</td>
<td>↑</td>
<td>↑/2</td>
</tr>
<tr>
<td><strong>T10+AEA</strong></td>
<td>≈</td>
<td>≈</td>
<td>↑</td>
<td>↓/2</td>
</tr>
<tr>
<td><strong>T10+Predamp</strong></td>
<td>↓/2</td>
<td>≈</td>
<td>↑</td>
<td>↑/2</td>
</tr>
</tbody>
</table>

* The equal consistency criterion is difficult to apply for the predampened mixture since, as presented in Section 6.4.1, its range of practical consistencies is particularly low.
The particle distribution of the binder in the mixture T10+SF is certainly improved due to
the addition of silica fume. The concept described above seems to apply, since rebound is
drastically reduced along with a substantial increase in the water/binder ratio; moreover,
supplementary laboratory observations confirmed an improved stability at low
consistencies (≤ 1 MPa). The increased fineness of the cement in mix T30 should offer a
slightly wider cement particle size distribution with a definite shift toward the finer range
compared to ordinary cement. The small rebound reduction corresponds to the better
particle distribution while the water/binder ratio increase corresponds to the assumed
effect of the finer particles present. Finally, as already suggested, the predampening of the
reference mixture, T10+Predamp, leads to a wider distribution of the cement particles,
both reducing the rebound and increasing stability at very low consistencies.

6.8 - CONCLUSION

From the discussion above, it is obvious that the type of binder and the water/binder ratio
exert the strongest influences on the consistency and the final proportions of the in-situ
mixture. In other words, the static and dynamic properties of the paste dictate, to large
extent, the final composition of the mixture and the wettest stable consistency value
reached.

It appears that the “ideal” mixture would be the one that provides the lowest viscosity, or
dynamic contact stress, in order to restrict rebound to a minimum for a given consistency.
Furthermore, this ideal mixture should allow one to reach very low consistencies (≤ 1
MPa) in a stable manner, since this seems to be the only way to limit the in-place cement
content and also to attain the absolute minimum rebound values. The binder particle
grading quality concept could certainly help to design shotcrete mixtures closer to that
ideal mixture. In parallel, our understanding of the effects of the aggregate grain size
distribution must be increased, in order to strengthen our understanding of the behaviour
of fresh dry-mix shotcrete.
CHAPTER 7

FAILURE OF FRESH DRY-MIX SHOTCRETE

7.1 – INTRODUCTION

This chapter deals with the evaluation and interpretation of the fundamental properties of the fresh shotcrete. The same mixtures described in Chapter 6 were shot and tested in the fresh tensile strength apparatus and the fresh shear strength apparatus, and were compared based on their shooting consistency. The results of these two tests are linked with the in-situ mixture compositions calculated using the relationships derived in the previous chapter.

The shear and tensile strength data are then implemented into a failure theory approach to compare the mixtures in terms of cohesion and angle of friction. Predicted values of strength and experimental results are compared and discussed.

7.2 – FRESH MECHANICAL PROPERTIES

The following sections present the results and the analysis of the fresh shear strength and fresh tensile strength tests. The evaluations were carried out for three typical consistencies, referred to as wet, normal and dry consistency, (having a penetration resistance of 1 MPa, 2 MPa and 3 MPa, respectively). An exception is made for the predampened mixture (T10+Predamp) where the evaluation was carried out for consistencies of 0.5 MPa and 1.0 MPa only.

The detailed data used to develop the various relationships are presented in Appendix C.
7.2.1 – Fresh Shear Strength

The fresh shear strength results obtained with the mixtures of Table 6.1 are presented in this section. The apparatus and test procedure have been described in Section 4.5; the only other quantity evaluated on the mixtures shot into the special mould was the consistency. Figures 7.1 and 7.2 present the results obtained for all of the mixtures; note the extremely good correlation for every mixture ($R^2_{\text{average}} = 0.95$). The results indicate a linear relationship between the shooting consistency and the fresh shear strength for all mixtures tested; an increase of 1 MPa in consistency augmented the shear strength by approximately 50%.

The best result (i.e., the highest shear strength) were obtained with the $T30$ and $T10+SF$ mixtures. Surprisingly, adding an air-entraining admixture seemed to be more effective than increasing the initial cement content of the mixture, while the increase in coarse aggregate content did not significantly improve the shear strength of the fresh material. The predampening of the basic mixture caused a slight increase in the fresh shear strength.

![Graph showing shear strength vs penetration stress for different mixtures](image_url)

**Figure 7.1:** Fresh shear strength as a function of the shooting consistency.
In order to identify the means by which the fresh shear strength of shotcrete could be improved, the test results of the fresh shear strength apparatus were compared to the estimated in-place proportions of the different mixtures (obtained using the relationships given in Chapter 6 between the in-place mixture composition and the consistency). Figure 7.3 and 7.4 show the fresh shear strengths of the mixtures plotted as a function of the in-place cement content and water/binder ratio.

A look at Figure 7.3 immediately yields vital information: the fresh shear strength is proportional to the C:A ratio, which means that the fresh shear resistance increases with a higher cement content and a lower aggregate content of the stiffer mixtures. Also, for a given C:A ratio, or binder content, the fresh shear strength varies by as much as a factor of two for particular mixture. This important effect could be generated either by the paste phase, by the water/binder ratio affecting the consistency and/or the type of binder itself, or by the aggregate phase. To verify this, consider Figures 7.3 and 7.4 together. Figure 7.4 shows the combined effects of the paste phase: changing the type of binder, from T10 to T30 or T10+SF, creates a clear separation in the relationships on the graph, 

\[ R^2_{\text{average}} = 0.95 \]
**Figure 7.3:** Fresh shear strength as a function of the in-place C:A and cement content.

**Figure 7.4:** Fresh shear strength as a function of the in-place water/binder ratio.
where two families of lines appear. For a given binder type, the effect of the water/binder ratio is important for the fresh shear strength, since all mixtures with Type 10 cement are grouped together on the graph. To confirm the apparent effects of the water/binder ratio and binder type on the fresh shear strength, Figures 7.3 and 7.4 need to be analysed in parallel. Figure 7.4 shows that for a given water/binder ratio, the average fresh shear strength obtained for either family of lines relates in Figure 7.3 to small variations of the C:A ratio. For example, a water/binder ratio of 0.3 gives an average shear resistance of 42 kPa for the lower family of relationships, which in turn yields C:A ratios varying from 0.38 to 0.45.

This demonstrates that the water/binder ratio and the binder type are the governing parameters on the fresh shear strength for the C:A ratio studied. The amount of paste is the second most significant parameter affecting the fresh shear strength for the range of consistencies studied.

Confirming the above findings, Holtz & Kovacs (1981) and Powers (1968) reported that the cohesion of a granular material is attributed to the interparticle forces, and not to the interlocking effect of the aggregates. Additionally, Powers (1968) stated that interparticle forces in fresh concrete are mainly attributable to the fines, especially cement and silica fume. The more water in the paste, the larger the distance between the smaller particles, thus reducing the net cohesive forces. This outcome is important, since it was assumed, in Chapter 4, that the fresh shear strength was similar to the cohesion \(c\) of the material. The results obtained in this section confirm this hypothesis.

### 7.2.2—Fresh Tensile Strength

This section presents the fresh tensile strength results obtained with the same mixtures along with their analysis. The related test procedure and apparatus have been described in Section 4.4. Similar to the fresh shear strength test, the only property evaluated on the mixtures shot in the special mould, apart from the tensile strength itself, was the consistency. Figures 7.5 and 7.6 present the results obtained for all the mixtures shot. The
Figure 7.5: Fresh tensile strength as a function of the shooting consistency.

Figure 7.6: Practical presentation of Figure 7.5.
relationships found are very similar to those of Figure 7.2 for the fresh shear strength. The coefficients of correlation are, however, inferior to those of the fresh shear strength test; this is attributed to the usual scatter encountered with “tensile” tests, because of the difficulty to apply perfect tension.

Figures 7.7 and 7.8 show the fresh tensile strength results relative to the in-place mix proportions. Note the almost identical relationships on the two graphs when compared to the corresponding ones in the previous section (Figures 7.3 and 7.4). The differences lie in the relative positions of mixtures T10+SF and T30 with regard to one another. Also, mixture T10+AEA is much closer to the reference mixture T10 for the fresh tensile strength relationships than it was for the fresh shear strength relationships. The dominant effect of the water/binder ratio and the binder type on the fresh tensile strength is still, however, clearly present.

The similarities between the fresh shear strength and fresh tensile strength results are not surprising. Indeed, the tensile capacity of the fresh shotcrete necessarily comes from the smaller particles which possess high interparticle attractions. Consequently, the richer the

![Graph showing fresh tensile strength as a function of in-place C:A and cement content.](image)

**Figure 7.7:** Fresh tensile strength as a function of the in-place C:A and cement content.
mixture and the stiffer the paste, the stronger the fresh shotcrete will be, as has already been deduced in Chapter 5, from Figure 5.7.

There is, however, one important difference between the fresh tensile strength results presented in this part of the project, and the results presented in Section 5.2.4, which involves the magnitude of the tensile strengths encountered. Figure 5.7 shows strengths ranging from 3 to 12 kPa, while they only range from 1 to 4 kPa in Figure 7.5. These latter values of fresh tensile strength are much closer to the cohesiveness values presented in Figure 5.6, which ranged from 0.75 to 2.50 kPa. The results given in this section are much closer to what is found in a maximum build-up thickness test. This may be attributed to an improvement of the test itself: the rail sections of the apparatus were modified in order to limit the access of debris or dust onto the sliding surfaces, and the test procedure was improved to limit more effectively any disturbance of the sample prior to testing. The general shape of the curves obtained also permitted for a more detailed interpretation of the results.

**Figure 7.8: Fresh tensile strength as a function of the in-place water/binder ratio.**
7.3 – **CONSTRUCTION OF A FAILURE SURFACE**

The results obtained in the two previous sections indicate that the workability of the paste and the binder type are the predominant factors responsible of both the tensile and shear resistance of the fresh dry-mix shotcrete. However, the difference in order of magnitude between the fresh tensile strength results and the fresh shear strength results requires further analysis. Also, the secondary role of the C:A ratio and the apparent lack of influence of the aggregate phase composition needs to be investigated.

As stated earlier, the tensile and shear tests evaluate mostly the cohesive properties of the mixtures, while the aggregate phase is known to affect mainly the mechanical interlocking of the particles (Holtz & Kovacs, 1981; Powers, 1968). To determine the influence of the aggregate phase, two shotcrete mixtures need to be shot with the same paste contents and paste properties but with different aggregate proportions and contents. Unfortunately, as was demonstrated in Chapter 6, this is impossible, since the paste properties control the in-place aggregate proportions.

One solution is to compare directly the angles of friction of the mixtures shot, which may be obtained by combining the tests results to construct a failure surface (see Chapter 3). In this way, the effect of the aggregate phase on the fresh mixture behaviour can be identified. This effect should have been reflected in the tensile and shear results, but was probably relatively too small to be detected. In terms of a failure criterion, the effect of the aggregate phase on the angle of friction, \( \phi \), is probably quite small compared to the effect of the paste rheological properties on the cohesion, \( c \). The goal of this section is to take the results presented above and analyse them from a failure theory point of view.

### 7.3.1 – **THE FAILURE THEORY APPROACH**

Rheology and plasticity of fresh dry-mix shotcrete have already been considered in Chapter 3. The Mohr-Coulomb criterion was proposed, since it has already been used to describe cohesive soils such as clays, and fresh concrete (Holtz & Kovacs, 1981; Terzaghi et al., 1996 and Powers, 1968). One advantage of this criterion is that it can be characterised by only two parameters, the angle of friction, \( \phi \), and the cohesion, \( c \) (see
In a two dimensional Mohr representation, the failure surface is then represented by a single line (symmetrical to the normal stress axis), as presented in Figure 3.3. It has been suggested, however, that the Mohr-Coulomb yield criterion cannot satisfactorily describe cohesive materials, and that a more complex surface should be defined to match the experimental results, especially on the tension side of the normal stress axis\(^1\) (Hill, 1983; Terzaghi et al., 1996). Consequently, an exact match between the experimental results and the Mohr-Coulomb criterion should not be expected.

**7.3.1.1 Limitations of a linear Mohr-Coulomb failure criterion**

The Mohr-Coulomb yield criterion is considered inadequate to characterise properly materials such as cohesive soils or, by extension, fresh dry-mix shotcrete. The reason stated by Hill (1983) concerns precisely the prediction of the stress state at failure for predominantly tensile situations for which, according to him, the linear yield surface of the Mohr-Coulomb criterion is only a practical approximation. He adds that there should be a distinction between the failure surface and the failure envelope. This distinction is necessary since the failure surface is by definition a relationship between the maximum shear at failure and the normal stress on the maximum shear plane, and thus forms a curve connecting all points of maximum shear at failure (broken line on Figure 7.9). On the other hand, the failure envelope is a mathematical expression derived from the failure criterion, and does not necessarily match the failure surface. In practice, the graphical representation of the failure envelope is useful since its intercept with Mohr circles identifies possible planes of failure (thin solid line in Figure 7.9).

This situation can lead to a stress state at failure for which the corresponding Mohr circles lies entirely inside the failure envelope because it has reached the failure surface first. In the case of the Mohr-Coulomb failure criterion, the important simplification made in the expression of the failure criterion in Eq. (3.9) generates the superimposed failure envelope and surface (thick solid line in Figure 7.9).

\(^1\) The tension side of the normal stress axis is the one to which the fresh tensile strength test and the maximum build-up thickness test refer.
Figure 7.9: Yield envelope and failure surface of a material under hydrostatic pressure (adapted from Hill, 1983).

These considerations are particularly pertinent in the case of fresh dry-mix shotcrete where heterogeneity and anisotropy at a mesostructural level (50 µm to 1 mm) are important. Compaction voids or air bubbles can act as stress concentrators in the tensile stress state and initiate rupture or yield at much lower values than predicted or expected.

However, the simplicity of the Mohr-Coulomb failure criterion both from an interpretation and an implementation point of view makes this the criterion of choice in this investigation.

7.3.1.2 Example of calculation

In order to demonstrate the steps required to obtain the angle of friction and the cohesion for a given mixture, an example calculation is presented here, using the reference mixture shot at a consistency of 2.0 MPa. The second line of Table 7.1 gives, for a normal consistency of 2 MPa, a fresh tensile strength of 2.3 kPa and a fresh shear strength of 44.3 kPa for mixture T10. Since the Mohr-Coulomb criterion requires only two points to identify its surface, the combination of the penetration resistance and the fresh shear strength tests will be used, first, to find $\phi$ and $c$. It was earlier concluded that the fresh shear strength test result gives directly the material's cohesion value. Therefore, the
cohesion, "c" is taken directly as:

\[ c = 44.3 \text{ kPa} \]

The remaining unknown, \( \phi \), is obtained using the consistency result. The development of a calculation method has been presented in Chapter 4; taking Eq. (4.19) and replacing "c" by its value and \( \sigma_1 \) by the penetration stress\(^2\), an iterative procedure leads to the correct value of \( \phi \). In this case:

\[ \phi = 33.3^\circ \]

These results, along with those of the same mixture shot at different consistencies, are presented in Figure 7.10. It shows clearly that there is a distinct failure surface for every consistency at which a given mixture is shot. A drier mixture will exhibit a higher cohesion and angle of friction. Inversely, a wetter mixture will exhibit a lower cohesion and angle of friction.

The other possible approach is to use the combination of the fresh tensile strength and the penetration stress results to find the values of "c" and "\( \phi \)". To do so, a pair of non-linear

---

\(^2\) The penetration stress value to use here is 2000 kPa reduced by 12%, i.e. 1760 kPa, to account for the cylindrical shape of the indenter as explained in Chapter 4, page 57.
equations are solved using a simple iterative procedure. For the example presented here, the set of equations is composed of Eq. (4.4) and Eq. (4.19):

\[
\frac{2c \cdot \cos \phi}{1 + \sin \phi} - \sigma_{ut} = 2c \cdot \frac{\cos \phi}{1 + \sin \phi} - 2.3 \text{kPa} = 0
\]

\[
\frac{1}{\tan \phi} \left[ c - e^{\left( \ln(c \cdot (1 + \sin \phi)) + \pi \cdot \tan \phi \right)} \right] + 1760 \text{kPa} \cdot (1 - \sin \phi) - c \cdot \cos \phi = 0
\]

For this set of equations, the solution is \(c'' = 3.5\ \text{kPa}\) and \(\phi'' = 53^\circ\).

There is a significant difference in the prediction of the Mohr-Coulomb criterion parameters, depending on whether the fresh shear strength result or the fresh tensile strength result is used with the penetration resistance (Figure 7.11). From the discussion in the preceding section, and because of the desirability of maintaining a simple comparison criterion, the combination of the fresh shear strength test result and the penetration stress result was selected to predict the angle of friction of a given mixture. As discussed previously, the fresh tensile strength result may not be adequate for prediction of a linear failure surface.

![Figure 7.11: Mohr representation of the two failure surfaces obtained for mixture T10.](image-url)
7.3.2 RESULTS AND ANALYSIS

In this section, the predicted values of cohesion and angle of friction for all the mixtures in Table 6.1 are presented. Similar to what was done earlier for the evaluation of the in-place composition of the mixtures, the predictions were made for three typical consistencies: wet, normal and the dry (i.e., having penetration resistances of 1 MPa, 2 MPa and 3 MPa, respectively). An exception was again made for the predampened mixture (T10+Predamp), where the evaluation was made for consistencies of 0.5 MPa and 1.0 MPa.

The values of fresh shear strength and fresh tensile strength, as derived from the relationships plotted in Figure 7.1 and 7.5 and the given consistencies, are shown in Table 7.1. The two next to last columns of this Table give the values of cohesion and angle of friction, predicted from the fresh shear strength test and the penetration test. Note that this Table is a continuation of the one presented in Appendix C and it is thus possible to compare the predicted yield parameters with the predicted in-place mix proportions. The numbers presented in last the column (\(\sigma_{ul}\)) will be analysed later.

As was mentioned at the beginning of Section 7.3, the variations in the angle of friction are relatively small compared to the variations in the tensile and shear strengths, varying by an average of only 5° (16%) for a given mixture over the range of consistencies considered, whereas tensile and shear strengths varied by as much as 100%. Surprisingly, however, the higher the aggregate content, or the lower the C:A, the lower is the predicted angle of friction. Because the angle of friction is normally attributed to the interlocking effect of aggregates, the opposite relationship, where the higher number of aggregates would create more interlocking forces, was expected. Here, the lubricating effect of the more fluid paste most probably overshadowed the interlocking effect of the more numerous aggregate contacts present in a wetter mixture, thus reducing the angle of friction, \(\phi\). This is probably why a significant influence of the aggregate phase composition and proportions was not detected in the work described earlier in the chapter. Indeed, Holtz & Kovacs (1981) explain that since the angle of friction refers to a “frictional” material, any factors decreasing the frictional resistance of grain surfaces
Table 7.1: Predicted cohesion and angle of friction using the combination of fresh shear strength and consistency results.

<table>
<thead>
<tr>
<th>MIX</th>
<th>Consistency</th>
<th>Fresh tensile strength (kPa)</th>
<th>Fresh shear strength (kPa)</th>
<th>$c$ (kPa)</th>
<th>$\phi^*$</th>
<th>$\sigma_{ut}^{**}$ (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10</td>
<td>Dry</td>
<td>3.4</td>
<td>60.6</td>
<td>60.6</td>
<td>34.4°</td>
<td>64.0</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>2.3</td>
<td>44.3</td>
<td>44.3</td>
<td>33.3°</td>
<td>47.8</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.2</td>
<td>28.0</td>
<td>28.0</td>
<td>30.5°</td>
<td>32.0</td>
</tr>
<tr>
<td>T10+SF</td>
<td>Dry</td>
<td>4.6</td>
<td>77.8</td>
<td>77.8</td>
<td>31.5°</td>
<td>87.2</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>3.4</td>
<td>59.2</td>
<td>59.2</td>
<td>29.8°</td>
<td>68.6</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.3</td>
<td>40.6</td>
<td>40.6</td>
<td>25.6°</td>
<td>51.1</td>
</tr>
<tr>
<td>T30</td>
<td>Dry</td>
<td>4.4</td>
<td>84.4</td>
<td>84.4</td>
<td>30.5°</td>
<td>96.5</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>3.3</td>
<td>62.4</td>
<td>62.4</td>
<td>29.1°</td>
<td>73.3</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>2.1</td>
<td>40.5</td>
<td>40.5</td>
<td>25.7°</td>
<td>50.9</td>
</tr>
<tr>
<td>T10@25%</td>
<td>Dry</td>
<td>3.4</td>
<td>67.5</td>
<td>67.5</td>
<td>33.1°</td>
<td>73.1</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>2.4</td>
<td>50.5</td>
<td>50.5</td>
<td>31.8°</td>
<td>56.2</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.3</td>
<td>33.4</td>
<td>33.4</td>
<td>28.3°</td>
<td>39.9</td>
</tr>
<tr>
<td>T10+Agg</td>
<td>Dry</td>
<td>3.1</td>
<td>59.2</td>
<td>59.2</td>
<td>34.6°</td>
<td>62.1</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>2.4</td>
<td>46.8</td>
<td>46.8</td>
<td>32.7°</td>
<td>51.1</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.6</td>
<td>34.3</td>
<td>34.3</td>
<td>27.9°</td>
<td>41.4</td>
</tr>
<tr>
<td>T10+AEA</td>
<td>Dry</td>
<td>3.6</td>
<td>68.8</td>
<td>68.8</td>
<td>32.9°</td>
<td>74.8</td>
</tr>
<tr>
<td></td>
<td>Normal</td>
<td>2.6</td>
<td>54.6</td>
<td>54.6</td>
<td>30.8°</td>
<td>61.9</td>
</tr>
<tr>
<td></td>
<td>Wet</td>
<td>1.5</td>
<td>40.3</td>
<td>40.3</td>
<td>25.7°</td>
<td>50.7</td>
</tr>
<tr>
<td>T10+Predamp</td>
<td>1.0</td>
<td>2.0</td>
<td>32.3</td>
<td>32.3</td>
<td>28.7°</td>
<td>38.3</td>
</tr>
<tr>
<td></td>
<td>0.5</td>
<td>1.4</td>
<td>19.8</td>
<td>19.8</td>
<td>26.0°</td>
<td>24.8</td>
</tr>
</tbody>
</table>

* $\phi$ is evaluated as in the first example in Section 7.3.1.2
** $\sigma_{ut}$ is the ultimate tensile strength predicted by Eq.(4.4).
should lead to a decrease of the angle of friction of the material. To verify this assumption, Figure 7.12 presents the variation of the angle of friction as a function of the water/binder ratio of the mixtures; there is a relatively good correlation between the angle of friction and the water/binder ratio, independent of the binder type.

![Figure 7.12: Variations of the angle of friction as a function of the predicted water/cementitious ratios of the mixtures.](image)

The two mixtures which were the most effective in terms of fresh shear and fresh tensile strengths, T10+SF and T30, had smaller angles of friction than did the other mixtures. From a yield criterion point of view, this means that the contribution of the interparticle attractions (or cohesion) is greater for a given consistency for those mixtures (see Figure 7.13). From a practical point of view, this is exactly what an engineer is looking for: a mixture that withstands thicker applications for a given consistency or, a lower consistency for a given thickness of application, which means improved finishability and reinforcement encasement.

This desired lower angle of friction, for a given mix, can be attained only by increasing the water/binder ratio, as illustrated in Figure 7.12. If one recalls the conclusions of Chapter 6, high water/binder ratios are obtained by shooting at the wettest stable
consistency. It turns out that shooting at the lowest stable wettest consistency value possible not only improves the basic in-place mixture properties by reducing overall rebound, but will also, for a given consistency, give the highest predicted fresh tensile strength to penetration resistance ratio. This is illustrated in Figure 7.13, where the fresh tensile strength is largest for mixtures $T10+SF$ and $T30$ for the consistency considered.

![Mohr representation of the failure surfaces obtained for the mixtures studied.](image)

**Figure 7.13:** Mohr representation of the failure surfaces obtained for the mixtures studied.

Now, the last column of Table 7.1 give the ultimate tensile strength calculated using the angle of friction and cohesion. Taking the first example of the preceding section, the fresh shear strength test combined with the penetration stress test gave a cohesion of 44 kPa and an angle of friction of 33°. Using Eq. (4.4), we obtain:

$$
\sigma_{ut} = 2c \cdot \frac{\cos \phi}{1 + \sin \phi} = 2 \cdot 44 \text{ kPa} \cdot \frac{\cos 33^\circ}{1 + \sin 33^\circ} = 47.8 \text{ kPa} = \text{tensile strength}
$$

Although it has already been noted in Section 7.3.1.1 that the predicted fresh tensile strength is much larger than the experimental result, there may still be a proportionality between these two values. Indeed, the graph in Figure 7.14 shows a direct relationship between the predicted and the evaluated fresh tensile strengths, independently of the mixture studied. Therefore, even though the Mohr-Coulomb failure criterion does not
7.4– CONCLUSIONS

In this chapter, the results obtained with two innovative testing procedures on fresh dry-mix shotcrete were presented. The two tests were the fresh tensile strength and the fresh shear strength tests. By combining these results with those of Chapter 6, through the
penetration resistance, it was possible to appreciate the parameters affecting the mechanical properties of the fresh material. The main conclusions are:

i. The *composition* and the *consistency* of the paste, followed by the *amount* of paste, are the governing parameters of the fresh tensile and shear strengths of a shotcrete mixture.

ii. The lubricating effect of the paste outweighs the interlocking effect of the aggregates when considering the changes in the *predicted angle of friction*. Indeed, an inverse linear relationship was found between the *angle of friction* and the water/binder ratio of the mixtures.

iii. Although the Mohr-Coulomb criterion is deficient in predicting the "correct" value of fresh tensile strength, there is a unique proportional relationship between the fresh tensile strength obtained experimentally and the one predicted by combining the fresh shear strength and the penetration resistance results into the Mohr-Coulomb failure criterion.

iv. In absolute value, the best way to increase the fresh tensile and fresh shear strengths is to shoot the shotcrete mixture at stiffer consistencies. The downside is an increased overall rebound, associated with gradually poorer in-place mix proportions.

v. However, by combining the findings of Chapter 6 and those of this chapter, it is found that shooting at the *wettest stable consistency* is the most efficient way to obtain a good quality mixture and an optimum fresh tensile strength/fresh shear strength ratio.

These two last conclusions bring up an important question: how stiff can a dry process shotcrete mixture be shot without significantly decreasing the in-place quality of the mixture? In other words, is there an upper limit of penetration resistance or consistency beyond which problems such as inadequate reinforcement encasement arise? Chapter 8 lays the basis for evaluating the importance of this problem.
CHAPTER 8
DYNAMIC PROPERTIES OF FRESH DRY-MIX SHOTCRETE

8.1 - INTRODUCTION

This chapter deals with the dynamic properties of the fresh dry-mix shotcrete. These properties are particularly important when studying the application process itself, which involves discrete particles travelling at high velocities and impinging on a surface of fresh shotcrete. While the previous chapters dealt mainly with the stability of a shotcrete layer already in-place, this one is concerned with the mobility of the shotcrete substrate, since mobility, or deformability, is required to allow the capture of the incoming aggregates and allow the placement of the fresh shotcrete behind the steel reinforcement.

The first section of the present chapter describes the principles related to the dynamic properties and the concepts inter-relating the various parameters of dry-mix technology, such as cement content, aggregate content, rebound, etc. The second section presents the test results obtained with a shotcrete flow apparatus designed to verify the reinforcement encasing capacity of a mixture. These results are correlated to the dynamic contact stress measured in the laboratory.

This chapter is of particular importance to the author. Indeed, it became obvious to him, from the laboratory observations made during the shooting of the mixtures presented in Chapters 6 and 7, that there was another parameter, called here the dynamic contact stress, controlling the “shootability” of the fresh dry process shotcrete. Apart from the variations of in-place composition of the different mixtures for a given consistency (shown in Figure 6.5), hints such as the difficulty of predicting the measured penetration stress for the air entrained mixtures, or the significantly increased ease of placement of the silica fume mixtures suggested that this new parameter needed to be investigated, at least to orient future research.
8.2 – DYNAMICS OF THE SHOTCRETE PROCESS

8.2.1 – IDEAL INDENTATION PROCESS

To begin the discussion on the dynamic properties of dry-mix shotcrete, the principle of a rigid particle hitting a deformable substrate needs to be reviewed. A good treatment of such an event has been presented by Armelin & Banthia (1998) and some of the relevant equations have already been briefly reviewed in Section 3.3.1. The basic element of the rebound mechanism is the penetration of a spherical aggregate into a fresh shotcrete substrate (Figure 8.1).

![Diagram of spherical rigid particle impinging an elastic-plastic substrate](adapted from Armelin & Banthia, 1998).

The incoming particle, or aggregate, of radius $R$, upon contact with the substrate, creates a zone which is at first deformed elastically. If the energy of the particle is great enough, and the yield value of the material is sufficiently low, deformation will continue and a zone of plastic deformation will be created around the particle ($r \leq a$). As explained before, the elastic portion of the phenomenon ($a < r < c$) must be considered in order to explain the reaction, or the energy restitution phase of rebound; if the energy restored to the sphere is larger than the debonding energy, rebound will occur. The debonding energy is the total work required to completely pull the particle out of the substrate from its deepest position, which is also the zero velocity position. The deepest position is not a constant value but depends on the speed of the particle upon contact and the properties of the shotcrete substrate.
Now, for a given strain rate, the plastic stain prevailing in the shaded area around the particle in Figure 8.1 generates a pressure $p$, which is constant if the penetrated material obeys a yield criterion independent of the hydrostatic stress. Because yielding of shotcrete is dependant on such stresses (Section 3.3.2), the pressure $p$ is not constant throughout the plastic zone. The exact pressure distribution is not needed, however, to pursue the rationale presented here.

The pressure, "$p$", is referred to as the contact stress. This contact stress can be designated either as the dynamic contact stress, $p_d$, or the static contact stress, $p_s$, depending on the type of event. The static contact stress is similar to the penetration resistance or consistency of the earlier chapters. The two quantities are, however, distinct since the stress states at failure are different for both cases, one being related to an indentation with a sphere and the second with a flat cylinder head, which generates different results\(^1\).

A possible equivalence between the contact stresses and the well known parameters of the Bingham flow model is shown schematically in Figure 8.2. Although strictly speaking the relationships between these parameters are probably not directly proportional, this correspondence offers an interesting basis of comparison.

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Figure 8.2: Possible correspondence between the contact stresses and the Bingham parameters.

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\(^1\) Because the two indenter shapes generate different stress conditions, the material will yield at different shear levels, i.e. two distinct Mohr circles are required to represent the stress states at failure.
8.2.2 - DESCRIPTION OF THE PHENOMENON

The behaviour of an aggregate hitting a soft substrate as depicted in this section comes mainly from visual observations made by the author while shooting in the laboratory, combined with information found in Johnson & Mellor (1983) and Johnson (1985).

It is understood intuitively that a softer shotcrete substrate will generate lower rebound values. It is interesting, however, to take the time to understand this phenomenon from a physical point of view, using the nomenclature and the schematic shown in Figure 8.1. First, consider a shotcrete substrate and an incoming spherical aggregate with a given amount of kinetic energy. The various possible stages of the penetration event are shown schematically in Figure 8.3. Figure 8.3(a) shows the stresses right after contact, when the stresses in the substrate are still all within the elastic range. The second sketch (b) shows the event at its contained elastic-plastic stage, while the third sketch (c) represents the uncontained elastic-plastic stage. The difference is that in the third stage, the plastic zone breaks out to the free surface and the displaced material is free to escape by plastic flow to the sides of the indenter (Johnson, 1985). Figure 8.3(d) represent a later stage where the indenter travels further into the material until its speed reaches zero.

Once the spherical indenter (aggregate) has transferred all of its kinetic energy into the substrate, it has reached zero velocity and its deepest position; some of the elastic energy stored in the substrate will then be returned to the indenter, possibly producing rebound, depending on the ratio of the amount of energy associated with the debonding work \( W_D \) and the returned elastic energy \( W_{REAC} \).

Depending on the velocity of the aggregate before impact and the properties of the substrate, the zero velocity point can be reached at any of the 4 stages sketched in Figure 8.3. Obviously, the higher the kinetic energy of the aggregate and the lower the dynamic contact stress of the substrate, the deeper the aggregate will penetrate; in turn, a deep penetration position will increase the debonding work required to pull out the aggregate, hence decreasing its probability of rebounding. On the other hand, a low velocity or a stiff substrate reduces the volume penetrated by the aggregate and the
Figure 8.3: Stages in the indentation of a rigid sphere into a soft substrate (shotcrete).

amount of elastic energy returned. When this happens, the debonding work is relatively small, due to the small contact area, which generates excessively high rebound values (sketches a and b). If the aggregate reaches the stage depicted in sketch (d), the probability of rebound is very low, because the debonding work in this case is particularly high; the material plastically deformed on the sides of the aggregate tends slightly to "close" the cavity behind it due to the elastic energy stored on each side.

The volume of shotcrete elastically stressed grows very rapidly at the beginning of the process (a & b). However, once the uncontained stage is reached (end of stage b), the material flows along the sphere (stage c), limiting the growth of the volume of elastically
deformed material (c & d). Thus, the elastic energy returned to the particle will become \textit{relatively smaller} with an increase of the penetration depth when compared to the debonding work. Indeed, the energy required to fully debond the particle obviously increases rapidly with the total volume penetrated.

Finally, a particle reaching a deep position does not only have the advantage of promoting a low rebound probability, but it also increases the volume of the plastic zone. The larger amount of plastically deformed material can be compared to "local mixing" due to the high shear levels encountered, which increases the homogeneity of the in-place mixture. Consequently, a soft shotcrete substrate will not only reduce rebound probabilities, it will also help produce a homogeneous shotcrete by allowing larger plastic zones to be created. Indeed, German (1989) states that the higher plastic deformation increases the number of contacts and lowers the interparticle distances.

\section*{8.2.3 – Practical Implication}

As stated above, the pressure "p" is not a constant value. Hence, a direct mathematical application of the concepts presented in the previous section is difficult. Indeed, the composition of the substrate varies locally, generating variable distributions of dynamic contact stresses. Combined with large variations in incoming aggregate sizes and velocities, this results in a broad range of responses from the shotcrete substrate.

However, similar to the consistency determined from the penetration stress, it should be possible to evaluate an \textit{average} dynamic contact stress for a given shotcrete mixture using the simple method described later.

Laboratory observations on the influence of mixture composition on rebound for a given consistency led the author to investigate the dynamic properties of fresh shotcrete. These dynamic properties control two important aspects of shotcrete: the amount of rebound and the reinforcement encasement. The amount of rebound decreases with a diminution of the dynamic contact stress, due to the relatively small ratio of debonding work (W_D) to the restored elastic energy (W_{REAC}). The reinforcement encasement capacity is related to the volume of plastically deformed material, which is in turn related to the dynamic contact

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stress. Chapters 6 and 7 have provided valuable information concerning the parameters affecting rebound and the final in-place composition of the mixtures. However, the reinforcement encasement capacity of a given mixture, an extremely important aspect of shotcrete quality, remained unexplored. Therefore, few mixtures were tested to evaluate their dynamic contact stress, $p_d$, along with their encasement capacity. The laboratory results and the description of this special test procedure are presented in Section 8.3.

8.2.4 - LIMITATIONS

According to the above discussion, the best way to reduce rebound is to obtain the softest substrate possible combined with a high aggregate velocity. The “soft substrate” requirement corresponds well to what was found in Chapters 5 & 6, where the lower penetration resistance led to low overall rebound values. However, the “high velocity” requirement is contrary to practical observations, in which excessive aggregate velocities led to increased rebound values. Indeed, Armelin (1997) and Lorman (1968) identified an optimum value of air flow at the nozzle in dry process shotcrete for which rebound is minimum when all other parameters are kept constant.

This contradiction originates from the assumption, made earlier, that the dynamic contact stress, $p_d$, is constant. The dynamic contact stress can be considered constant only over a small range of strain rates. Thus, shooting at high air output or high aggregate velocities produces high strain rates in the substrate and large values of dynamic contact stress. Eventually, these large $p_d$ values reverse the situation depicted in Figure 8.2, by increasing the elastic energy restored to the particles and limiting their penetration into the substrate.

Taking the dynamic contact stress, $p_d$, as a constant is considered correct only if the shooting parameters, such as the air flow and the material delivery rate, are kept constant as in this research project.
8.3 – INVESTIGATION OF THE DYNAMIC PROPERTIES OF SHOTCRETE

This section describes the steps taken to evaluate the dynamic properties of fresh dry process shotcrete in the laboratory. The main goal was to establish a method which would enable comparisons, based on dynamic behaviour, between different mixtures. To carry out this part of the investigation, two tests were used, the lateral flow test, and a test for evaluating the dynamic contact stress, \( p_d \).

8.3.1 - LATERAL FLOW APPARATUS

The lateral flow apparatus, as its name suggests, was designed to evaluate the capacity of a given shotcrete mixture to encase reinforcement. The result obtained with this apparatus is the distance the fresh shotcrete can travel laterally under its own compacting energy. A schematic of the test is shown in Figure 8.4. Because the shotcrete is shot perpendicular to the apparatus, the only way for it to get under the two lateral doors is to flow, or plastically deform. The internal faces of the two lateral doors have a rounded bevelled edge with a 12.2 mm radius, to simulate the face of a reinforcing bar.

![Figure 8.4: Schematic of the Lateral Flow Apparatus.](image-url)
The test procedure is relatively simple; the shotcrete consistency is first adjusted to the desired level on an adjacent panel, and the shotcrete is then shot directly onto the lateral flow panel which is mounted vertically in the rebound chamber. To conduct a meaningful test, the nozzleman must hold the nozzle perfectly perpendicular to the small testing panel and fill it as evenly as possible with a relatively small circular nozzle motion.

Once the panel is filled with fresh shotcrete, it is placed onto a horizontal working surface and the two lateral doors are opened. Then, minimum, maximum and average lateral flow length measurements are taken and noted. Photographs of actual tests are presented later in Figure 8.8. A few layers of wax paper were placed at the bottom of the panel, and changed for every test, in order to assure similar surface conditions for all tests.

8.3.2- LABORATORY EVALUATION OF $p_d$

The method used to evaluate the dynamic contact stress, $p_d$, was based on work by Armelin (1997), who made use of the relationship given by Eq. (3.3), which can also be written as:

$$p_d = \frac{\text{Work of the penetration phase}}{\text{Volume displaced during penetration}} = \frac{W_{\text{PEN}}}{V_{\text{PEN}}} \quad (8.1)$$

Thus, to evaluate $p_d$, one needs to drop an impacter on the fresh shotcrete surface and to record both the energy it had upon contact and the volume of displaced material. Practically, measuring the diameter of the circular indentation produced greatly simplifies the evaluation of the volume of material displaced. The work done by the impacter is equivalent to its kinetic energy at the moment of impact, which is easily found using Newton's second law of motion (see Figure 8.5).

Rigorously speaking, the evaluation of the dynamic contact stress would require one to drop a number of spheres with different diameters and masses from different heights, to obtain values for $p_d$ over a wide range of dynamic events (the variables being velocity and mass). However, as explained above, it is much simpler to work with an average value of dynamic contact stress which gives, as presented in the next section, acceptable results if the shooting parameters are kept constant.
\[ p_d = \frac{W_{\text{PEN}}}{V_{\text{PEN}}} = \frac{\text{mass} \cdot (\text{velocity})^2}{2 \cdot V_{\text{PEN}}} \]

where, using Newton's equation:

\[ (\text{velocity})^2 = 2 \cdot g \cdot s \]

The volume penetrated is related to the diameter of the imprint, "a", by:

\[ V_{\text{PEN}} = \frac{1}{3} \pi \left( R - \sqrt{R^2 - a^2} \right)^2 \left( 2R + \sqrt{R^2 - a^2} \right) \]

note: If the sphere penetrates deeper than half of its diameter, the volume displaced is evaluated assuming the geometrical shape of a half sphere and a cylinder, both with a diameter 2R.

**Figure 8.5: Evaluation of the dynamic contact stress, \( p_d \).**

In this project, the spheres and the height of drop were selected to give velocities and kinetic energies as close as possible to those of a large aggregate travelling in the shotcrete material air stream. Table 8.1 gives an idea of the ranges expected. For every mixture tested, ten spheres were dropped and an average dynamic contact stress was then calculated using the diameter measurements of their imprints and their energies at contact.

**Table 8.1: Velocities and energies of the selected impacters.**

<table>
<thead>
<tr>
<th>Spherical impacter</th>
<th>Diameter (mm)</th>
<th>Mass (g)</th>
<th>Height of drop (m)</th>
<th>Velocity at impact (m/s)</th>
<th>Kinetic energy (j)</th>
</tr>
</thead>
<tbody>
<tr>
<td># 1 &amp; # 2</td>
<td>41.5</td>
<td>95</td>
<td></td>
<td></td>
<td>2.7</td>
</tr>
<tr>
<td></td>
<td>(Plastic spheres)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># 3 to # 7</td>
<td>25.3</td>
<td>67</td>
<td>2.946</td>
<td>7.6 (calculated)</td>
<td>1.9</td>
</tr>
<tr>
<td></td>
<td>(Steel spheres)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td># 8 to # 10</td>
<td>34.4</td>
<td>54</td>
<td></td>
<td></td>
<td>1.6</td>
</tr>
<tr>
<td></td>
<td>(Plastic spheres)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Armelin (1997)</td>
<td>10 – 20</td>
<td>n/a</td>
<td>shotcreted</td>
<td>10 – 15 (Measured by high speed photography)</td>
<td>1.0 – 3.5</td>
</tr>
<tr>
<td></td>
<td>(Coarse aggregates)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
8.3.3- RESULTS AND ANALYSIS

A small investigation was undertaken with a few dry process shotcrete mixtures to which the two test procedures described above were applied, along with the usual consistency measurement test. Because the goal was mainly to verify whether the proposed method for evaluating the dynamic properties gave useful results, only four shotcrete mixtures were selected. Figure 6.5 was used to assist in choosing the mixtures to be investigated. Indeed, this Figure indirectly highlights some useful information on the dynamic properties of the fresh mixtures studied; it shows that for a given consistency, the in-place proportions of the constituents, C:A, could vary significantly. Thus, at an identical penetration stress, the dynamic contact stress of two mixtures may vary considerably. Mixtures which stood out in Figure 6.5 were therefore the ones that were most likely to show significant variations in their lateral flow and dynamic contact stress measurements; the obvious choices were mixtures T10 and T10+SF. Although the addition of an air-entraining admixture did not significantly influence the C:A in Chapter 6, its influence on rebound rates, as reported in Chapter 5, and laboratory observations made by the author justified its inclusion in this part of the project. Finally, one single mixture was shot with a superplasticizer, silica fume and air-entraining admixture (TSF+AEA+SP). The compositions of the four mixtures tested in this part of the research project are presented in Table 8.2.

Table 8.2: Composition of the mixtures used for the dynamic properties evaluation.

<table>
<thead>
<tr>
<th>Binder Type</th>
<th>Binder (%)</th>
<th>Sand (%)</th>
<th>Coarse agg (%)</th>
<th>Air entrain. Admixture</th>
<th>Superplasticizer</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10*</td>
<td>10</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>TSF</td>
<td>10+SF**</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>-</td>
</tr>
<tr>
<td>TSF+AEA***</td>
<td>10+SF</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>20 ml/l</td>
</tr>
<tr>
<td>TSF+AEA+SP***</td>
<td>10+SF</td>
<td>20</td>
<td>64</td>
<td>16</td>
<td>20 ml/l</td>
</tr>
</tbody>
</table>

* In all cases, normal Portland cement was used.
** The binder was made with normal Portland cement with 10% of its mass replaced by silica fume.
*** The air entraining admixture and/or the superplasticizer were mixed with the shooting water.
Some of the mixtures were shot at different consistencies, to verify the variations of the lateral flow values and the dynamic contact stresses. The results obtained for all the mixtures are presented in Table 8.3. The first significant observation is the absence of a direct relationship between the penetration resistance (consistency) and the dynamic contact stress, as shown in Figure 8.6. Instead, there seems to be a proportionality between the two quantities for a given mix design only.

In Figure 8.6, the steeper slope of the TSF mixture relative to the T10 mixture is consistent with the reduced rebound, or C:A, found with the same mixtures in Chapter 6. Indeed, it shows that the dynamic contact stress is smaller (for a given con-

Table 8.3: Experimental results of dynamic properties evaluation.

<table>
<thead>
<tr>
<th>Mixture</th>
<th>Consistency (MPa)</th>
<th>Dynamic contact stress (MPa)</th>
<th>Average lateral flow (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>T10</td>
<td>0.8</td>
<td>0.8</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>1.9</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>2.8</td>
<td>4.7</td>
<td>12.5</td>
</tr>
<tr>
<td>TSF</td>
<td>0.6</td>
<td>0.5</td>
<td>24.0</td>
</tr>
<tr>
<td></td>
<td>0.7</td>
<td>0.7</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td>0.6</td>
<td>22.0</td>
</tr>
<tr>
<td></td>
<td>0.9</td>
<td>0.7</td>
<td>20.0</td>
</tr>
<tr>
<td></td>
<td>1.4</td>
<td>0.8</td>
<td>18.0</td>
</tr>
<tr>
<td></td>
<td>2.1</td>
<td>1.2</td>
<td>19.5</td>
</tr>
<tr>
<td>TSF+AEA</td>
<td>1.5</td>
<td>0.3</td>
<td>42.5</td>
</tr>
<tr>
<td></td>
<td>1.8</td>
<td>0.8</td>
<td>15.0</td>
</tr>
<tr>
<td>TSF+AEA+SP</td>
<td>1.5</td>
<td>0.5</td>
<td>24.5</td>
</tr>
</tbody>
</table>
sistency) for the silica fume mixture, hence increasing the volume penetrated by an aggregate, which positively reduces its rebounding probability. The results obtained with the silica fume air-entrained mixtures (TSF+AEA and TSF+AEA+SP) show an even more significant reduction of the $p_d$ for a given consistency, thus suggesting lower rebound rates and C:A for those mixtures (unfortunately not tested in Chapter 6).

![Penetration resistance vs. the average dynamic contact stress.](image)

**Figure 8.6: Penetration resistance vs. the average dynamic contact stress.**

Figure 8.7 shows the lateral flow results for each mixture as a function of the dynamic contact stress. This graph shows a strong and unique correlation between the shotcrete lateral flow capacity and the dynamic contact stress. The shape of the curve suggests a limit value of dynamic contact stress over which the lateral flow is constant and minimum. Below this limit value of approximately 1 MPa, the amount of lateral flow increases rapidly. The three mixtures identified on Figure 8.7 are shown in Figure 8.8 (mixtures #306, #309 and #310). Figure 8.8, along with laboratory observations, led to
Figure 8.7: Lateral flow vs. the average dynamic contact stress.

A minimum lateral flow value of approximately 2 centimetres below which it is believed that the encasement of a 15 mm diameter steel bar would not have been adequate.

The combination of Figures 8.6 and 8.7 shows that the use of silica fume is extremely beneficial to the quality of in-place shotcrete. The same conclusion is applicable to the addition of an air-entraining admixture\(^2\). Moreover, although their dynamic contact stresses were lower, the TSF and the TSF+AEA mixtures exhibited significantly higher penetration resistances. Thus, in practice, these mixtures would exhibit an increased stability, e.g. maximum build-up thickness, resistance to sloughing, vibrations, etc., as well as an improved reinforcement encasement capacity; two qualities leading both to better in-place quality shotcrete and to better overall application. Figure 8.9, in which the

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\(^2\) This conclusion is very satisfactory to the author who, by acting as the nozzleman in this project, had suspected this beneficial effect of an air-entraining admixture, without being able to pinpoint the exact mechanisms behind it.
Mixture 770:
Penetration stress: 2.8 MPa
Lateral flow: 12.5 mm
Dynamic contact stress, $p_d$: 4.7 MPa

Mixture $T10$:
Penetration stress: 0.7 MPa
Lateral flow: 16.5 mm
Dynamic contact stress, $p_d$: 0.7 MPa

Mixture $T10+SF$:
Penetration stress: 0.7 MPa
Lateral flow: 42.5 mm
Dynamic contact stress, $p_d$: 0.3 MPa

Figure 8.8: Photographs of mixtures 306, 309 and 310.
lateral flow is plotted as a function of the ratio of the penetration resistance to the dynamic contact stress illustrates these conclusions. A high position on the graph means a better encasement capacity; and positions to the right yield more stable mixtures, as demonstrated in Chapter 7. Indeed, it was shown in the previous chapter that a high penetration resistance resulted in an increase in fresh shear strength and fresh tensile strength for every mixture tested.

![Figure 8.9: Lateral flow vs. the contact stresses ratio.](image)

8.4 DISCUSSION

From the beginning of this Chapter, it was assumed intuitively that rebound is related to the dynamic contact stress. Because a relationship independent of the mix design was found between the lateral flow value and the dynamic contact stress, it would be interesting to determine whether a similar relationship exists between the overall rebound value and the dynamic contact stress, as presented in Figure 8.10a. Figure 8.10b, which is a partial reproduction of Figure 6.5, shows the relationship between the overall rebound
value and the penetration resistance. In Figure 8.10a, only the T10 and the TSF mixtures are presented since the rebound values were evaluated using the relationships found in Chapter 6, unfortunately available only for those two mixtures.

Although the number of mix design and mixtures presented in Figure 8.10a is relatively small, they seem to indicate a unique relationship between overall rebound and the dynamic contact stress. This is particularly interesting because it suggests that a single parameter, the dynamic contact stress, might be sufficient to predict the overall rebound of any dry process shotcrete mixture, for a given shooting parameter set-up. Also, the shape of the relationship proposed is a horizontal reflection of the one shown in Figure 8.7, supporting the assumption made earlier that the lateral flow value would increase if the amount of plastic deformation increased in the fresh shotcrete; also shown indirectly by the lower rebound values when more large aggregates were embedded (as seen in Chapter 6).

To understand the mechanisms of action of the silica fume on the fresh shotcrete, the reader is referred to Section 6.7.2, where the concept of “binder granular distribution” was described. This concept supports the idea that a wider binder particle size distribution
leads to a lower material viscosity. According to the correspondence established in Figure 8.2, a lower viscosity is reflected in fresh dry-mix shotcrete by a lower dynamic contact stress, as was found with the addition of silica fume. Indeed, silica fume is well known to reduce the plastic viscosity of concretes for the addition rates used here (Gjørv, 1992).

The effect of the air-entraining admixture is to produce a large number of relatively small bubbles. From a rheological point of view, an increase in air content usually significantly decreases the viscosity, which translates, as observed again in Table 8.3, to a reduced dynamic contact stress. A reduced dynamic contact stress should lead to a reduced rebound value; unfortunately, such an effect was not uniformly observed in Chapter 6. There are two possible causes for this: the difference in rate of addition of the admixture, (15 ml/l previously and 20 ml/l for the mixtures presented here) and/or the use of the air-entraining admixture in conjunction with the silica fume in this Chapter. It may be that for the viscosity reduction to be noted, the air-entraining admixture must be capable of generating a sufficient amount of air bubbles; the dosage or the use of another viscosity reducing product, such as silica fume, may play an important role in the capacity of the admixture to entrain a sufficient volume of bubbles in dry process shotcrete.

Finally, even though the addition of a superplasticizer did not present any significant effect on the behaviour of the fresh shotcrete, it is believed that a higher addition rate would reduce the consistency measured, as expected from conventional concrete rheology (Table 3.1). Indeed, it was found by Lamontagne et al. (1995) that to entrain an adequate amount of air, the air-entraining admixture had to be added at a rate 10 times larger in dry-mix shotcrete than in conventional concrete. It may also be the case for superplasticizer additions.
8.5 - CONCLUSION

The first part of this Chapter consisted of a theoretical development of the key mechanisms behind the capture of a high velocity spherical particle hitting a soft surface. Although a few limitations were found (especially concerning the variations of the shooting parameters), this approach suggests that the rebound probability of a particle will decrease with a higher particle velocity and a lower substrate dynamic contact stress. Moreover, it was determined that these conditions also favour the homogeneity of the in-place mixture by expanding the zone plastically deformed around the entering particle.

The second part of the Chapter presented the importance of the dynamic properties on the reinforcement encasement capacity, an important aspect of the shootability of fresh dry-mix shotcrete. This was accomplished by using a specially designed panel into which the lateral flow of the fresh material could be evaluated, and by evaluating an average dynamic contact stress for every mixture shot. The results obtained lead to the following conclusions:

1. The determination of a unique value of dynamic contact stress for a given mixture was sufficient for the comparisons presented above.

2. There is a direct relationship between the penetration resistance and the dynamic contact stress for a given mix design.

3. There seems to be a unique relationship between the lateral flow value and the dynamic contact stress notwithstanding the mix design considered. Moreover, the shape of the lateral flow vs. dynamic contact stress curve suggests a strong relationship between the two parameters within the range of useful values (lateral flow values larger than 2 cm in this case).

4. The limited data produced suggest a unique relationship between the overall rebound value and the dynamic contact stress. In other words, a single parameter, $p_d$, seems sufficient to predict the overall rebound of any dry process shotcrete mixture (within given limitations concerning the shooting parameters).

5. A very strong effect of the combine use of silica fume and air-entraining admixture was detected on the dynamic properties.
These conclusions, along with those of Chapter 6, highlight a few points for which more discussion is required. First, admixtures such as those used to entrain air, which generally work by reducing surface tension, can play a significant role in increasing the chances of obtaining a sound placement of the shotcrete layer\(^3\). Thus, different types of admixtures should be evaluated, as it is suspected they could represent cornerstones in dry process shotcrete technology.

Second, although the size distribution of the aggregates was not a parameter in this part of the study, previous results obtained in Chapter 6 suggest it has a strong influence on the overall rebound rate. This effect, associated with the fourth conclusion presented above, could permit one to identify ways of further reducing rebound, thus reducing the in-place cement:aggregate ratio, C:A, which is of prime importance for shrinkage and crack control.

Finally, the shape of the relationship found between the lateral flow value and the dynamic contact stress, along with the large variation of the in-place mixture composition for a given mix design with the penetration stress, should require on-site quality control of the fresh dry-mix shotcrete, using a manual penetrometer (see Chapter 9).

\(^3\) The chance of obtaining a sound placement of the shotcrete layer increases if the lateral flow value is high and the penetration resistance is also high.
CHAPTER 9
GENERAL CONCLUSIONS AND
RECOMMENDATIONS

9.1 - GENERAL CONCLUSIONS

Throughout this thesis, specific conclusions have been drawn at the end of each chapter, and the reader should refer to those for a detailed description. However, some general conclusions can be extracted and put into perspective.

1. The shooting consistency is the key parameter in dry process shotcrete technology. It was shown in Chapters 6 & 8 that the consistency is a measure of the static and dynamic properties of the cement paste, which in turn control to a large extent the capacity of positively embedding the incoming aggregates. The fluidity of the paste and its volume in the mixture seem to be the governing parameters for the consistency. Thus, the shooting consistency is a control of the in-place proportions of the fresh shotcrete, for a given mixture design. Moreover, it has been shown that variations of the consistency can change rebound by as much as a factor of 2.0, cement content by a factor of 1.5 and the coarse aggregate content by a factor of 3.5.

2. The properties of the freshly applied dry process shotcrete are strongly affected by the shooting consistency and the mix design used. A rationale for fresh shotcrete behaviour or stability has been developed by showing that fresh shotcrete obeys a failure criterion similar to that of Mohr-Coulomb. Tools are available to characterise the behaviour of fresh dry-mix shotcrete as a solid (as opposed to a fluid in the case of the rheological approach). However, not only are distinct failure surfaces required for different mix designs, but also distinct failure surface are required when
changing the consistency of a given mixture. In conjunction with the observations of Chapter 6, it was also concluded that the cohesion and the angle of friction are closely related to the paste characteristics.

3. A major recommendation that comes out of the entire thesis is the importance of quality control in dry process shotcrete technology. Strict control of the mix design proportions must be performed. It has been shown in Chapters 5 to 8 that extremely significant property changes can arise from mix design variations. Thus, the control of the mix consistency using a simple pocket penetrometer would, at least, help to make sure the sample panels taken on site actually reflect the in-place shotcrete consistency and composition. Better, a maximum consistency value could be set to guarantee a minimum quality of the in-place shotcrete (see Figures 6.5 to 6.7). Finally, extending the reach of the consistency measurement into the dynamic properties, and setting a maximum consistency value, would also guarantee a minimum reinforcement encasement capacity.

4. The measurement of the dynamic properties of the fresh dry-mix shotcrete using the dynamic contact stress evaluation method or the lateral flow apparatus proved extremely promising. Indeed, the dynamic contact stress was sufficient to characterise the lateral flow capacity for the mixtures tested. Although only two mixtures were used in the analysis, the dynamic contact stress also seemed sufficient to characterise the overall rebound rate. Future advances should be oriented toward the use of a "dynamic penetrometer", which would permit on-site evaluation of the dynamic contact stress.

5. Finally, shooting at the wettest stable consistency is the best way to obtain quality shotcrete; the results of Chapter 6 shows that this method of shotcrete placement produces an in-place mixture with constituent proportions closer to those of the mix design. Further, the results of Chapter 8 show that the wettest consistency produces the larger lateral flow values, indicating a better reinforcement encasing quality and, by extension, a more homogeneous mixture.
9.2 - **FURTHER DISCUSSION**

A few items have remained undiscussed to this point, due to the lack of a general understanding of the material. They are, at least in part, treated in this section in the light of the knowledge gained through this research. This should help to generate new ideas or research orientations.

9.2.1 - **“HOW DOES IT HOLD ONTO THE WALL?”**

This simple question can generate a lot of discussion. However, from a theoretical point of view, there are two possible answers. Either shotcrete holds onto the wall due to the presence of numerous menisci holding the particles together, or it holds because of the shear threshold of the paste (yield value), as shown schematically in Figure 9.1. Of course, from a practical point of view, the answer is most probably that both mechanisms co-exist. In fact, it is the belief of the author that the wetter the shotcrete mixture is placed, the larger the proportion of the shear threshold mechanism. At the wettest stable consistency, it should be the only mechanism present, due to the relatively large plastic

![Figure 9.1: Schematic of (a) a menisci mechanisms environment and (b) of a saturated paste environment.](image)


deformation applicable\textsuperscript{1}. Conversely, the structure of a mixture shot relatively dry would exhibit areas of consolidated material and areas of under-consolidated material in which the water surface may consist partly of menisci and partly of irregular contours determined by the shape of the particles (Figure 9.1a). As water is more abundant in relatively wetter mixtures, the proportion of the areas of consolidated material increases, that is the hydrostatic tension component becomes smaller and smaller. In that case, the stability of the fresh material relies progressively on the shear threshold of the paste (Figure 9.1b). The existence of the shear threshold of the paste, or the yield value (Tattersall & Banfill, 1983), is attributed to the interparticle attraction amongst the small binder particle (Powers, 1968). According to Powers, when a sufficient amount of water is present to cause hydrostatic tension to vanish, true plastic deformation is possible, though usually limited, owing to the smallness of the initial degrees of separation of the particles.

The concept described above is of particular interest when considering the method of placement of shotcrete. For a given equipment set-up, the sprayed material exits the nozzle at a given velocity, thus with a constant kinetic energy or compacting energy. Now, whether or not this amount of energy is sufficient to densify the fresh shotcrete adequately will depend on the ease of bringing the particles closer together, which is, according to Figure 9.1, mainly linked to the properties of the paste. Once again, the importance of the paste phase properties is highlighted.

\section*{9.2.2 - ON THE AUTO-ADJUSTING EFFECT OF DRY PROCESS SHOTCRETE}

What should be done to reduce rebound of a mixture or increase the early stability of a fresh shotcrete layer? There are no simple answers to those questions, because changing one parameter usually affects the entire system. For example, cutting back on the amount of water to increase early stiffness will automatically change the in-place proportions, the amount of rebound and the reinforcement encasement capacity. Similarly, only replacing

\textsuperscript{1} The capacity for relatively large plastic deformation was observed for the wetter mixtures in the penetration stress and fresh tensile strength tests. Indeed, for the drier mixtures, the plateau shown in
part of the cement with silica fume will greatly affect the properties of the paste, which in turn will affect the rebound kinetics, the in-place proportions, etc. In fact, the material produced using the dry-process is, in some way, self-adjusting on the wall. This effect is particularly evident when one tries to decrease the binder content of the design mixture, which increases rebound; the coarser material cannot embed itself until a sufficiently thick layer of paste has formed on the surface.

Dry process shotcrete is a complex system in which it is difficult to study the effect of only one parameter. Therefore, future studies should always include a complete characterisation of the in-place mixture such as the one performed in Chapter 6. This will be especially useful when one tries to use conventional concrete knowledge in dry shotcrete technology.

9.2.3 - THE IDEALISED DRY PROCESS SHOTCRETE MIXTURE

A dream shared by many shotcrete technologists is to produce an in-place shotcrete having the smallest rebound proportions, therefore enabling better prediction of the in-place proportions of the constituent and properties of the material. The information gathered in this thesis allows one to establish what fresh properties this hypothetical mixture should possess. In the light of the results of Chapter 8, the solution to minimise rebound is to shoot a mixture possessing a very low dynamic contact stress\(^2\). On the other hand, to optimise stability, the mixture should exhibit a minimum consistency or penetration resistance. This material is basically one which possess a relatively large yield value or shear threshold and a very small plastic viscosity or a shear thinning behaviour, in which the viscosity decreases when the shear rate increases.

The results presented in Chapter 8, when an air-entraining admixture was added to the mixture, are an example of a mixture having a lower dynamic contact stress for a given penetration stress. In this sense, this mixture is most probably a glimpse of the future standard dry process shotcrete mixture.

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2 According to the discussion of Sections 8.2.2 and 9.2.1, this requirement also insure an increased homogeneity by allowing better compaction and more plastic deformation.
9.3 - RECOMMENDATIONS FOR FUTURE PROJECTS

Throughout this research project, a number of topics have emerged for which further work is required.

1. Except for predampening, none of the classic shooting parameters were studied (water pressure, air flow, etc.). Their effects on the consistency, the in-place proportions, the stability and the dynamic properties most certainly play a significant role. Therefore, until these parameters are studied, they should be controlled and fixed on site. Items such as the in-line air flow meter described in Section 4.2 could be used at minimum expense and equipment modifications.

2. Aggregate gradation showed up in this work as being important primarily with regard to rebound. A tentative explanation based on the quality of the grading from a compactness point of view was brought forth. Further exploration needs to be conducted into this concept. Ultimately, this could allow one to optimise the aggregates structure of the in-place shotcrete. In that sense, a rationale helpful for the selection of a combined aggregate gradation curve could be derived.

3. The controlling effect of the paste properties on the overall behaviour of the fresh shotcrete was established through Chapters 6, 7 and 8. Investigation of new or different types of binder, in the light of the information presented here, could allow us to develop new types of dry process shotcrete having optimised properties. In that sense, admixtures should also be considered since it was shown they can have side effects of great importance.
References


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Stewart, E.P., (1933), "New Test Data Aid Quality Control of Gunite", Engineering News Record, November 9th, 1933.


Appendix A  Particle Size Distribution

![Graph showing particle size distribution with sand and ACI limits #2](image1)

![Graph showing particle size distribution with coarse aggregate](image2)
## Appendix B Laboratory Results

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<tr>
<th>Mixture Identification</th>
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<th>Water Flow (l/min)</th>
<th>Dry mix delivery rate (lbs/min)</th>
<th>Fresh shear strength (kPa)</th>
<th>Fresh tensile strength (kPa)</th>
<th>Rebound</th>
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- **Note:** The table lists various mixtures with their corresponding designations, positions, and measured properties such as penetration stress, water flow, rebound number, water-cement ratio, fresh tensile strength, and fresh shear strength.
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<th>W/C evaluated</th>
<th>Fresh tensile strength (kPa)</th>
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<td>541-159</td>
<td>T10+Prehum</td>
<td>Vertical</td>
<td>-</td>
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<td>34.6%</td>
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<td>2.2</td>
<td>1.0</td>
<td>32.7%</td>
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<td>2.4</td>
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<td>31.7%</td>
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<td>Fresh shear strength (kPa)</td>
<td>W/C</td>
<td>Vertical Rebound (%)</td>
<td>Cement (kg/m³)</td>
<td>Water (kg/m³)</td>
<td>Coarse aggregate (kg/m³)</td>
<td>C/A</td>
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