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# Characterization of fresh dry-mix shotcrete and correlation to rebound

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## HIGHLIGHTS

- The relation between fresh properties and rebound of shotcrete is studied.
- Verification and consolidation of some results are added to the literature.
- The correlations between rebound and penetration stresses are verified.
- This leads to a discussion on how to study shotcrete, whether as a fluid or a solid.
- New insight is brought to understand the relation "rebound vs mixture design".

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## ABSTRACT

Dry-mix shotcrete has all the components of concrete but its particular placement technique generates losses due to rebound. These losses induce a cost increase and a difference between the initial and in-place composition of the concrete. Many parameters influence rebound, but this study focuses on mixture design via supplementary cementitious materials (SCMs). The aim of the paper is to study the relation between fresh properties and rebound of shotcrete, and evaluate how SCMs act on it. This will eventually help to understand what mixture properties are needed to limit rebound and help with the design of mixtures. In this study, 5 mixtures in which cement was partially replaced by metakaolin, ground granulated blast furnace slag or silica fume were shot at different consistencies, in a full scale laboratory facility. Fresh shotcrete was evaluated by penetration tests (static and dynamic). It appeared that the SCMs were efficient in reducing rebound and their efficiency depended on consistency. Water is one of the main parameters in rebound but it is difficult to control because it is adjusted by the operator. Mixtures with metakaolin and silica fume seem to lower this dependence. Static and dynamic penetration stresses seem to be correlated with rebound and, more precisely, the relation between dynamic measurement and rebound seems independent of the mixture tested. Understanding the levels of static and dynamic penetration stress could make mixture design easier.



## 1. Introduction

This paper studies rebound in dry-mix shotcrete. Shotcrete is a "mortar or concrete, pneumatically projected onto a surface at high velocity" and rebound is defined as the proportion of "shotcrete material that ricochets off the receiving surface" [1]. As shotcrete can be used in wet or dry processes, a clear distinction must be made between those two methods. Wet-mix shotcrete is batched with water before being introduced into the delivery hose for pneumatic placement, while dry-mix shotcrete is a process in which dry or slightly moist constituents of concrete are introduced into the machine and conveyed pneumatically through a hose to the nozzle where the water is added. The main difference lies in the location where water is introduced and therefore in the time of contact with water before the mixture reaches the receiving surface. In both cases, it is the high velocity imparted to the flow that induces consolidation of the material on the surface.

The dry-mix process is used in various civil engineering and construction projects, from tunneling or anchored retaining walls to repairs or building construction. Unfortunately, the dry-mix shotcrete process can lead to high losses of concrete due to rebound [2–5]. Such losses induce overconsumption of material, which is detrimental for the cost of the work, the environment, and to some extent, to the material itself as rebound tends to create an in-place mixture that is richer in terms of cement content and thus undergoes increased shrinkage [2,6]. Rebound in the

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dry-mix shotcrete process is dependent on many technical parameters such as air flow, orientation of the hose and temperature [6–8], and also on mixture properties such as binder content, water, amount and size of coarse aggregates, and type of admixture [3,8–11].

Some mix design solutions exist to reduce rebound, such as partial replacement of cement by silica fume, carbon black or high reactivity metakaolin [3,12,13] but few explanations have been given regarding the role of SCMs in shotcrete. Pfeuffer and Kusterle [3] evaluated rebound and rheological properties, but the material tested for rheological evaluation was batched with a fixed amount of water and a liquid admixture, without being shot. This changed the overall structure of the material and probably altered interpretations. In order to evaluate fresh shotcrete properties and have direct information on the mixture shot, static and dynamic methods of measurement have been developed [14,15]. A static method (based on needle penetration in fresh shotcrete) is often used and related to rebound but dynamic methods (based on impact measurement) have rarely been exploited. Moreover, the measurements obtained have not been linked to standardized physical or rheological properties. In order to discuss this connection, static, dynamic and rebound measurements were made on mixtures containing supplementary cementitious material. The aim of the paper is to study the relation between fresh properties, measured by static and dynamic tests, and rebound of shotcrete made with supplementary cementitious material. The tests performed in this project are intended to improve the knowledge on this very particular type of concrete, which differs from traditional concrete in terms of technology and constituents (finer aggregates and accelerating agent), but is still a cement-based material with a close behavior to that of ordinary concrete in certain extreme situations, like in fire and at high temperature [16].

## 2. Experimental program

### 2.1. Method

The test program was carried out at the Laboratory of Materials and Durability of Constructions (LMDC) in Toulouse (France), with an original experimental setup designed especially for the study of dry shotcrete [17]. The shooting took place in an intermodal container divided into two parts (Fig. 1). The right part was used for water adjustment (done by the nozzleman), and the left part for rebound measurement. Once the setting of water was achieved, the hose was oriented toward the left part to start the evaluation of rebound. All mixes were shot with a rotating-barrel type machine (Meyco® Piccola) often used in real construction sites. The hose used had an internal diameter of 50 mm and the water-ring was at a fixed distance of 2.5 m from the nozzle. Air flow was set at 10 $m^3$/min with a pressure of 6.5 bar. In order to study the influence of only the mixture on rebound, the operational setup was kept unchanged during the shooting.

#### 2.1.1. Rebound measurement

The rebound measurement was carried out by spraying the shotcrete on to a 500 × 500 mm rebound mold, as shown on Fig. 1, placed near the bottom of a vertical wall of the container and at a distance of 1.2 m from the nozzle (this distance is optimized experimentally and is dependent of the air flow). The rebound mold had an opening on the side to allow material to be evacuated and avoid creation of an aggregate pocket that might distort the rebound results. The amount of material that did not stick to the mold was collected in a tarpaulin. At the end of the shooting, the mold and the tarpaulin with the lost material were weighed. Rebound was then calculated as:

$$\text{Rebound}\ (\%) = \frac{\text{Mass of material in the tarp}(\text{kg})}{\text{Mass of material in the tarp}\ (\text{kg}) + \text{Mass in the mold}\ (\text{kg})} \cdot 100$$

#### 2.1.2. Fresh properties measurement

In addition to the rebound value, dynamic and static consistencies were measured. The static penetration strength ($P$) was evaluated with a static penetrometer, also called a Proctor needle. This measurement has been used in many studies with different shapes of indenters [5,15,18,19]. In our case, the needle was a 6 mm diameter flat indenter as shown in Fig. 2a. The needle was pushed into the substrate 5 min after spraying, and the strength $p$ was indicated by a spring system. The penetration strength ($p$) was defined as being proportional to a yield stress by Johnson [20].

The other fresh parameter evaluated was the stress arising under dynamic conditions ($p_d$). This value first appeared in the rebound theory presented by Armelin [21], and was calculated as the energy of an impacting ball divided by the volume of the imprint after impact [5,15]. These authors calculated $p_d$ as:

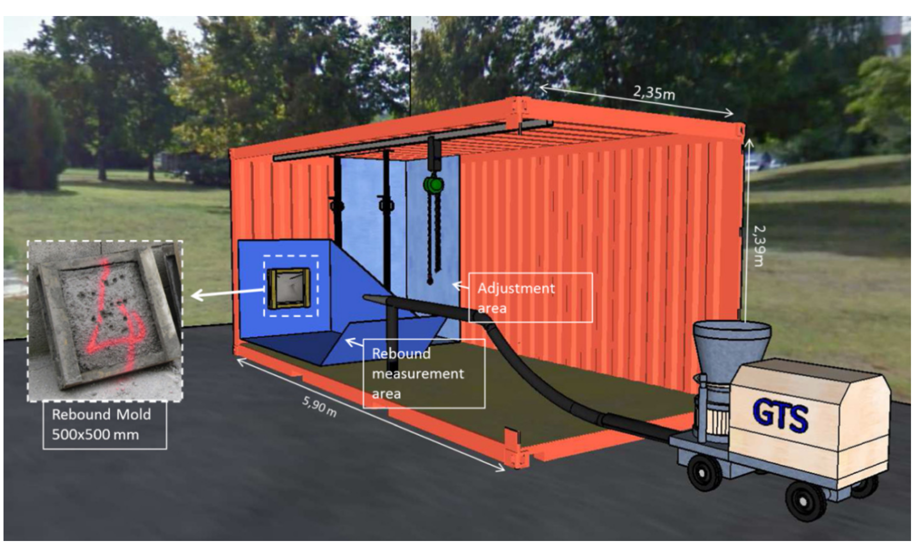


**Fig. 1.** Container layout: right part for adjustment, left part for rebound test. The tarp for rebound collection is on the left part of the container.