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Durability of dry-mix shotcrete using supplementary cementitious materials

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HIGHLIGHTS

- Dry-mix shotcrete has a higher porosity than ordinary concrete.
- This is probably due to the mixture design rather than to the compaction process.
- It has similar or better compressive strength, permeability and chloride migration.
- The durability of dry-mix shotcrete is assessed.
- Using a performance-based approach is more appropriate than a prescriptive approach.
- But it requires to introduce specific shotcrete porosity thresholds.

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ABSTRACT

Dry-mix shotcrete has all the components of concrete but its particular placement technique makes it harder to study than ordinary concrete. Its durability has not been the subject of much analysis and the aim of this paper is to bring new insights in that field. This work focuses especially on the durability of dry-mix shotcrete containing supplementary cementitious materials (SCM) with different aggregate size distributions. The use of SCM in dry-mix shotcrete aims at limiting rebound, reducing the carbon footprint of the binder and enhancing durability. The durability indicators introduced in this work are related to compressive strength, porosity, gas permeability, and chloride migration. Laboratory and on-site tests were carried out. It appears that, despite the high porosity (due to the adopted aggregate-size distribution characterized by very fine particles), shotcrete compressive strength, permeability and chloride penetration resistance are equivalent to or better than those of ordinary concrete. Additionally, this study underlines the limits of a prescriptive approach for achieving a given performance level, as dry-mix shotcrete is defined by its components as well as by its setup (water and final binder contents are very dependent on the nozzelman's adjustments). In these conditions, the performance-based approach seems more appropriate, even if a large data-base on the properties of dry-mix shotcrete (porosity included) is required. Extending the data-base on dry-mix shotcrete is, therefore, among the expected contribution of this research project.

1. Introduction

This paper studies the performance of dry-mix shotcrete using supplementary cementitious materials such as metakaolin, silica-fume and ground granulated blast furnace slag (GGBS), which have a lower carbon footprint than clinker [1]. Shotcrete is a cementitious composite characterized by a specific placement method and is defined as a "mortar or concrete, pneumatically projected onto a surface at high velocity" [2]. It is the high velocity imparted to the flow that induces consolidation of the material on the surface. This process is used in a variety of civil engineering and construction projects, from tunneling to anchored retaining walls, or for any work where formworks are difficult to assemble. The dry process (in opposition to the wet process) is very specific because constituents (sand, aggregate and binder) are introduced into the machine in a dry or slightly moist state and conveyed pneumatically through a hose to the nozzle, where the water is added. The dry-mix process leads to losses due to rebound [3–6] and,

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therefore, mixture designs are oriented towards rebound reduction [7]. For that purpose, dry-mix shotcrete mixtures generally have a high binder and sand content. The placement process and specific mix design lead to specific properties and research on dry-mix shotcrete durability is less abundant than that on ordinary concrete.

Nevertheless, some research has been done on dry-mix shotcrete durability. In 1989, Glassgold's review and Seegebrecht's work [8,9] pointed out that:

- dry-mix shotcrete quality and durability depend on 5 factors: design, materials, application equipment, craftsmanship, and placement technique.
- a properly placed and designed shotcrete can provide high strength, good resistance to freezing and thawing, and good resistance to chloride ion penetration; silica fume can enhance those properties.

More recent studies [10–12] show that:

- rapid set accelerators can be detrimental to the freezing and thawing behavior of dry-mix shotcrete.
- transportation properties (permeability, chloride penetration, absorption) are dependent on binder quality, type (containing fly ash or silica fume) and content, and are often better than those of ordinary concrete.

However, contradictory results have been obtained when comparing dry-mix shotcrete and ordinary concrete, especially for chloride penetration. These different results may be due to one or several of the 5 factors defining shotcrete quality.

The aim of this paper is to shed more light on the durability of dry-mix shotcrete containing SCM (particularly metakaolin and ground granulated blast furnace slag, which have been less studied in dry-mix shotcrete), with different aggregate size distributions. In order to estimate durability, general indicators such as porosity, permeability, and chloride migration are used [13] in addition to compressive strength. Shotcrete mixtures are evaluated in laboratory and on-site conditions and compared to ordinary concrete.

2. Experimental program

2.1. Methods

2.1.1. Shotcrete

To evaluate the durability of dry-mix sprayed concrete, an experimental program was set up in the laboratory [14] and two mixtures were also sprayed on site. Properties, such as compressive strength, porosity, gas permeability, and chloride migration were evaluated, the last three parameters giving indications on the transportation, inside the concrete matrix, of aggressive elements that could lead to structural deteriorations.

All laboratory mixtures were sprayed by the same operators, in the same environment (an intermodal container allowing mold filling once the desired consistency was reached – through water adjustment), with the same equipment (a rotating-barrel type machine (Meyco® Piccola) as used on construction sites). The water content of each mixture was measured in the fresh state after spraying. The use of 50 cm × 50 cm × 10 cm wood molds, open at the sides to avoid encapsulation of rebound material, allowed homogeneous concrete panels, at least 10 cm thick, to be sprayed. Those panels were then stored in a curing room at 20 °C and humidity >95%, before being cut into cubic or cylindrical samples for durability tests.

2.1.2. Ordinary concrete

In order to compare the influence of the placement of concrete, two shotcrete mix designs with a W/B ratio set to 0.5 were cast in cubic and cylindrical molds and compacted by vibration. Curing and measurements were performed following the same procedure as for sprayed concrete.

2.1.3. Measurements

2.1.3.1. Compressive strength. The compressive strength was measured on 50 mm cubic samples after a cure of 28 days. This is in accordance with the European standard NF EN 12504, which recommends samples with dimensions at least 3 times the size of the largest grain – 10 mm in our case. The machine used was a force-controlled-press, with a capacity of 400 T, a loading rate of 0.5 MPa/s and an initial loading of 30 kN for all the samples. The average compressive strength was obtained with at least 3 samples from a given panel.

2.1.3.2. Porosity. The porosity was measured according to standard NF P18-459, by determining the volume of pores accessible to water, after a cure of 28 days (20 °C and H > 95%). Cubic samples of 50 mm edge were weighed after saturation with water under vacuum and drying at 105 °C until their weight stabilized (approximately 10 days). Three cubic samples were used to calculate the average porosity.

Porosity was calculated as:

$$p = \frac{Mair - Mdry}{Mair - Mwater} * 100$$

with:

- p: porosity (% volume)
- M_{dry}: Weight of the specimen after drying at 105 °C (kg)
- M_{air}: Weight of the specimen saturated with water (kg)
- M_{water}: Weight determined by hydrostatic weighing of the specimen saturated with water (kg)

2.1.3.3. Gas permeability. Gas permeability was measured with a CEMBUREAU permeameter after a cure of 365 days (20 °C and H > 95%). Specimens were cylinders 110 mm in diameter and 50 mm high, dried at 105 °C until mass stabilization. The intrinsic permeability was determined by using the results of three apparent permeability measures. Apparent permeability for a given pressure was calculated as:

$$\mathrm{k} = \frac{(2.P_a.Q.L.\mu)}{A.(\mathrm{P}_0^2 - \mathrm{P}_a^2)}$$

with:

- k: apparent permeability (m^2)
- A: specimen cross sectional area (cm^2)
- L: specimen thickness (cm)
- P_0: absolute insertion pressure (bar)
- P_a: atmospheric pressure (1 bar)
- Q: flow rate of gas ($cm^3\ s^{-1}$)
- μ: dynamic viscosity of the gas (Pa s)

The intrinsic permeability was determined using the linear relation between apparent permeability and the inverse of the average pressure. The intrinsic permeability was the intercept of the regression line. At least three values of apparent permeability were needed to determine the linear function.