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Thermal properties of lightweight dry-mix shotcrete containing. expanded perlite aggregate

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ABSTRACT

This paper describes the thermal properties of lightweight dry-mix shotcrete using expanded perlite aggregate (EPA). Mixes made with different EPA/sand ratios were sprayed through the dry-mix shotcreting technique onto wooden molds to produce panels for mechanical and thermal testing. The density, uniaxial compressive strength (UCS), splitting tensile strength (STS), and the ultrasonic pulse velocity (UPV) were measured at various ages. Further, the ISO approved transient plane source (TPS) technique was employed to measure the thermal properties at 28 days. The results illustrate that shotcrete mixes with EPA have similar UCS and superior STS compared to cast concrete. Adding EPA led to a drop in thermal conductivity and diffusivity. When compared with cast concrete, shotcrete had lower specific heat capacity. This study found dry-mix shotcrete incorporating EPA at up to 75% sand substitution as a mechanically viable and thermally resistant alternative to cast concrete containing regular aggregates.

1. Introduction

As the demand for minerals increases the world over, it takes mining ever deeper. As a result, one has to contend with increasing temperatures in the working area due to the geothermal heat trapped in the surrounding rocks. One consequence of this is an escalating cost related to ventilation and cooling systems in order to keep the working environment comfortable for the miner [1]. It is here that the application of a thermal insulation, which is also mechanically sound, assumes importance [2–4].

Shotcrete, also termed as sprayed concrete, refers to a cement-based mixture that is projected pneumatically at high velocity towards the target surface [5]. Further, it is stipulated that it must be compacted by its own momentum [6]. This technique has been used in a wide range of applications in construction and mining industries. The latter has now become a major consumer of shotcrete especially for use in underground rock support [7], so much so that the annual consumption of shotcrete in North America is estimated to be over 200,000 m^3 [8].

There are two methods of producing shotcrete, namely, the dry-mix and the wet-mix processes, and both of them are routinely used in tunnels and mines. Specifically, in the dry-mix process, the bone-dry ingredients, including the cementitious binder, the aggregates, and any powder admixture are pneumatically conveyed from the spraying equipment through the delivery hose to the spraying nozzle, at which point a water ring introduces the water under pressure from another hose. The water mixes with the dry ingredients inside the nozzle and the fresh mix is then projected to the target at high velocity. As a result of this distinctive production process, shotcrete differs from the conventionally cast concrete both in its rheology and in its hardened properties [9]. While the rheology of fresh shotcrete influences the shootability and pumpability, using lightweight aggregates has been shown as favourable to producing shotcrete, especially through the dry-mix process [10]. Shotcrete has been extensively used as a support to tunnels and its mechanical performance including resistance to rock burst has been widely documented [7,11]. However, barring a single report from the USBM [12], no research has yet been undertaken to characterize its thermal properties, especially as resulting from lightweight inclusions.

In this study, expanded perlite aggregate (EPA) was incorporated as a lightweight substitute for sand. Raw perlite occurs in nature as a siliceous volcanic rock, which contains 2–5% water [13]. After heating at over 870 °C, this water vaporizes and causes the volume of raw perlite expanding from 4 to 20 times [14] and thereby it forms the lightweight porous expanded perlite. It is well known that expanded perlite can be blended with normal aggregates in suitable proportions to achieve a variety of benefits including lightweight, superior thermal resistance, acoustic insulation and shrinkage resistance in conventional cement-based systems [15]. The material has been applied in tiles, stucco, brick/block masonry,

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precast products, roof fill, pipe coating, oil–gas and geothermal wells, *etc*. While extensive studies have been made on the mechanical and thermal properties of concrete containing expanded perlite [16–19], limited information is available with regard to its use in the mining industry. To the authors' knowledge, the only prior study was done by the U.S. Bureau of Mines (USBM) [12] who sprayed an insulation of shotcrete containing expanded perlite, to achieve a thermal conductivity of 0.36 W/(m K), and a 90-day uniaxial compressive strength (UCS) of 20 MPa. Unfortunately, this promising research track was apparently discontinued following the disintegration of USBM in 1995.

The objective of this study is to examine the use of expanded perlite as fine aggregate in dry-mix shotcrete and characterize the thermal properties of the resulting material. Further, this study also highlights the process dependence if any, of thermal properties by comparing those derived for a sprayed mix with those from a conventionally cast counterpart.

2. Experimental details

2.1. Materials and mixtures

The expanded perlite aggregate (EPA), Type GU Portland cement [20] and sand were locally sourced in Edmonton. The EPA was mainly composed of SiO_2 (70–75%) and Al_2O_3 (12–18%). As shown in Fig. 1, it had a porous structure and with a bulk density of 71 kg/m^3 in oven-dry conditions, it was rated to absorb water at 100% of its dry mass. The sand was at saturated surface dry (SSD) condition, corresponding to a moisture content of 2.04% by mass. It had a bulk density of 1675 kg/m^3 in oven-dry (OD) conditions. As shown in Table 1, the mixes were designed in accordance with ACI 506.5R-09 [21]. The sieve analyses of the EPA and the sand used along with their blends were conducted as per ASTM C 126 [22] by means of a mechanical shaker. As plotted in Fig. 2, the grain size distribution for the aggregate blends in all the mixes was in each case, within the shotcrete grading zone No. 1 given in ACI 506R-05 [23]. Besides the reference mix with no EPA, four other mixes were produced where sand was replaced with EPA at four levels of volumetric substitution namely, 25%, 50%, 75%, and 100%. First, a series was cast in the conventional manner and these five mixes were designated CP0, CP25, CP50, CP75 and CP100, respectively. They have been described separately in an earlier report [24]. A second series was sprayed using the dry-mix process and the resulting five mixes were designated SP0, SP25, SP50, SP75 and SP100, respectively.

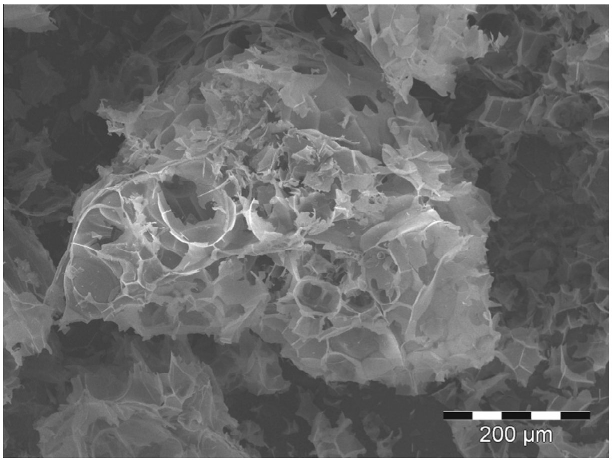

Fig. 1. Scanning electron micrograph of expanded perlite.

2.2. Shotcreting process and sample preparation

The dry-mix shotcrete was prepared with the assistance of a local industrial facility, and the shotcreting process was supervised by a certified nozzleman. In all, 15 panels were prepared upon spraying on to wooden moulds 610 mm (width) × 610 mm (length) × 90 mm (depth) in dimension. The SP0 batch was pre-mixed in the late afternoon on the day before the shooting, whereas the other 4 mixes were pre-mixed early in the morning of the shoot. Three specimens were prepared for each mix and all five mixes were shot on the same day, inside a specially fabricated hut. A plastic sheet was placed on the floor to collect the rebound after each shooting. As shown in Fig. 3, the molds were propped on the hut's facing wall at an approximate angle of 45°. After shotcreting, all panels were immediately finished and covered with plastic wraps and then transported to the curing room that was set to a temperature of 25 ± 2 °C and relative humidity between 95% and 100%. The specimens were obtained by coring cylinders from each panel at 6 stages of curing, namely, after 1 day, 3 days, 5 days, 7 days, 14 days and 28 days. The cores (50 mm in diameter) were designated as follows: three cored cylinders were examined for density as well as the volume of permeable voids as per ASTM C642 [25]; three cylinders were tested per ASTM C42 [23] to establish compressive strength and a further four cylinders were tested to evaluate the splitting tensile strength in accordance with ASTM D3967 [26]. Thus, at each stage 10 cylinders were cored out for each shotcrete mix. In addition, three cored cylinders were slated for thermal testing at the end of the 28th day. The drilled cores were end ground and this resulted in a variation in the Length/Diameter ratio (L/D) for the shotcrete cylinders between 1 and 1.78. Only those cores that conformed to Grade 1 and Grade 2 as specified in ACI 506.2-95 [27] were accepted for further testing in this study.

2.3. Testing methods

2.3.1. Mechanical evaluation

The density and water absorption in the shotcrete specimens were determined according to ASTM C 642 [25]. The mechanical properties, namely the unconfined compressive strength (UCS) was evaluated per ASTM C42 [28], as illustrated in Fig. 4a. As stated earlier, the splitting tensile strength (STS) was evaluated per ASTM D3967 [26]. Subsequently, the ultrasonic pulse velocity (UPV) was measured per ASTM C597 [29], as illustrated in Fig. 4b. The frequency of the two transducers was 54 kHz. The diameter of

Table 1
Mix proportions of shotcrete and corresponding rebound.

Mix number	Replacement percentage (%)	Cement (kg/m^3)	Sand (kg/m^3) (OD)	EPA (kg/m^3) (OD)	Rebound (%)
SP0*	0	519.5	1623.5	0.00	21.0
SP25	25	519.5	1217.6	17.3	11.4
SP50	50	519.5	811.7	34.6	16.6
SP75	75	519.5	405.0	52.0	15.0
SP100	100	519.5	0.00	69.3	29.1

* SP0 was pre-mixed by drum mixer one day before the shooting process to tighten schedule, but the mix started to hydrate, resulting in hardened blocks. However it was still shot to obtain the rebound.