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Experimental investigation of the utilization of quarry dust for the production of microcement-based building elements by self-flowing molding casting

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HIGHLIGHTS

- Use of limestone dust for the production of self-flowing castable building elements.
- Cement/filler ratio affects compressive strength and water absorption of specimens.
- Microsilica/cement ratio plays an important role in water absorption values.
- All specimens fulfill technical specifications for load bearing building elements.
- Developed mix design methodology was proven reliable and practical.

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ABSTRACT

The management and disposal of fine by-products produced by the aggregate industry, ready-mix concrete and asphalt concrete installations (also known as filler or quarry dust), emerges as a major environmental problem of quarrying and construction sector. Even though considerable research has been undertaken for the utilization of this fine by-product in several applications, it still remains underutilized, while its disposal and stabilization is also problematic due to resulting emissions of airborne particle pollutants. In this study the production of self-flowing castable cement-based building elements incorporating high amounts of quarry dust was investigated in laboratory scale. Quarry dust, microcement, water and concrete admixtures were mixed and casted in steel molds for the production of the specimens. The initial study of mixtures composition was based on the Andreassen particle packing model, while the final mix design was determined via Box–Behnken fractional factorial design of experiments, in combination with the response surface method. The compressive strength and water absorption values of hardened specimens exceed the relevant technical requirements currently in force, regarding load-bearing as well as decorative building elements, thus opening a new promising field for the utilization of this by-product.

1. Introduction

The accumulation of fine quarry by-products (<63 μm according to EN standards) during aggregate production, also known as filler or quarry dust, is one of the major problems of the quarrying industry, since they can represent up to 10–15% of total aggregates production. The removal of a significant part of this fine material from aggregates reserved for the production of concrete, asphalt and ready-mix mortars is imposed by the relevant regulations and quality standards that determine the maximum allowed filler content of aggregates, according to their end use. The management and handling of filler removed is an important environmental problem since it consists of very fine, otherwise inert material, causing serious problems of dust liberation [1,2]. The magnitude of the filler management problem is particularly large for Greece, due to large aggregate consumption rates, mainly used in the construction sector. Annual aggregate production achieved in 2008, following the construction boom, amounted to 100 million tones, but since 2009 it has been constantly declining. The cumulative reduction by the end of 2013 was estimated to approximately 45% [3,4].

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These fine quarry by-products remain largely unexploited, while they could be an important source of raw material for the construction industry in times of economic recession and strict environmental regulations pressing the construction industry. They could be recycled as they are, or after minor processing for the manufacture of innovative products, prolonging significantly the life of limestone reserves and existing quarries. Moreover, consumption of large quantities of such a fine material will have economic and environmental benefits due to reduced costs for disposal or discharge and additional revenues from the sale of new products.

Based on the above, an experimental investigation of the utilization of limestone fine quarry by-product (filler), produced still in significant quantities from quarries of crushed aggregates in the island of Crete (Greece), used as raw material for the production of building elements, was carried out. In order to avoid complex or energy intensive processes, the production of building elements from castable (self-flowing) filler-cement mixtures with the addition of chemical additives, used in concrete production, was investigated. This process emerges as technically and economically attractive, having small energy requirements, being direct applicable in the workplace of the quarry or concrete and/or asphalt ready-mix plant, while at the same time facilitating the consumption of the produced building elements by the construction industry. Direct implementation of such a recycling method would supply the aggregate and building material industry sector with a significant technological and competitive advantage, while improving indicators related to environmental performance and sustainability. The latter is particularly important for the quarrying industry which in recent years has been experiencing strong social pressure to improve its environmental performance [5].

However, the high volume use of quarry dust in cement-based building products poses several challenges. The behavior of fresh and hardened cement-based products depends highly on the intrinsic properties of fines notably the so-called 'filler effect' thus the use of these by-products requires a thorough characterization in terms of the specifications which must be fulfilled (e.g. composition and grading). Moreover, the addition of high quantities in cement-based products results in high water demand, which causes high drying shrinkage and inferior mechanical and physical properties [6,7]. Therefore the development of sophisticated mixture design methods ensuring optimal particle packing and the use of suitable binders and chemical additives to reduce water demand is of great interest.

This study aims to develop a mix design methodology for the production of self-flowing microconcrete, consisting of quarry dust, cement, water and concrete admixtures (additives), which are suitable for the production of building elements. The mix design of such type of concrete, known also as powder concrete, has recently gained considerable attention due to its potential as material for 3D printing inspired construction techniques that have recently been developed at laboratory scale for cement-based materials [8].

The structure of the paper is as below: In Section 2 the quarry dust quality characteristics which are crucial in mixture design are presented. The used microcement and admixtures are also described. Moreover, the mixture design model as well as the specimens' preparation, curing and laboratory testing are described. Emphasis is given on the experimental design by utilizing the Box–Behnken fractional factorial design. In Section 3 the obtained results are discussed and analyzed according to the standard procedure proposed by the factorial design of experiments. The optimal mixture composition is also determined by employing the response surface methodology. Finally the conclusions and the suggestion for further investigation are given in Section 4.

2. Materials and methods

2.1. Filler characterization

Filler used in this study was collected from a dry mortar plant located in the island of Crete (Greece). Filler is accumulated during drying and dedusting of marble sand, which is the main aggregate of dry mortars. The ultrafine fraction of marble sand (filler) is removed using an air stream, while bag filters are used for its collection. Collected dust is then carried and disposed in large silos. Removal of filler from marble sand is imposed by the specifications regarding the grain size gradation of aggregates used in dry mortars. The amount of excess filler removed sums up to a significant percentage of total marble sand (~25%). From filler storage silos representative samples were collected and their particle size distribution, their specific surface area and their mineralogical–chemical composition were calculated. Particle size analysis was determined by a laser particle size analyzer (Malvern Instruments, Mastersize-S), specific surface was estimated according to Blaine method, while mineralogical analysis was carried out by using an X-ray diffractometer (Siemens D500).

The grain size analysis of examined filler samples, shown in Fig. 1, indicated that the removed excess fine material from the marble sand during drying and dedusting processes is coarser than the conventionally defined filler, as described by relevant European standards (<63 μm), since a significant percentage of it (~30%) was measured to exceed 63 μm in size.

Specific surface area (air permeability), as measured by the Blaine method, for samples of filler tested, ranged from 1500 to 1580 cm^2/g, with mean value 1540 cm^2/g, standard deviation 30 cm^2/g and coefficient of variability 1.92%. Coefficient of variability proves very small indicating that marble filler is homogeneous regarding its granulometric composition, since specific surface area of a fine material, as measured by the Blaine test, is in direct conjunction to its size distribution. Mineralogical analysis showed that marble filler consists almost exclusively (97%) of calcite ($CaCO_3$), with small amount (3%) of dolomite ($CaMg(CO_3)_2$).

2.2. Microcement and admixtures

Microcement is an ultra-fine cement used primarily in grout for sealing extremely thin fissures, smaller than 100 μm (cement slurry for stabilizing rock mass in tunnels and other applications). This type of cement was preferred in this study instead of the common used cements like CEM I or CEM II in order to use a binder considerable finer than the quarry dust. The type of microcement (CEM I 52.5 R – SR 3 LA, Ultrafine 12), used in this study, is sulfate resistant, with reduced chromate and alkaline content and is produced by Heidelberg Cement Group (www.cementa.se). It is extremely fine since 95% of its grains have a size of less than 12 μm, as shown in Fig. 1.

The admixtures used in the preparation of microcement/filler mixtures in order to improve rheological characteristics of fresh product, as well as the mechanical characteristics of the final (hardened) specimens were a polycarboxylate-based superplasticizer and silica fume. Superplasticizers improve the plasticity and increase the fluidity of the mixture, without the addition of extra water, while at the same time maintaining or even increase mechanical strength of the final hardened product. Dosage recommended by the manufacturers of the particular used superplasticizer varies from 0.05% to 1.00% by weight of used cement.

Silica fume (or microsilica) is an ultrafine powder of silica consisting of spherical particles (microspheres), having an average diameter of roughly 0.11 μm with a very high specific surface area (15–25 m^2/g). It consists of at least 85% w/w non-crystalline SiO_2, while the alkali content is lower than 1%. Silica fume contributes to the reduction of water required, thus increasing strength and reducing water absorption of the final hardened material [9].

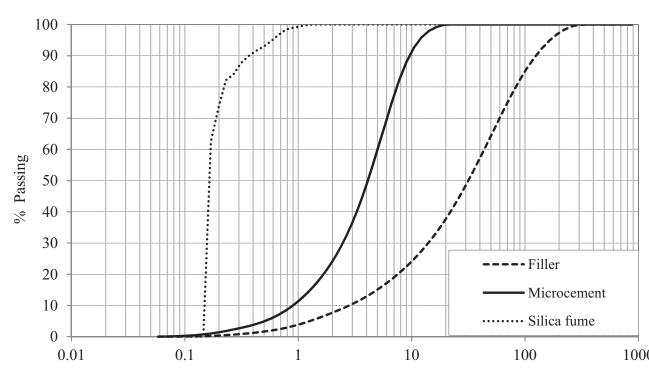

Fig. 1. Particle size distributions of filler collected from dry mortar plant as well as microcement and silica fume used.