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Rheology and mechanical characteristics of self-compacting concrete mixtures containing metakaolin

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HIGHLIGHTS

- Workability is affected by the introduction of mk as a replacement material of *c* or lp.
- Higher mk/*c* or mk/lp levels lead to linearly higher compressive strengths.
- Regardless of the replaced material (*c* or lp), f_{cc} is similarly affected by mk.
- Higher mk/*c* or mk/lp levels lead to higher tensile splitting strengths.
- Code curves overestimate the tensile splitting strength for a given compressive strength.

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ABSTRACT

Metakaolin is a supplementary cementing material (SCM), which has been recently used in Self-Compacting Concrete (SCC). This study investigates the effect of replacement of cement or limestone powder by metakaolin, on the rheology and the mechanical characteristics of the concrete mixtures. It has been found that the rheological behaviour of SCC is affected by the incorporation of metakaolin. Yet, this effect is not always traceable in the assigned rheological classes. The compressive strength is significantly enhanced and a similarly increasing trend is observed for higher replacement levels, regardless of the replaced material. A lower but still considerable improvement of the tensile strength is also evident. Finally, code or literature curves for NVC tend to overestimate the tensile strength for SCC.

1. Introduction

Self-Compacting Concrete (SCC) is a concrete that can be placed and compacted under its own weight, without requiring any consolidation, and which assures complete filling of formwork, even where access is hindered by narrow gaps between dense reinforcement bars. In order to achieve this behaviour, the fresh concrete must exhibit both high fluidity and stable homogeneity [1–14]. The stability of SCC can be enhanced by incorporating fine inert or pozzolanic materials, the latter being known as supplementary cementing materials (SCM). Commonly used SCM's include silica fume, fly ash, ground granulated blast furnace slag and metakaolin.

The incorporation of different SCM's in concrete can have a considerable effect on both fresh and hardened properties [15–19]. When used either as a mineral additive or as a partial cement replacement material, SCM's are known to be enhancing the engineering and performance properties of Normally Vibrated Concrete (NVC), in terms of its mechanical characteristics and durability [20–24]. Apart from the significant effect on hardened concrete properties, the incorporation of SCM's in concrete is also known to have a considerable effect on its fresh properties. The use of such powders provides greater cohesiveness by improving the grain-size distribution and particle packing (physical action). Moreover, their high pozzolanic activity leads to a further particle packing enhancement that is achieved by the pozzolanic products (chemical action) and acts complementary to the physical action [16,25].

Metakaolin is a known material even before the 1960s, but its application, either as a pozzolanic material in cement or as SCM in concrete, gained the interest of researchers only after the early 1980s [17,23,26,27]. Metakaolin is an ultrafine pozzolan that is produced by the calcination of purified kaolinite clay at moderately high temperatures, ranging from 650 to 800 °C [26,28,29]. This heat treatment aims to destroy the crystalline structure and to expel the chemically bound water [30,31]. The utilisation of metakaolin is known to significantly refine the pore structure and reduce the calcium hydroxide, $Ca(OH)_2$, of the cement paste

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matrix of concrete, due to the higher degree of purity, its pozzolanic reactivity, and its finer grading. Metakaolin reacts with $Ca(OH)_2$, which is produced during cement hydration, thus creating additional products (secondary C–S–H gel) that modify concrete micro-structure and contribute to the durability improvement of the material, in terms of its porosity, permeability, chloride ion diffusivity, etc. [15–17,22,32]. At this point, it should be noted that, apart from its advantages on the performance of concrete, metakaolin has also been recently preferred due to its environmental merit, in the sense that, as a cement replacement material, it contributes to the reduction of CO_2 emissions by decreasing the ordinary Portland cement consumption [23,24]. Further information about the reacting mechanism (pozzolanic reaction) and a complete literature review of metakaolin as a material and its use in concrete can be found in literature [16,17,22,24,26,33–37].

Metakaolin has been successfully used for the production of NVC for more than two decades [15,19,26,32,38–40]. Relevant studies for its exploitation in SCC have only been recently conducted, covering a wide range of topics, in regard to the rheology, the mechanical characteristics and the durability properties [2–14,27,37,41]. Yet, most of the researchers recognise the need for further investigation, in order to complement previous studies, by confirming their findings or clarifying some of the still ambiguous effects of metakaolin.

Opposite to NVC, there is an uncertainty about the actual contribution of metakaolin to the total performance of SCC, in combination with other characteristics of the latter concrete type, such as the normally high content of powerful superplasticizer, powder materials and/or viscosity-modifying admixtures, as well as the low coarse aggregate content. It has also been recently reported [9] that previous studies led to contradictory results, regarding the effect of metakaolin on workability. In any case, it is clear that the rheological properties of SCC are expected to be influenced by the addition of metakaolin, due to its physical properties. Specifically, metakaolin particles are usually finer than the particles of cement and present different shape characteristics, compared to cement or filler. According to literature [42,43], particles with an irregular shape tend to more easily show a shear thickening behaviour and, therefore, an increase of the viscosity. Thus, the replacement of either the cement or the inert limestone powders that are frequently used in SCC by metakaolin is expected to significantly affect the flowability and the viscosity of the mixture.

The scope of the present study, which is part of a wider project on SCC incorporating mineral admixtures [11–14], is to investigate the effect of metakaolin on the fresh concrete properties and on the major mechanical characteristics of SCC mixtures. In this frame, metakaolin is used as a replacement material of either cement or limestone powder, in various levels. Specifically, two distinctive replacement cases are examined:

- Replacement of a hydraulic material (cement) with a finer pozzolanic material (metakaolin), aiming at the investigation of the pozzolanic reactivity of metakaolin, together with its physical action, regarding packing density enhancement.
- Replacement of an inert fine material (limestone powder) by a pozzolanic material (metakaolin) of a similar fineness, mainly focusing on the effect of the pozzolanic reactivity of metakaolin.

It is worth mentioning that a similar replacement method of cement by metakaolin has been previously examined in other research studies, conducted for both NVC and SCC mixtures [4,8,10,15,19,21,23,27,38,40,41]. A comprehensive literature review regarding the effect of metakaolin level of cement replacement on the compressive strength of concrete is performed and previous findings are used to comparatively evaluate the results of the present study. On the other hand, according to an extensive literature review, it appears that the use of metakaolin as a

Table 1
Chemical analysis (%w/w) of kaolin (k) and physical properties of metakaolin (mk).

Kaolin chemical analysis						Metakaolin physical properties	
SiO_2	Al_2O_3	CaO	MgO	Fe_2O_3	L.O.I.	Density (t/m^3)	Specific surface area (m^2/g)[a]
47.85	38.20	0.03	0.04	1.29	12.30	2.5	1.41

[a] Calculated by grain size analysis.

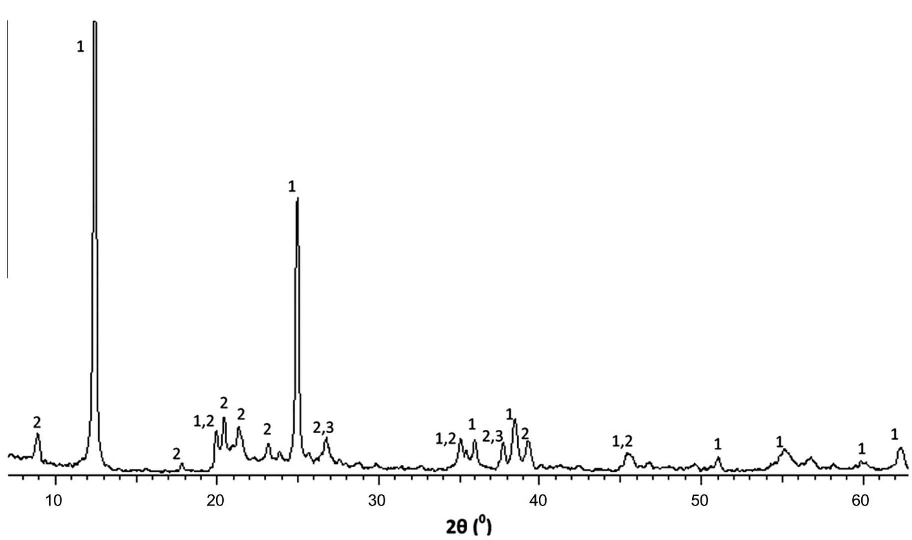

Fig. 1. XRD pattern and mineralogical phases of kaolin (k): (1) kaolinite, (2) illite and (3) quartz.