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Properties of mortars produced with reactivated cementitious materials

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The production of reactivated cementitious materials is an option for the recycling of hydrated-cement-rich fines discarded during recycled aggregate production. Reactivation is based on a thermal process where calcium silicate hydrates present in the fines decompose forming new hydraulic compounds. In the reported study, materials reactivated at temperatures between 660 °C and 940 °C were characterized using X-Ray diffraction and particle size analysis, and evaluated as binders using a central composite experiment to model the effects of reactivation temperature and reactivated material substitution level on the flowability, compressive strength and expansion of mortar mixtures. Reactivation temperature effects correlated with the relative concentration of reactive phases, particularly a stabilized form of alpha'-C_2S identified in the materials. Substitution effects depended on the supplementary material tested, and lacked significant interaction with reactivation temperature. In the region explored, mortars based on materials produced at 800 °C, 40% substituted by silica fume, achieved highest strength but lowest flowability.

1. Introduction

Concrete contributes a large fraction of the solid wastes generated in developed countries, constituting the largest single component of construction and demolition wastes [1,2]. In order to reduce the environmental impact of the construction industry, increasing amounts of concrete wastes are crushed to produce recycled aggregates for new construction works, particularly in countries with limited access to appropriate landfill areas and reduced availability of natural aggregate sources [3]. Reclamation process is based on the mechanical separation of the original aggregates from the mortar (cement paste and sand) adhered to them, which would otherwise adversely affect the fresh and hardened properties of concretes made with the recycled aggregates [4,5]. In order to obtain higher quality aggregates successive crushing stages and additional thermal or chemical processes can be combined to enhance the separation of the adhered mortar. However, as separation improves, the weight percent of crushed concrete reclaimed as aggregate decreases. In addition, since attached mortar content increases as the size fraction of the aggregate decreases [4], production is usually limited to coarse recycled aggregates. As a consequence, the largest part of the concrete wastes is transformed into fines and powder, which find little use in construction except as a backfilling material.

Due to their high concentration of residual hydrated cement paste, fines left from the production of recycled aggregates are avoided in conventional concrete mixtures [6,7]. Nevertheless, their chemical composition, also a result of their high content of hydrated cement, makes them an interesting raw material for the production of recycled cementitious materials. Through a thermal reactivation process the binding capacity of the cementitious material can be partially recovered. Dehydration of calcium silicate hydrates at temperatures over 600 °C leads to the formation of unhydrated compounds which have been described as similar in composition and structure to the dicalcium silicate present in Portland cement [8]. The rehydration of these compounds displays cementitious behavior, developing strength and thus potentially enabling the recycling of the hydrated cement wastes as a valuable construction material [9]. Using laboratory sourced pastes as raw material, Shui et al. [10] found that the maximum temperature used in the dehydration process significantly affect the water requirement for standard consistency, the degree of hydration and the compressive strength of pastes based on the reactivated material. Compressive strength was found to increase with increasing

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dehydration temperature between 300 and 800 °C. The 28-day compressive strength of pastes based on material dehydrated at 800 °C was reported to be 60% of the strength achieved by the original Portland cement paste. However, compressive strength decreased when dehydration temperature was further increased to 900 °C.

In a previous study, we investigated the main and interaction effects of nine material and process factors on the 7, 28 and 90-day compressive strength of pastes based on reactivated cementitious material (RCM) [11]. Effects of factors and interactions were estimated by linear regression of results from a fractional factorial experiment in two-levels. Higher compressive strengths observed were 20.0, 32.4 and 39.0 MPa at 7, 28 and 90 days, respectively. Several material and process factors displayed significant main and interaction effects. Degree of hydration of the raw material was found to have a positive effect on the strength of RCM-based pastes, particularly at 7 days of hydration. Considering degree of hydration affects the concentration of C—S—H in the raw material, it was proposed that the main cementitious compound in the RCM is a dehydrated product of C—S—H. As expected, dilution of the raw material by inert fines of either silicate (sand) or argillaceous (bricks) composition was found to have a negative effect on strength of RCM based pastes. The extent of grinding of the raw material before the thermal treatment displayed a significant interaction effect with the presence of silica fume in the raw material. According to this interaction, increasing both the content of silica fume in the raw material and the grinding time has a positive effect on the strength of the RCM-based pastes. This was probably due to unreacted silica fume remaining in the raw material being more exposed by the longer grinding. After the thermal treatment, the remaining silica fume can participate in pozzolanic reactions with the newly formed compounds in the resulting RCM. It was found that RCMs have a substantial capacity to promote pozzolanic reactions, as indicated by the significant positive effect of partial substitution of RCM by silica fume in the new mixtures. Silica fume was selected due to its simpler chemical composition and its known pozzolanic behavior. Finally, it was found that increasing the temperature used in the reactivation process from 700 to 800 °C decreases 7-day strength but increases 28 and 90-day strength of RCM pastes. In addition, results from experiments performed at the average level of the factors evidenced significant non-linearity of the response. The source of the non-linearity could not be identified from the results of the experimental design used, as it was limited to first order effects and interactions.

The research reported in this paper continues the exploration initiated in the previous study, characterizing the effects of selected process and mixture proportioning factors over a wider range of factor levels and on a wider set of mixtures responses. Factors previously reported as having significant main and interaction effects on the strength of RCM based pastes have larger potential for optimization of the relevant properties of mixtures based on RCMs, particularly those that can be easily controlled during reactivation process or in mixture proportioning. Accordingly, the maximum temperature of the reactivation process and the level of substitution of RCM by supplementary cementitious material (SCM) in the new mixtures were selected for this second part of the study. The goal was to determine if an optimal level exists for either of them, where specific mixture responses are maximized, and to evaluate if the optimal level of either factor depends on the level of the other due to factor interaction. A central composite experimental design for two factors was selected in order to explore the factor-response relationship, estimating main, interaction and second order effects of factors.

As opposed to previous studies based exclusively on pastes, this study evaluated the performance of the RCM as a binder for the production of mortars. Consequently, selected responses were: the flow behavior, expansion and 28-day compressive strength of RCM mortars. In order to compare results with our previous study, silica fume was used as the main SCM. However, fly ash was also used to contrast the effect of silica fume on flow and strength of RCM mortars. In addition to studying the binder performance of the RCM, complementary tests were carried out in order to obtain data upon which plausible explanations for the observed behavior can be proposed. These tests included: density measurements, particle size analysis of raw and reactivated materials, XRD analysis of RCM and measurements of evaporated water during mixing of RCM pastes.

2. Experimental design

Considering results from previous studies, an experimental region of interest was defined, limiting the range of reactivation temperatures and RCM substitution levels to be explored. The base range of reactivation temperatures was centered on 800 °C ± 100 °C. Pastes of RCM produced over this range of temperatures are known to develop significantly different strengths [10]. The base range of RCM substitution levels was centered on 20% ± 10%. According to previous results, obtained using silica fume as the substituting material [11], the range selected extends the experimental region in the direction of increasing strength. The factor-response relationship in the selected experimental region was explored using a central composite experimental design (Fig. 1), which enables efficient use of second order regression to produce quadratic response surface models [12]. The core of the design is a full factorial experiment in two levels that allows estimation of the linear effects of factors and factor interactions (first order regression coefficients). This core is augmented with axial points, which allow estimation of the second order effects of the factors (second order regression coefficients), and central points, which allow estimation of the experimental variance of the response. The levels of the factors for the axial points were chosen according to the rotatability criteria. In response surface models derived from rotatable designs, the variance of the predicted response is a function of the distance from the center of the design only. This is a desirable feature when the behavior of the response in the experimental region is not known in advance. In central composite designs each factor is applied in five levels: -α, -1, 0, 1, α, where $\alpha > 1$ is the coded level of the factor at the axial points. Choosing $\alpha = (n_f)^{1/4}$, where n_f is the number of factorial points in the design, a rotatable design is obtained. Therefore, $\alpha = 1.414$ for the selected design. For execution purposes the experiment was

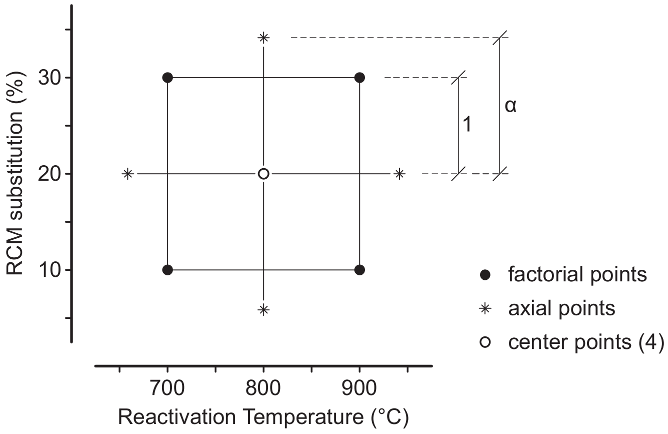

Fig. 1. Experimental region covered by the central composite design.