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Study of the rheology of self-compacting concrete with fine recycled concrete aggregates

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HIGHLIGHTS

- Self-compacting concrete (SCC) is a rapidly increasing trend in the construction industry.
- Recycled aggregates (RA) are already used in concrete production but normally the fine fraction is not.
- The fresh state behavior of concrete with recycled aggregates is one of the barriers to its applications.
- The use of fine RA in SCC production is proved to be feasible.
- If SCC characteristics are requested 90 min after mixing, no more than 20% of fine RA should be used.

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ABSTRACT

This work studies the effect of incorporating fine recycled aggregates on the rheology of self-compacting concrete over time (at 15, 45 and 90 min). The fine fraction of the natural aggregates was replaced at 0%, 20%, 50% and 100% with recycled sand. The fresh-state properties were studied by empirical tests (slump-flow, J-Ring, L-Box) and fundamental ones in an ICAR rheometer. The mixes with 50% and 100% recycled sand lost their SCC characteristics at 90 min. Contrarily the mix with 20% replacement maintained suitable passing and filling ability. The causes of this trend were an initial increase of plastic viscosity and afterwards an increase of yield stress. The compressive strength of the 50% and 100% replacement mixes decreased significantly and that of the 20% replacement mix less than 10%.

1. Introduction

The most widely used material in building and infrastructure construction is concrete with a consumption in Europe greater than 800 Mt/year [1]. The main raw materials in concrete are the aggregates with a proportion of 60–80% in volume. This represents a huge demand of materials that is satisfied mostly by natural resources. At the same time, the demolition and repair works produce large amounts of construction and demolition waste (CDW). In this context, the use of this CDW debris as aggregates in concrete production is a logical step with both economic and environmental benefits [2,3] that has been growing in the last two decades [4].

Research on CDW has reached some consensus concerning the homogeneity and acceptable quality of coarse recycled aggregates (CRA) from crushed concrete. Based on these works, policies and regulations have allowed their use in general concrete production

Abbreviations: W_{24h}, aggregates' absorption at 24 h; W_{10min}, aggregates' absorption at 10 min; CRA, coarse recycled aggregates; CEM, concrete equivalent mortar; CDW, construction and demolition waste; FRA, fine recycled aggregates; SCC, self-compacting concrete.

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at various maximum replacement ratios from 20% to 100% [4,5]. Nevertheless, in most cases the fine fraction of CDW is not allowed in any ratio although there are several works where its quality has been assessed [6–8], which leads to believe that regulations will soon lower these restrictions to its use.

Fine recycled aggregates (FRA) have higher absorption values than the coarse ones [8–11]. This leads to a loss of workability in concrete and, therefore, it is necessary to compensate this effect with an extra amount of water or superplasticizer. The incorporation of FRA also hinders the mechanical performance of concrete.

Self-compacting concrete (SCC) is a variety of concrete with the capacity of filling the forms with no assistance during placing and no blockage by the reinforcement or segregation of the mix. These capabilities lead to such advantages as lower workforce, improved finishing quality and reduced working time. In order to achieve these characteristics, this composite material needs to be designed with a larger amount of fines that reduce the coarse aggregate interaction [12]. Therefore, SCC seems an interesting opportunity to host and recycle the fine fraction of the recycled aggregates. This possibility of using FRA in SCC has been demonstrated as feasible by Kou and Poon [6] but one relevant question that has not been addressed is the effect of this type of recycled aggregate, with very high absorption, on the fresh-state properties of SCC.

In this context, this research intends to study the rheology of self-compacting concrete incorporating fine recycled aggregates and determine the effect of their incorporation on its fresh-state properties over time.

2. Literature review

2.1. Use of FRA in ordinary concrete and SCC

The feasibility of using FRA in SCC was demonstrated by Kou and Poon [6], who obtained SCC with acceptable workability and compressive strength using up to 100% of both FRA and CRA. The cementitious materials they used were Portland cement blended with fly ash and rejected fly ash as filler (inexpensive fly ash that does not fulfil the legal requirements of class F fly ash). Water/cement ratios of 0.53, 0.44, 0.40 and 0.35, 340 kg/m^3 of cement, 70 kg/m^3 of fly ash and 200 kg/m^3 of rejected fly ash were used.

The replacement ratios of FRA were made in volume at 0%, 25%, 50%, 75% and 100% (all mixes incorporated 100% of coarse recycled aggregates). In every case a decrease in compressive strength as the replacement ratio increased was reported. Moreover, the most negative effect detected concerned drying shrinkage that was more than twice that of the reference concrete for the 100% replacement ratio. This phenomenon is produced by the evaporation of the water trapped in the higher amount of pores of the recycled aggregates.

In this work [6] the mixing water was adjusted by adding the water that the aggregates absorb at 24 h (W_{24h}). The slump flow grew with the replacement ratio, which indicates that the recycled aggregates do not absorb 100% of W_{24h}. The authors repeated this test after 1 h and they found a positive correlation between replacement ratio and loss of workability. This work does not include a reference concrete with coarse natural aggregates only, i.e. all mixes incorporated coarse recycled aggregates (CRA). So it is not possible to determine quantitatively the individual influence of the CRA and FRA on the absolute value of the workability. The ratio between the absorption at 10 min (W_{10min}) and at 24 h for CRA and FRA was significantly different (70% and 51% respectively). Then, it seems plausible that the FRA may be the main component responsible for the loss of workability.

Corinaldesi and Moriconi [13] produced SCC incorporating separately CRA and FRA at 0% and 100%. In this work the w/c ratio was set to 0.45 and the cement content was 440 kg/m^3 plus 100 kg/m^3 of filler. These fines were alternatively limestone, fly ash and powder from recycled aggregates. The main effect of this last type of powder was to reduce the workability of the paste over time; this was evidenced by the yield stress and plastic viscosity values. Finally, there was also a significant reduction in compressive strength, much larger in the case of FRA than CRA.

There are also works on CRA in SCC, such as the ones of Safiudin et al. [14] and Grdic et al. [15]. They agree in two points:

- The higher water absorption of the recycled aggregates must be compensated. This adjustment is made by adding extra mixing water or superplasticizers;
- There is a reduction in compressive strength and modulus of elasticity as the replacement ratio increases.

The use of FRA in ordinary (not self-compacting) concrete is not extensive. The main effect that is reported in all the references is the loss of compressive strength with the replacement ratio. Khatib [16] refers that mixes with 25% and 100% suffer reductions of 15% and 30%, respectively, relative to the reference mix. Evangelista and de Brito [8] refer that for replacement ratios up to 30% there were no significant reductions. The other important effect described is loss of workability due to the higher absorption of FRA. Some authors add more water to compensate this effect, others add superplasticizer, and a few simply accept that there is going to be a loss of workability.

Another significant issue is the quality scatter of the FRA. Pereira et al. [17] refer a FRA with 13.1% water absorption, Khatib [16] mention a 6.3% value and Zega et al. [11] use a FRA with 8.5% absorption. These differences obviously should have a significant effect on the properties of the resulting concrete. However, in all cases this absorption is higher in recycled aggregates than in the natural ones. The main lesson is that there is a negative relationship between the absorption of the recycled sand and the quality of the resulting concrete. This follows the same trend that is well established for CRA [4].

2.2. Concrete equivalent mortar (CEM) for design purposes

There are many references on the design of SCC with different methodologies. There are two groups of procedures to adjust the composition: on the one hand, one can set the target strength level and then the components' content needed to meet this objective; on the other hand, one can start from a given standard formulation that will be corrected to achieve the workability appropriate to the target application. In this work, the second option was used.

Schwartzentruber and Catherine [18] proposed the use of the concrete equivalent mortar (CEM) concept to study the rheology of fresh concrete with the assumption that the rheological properties of CEM should be correlated with those of the corresponding concrete. For CEM design it is considered that all friction phenomena take place at the cement paste/aggregate interface. Therefore, the total specific area of the aggregates is a fundamental variable to understand the level of workability of concrete.

When the composition of CEM is determined, the following main relationships concerning the original concrete composition should be kept constant: cement and filler content, water/cement ratio, and fine aggregates content necessary to achieve the same total surface area of the coarse aggregates replaced. An example of this procedure can be seen in the Rubio-Hernández et al. work [19].

Since the start of the CEM method there have been various approaches to obtain the equivalent mortar of a specific concrete mix. In this context, the Nepomuceno et al. method [20] used in this work is a generalization of the one proposed by Ouchi et al.