Thixotropy and interlayer bond strength of self-compacting recycled concrete

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HIGHLIGHTS

- Thixotropy and thixotropic changing rate of SCRC were evaluated.
- Effect of the structural build-up at rest on interlayer bond strength was analysed.
- High percentages of recycled aggregate lead to high degrees of thixotropy.
- Non-compensated absorption, fines, recycled aggregate friction affect SCRC thixotropy.

ARTICLE INFO

ABSTRACT

This work is focused on assessing the thixotropy of self-compacting recycled concrete (SCRC) and on evaluating the interlayer bond strength. To do so, four SCRC mixes with 0%, 20%, 50%, and 100% of recycled coarse aggregate (by volume) were studied. This aggregate was used in dry-state conditions and an extra quantity of water was added during mixing in order to compensate its absorption.

Three testing methods were used to assess the degree of thixotropy of SCRC: structural breakdown curves at various rotational speeds, hysteresis loop flow curves and yield stress at rest. To evaluate the effect of the structural build-up at rest on SCRC interlayer bond strength, two methods were used: flexural tests and water permeability tests.

The results indicate that the increase of thixotropy and interlayer bond strength with the replacement percentage is due to the difference in the effective w/c ratio, result of the non–compensated water absorption, to the higher amount of fines in the recycled aggregates and generated from the old adhered mortar and also to the higher internal friction of recycled aggregates. Moreover, as water absorption is compensated in the mixing protocol, changes over time in the effective w/c ratio are negligible. Therefore, the thixotropic changing rate is similar in all studied mixes.

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1. Introduction and objectives

Thixotropy is by definition a time-dependent, isothermal and reversible process [1,2]. When a cementitious suspension is sheared, its network structure is broken into smaller agglomerates and, with continued shearing, eventually there is an equilibrium state in which the agglomerates cannot be broken down into smaller fragments. When the suspension is at rest, the particles can form weak physical bonds and agglomerate into a network [3].

In this way, when a fresh concrete is subjected to deformation (shearing), thixotropy describes the reversible and time-dependent reduction of its viscosity, which is caused by the build-up of a structure in fresh concrete at rest [4]. This structure, which provides an initial resistance to deformation, is destroyed once sufficient deformation is applied to the concrete [5]. This means that the physical structure building up with time in the material at rest can be broken down and that the steady-state rheology characterising the material before rest can be regained [6]. In the absence of shear during rest, the damaged structure rebuilds. The physical origin of this rebuilding might find its foundations in the Brownian motion that could induce a slow rearrangement of the particle configuration or in an evolution of the colloidal interactions between particles [7,8].

For cementitious materials, however, an irreversible chemical reaction is also under way from the moment the cement is intermixed with water. In practical terms, this appears as a loss in

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slump over time [1]. Then, the structural build-up phase of cementitious materials is a function of both the reversible structural changes from the thixotropic phenomena and the irreversible structural changes due to hydration mechanisms and the resulting microstructure [3]. The thixotropic properties of cement pastes that are measured macroscopically are strongly dependent on microstructural considerations [9].

The apparent viscosity of the material is permanently evolving [10]. Over short timescales, flocculation and de-flocculation processes dominate, which lead to rapid thixotropic (reversible) effects, while over larger timescales, hydration processes dominate, which lead to irreversible evolutions of the behaviour of the fluid. These two effects might in fact act at any time. As a consequence of this, it is reasonable to consider that there is an intermediate period, at about a couple thousand seconds, in which irreversible effects have not yet become significant. This means that it seems possible to model thixotropy and only thixotropy during short periods of time (not more than 30 min as an order of magnitude) during which the irreversible evolutions of the concrete can be neglected [11].

Thixotropy is strongly dependent on the composition of the mixture: cement characteristics, chemical admixtures, supplementary cementitious materials and water to cement (w/c) ratio are parameters that affect the thixotropic phenomenon. In addition, external parameters such as mixing and vibration influence thixotropy [9].

The total amount of powders in the mixture, as the particles contained in these various powders are the only particles at the origin of thixotropy in SCC [12]. It is accepted that thixotropy should increase when powder content increases.

The weight ratio between water and powders affects the average distance between cement (or other alternative powders) particles and thus their mutual interactions. Thixotropy should increase when water to powder ratio decreases. It should also increase with the specific surface of the powders. The fineness of powders affects the structuration rate as the amplitudes of Brownian and colloidal effects increase when particle size decreases [13]. Then, a lower water to cement ratio and a higher content of powder (i.e. content of fines) implies a higher degree of thixotropy.

Regarding coarse aggregates, their effect in thixotropy will be more related to their volume concentration, i.e. the amount of granular skeleton (sand and gravel) in mixture. In fact, both the sand-to-total aggregate ratio and the volumetric ratio of the paste-to-coarse aggregate were found to affect thixotropy due to the increase of the degree of internal friction resulting from greater coarse aggregate content. The aggregate-to-aggregate contact, that induces greater degree of internal friction within the mixture, will increase the shear stresses necessary to break down the material. The decrease of paste volume or increase of coarse aggregate volume can lead to higher thixotropy [14].

Moreover, Mahaut et al. [15] considered (Eq. (1)) that if the mechanical impact of the coarse particles is to increase the yield stress by a factor f(Ø), then their impact on the structuration rate of the paste is to also increase it by a factor f(Ø). It is thus sufficient to measure the cement paste yield stress evolution in time (i.e. A_{thix}) and to measure the increase of the yield stress with the volume fraction (i.e. f(Ø)) for a single resting time to infer the A_{thix}·f(Ø) value of the structuration rate of the suspension (and more generally of fresh concrete).

$$\tau_c(\varnothing, t) = \tau_c(0) \cdot f(\varnothing) + A_{thix} \cdot f(\varnothing) \cdot t \qquad (1)$$

τ_c is the yield stress of concrete, Ø is the solid volume fraction, t is the elapsed time, A_{thix} is the structuration rate of the paste.

Mahaut et al. [15] concluded that it is sufficient to know how the interstitial cement paste evolves in time to predict the suspension evolution at rest (suspension of coarse particles in a cement paste). This is important for fresh concrete as its behaviour is hard to measure. Their results showed that the knowledge of the cement paste structuration rate at rest (A_{thix}) is sufficient to predict the fresh concrete structuration rate.

Lastly, it can be concluded that thixotropy is of particular interest to users of SCC, as it may provide another link into predicting its flow behaviour [16]. The rheological behaviour of concrete is related to this network structure and the rate at which it can form. Thixotropy, which is manifested in the difference between static and dynamic yield stress or in the breakdown area between upward and downward rheometer flow curves, contributes by increasing segregation resistance and reducing formwork pressures. Too much thixotropy, however, reduces placeability and can affect interlayer bond strength [5,17].

In this work, self-compacting recycled concrete (SCRC) is defined as a self-compacting concrete made with recycled concrete coarse aggregate. This concrete has not been suitably researched yet. Most of studies focus on workability and strength characteristics [18,19] and recent works have also studied some SCRC rheological properties [20–23]. The effective water to cement ratio of SCRC evolves over time according to the evolution of the recycled aggregate water absorption. It is expected that the time-dependent rheological behaviour of a SCRC will be different from a conventional SCC, especially when water absorption is not compensated, when high percentages of recycled aggregate are used, when SCRC is designed with a lower w/c ratio and/or when long term self-compacting behaviour is measured [24]. However, there is still a gap in the knowledge about how recycled aggregate can influence on thixotropy of a self-compacting concrete and on the possible risk of the development of cold joints between successive layers of SCRC.

Therefore, the first objective was to analyse the degree of thixotropy developed in SCRC mixes according to the following methods: structural breakdown curves at various rotational speeds (steady state approach), hysteresis loop flow curves and yield stress at rest (also referred to as static yield stress and shear-growth yield stress).

Moreover, the structural build-up developed after a certain period of rest (due to thixotropy) can affect interlayer bond strength in SCRC. Then, the second objective was to evaluate the effect of the structural build-up at rest on interlayer bond strength in SCRC throughout the following two methods: interlayer bond strength using flexural tests and interlayer bond strength using water permeability tests.

2. Experimental procedure

2.1. Materials and concretes

Regarding materials, a Portland cement and a limestone filler were used as powder fraction. The Portland cement, CEM-I 52.5-R, showed a density of 3.11 t/m^3, a specific surface (BET) of 1.02 m^2/g, an initial setting time of 190 min and a final setting time of 260 min. The physical properties of the limestone filler were a density of 2.71 t/m^3, loss on ignition (1000 $^\circ$C) of 41.8% and a specific surface (BET) of 1.77 m^2/g. The chemical composition of both materials is shown in Table 1.

A modified polycarboxylate was used as superplasticiser. A limestone sand was used as natural fine aggregate (NFA) and two types of coarse aggregates, natural (NCA) and recycled (RCA), were used. The recycled aggregate was obtained from real demolition debris of structural concrete. It was made up mainly of concrete and stone. Table 2 shows the basic properties of all aggregates.

Four concretes were studied, a reference concrete and three recycled concretes (Table 3). The replacement percentages of