Thermal deformability of recycled self-compacting concrete under cyclical temperature variations

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Abstract

Recycled Concrete Aggregate (RCA) has greater elasticity than natural aggregate, due to the presence of adhered hydrated mortar in the coarse fraction, and mortar particles in the fine fraction. To evaluate this aspect under temperature variations, four Self-Compacting Concretes (SCC) made with 100 % coarse and/or fine RCA were subjected to cyclical temperature variations between 70 °C and 20 °C and between -15 °C and 20 °C. The addition of RCA, especially in the coarse fraction, increased the thermal deformability, although the difference tended to decrease with the number of cycles, especially in positive temperature variations. This study concludes that the traditional upper limit of the linear thermal expansion coefficient for concrete ($1.2 \cdot 10^{-5}$ $°C^{-1}$) is also suitable when RCA is incorporated.

Keywords: Recycled Concrete Aggregate (RCA); Self-Compacting Concrete (SCC); cyclical temperature variations; thermal deformability; thermal remaining strain; linear thermal expansion coefficient.

1. Introduction

The dimensional stability and thermal deformability of concrete are conditioned by the curing conditions (temperature and humidity) [1], the environmental temperature during its lifetime [2], some of its properties (porosity, or workability) [3], and the elasticity/expansivity of its components, including by-products [4; 5].

Recycled Concrete Aggregate (RCA), obtained from the crushing of rejected or demolished concrete elements, is one of the most studied wastes, due to its great abundance around the world and its interesting mechanical properties [6]. Its addition to concrete causes varied effects, shrinkage increase, among others, that usually depend on the original concrete´s strength [7] or the RCA fraction used [8], although an accurate estimation of these effects is possible [9]. Nevertheless, there is a lack of knowledge regarding the effect of RCA on the concrete deformability due to temperature variations.

This letter aims to evaluate the effect of RCA on the thermal expansion of concrete. The effect of coarse and fine fractions is analyzed in both increase and decrease of temperature. This study was performed on Self-Compacting Concrete (SCC), with high content of fine aggregate to reach self-compactability, so it is very sensitive to the harmful effects of fine RCA [5].

2. Materials and methods

Four SCCs were manufactured with CEM I 52.5 R (EN 197-1 [10]), a plasticizer, a viscosity regulator, limestone fines 0/1 mm, limestone filler, siliceous or RCA gravel (4/12.5 mm) and siliceous or RCA sand (0/4 mm). The RCA used was obtained from concrete with a minimum compressive strength of 45 MPa. The mixes were labelled as *N* (100 % natural aggregate), *F* (100 % fine RCA), *C* (100 % coarse RCA) and *CF* (100 % coarse and fine RCA). In mix N a water-to-cement ratio of 0.55 was established. The high water absorption and the irregular shape of RCA required an increase in the water content to maintain similar flowability in RCA mixes. Table 1 shows the mix design and the aggregates' physical properties.

The mixtures were tested to slump flow (EN 12350-8), capillary porosity in 72 h (UNE 83982), compressive strength (EN 12390-3) and modulus of elasticity (EN 12390-13) at 28 days (two 10x20-cm cylindrical specimens for each test). The freezing and heating tests (two 7.5x7.5x28.5-cm prismatic specimens for each test) were performed at 90 days and consisted in 20 cycles of 12 hours at -15 °C in a freezer (freezing test) or at 70 °C in an oven (heating test), followed by 12 hours at 20 °C in a climatic chamber. During the cycles, the strain was continuously recorded. The temperature variation in the specimens until stabilization was 0.1 °C/minute.

	Aggregates' physical properties	**Mix design (kg)**			
	Density (Mg/m^3); 24 h water absorption (%); fineness modulus	**N**	**F**	**C**	**CF**
CEM I 52.5 R	-	300			
Water	-	165	230	190	285
Plasticizer	-	4.50			
Viscosity regulator	-	2.20			
Limestone filler	2,77; 0.54	225			
Limestone fines	2.62; 2.53; 2.12	115			
Siliceous gravel	2.62; 0.54; 5.27	575		0	
Siliceous sand	2,58; 0.25; 3.49	940	0	940	0
Coarse RCA	2.42; 6.25; 6.30	0		530	
Fine RCA	2.37; 7.36; 3.12	0	865	0	865
Slump flow (mm)	-	765	810	750	800
Capillary porosity (%)	-	3.7	7.3	5.3	10.2
Compressive strength (MPa)	-	55.7	42.1	44.3	27.8
Modulus of elasticity (GPa)	-	37.5	29.2	32.9	20.9

Table 1. Mix design. Properties of aggregates and mixes

3. Results and discussion

All mixtures had a slump flow between 750 and 850 mm. Furthermore, as expected [7; 8], the mechanical properties and capillary porosity were worse when RCA was added. The adjustment of water content in the mix design produced similar impact in mixes C and F, and the joint use of both RCA fractions had the most harmful effect.

In thermal tests, all the mixtures had the same general behavior regarding the evolution of strain throughout the cycles (Figure 1). On the one hand, during the freezing test, all the mixes increased their absolute strain, due to the remaining negative strain that appeared progressively, mainly from cycle 9-10. However, the strain increase of each individual cycle was approximately the same. The remaining strain is explained by the inability of some cement hydration products (gel Calcium-Silicate-Hydrate, C-S-H) to recover their original dimensions after being cyclically subjected to sub-zero temperatures [11]. On the other hand, in the heating test, the temperature variation (between 70 °C and 20 °C) caused that some gel C-S-H products were less sensitive to positive temperature variations, which led to smaller strain increases in the last cycles, than in the first ones. The phenomena observed in both tests showed a tendency for all mixtures to shrink when they were subjected to cyclical temperature variations.

If the maximum strains of each mix are analyzed, the effect of RCA, mainly characterized for the presence of adhered mortar in the coarse fraction and of mortar particles in the fine fraction [8], can be defined. The maximum strains for the reference mix N were -0.3 and 0.41 mm/m. Mix C reached maximum strains in both tests of -0.38 and 0.48 mm/m respectively. The values for mix F were -0.32 and 0.45 mm/m and, finally, mix CF presented values of -0.40 mm/m and 0.48 mm/m. Therefore, the effect on the thermal deformability of the adhered mortar was greater than the effect of the mortar particles of fine RCA. The average remaining strain in the freezing test for the mixes N, F, C, and CF was 0.030, 0.035, 0.045 and 0.050 mm/m respectively, while the strain decrease in the heating test was 0.110, 0.140, 0.180 and 0.175 mm/m. The use of RCA, especially the coarse fraction, increased the tendency of the mixtures to shrink due to cyclical temperature increases, because of the incorporation of an additional volume of gel C-S-H products, present in the mortar particles of fine fraction and, especially, in the mortar adhered to the coarser particles of RCA [11]. There was no clear influence of porosity on any phenomena discussed.

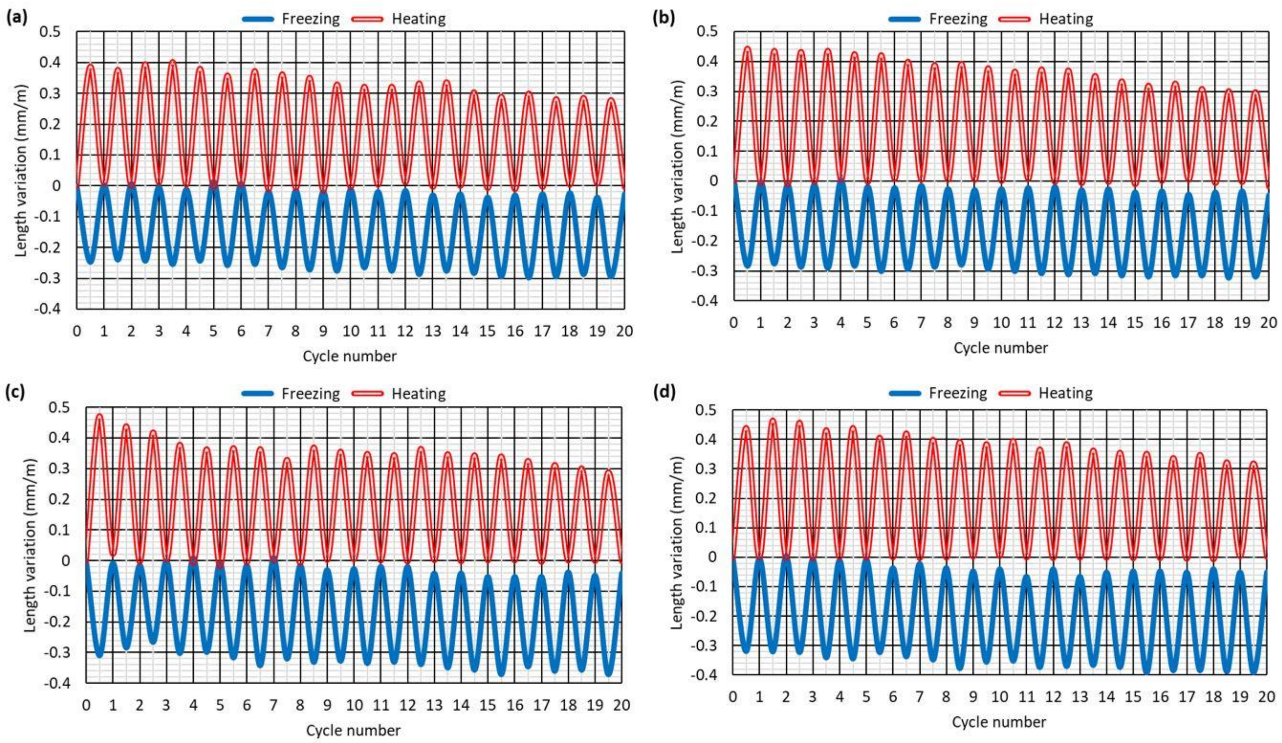

Figure 1. Maximum and minimum strains during freezing and heating tests: (a) mix N; (b) mix F; (c) mix C; (d) mix CF

The linear thermal expansion coefficient (α, $°C^{-1}$) is calculated by equation (1), in which $\Delta\varepsilon$ is the strain increase (m/m) and ΔT is the temperature increase (°C). Its common value for concrete is $1{\cdot}10^{-5}$ $°C^{-1}$, although in climates with large temperature variations, a value of $1.2{\cdot}10^{-5}$ $°C^{-1}$ is considered to estimate the thermal strains more safely. Figure 2 shows this coefficient calculated from the strain of each cycle. Its initial value for all the mixtures was between $7 \cdot 10^{-6}$ and $9 \cdot 10^{-6}$ °C^{-1}.

- The value obtained from the heating test results was, on average, 6 % lower than the one from the freezing test, and showed a clear downward trend, due to the strain decrease over the cycles. The final value was 30 % lower than the initial one.
- The coefficient calculated from the freezing test results of each cycle was practically constant. Nevertheless, if the accumulated strain was considered (the strain calculated from the initial length of the specimen before the test), see Figure 3, an upward trend appeared, due to the influence of the remaining strain, although with a lower slope than the heating test. Therefore, it is advisable to estimate thermal strains of concrete with the values from Figure 3, as they consider the evolution of the concrete's behavior throughout all the cycles. The maximum value obtained was $1.14 \cdot 10^{-5}$ °C^{-1} (mix CF, freezing test, accumulated strain).

The addition of RCA, especially in the coarse fraction, increased the linear thermal expansion coefficient of concrete. Nevertheless, in all cases, the upper limit of the interval traditionally considered ($1.2 \cdot 10^{-5}$ °C^{-1}) would be valid in RCA concrete.

$$\Delta\varepsilon = \alpha \cdot \Delta T \quad (1)$$

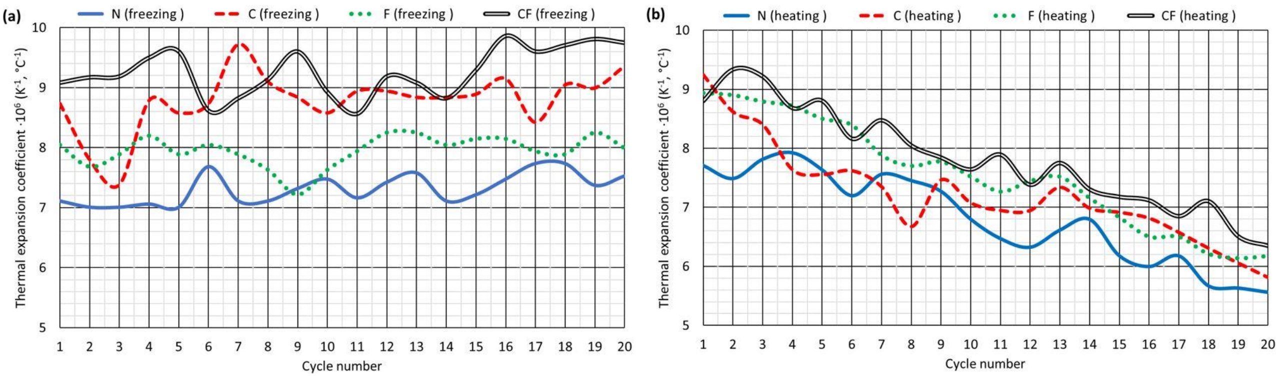

Figure 2. Linear thermal expansion coefficient calculated from the strain of each cycle: (a) freezing; (b) heating

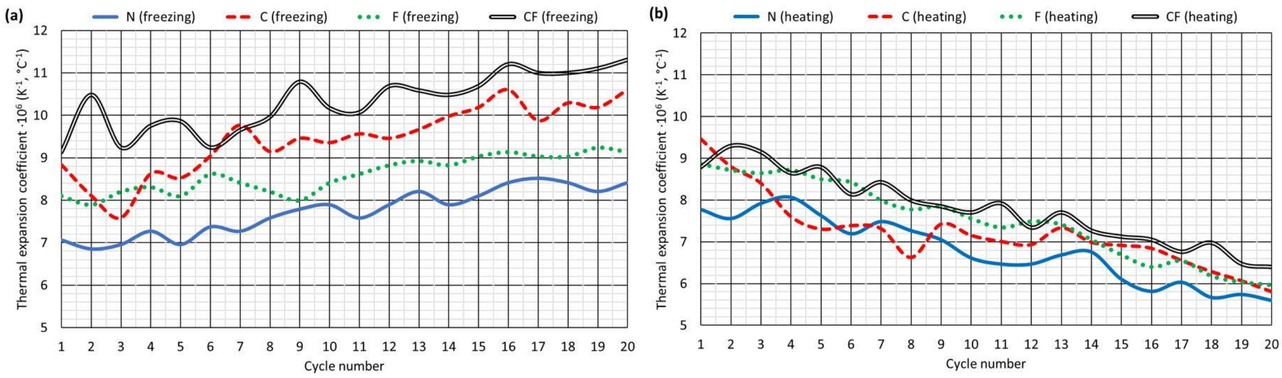

Figure 3. Linear thermal expansion coefficient calculated from the accumulated strain: (a) freezing; (b) heating

4. Conclusions

Regardless of the SCC composition, its linear thermal expansion coefficient decreases when subjected to cyclical positive temperature variations. However, if negative cyclical temperature variations are applied, a remaining strain appears, which causes this coefficient to increase, although the strain in each cycle remains constant. This behavior is mainly attributed to cement hydration products. The common upper limit of this coefficient for concrete, $1.2 \cdot 10^{-5}$ °C^{-1}, is also valid when RCA is incorporated. The addition of RCA, especially in the coarse fraction with adhered mortar and, therefore, gel C-S-H products, makes SCC more sensitive to temperature variations, thus experiencing greater strain for an identical temperature increase.

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