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Influence of cement and expansive additive types in the performance of self-stressing and self-compacting concretes for structural elements

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HIGHLIGHTS

- This work researches the properties of self-stressing SCC for structural elements.
- Expansive additives influence self-compacting properties and compressive strength.
- Without watering, type G additives promote larger total longitudinal expansion.
- The cement chemical composition influences the type K additive efficacy.
- Different microstructural mechanisms are responsible for the obtained expansion.

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ABSTRACT

Self-stressing self-compacting concretes were developed for structural elements, considering two types of expansive additives (types K and G) and two cement types. The influence of different parameters in their performance was evaluated. The addition of expansive additives resulted in compressive strength reductions that mainly depended on the total expansion reached. This total expansion depended on the alumina and sulfates contents of cement when using type K additive and, without watering, type G promoted larger total longitudinal expansion by forming amorphous calcium hydrated agglomerates. In contrast, when using type K additive, an indiscriminate formation of ettringite was observed.

1. Introduction

Concrete experiences volume changes independent from external loads, usually shrinkage. In fact, there are many types of shrinkage but the more relevant ones are autogenous shrinkage and drying shrinkage [1–3]. Considering certain structural uses, concrete shrinkage may cause cracking that must be avoided so the development of expansive concretes is a good alternative to increase the durability parameters of many construction applications, both for new construction and refurbishment.

Expansive concretes can be fabricated by using expansive cements or expansive additives that promote the formation of certain hydrated phases (ettringite or portlandite). These concretes, in contrast to conventional concretes based on Ordinary Portland Cement (OPC), expand during the first hydration steps. Two basic classes for expansive concrete are shrinkage compensating-concrete and self-stressing concrete. The main difference between them is the magnitude of the eventual expansion, larger in the latter. In most cases where expansive concretes are applied, such as pavements without expansion or contraction joints, roofs made of monolithic concrete without roofing or taxiways without joints, shrinkage compensating-concrete is used. However, there are certain cases where a larger amount of expansion is required, thus the use of self-stressing concretes is mandatory. For instance, when concrete is heavily restrained by the steel action, such as dense rebar reinforcement or concrete confined in steel tubes, large early tensile stresses can develop before concrete reaches its full tensile strength and cracking appears. In these cases, pre-stressing of the concrete can compensate these weaknesses and, in this sense, the use of self-stressing concretes (the concrete member is pre-stressed by chemical stress) is a good alternative [1,4–14].

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However, there are many parameters to consider that influence the performance of expansive concretes, such as curing conditions, expansive additive type and dosages, concrete composition, aggregate type, w/c ratio, etc. [1,5–7,9–13].

The present paper focuses on the design and the development of self-stressing concretes used as filling of steel tubes to be employed in structural elements. The tubes act simultaneously as structural beams or columns, concrete reinforcement and formwork. The expansive concrete induces stresses in the radial direction that pre-load the steel tube and confine the concrete, resulting in an increased service load [15]. Additionally, the concretes developed in this research are designed as self-compacting concretes (SCC) in the fresh state in order to make easier the delivery and casting at site. Two expansive additives were used: type K (based on calcium sulfoaluminate) and type G (based on calcium oxide). The first one promotes the ettringite formation while the second one causes the generation of portlandite.

The design of the self-stressing and self-compacting concretes under consideration implies an extensive understanding of the influence of different parameters in their performance, during both the fresh and hardened states. This is not a straightforward aspect considering that the mechanisms of expansion caused by ettringite or portlandite formation are not fully understood yet [11,12,16–18]. Because of that, the present paper evaluates in depth the influence of different parameters in the self-compacting performance, the mechanical strength gain and the expansive regime, including the expansive additive type and content and the cement type (conventional or pozzolan cement, with different initial alumina content). Pozzolan cement is considered due to the use of blended cements in the construction market is currently seen as a choice that increases the initial environmental sustainability of concrete construction. In this sense, so far the development of expansive concretes by using expansive additives has been only focused on the use of plain OPC. The challenge is to obtain a similar or improved expansive SCC by using cements with lower Portland clinker content, thus also improving the related sustainability of the industrial process.

In order to give a further understanding of the basic deformation of the fabricated self-stressing SCCs, their expansive behaviors were evaluated both in reinforcement-free and under steel bar restraining conditions. Additionally, the microstructure evolution induced by the use of the expansive additives was assessed in some of the fabricated concretes.

2. Experimental

2.1. Materials and mix proportions

Three different types of cements were used, two OPC CEM I 52.5N according to EN 197-1 with different alumina contents (named as “a” and “b” in this paper, the former with higher alumina content), and one blended pozzolan Portland cement labeled as CEM II/A-P 42.5R that implies a natural pozzolan content between 6% and 20%. As commented in the introduction, two expansive additives were used: a type K additive (based on calcium sufoaluminate) and a type G additive (based on calcium oxide). The chemical compositions of the raw materials are shown in Table 1 while Table 2 presents the mineralogical composition of the two CEM I used, calculated by means of the Bogue equations. Regarding the three cements used, the blended Portland-pozzolan cement (CEM II/A-P 42.5R) has the highest alumina and silica contents and the lowest calcium oxide content. Considering only the two CEM I type cements, although their chemical compositions are quite similar, there are some slight differences in the calcium oxide, silica, alumina and sulfates contents. These differences are reflected in the mineralogical compositions shown in Table 2. In this sense, the C_2S and C_3A contents are higher in CEM I 52.5N-a while the C_3S content is higher in the CEM I 52.5N-b cement. About the used expansive additives, type K is a mix of calcium sulfoaluminate and calcium sulfate that promotes the ettringite formation, and type G is mainly calcium oxide that promotes the portlandite formation.

Table 1
Chemical composition (%) of the cements and the expansive additives.

	CaO	SiO_2	Al_2O_3	SO_3	Fe_2O_3	MgO
CEM I 52.5N-a	60.5	20.8	5.41	2.86	3.55	2.33
CEM I 52.5N-b	62.8	19.9	4.80	3.51	3.52	1.26
CEM II 42.5R A-P	53.0	25.0	7.16	3.62	3.54	1.24
Additive type-K	54.0	1.88	13.6	26.5	0.49	1.33
Additive type-G	95.6	1.97	ND	ND	0.19	0.69

ND: not detected.

Table 2
Mineralogical composition (%) of the CEM I used.

	C_3S	C_2S	C_3A	C_4AF
CEM I 52.5N-a	30.0	37.8	8.33	10.8
CEM I 52.5N-b	49.4	19.8	6.77	10.7

The used aggregates were crushed stone from volcanic origin (6–12 mm gravel and 0–6 mm coarse sand) and natural fine sand from Sahara dunes (0–3 mm). The physical properties of the used aggregates are given in Table 3. The main characteristics of all the fabricated concretes were: cement content of approximately 500 kg/m^3, $w/c = 0.4$ and a cement:aggregate volume ratio of approximately 1:4. Besides, 2% in weight cement of superplasticizer (policarboxilate type) was added. Expansive additives contents ranged between 15% and 20% when using the type K one, and between 10% and 11% when using the type G additive. The latter was only evaluated when using CEM I type cements. A SCC fabricated without expansive additive and using the CEM I-52.5N-a cement was considered as reference. Changes in the expansive additive contents implied the subsequent adjustment of the different aggregates fractions. A total of 11 SCC mixes were considered in the present study, as can be seen in Table 4. The expansive additive contents were high in order to obtain the required expansion of the structural element (concretes used as filling of steel tubes). A high degree of expansion is required in order to ensure the confining pressure of the steel casing. Simultaneously, the steel tube prevents concrete cracking.

2.2. Test procedures

The fresh state of the fabricated concrete mixes was assessed by measuring slump flow according to EN 12350-8 standard, density (EN 12350-6) and air content (EN 12350-7). Fig. 1 shows as an example the slump flow measured in Ia-20K and II-15K concretes. In the hardened state, the mechanical properties and the expansion characteristics under two expansion regimes were evaluated. In all cases Ø150 × 300 mm sized cylindrical concrete specimens were fabricated to assess the compressive strength at 28 days according to EN 12390-3. Most of the fabricated concretes had an explosive failure as shown in Fig. 2. Prismatic specimens under two different conditions, free expansion and uniaxial restraining, were used to evaluate the expansion behavior of the fabricated SCCs; expansion in both regimes was measured up to 14 days. The free expansion was assessed according to ASTM C157 “Standard test method for length change of hardened hydraulic-cement mortar and concrete” so 286 × 76 × 76 mm sized prismatic specimens were fabricated (two per concrete mix) without any embedded reinforcement. The expansion under uniaxial restraining was evaluated following the ASTM C878 “Standard Test Method for Restrained Expansion of Shrinkage-Compensating Concrete”; thus, two square end steel plates connected by a steel bar were placed on each end of the prismatic molds before specimens of 253 × 76 × 76 mm size were cast (two per concrete mix). In all cases longitudinal expansion along the main axis of the prism was measured by using a digital comparator with 0.002 mm accuracy. All the fabricated specimens were cured during the first 24 h in a humid chamber at 98%RH and 20 °C. After that, they were demoulded and wrapped in film retractable (and maintained in the humid chamber) with the aim of better simulating real work conditions (filled steel tubes) where concrete cannot be cured (no watering) as it can be assumed that the steel tube does not allow moisture exchange between the concrete core and the environment. For Ib concretes (Table 4), only the free expansion regime was followed.

Table 3
Physical properties of the used aggregates.

	Gravel 6–12	Coarse sand 0–6	Natural sand 0–3
Particle density (g/cm^3)	2.48	2.66	2.69
Absorption (%)	3.34	1.96	0.52
Water content (%)	1.32	1.46	0.38
Fine materials (%)	0.5	15.1	6.3
Los Angeles coefficient (%)	17	–	–