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Long-term behavior of self-compacting and normal vibrated concrete: Experiments and code predictions

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HIGHLIGHTS

- SCC was achieved with a slight change in the mix-design of NVC (mainly by changing the amount of fly ash).
- SCC exhibited higher shrinkage, while the total creep deformation was similar.
- NVC and SCC specimens subjected to constant load seem to reach an asymptotic value at about 500 and 550 days, respectively.
- Codes seem to underestimate the experimentally observed deformation.
- By inserting in the code formula the experimental modulus of elasticity the code predictions significantly improve.

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ABSTRACT

The paper presents an experimental investigation that compares the long-term behavior (creep and shrinkage up to 680 days) of a Normal Vibrated Concrete (NVC) and a Self Compacting Concrete (SCC), with the latter being obtained by a slight change in mix-design (mainly an increase of the fly ash content to achieve self-compactability). It is shown that SCC exhibits higher shrinkage but the creep behavior is almost similar. As observed in other researches, this investigation confirms the influence of some parameters (i.e. cement content, water/cement ratio, type of filler) on the long-term behavior.

The tests were conducted for a very long period (680 days) with respect to data usually available in literature and, for this reason, it was possible to measure the asymptotic values and compare them with the code predictions. This comparison showed the importance of the modulus of elasticity (experimentally detected and different from the code based value) to predict the service behavior of a reinforced concrete element.

Most codes seem to underestimate the creep behavior of the SCC concrete mix, thus they cannot be applied directly and the MC2010 suggestion to consider higher (10–20%) long-term deformation for SCC powder type concrete seems to be reasonable, as well as the suggestion to perform tests on the material for structures sensitive to variations in creep/shrinkage (i.e. redundant structures).

1. Introduction

In the last two decades the applications of Self Consolidating Concrete (SCC) have become very popular due to its peculiar characteristics. The basic feature consists in its ability to be poured into formworks without using vibration [1,2], with evident benefits in precast plant as well as in building systems with complex structural scheme and dense reinforcements.

To achieve these properties, the proportion of the mix constituents differs from Normal Vibrated Concrete (NVC). Higher volume of fines, addition of chemical admixture, limited amount of coarse aggregate and reduced size of the aggregate are basic requirements to be successful in manufacturing SCC [2,3].

These differences in the mix-design with respect to NVC cause a completely different internal structure, thus many researchers studied not only the fresh state, but even the hardened state mechanical properties (i.e. compressive strength, bond strength, shear strength…) [4–9]. The long-term behavior has been investigated as well, but most of the studies focused on shrinkage only, considering different aspects such as the paste volume, the water

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content, the mineral admixtures, the coarse aggregate volume and grading *and the type of testing* [10–17]. Some researches paid particular attention on the autogenous shrinkage which appears to be affected by several parameters such as the water/cement ratio and the fines/cement ratio [10–15]. Oliviera et al. [13] showed that with a proper balance between expansive and shrinkage reducing admixture (SRA) it was possible to design a mix with a prescribed shrinkage. In [15] it is shown that Eurocode 2 [18] underestimates the autogenous shrinkage while total shrinkage is generally overestimated.

Nevertheless, due to the timing in testing, studies on creep are rather limited and some contradictory results can be found in literature [19–25].

Creep behavior is strongly affected by several parameters (such as curing conditions, age of loading, cement content, aggregate type and size, water cement ratio, relation of coarse to fine aggregates as well as fineness – blaine – and content of ultrafines which affect the paste volume) and, for this reason, in the available research investigations it is not easy to separate the single effects.

Maia et al. [19] focused on the effect of the age of loading and of the stress level on the total deformation. Even though the considered concrete was not common (24 h compressive strength higher than 60 MPa), the authors' conclusions highlight that Eurocode 2 [18] only in some cases well predicts the total deformation, and thus the authors suggest to measure deformation at least for one year.

The serviceability limit state and the overall behavior of a reinforced or prestressed concrete structure strongly depends on the long-term properties, which can significantly affect the overall response, in terms of excessive deformations, displacements and cracks, and cause several damages [26–32]. For instance, even in simple cases such as precast composite concrete-glass panels [32], long term deformations caused cracks which affected the aesthetic and the durability of the building, with relevant economic consequences. Thus, designers need to be confident of reliable code provisions that allow to evaluate the long-term strains. Nonetheless studies on creep for SCC concrete are rather few, and reviews on this topic [33–35] suggest the need of additional research, even if in the meantime they propose some general conclusions.

It seems that the paste volume strongly affects the shrinkage behavior [16], while the effect on creep is less pronounced. At the same time, creep is strongly affected by the binder type and content [21,24]. These findings were confirmed by Arezoumandi et al. [20], who compared two concretes (NVC and SCC) with the same composition with self-compacting ability achieved through a Viscosity Modifying Agent. They found higher compressive strength (of about 22%) of SCC while creep and shrinkage behavior of the two concretes were very similar. In addition, they found in their case study that the creep coefficient was overestimated by both ACI209 [36] and CEB-FIP Model Code 2010 [37], while shrinkage is well predicted by ACI209 [36] and underestimated by CEB-FIP Model 2010 [37]. On the other hand, Long [24] found that CEB-FIB MC90 [38] seems to well predict creep values with respect to ACI209 [36].

The code provisions are empirically based on a wide database of experimental NVC results, thus they could not be suitable for SCC.

In this paper, the comparison between shrinkage and creep behavior (specimens loaded for 680 days) of an ordinary (NVC) and a self-consolidating concrete (SCC) is presented. Sealed and unsealed specimens were considered. The mix-designs of the two concretes were similar, since they were conceived to achieve self-compacting ability with minimum changes in powder content. The maximum aggregate size was 22 mm, and fly ash was used as filler.

The obtained results are compared with other researches available in literature, to find similarity or discrepancy in the behavior and identify the most important parameters affecting the long term behavior of a concrete component. Although the shrinkage has been studied by several authors, the creep behavior, to date, has been investigated in few researches and for a limited time (usually less than one year). The tests last for 680 days and allow to identify the time when an almost asymptotic value of deformation was reached. Strength and Young's modulus were determined and discussed as well. Finally, a comparison with some of the most common code provisions (EC2 [18], CEB-FIB MC90 [38], CEB-FIP Model 2010 [37], ACI209 [36]) is presented, to check their capacity to predict the long term behavior of SCC concrete.

2. Experimental program

2.1. Materials

The experimental tests were performed on specimens made with SCC and NVC concrete designed for a cubic compressive strength (f_{cc}) of about 37 MPa (C30/37). Mix-components of the cement-based materials used for this investigation are summarized as follows: a Portland cement CEM II-A/LL 42.5R (340 kg/m^3 and 370 kg/m^3 for NVC and SCC, respectively); fly ash (6% and 22% cement content by weight for NVC and SCC, respectively); an acrylic superplasticizer (1.05% and 1.1% cement content by weight for NVC and SCC, respectively); a maximum aggregate size of 22 mm. NVC and SCC had an aggregate/binder ratio of 5.2 and 4.0, a water/cement ratio of 0.49 and 0.47 and a water/binder ratio of 0.46 and 0.39, respectively.

Workability was evaluated with slump for NVC (245 mm) and slump-flow tests for SCC (690 mm). The mechanical characteristics of the two concretes (NVC and SCC, respectively) can be summarized as follows: average compressive cubic (side 150 mm) strengths (f_{cc}) at 7 days 34.1 MPa and 35 MPa, increasing to 44.7 MPa and 45.5 MPa at 28 days (evaluated according to EN12390-3 [39]), while the elastic modulus (cylinder with diameter of 150 mm, height 300 mm) at 28 days were 27.2 GPa and 26.7 GPa, respectively (evaluated according to EN12390-13 [40]).

2.2. Test specimens

Sixteen cylindrical specimens (8 SCC and 8 NVC) were casted (diameter 150 mm, height 400 mm).

Four specimens of each mix were sealed with a self-adhesive plastic sheet to prevent any moisture loss due to drying.

For each type of concrete, two sealed and two unsealed specimens were subjected to constant load (creep tests), while the other specimens (two sealed and two unsealed) were left unloaded to measure shrinkage. Thus, two twin specimens were considered for each type of test.

Each specimen had a proper code as shown in Table 1: Concrete type (SCC or NVC), measure (S- shrinkage or C-creep), curing conditions (S-sealed, F-free), specimen number (1 or 2).

2.3. Test procedure

The specimens were demolded after 24 h. The specimens identified by code XXX-X-S-X were wrapped with a self-adhesive

Table 1
Specimens' code.

Unloaded and sealed	Unloaded and unsealed	Loaded and sealed	Loaded and unsealed
SCC-S-S-1	SCC-S-F-1	SCC-C-S-1	SCC-C-F-1
SCC-S-S-2	SCC-S-F-2	SCC-C-S-2	SCC-C-F-2
NVC-S-S-1	NVC-S-F-1	NVC-C-S-1	NVC-C-F-1
NVC-S-S-2	NVC-S-F-2	NVC-C-S-2	NVC-C-F-2