



Expansive high-performance concrete for chemical-prestress applications

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ABSTRACT

By inducing a large expansion in concrete at early age, chemical-prestressing of reinforcement can be achieved. Expansions sufficient to achieve this purpose are normally obtained with a combination of admixtures (or expansive cement) and special curing methods. However, these special concrete mixtures may suffer from excessive expansion and the resulting loss of mechanical properties and durability. In this work, a combination of expansion-promoting (based on calcium sulfoaluminate, CSA) and shrinkage reducing additives (superabsorbent polymers, SAP and shrinkage-reducing admixture, SRA) is applied to produce concrete with outstanding mechanical properties and good durability. After initial underwater curing until 28 d and further drying at 70%RH, a residual expansion in unrestrained conditions of about 4000 $\mu\text{m}/\text{m}$ was obtained, which enables reaching a central concrete prestress of about 2.5–3 MPa. In spite of the high residual expansion, compressive strength of about 100 MPa was obtained and the concrete had very high freeze-thaw resistance.

1. Introduction

Expanding concretes have been explored for many years as one of the measures against shrinkage-induced cracking or for providing chemical prestress [1]. Chemical prestress was proposed as an alternative to conventional prestressing; however, reports on successful and efficient application of chemical prestress in concrete are sparse and usually lack information on the durability of the concrete [2–4]. This study aims at filling this gap by developing recipes and approaches to obtain high-performance, self-compacting concrete with high chemical prestress (self-prestress) capacity and good durability.

Conventionally-prestressed elements require externally applied tensile stress on the tendons [5,6]. This can be either done before or shortly after casting of concrete (pretensioning) or after hardening of concrete (post-tensioning). In the case of pretensioning, the clamped tendons are usually pulled by hydraulic jacks and are anchored in frames/beds until hardening of the concrete. After releasing the pretensioning force from the frame when the concrete is hardened, the tension from the tendon is directly transferred through the bond to the concrete, inducing a precompression in the concrete.

On the contrary, the chemical prestress approach is based on using highly expansive concrete that, while expanding during hardening, exerts a tensile stress on the tendons and – per equilibrium – compressive stresses (prestress) in the concrete. Chemical prestressing has been used with either steel reinforcement [4,7] or FRP [8,9]. The

recommended levels of expansion capable of producing chemical prestress range from 200 to 700–1000 $\mu\text{m}/\text{m}$ [10]. At the same time, obtaining durable concrete with chemical prestress abilities thanks to expansion is very challenging. This is due to the fact that, in order to produce sufficient expansion in restrained conditions (e.g. 200–1000 $\mu\text{m}/\text{m}$) and sufficient tensile stress in the reinforcement, the free (unrestrained) expansion of the concrete needs to reach very high levels, which considerably exceed recommended values. The excessive expansion that would be required to produce sufficient pretensioning in the tendons and prestress in the concrete could lead to cracking or even loss of integrity of concrete elements and reduction of mechanical properties and durability [1,8,10,11].

To this end, the present study was devoted to developing concrete that could expand to high levels in free and restrained conditions, yet maintaining high mechanical properties and good durability, in particular in unrestrained conditions. The latter requirement is necessary to enable field application of such concrete if one considers that even reinforced (i.e. restrained) concrete elements can experience excessive expansion and therefore risk of cracking in regions remote from the restraining reinforcement, i.e. at the surfaces. At the same time, autogenous and drying shrinkage should be limited in order not to lead to significant decreases of the prestressing ability of the concrete. A further challenge was to achieve these goals while applying only simple curing measures, e.g. sealed or underwater curing. This is opposite to previous approaches to self-prestressing, where special curing was

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required, e.g. autoclave curing or curing in pressurized water at high temperature [7].

In expanding concrete, the initial expansion, either in an amount sufficient only for compensating shrinkage, or for generating actual chemical prestress, is usually obtained by blending into concrete mineral expansive additives [1]. Alternatively, blended cements, into which such admixtures are incorporated, can be used. Among different admixture types, those based on calcium-sulfoaluminates (CSA) are most common [1,12–14]. The action of these admixtures is linked primarily with the formation of a calcium sulfoaluminate hydrate, ettringite [1,12,14–17]. Different theories explaining the expansive action of ettringite on the microstructure of hardened cement paste have been proposed, e.g. formation of crystals that exert pressure on the microstructure leading to its expansion (crystal growth theory) or absorption of water by the ettringite crystals of colloidal nature (swelling theory), see [1,12,16]. It has been observed that formation of ettringite leads to expansion of the cement paste only after it has set, and that too late expansion may lead to deterioration of the microstructure (cracking) [14,16,18].

Expansion of concrete with expansive additives is in general enhanced if wet curing is applied. This is first due to promoting formation of ettringite (hydration of CSA) and possibly through further expansive action of ettringite according to the swelling theory. Furthermore, for concretes with low water-to-binder ratio (w/b), the observed higher expansion in the case of water curing may be also due to reduction of the concurring autogenous shrinkage. To this end, apart from external water curing, that may not be efficient due to low permeability of the concrete, internal curing can be applied [19–21]. This method is based on introducing into the mixture small, uniformly-distributed water reservoirs that release the preabsorbed water during hardening of the cement paste. Internal curing reservoirs can be obtained by adding presaturated lightweight aggregates (LWA) or superabsorbent polymers (SAP) that absorb water during mixing. The combination of internal curing with expansive admixtures has been investigated both for LWA [22] and for SAP [23]. The latter cases however regarded only shrinkage-compensated concretes and the obtained expansions were insufficient to achieve any significant chemical-prestress.

It has been also observed that the application of expansive additives together with shrinkage reducing admixtures (SRA) leads to enhanced expansion of concrete [24–26]. The early-age expansion can be further enhanced by special curing conditions, e.g. autoclave curing or pressurized-water treatment [7]; such methods lead however to increase in labor and equipment costs.

In the present work, a mix design containing CSA-based expansive additive, SRA and SAP was developed. Expansion/shrinkage was measured both in restrained and unrestrained conditions on samples under different curing regimes. The deformations were measured on prismatic samples after their demolding at 1 d. Additionally, corrugated tubes were used for measurements of deformations in autogenous conditions

starting from earlier ages. The durability of the expansive concrete mixtures was assessed by means of freeze-thaw tests, while the mechanical performance was assessed by means of measuring the compressive and bending strength and the quasi-static Young modulus.

2. Materials and methods

2.1. Mix design

Concrete mixtures were prepared with ordinary Portland cement CEM I 52.5 R (Jura, Switzerland) with the following oxide composition (XRF, by mass): CaO 63.15%, SiO₂ 19.53%, Al₂O₃ 4.86%, Fe₂O₃ 3.49%, MgO 1.59%, K₂O 0.89%, Na₂O 0.14%, SO₃ 3.28%, loss on ignition 2.34%. The cement had density of 3.12 g/cm³, specific surface of 0.51 m²/g and median particle diameter d₅₀ = 10.3 μm (laser diffraction).

A commercially-available CSA-based additive (CSA#20 by Denka) was used in the amounts of 5%, 10%, 15% and 20% (by mass of cement), see mix compositions in Table 1. The CSA additive had the following composition (determined with Rietveld analysis): anhydrite 48%, ye'elimite 22%, lime 19%, portlandite 9%, periclase 1%, calcite 1%. The Blaine fineness of the CSA additive was 0.36 m²/g and the density was 2.91 g/cm³. In one mix (see Table 1), fly ash was used. The fly ash had the following oxide composition (XRF, by mass): CaO 9.09%, SiO₂ 50.83%, Al₂O₃ 19.65%, Fe₂O₃ 8.36%, MgO 2.13%, K₂O 2.61%, Na₂O 0.72%, SO₃ 0.87%, loss on ignition 3.35%.

Limestone powder with 99.2% CaCO₃ content (by mass), density of 2.7 g/cm³ and a median particle size d₅₀ = 4.5 μm was used as filler in an amount of 5% by mass of cement.

The aggregate was alluvial sand from Switzerland with particles of 0–4 mm size and density of 2.65 g/cm³. Aggregates smaller than 4 mm were employed in order to enable casting of relatively small samples (25 or 40 mm smallest dimension) and in perspective filigree concrete elements [27].

The workability of the concretes was controlled with a polycarboxylate-based superplasticizer (Viscocrete-1 S by SIKA). The mass of the liquid was not accounted for in the water-to-binder ratio, w/b. The shrinkage reducing admixture was a liquid commercial product, based on hydroxyl-bounds (Control 60 by SIKA). A solution-polymerized SAP with particle sizes (in the dry state) in the range 63–125 μm was used as internal-curing agent. The pore solution absorption of the SAP was estimated as 17 g/g [28].

All dry constituents were initially mixed and next water with incorporated liquid additives (SRA and superplasticizer) was added during mixing; the mixing sequence in a planetary mixer took 5 min. Directly after mixing, the fresh properties were determined and the test specimens were prepared. No vibration was necessary for compacting the samples. The spread was determined with the Haegermann cone. Mixing, sample storage and all the tests took place at the temperature of 20 ± 0.3 °C.

Table 1
Mix composition and spread of fresh mixtures (Haegermann cone).

Material	Mass [kg/m ³]				
Mix name/material	5%CSA + SRA + SAP	10%CSA + SRA + SAP	15%CSA + SRA + SAP	20%CSA + SRA + SAP	20% Fly ash
Cement CEM I 52.5R	565	540	520	500	432
CSA-based expansive agent	28	54	78	100	–
Fly ash	–	–	–	–	108
Limestone powder	28	27	26	25	–
Water	217	217	218	219	205
Superplasticizer	18.6	16.1	15.0	14.4	8.9
SRA	15.5	15.5	15.6	15.6	–
SAP	1.83	1.83	1.84	1.84	–
Aggregates	1462	1458	1473	1458	1594
w/b	0.35	0.35	0.35	0.35	0.38
Spread mm	250	235	215	245	210

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