Construction and Building Materials 183 (2018) 626–641

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Effects of stress on concrete expansion due to delayed ettringite formation

Yvan Thiebaut [a,b,*], Stéphane Multon [a], Alain Sellier [a], Laurie Lacarrière [a], Laurent Boutillon [b], Djemal Belili [c], Lionel Linger [b], François Cussigh [d], Sofiane Hadji [e]

[a] Université de Toulouse, LMDC (Laboratoire Matériaux et Durabilité des Constructions), UPS/INSA Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse Cedex 04, France
[b] Vinci Construction Grands Projets, Direction Scientifique, 5 cours Ferdinand-de-Lesseps, 92 851 Rueil-Malmaison Cedex, France
[c] Cofiroute, 12-14 rue Louis Blériot, 92500 Rueil-Malmaison Cedex, France
[d] Vinci Construction France, 61 avenue Jules Quentin, 92730 Nanterre, France
[e] Sixence Concrete, 2-4 rue Jean-Baptiste Huet, 78350 Jouy-en-Josas, France

HIGHLIGHTS

- DEF expansion in reinforced and prestressed concrete specimens has been studied.
- Expansions decrease in restrained directions but remain unchanged in free direction.
- The final volumetric expansion is reduced when restraint is applied.
- Expansion due to sulfate attack under uniaxial loading is anisotropic.
- Expansion appears to be independent of loading applied in other directions.

ARTICLE INFO

Article history:
Received 18 December 2017
Received in revised form 18 June 2018
Accepted 20 June 2018

Keywords:
Anisotropy
Delayed ettringite formation (DEF)
Expansion
Sulfate attack
Modelling

ABSTRACT

Delayed ettringite formation (DEF) is a sulfate attack affecting civil engineering structures. This chemical reaction takes place within the concrete matrix of structures and causes damage in concrete and tension in reinforcements. For managers and owners, the ability to predict and reassess the mechanical behaviour of such structures is a major challenge. The influence of both reinforcements and prestress on DEF expansion were studied in the present work. Several tests were performed in laboratory: expansion under both uni and tri-axial restraint due to reinforcements and expansion under prestress (stress level of 14.5 MPa). Uniaxial restraint led to decreased strain in the restrained direction. For prestressed concrete, the loaded direction exhibited creep strain. In both cases, expansions were not impacted in transversal free directions. Therefore, DEF expansion under uniaxial stress is anisotropic. Cracks were observed parallel to the restrained direction. The final volumetric expansion was lower than in stress-free conditions (decrease of 27% for uni-axially restrained condition). For triaxially restrained tests and prestressed specimens, the volumetric decreases were 56% and 34% respectively. Data provided by these results will be used for numerical reassessment of DEF damaged structures.

1. Introduction

Sulfate attacks are the result of chemical reactions between sulfates, water and hydration products of Portland cement [1–6]. These pathologies lead to ettringite formation and result in concrete expansion and damage [7–11]. Reinforcements and applied stresses delay or prevent concrete cracking, with a major effect on resulting expansions [8,10,12–14]. Delayed ettringite formation (DEF) is a sulfate attack occurring in structures under certain circumstances that is likely to affect their durability [10,15–17]. In this case, sulfates come exclusively from an internal source, which is primary ettringite dissolution [18–23]. This is mainly due to heat treatment or natural exothermic reactions of cement hydration and occurs when the temperature exceeds a given threshold, typically 65 °C for Portland cement [18,24,25].

The aim of this article is to highlight the influence of reinforcements and stresses on concrete affected by DEF and, more broadly, by sulfate attacks. Some authors have designed experimental plans

* Corresponding author at: LMDC, Université de Toulouse, INSA/UPS Génie Civil, 135 Avenue de Rangueil, 31077 Toulouse Cedex 04, France.
E-mail address: yvan.thiebaut@vinci-construction.fr (Y. Thiebaut).

https://doi.org/10.1016/j.conbuildmat.2018.06.172
0950-0618/

to quantify these effects on cement based materials. The effects of homogeneous restraint imposed by external reinforcements on immersed mortar have been studied on prisms (40 × 40 × 160 mm) affected by DEF [8] and on thin-walled hollow cylinders (diameter 30.0 mm, wall thickness 2.5 mm) affected by external sulfate attack [26]. Other studies have considered reinforced concrete beams (610 × 914 × 5486 mm and 250 × 500 × 3000 mm) in heterogeneous hydric and mechanical conditions [10,14,27]. In all these studies, expansions decreased in restrained directions. Bouzabata et al.'s and Müllauer et al.'s studies were performed using mortar mix and cannot be generalised to concrete. Moreover, only uniaxial restraint was investigated. On the opposite, Karthik et al.'s, Deschenes et al.'s and Martin's results are largely impacted by both thermal, hydric and mechanical gradients. The direct assessment of a DEF affected concrete behaviour law depending only on stresses is consequently difficult. In this context, the main aim of the experimental plan reported in this article was to extend Bouzabata et al.'s results to concrete. To do so, plain, uniaxially or triaxially reinforced and prestressed concrete specimens in homogeneous thermal, mechanical and saturation conditions has been studied. For this purpose, "pathologic" concrete prisms (100 × 100 × 500 mm) were exposed to a heat treatment representative of what could be experienced on site for massive structures and then immersed in water in order to trigger delayed ettringite formation reactions and to allow alkali leaching [28–31]. Because of alkali leaching, the chemical conditions were not homogeneous and this had an impact on the delayed ettringite formation and thus on the expansion of specimens [32]. The alkali concentration in the storage water was measured throughout the tests so that chemical boundary conditions were known all times during the monitoring. In the case of reinforced specimens, steel bars and stirrups were embedded in the concrete. Homogeneity of the mechanical loading was ensured in the longitudinal direction by the positioning of steel plates and restraint systems on both sides of the specimens and, in transversal directions, by the placing of stirrups, when needed, along the specimens. Prestressed specimens were loaded by means of a creep test device that maintained a constant pressure in the hydraulic system. A calibrated extensometer measured the longitudinal and transversal expansions between stainless steel studs glued on the central part of concrete surface. The first part of the paper presents the experimental conditions. The expansions measured on each specimen and the evolution of the cracking pattern are then detailed in Section 3. Finally, the results are analysed and compared with those found in the literature.

2. Experimental conditions

2.1. Materials

Experiments on the effect of reinforcement and stress on expansion due to DEF were performed on concrete with a water/cement ratio of 0.48 and a cement content of 410 kg/m^3 (Table 1).

Table 1
Concrete composition.

Component	Proportion (kg/m^3)
Cement	410
Water	197
Siliceous sand 0/0.315	93.5
Siliceous sand 0.315/1	174
Siliceous sand 1/2	184
Siliceous sand 2/4	196
Siliceous gravel 4/8	188
Siliceous gravel 8/12.5	878
NaOH addition	5.0

The water amount takes into account water absorption of the aggregates. Aggregates were siliceous and qualified as non-reactive regarding Alkali-Silica Reaction [33]. They were supplied from Palvadeau quarry typically used as reference aggregates for numerous research programs. The binder was a standard Ordinary Portland Cement (OPC, CEM I 52.5 R). Table 2 presents the cement compositions obtained by inductively coupled plasma optical emission spectrometry (ICP-OES) and chromatography analysis. Sodium hydroxide, NaOH, was added to the mixing water at a dose of 5.0 kg/m^3 of concrete. Specimens were cylinders for the mechanical property measurements and prisms for assessing the impact of the reinforcement and stress on expansion. They were all cast at the same time.

2.2. Curing and storage conditions

Approximately 80 min after casting, most of the specimens were cured at high temperature: increase from 20 to 80 °C in 33 h, a slow decrease from 80 to 72 °C in 63 h, and a return from 72 °C to 20 °C in 240 h. This heat treatment corresponded to the temperatures recorded at the heart of massive concrete structures (14.0 × 3.5 × 2.0 m) during hydration [34]. All "DEF reactive" specimens were placed together in a climatic chamber. This heat treatment was realised in autogenous conditions: the concrete specimens were sealed during the cure by placing a silicone seal and a screwed wooden top on the moulds and the relative humidity in the climatic chamber was maintained close to 95% all along the thermal cycle. Temperature measurements in the centre of the samples had been made on a previous study using the same concrete composition (from another batch) and thermal and hydric conditions: differences between instructions and measurements never exceeded 2 °C. At the same time, other specimens from the same batch were stored at 20 °C in similar autogenous conditions. After the 14 days required for the heat treatment, all the specimens were unmoulded and stored for an additional 14 days period at a temperature close to 20 °C and 50% of relative humidity. Drying shrinkage might have induced micro cracking during this period. Porosity might have been impacted, with consequences on the specimen's behaviour. First of all, initial water absorption expansion after immersion could have been increased compared to undried concrete. Secondly, alkali leaching during the tests could have been accelerated because of a better water diffusion in concrete. As ettringite stability is improved when alkali content decreases, this phenomenon could lead to faster DEF reaction. Finally, large initial voids might have been created in the concrete matrix by drying shrinkage macro cracking, providing precipitation sites for delayed ettringite. According to Brunetaud, DEF expansion are mainly due to ettringite formation in small pores. In this case, both strain kinetic and final amplitude might have been impacted. Specimens were then immersed in agitated, non-renewed water maintained at 38 °C from 28 days after casting. The water volume remained constant and was close to 0.28 m^3. The concrete/water volume ratio of the storage bath was 0.23. Fig. 1 summarizes the evolution of the curing, storage and mechanical conditions (in the case of prestressed specimens) after casting. Both heated and non-heated specimens were stored together in the bath of water, with a heated/total concrete volume ratio equal to 0.77.

Alkali content in the storage bath was regularly measured on water samples by ICP-OES. The results highlighted alkali leaching from the concrete into the water (Fig. 2). This phenomenon implied a decrease of alkali content in the concrete paste, which may lead to an acceleration of the delayed ettringite formation [28–31]. The estimated free-alkali content in the pore solution fell from 1.05 mol/L to 0.56 mol/L between 0 and 323 days after immersion. These values were assessed taking the cement alkali content and sodium hydroxide addition into account. The porosity was