Experimental and numerical investigation of drying effets on concrete's mechanical properties.

François Soleilhet, Farid Benboudjema, Fabrice Gatuingt, Xavier Jourdain

International RILEM Conference on Materials, Systems and Structures in Civil Engineering
Conference segment on Service life of cement-based materials and structures
22-24 August 2016, Technical University of Denmark, Lyngby, Denmark

EXPERIMENTAL AND NUMERICAL INVESTIGATION OF DRYING EFFETS ON CONCRETE'S MECHANICAL PROPERTIES.

François Soleilhet (1), Farid Benboudjema (1), Fabrice Gatuingt (1), Xavier Jourdain (1)

(1) École Normale Supérieure de Cachan , Cachan, France

Abstract

THIS COMMUNICATION DEALS WITH THE EFFECT OF DRYING ON CONCRETE'S MECHANICAL PROPERTIES. THIS STUDY IS CONDUCTED THROUGH EXPERIMENTAL AND NUMERICAL SIMULATIONS WITH OR WITHOUT DRYING. A VISCO-ELASTIC MODEL WITH DAMAGE FOR CONCRETE PROVIDES THE STATE OF STRESS AND DAMAGE BEFORE LOADING DUE TO DRYING SHRINKAGE. THE MECHANICAL BEHAVIOR OF SPECIMENS, WITH OR WITHOUT DRYING, IS THEN COMPARED IN TERMS OF OVERALL BEHAVIOR. THIS INVESTIGATION WILL THUS ALLOW TO UNDERSTAND AND TO MODEL THE EFFECTS OF DRYING ON THE MECHANICAL BEHAVIOUR OF CEMENTITIOUS MATERIALS.

1. Introduction

Concrete is one of the major construction materials due to its resistance and easy use. Its use in numerous applications leads to different stakes. Currently, one of the major concerns for concrete structure is the long-term behaviour and durability of the construction. Multiple kind of solicitations combined with concrete heterogeneous mixture make it difficult to be fully defined. The purpose of this present work is to deal with the effects of drying process on tension mechanical properties of concrete.

Conventionally, when mechanical properties of concrete are characterized, internal stresses are assumed to be equal to zero and drying phenomenon are not taken into account. However, differential drying between the surface and the core of the structure can induce significant micro cracking. In some particular cases, this phenomenon could be important.

The impact of drying and micro cracking on mechanical properties is not well studied whereas it seems to have a significant impact on the mechanical properties. Regarding Young's Modulus most authors report a decrease of 4 to 30 % as concrete dries [9-14]. Conversely, there is no consensus regarding the compressive and tensile strengths so far: concerning compressive strength, some authors report an increase [10,11,13,14] while others report a decrease [9, 15-17]. Concerning tensile strength, a slight increase was found in a splitting test [17] while an initial decrease followed by a progressive increase up to zero percent relative humidity was observed in bending [12,16,18]. A decrease followed by an increase was also measured in direct tensile tests [18,19].

Relatively few evaluations comparing each of the methods to determine concrete's mechanical properties available today have been made. Firstly, this communication presents the effect of drying, on constant relative humidity, following each methods of characterisation: flexural test, splitting test, compressive test and direct tensile test. Secondly, the results will be compared to numerical simulations.

2. Experimental program

2.1 Material data

The concrete considered in this study, is the one used in the VerCors project's framework. It is based on ordinary Portland cement (CEM I) and its water to cement ratio is equal to 0.62. In addition, a plasticizer is used for a better workability.

Its characteristic parameters are: an average compressive strength at 28 days equals to 40.75 MPa on 16x32 cylinder, a tensile strength equals to 3.5 MPa (using splitting test) and an Young modulus equals to 32.2 MPa.

Table 1: Concrete composition.

Compound	**Nature**	**Quantity**	**Unit**
Cement	CEM I 52,5 R	320	kg/m^3
Sand		830	kg/m^3
Aggregate (4-11mm)	Calcareous	445	kg/m^3
Aggregate (8-16mm)	Calcareous	550	kg/m^3
Water		197.6	kg/m^3
Plasticizer	SIKAPLAST Techno 80	2.75	kg/m^3

2.2 Experimental campaign

For the purpose of this present work, each specimen is made with the same concrete mixture in order to reduce the impact of concrete variability and manufactured in mould. Prismatic samples (7x7x28) are casted into a steel mould, compressive and splitting samples (11x22) are made in a carton mould, and flexural (10x10x84) and direct tensile ones are poured in reusable formwork specifically built for that purpose. After this production, samples are stored in water during 28 days. At the end of the curing period, half of the samples is placed into a humidity- and temperature-controlled room, where they are exposed to drying conditions until they reach a percentage of mass loss above 40 with respect to the maximum one. The other half of the samples remains in water until the tests of all the samples are carried out.

2.3 Experimental tests

For each test, three samples of each specimen are used in order to obtain mean values.

2.3.1 Drying test

Isothermal drying test is performed to quantify the drying of every specimen. After the curing period, drying samples are put into a climatic chamber with an average relative humidity and temperature of 34% ± 13% and 25°C ± 1°C respectively (Figure 1). The water in excess on the sample surface is removed with a wet cloth then each sample is weighed in open air using the same weighing device. At the beginning, samples are weighed every hour and then daily. It was not possible to weigh flexural samples (about 20 kilograms) because they are too heavy for the weighting device (15 kg ± 0.1 g).

As the study is made on multiple methods of characterisation, the drying is performed under a unique relative humidity.

Figure 1 : Drying samples in the climatic chamber

2.3.2 Splitting and Compressive tests

Standard splitting and compressive tests were carried out using a 2500 kN hydraulic machine. It is composed of a lower platen rigid and an upper platen pivoting. The whole machine is controlled by a [name of the controller] and all data are saved on a computer.

Splitting test is the first made. The settings of this test are presented in Figure 2. It is performed under strength-controlled conditions with a rate of 1.94 kN.s^{-1} until failure. Special attention is paid to limit loading eccentricity.

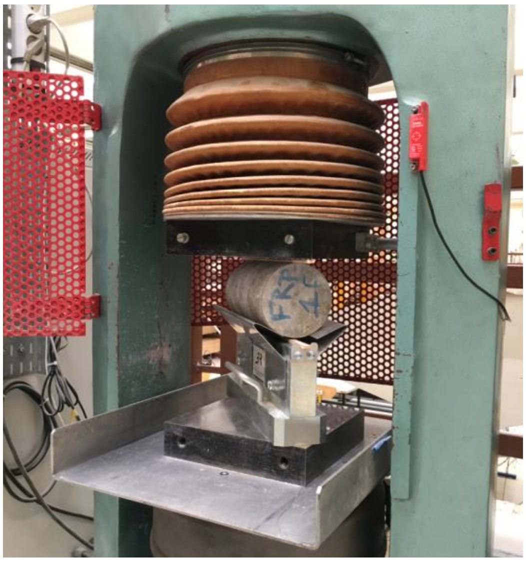

Figure 2 : Settings of the splitting test

Regarding the compressive test, samples are firstly planed to obtain a good flatness and to avoid press fitting and eccentricity. The test is then performed under strength-controlled conditions with a rate of 5 kN.s^{-1}. A cage strain, composed of three LVDT, is placed on the sample to measure strain. At the beginning of the test, to calculate the Young's modulus of the sample, three unloading and reloading are accomplished up to 30 percent of tensile strength. Finally, the test is conducted to completion, until the failure of the sample.

2.3.3 Flexural strength test

[A finir. Je ne connais pas encore bien la procédure. Je fais les essais demain avec Xavier]

2.3.4 Direct tensile test

3. Numerical modelling

3.1 Drying effects modelling

3.1.1 Drying modelling

The drying of cement-based materials is a complex phenomenon. Several, more-or-less coupled, mechanisms are involved: permeation, diffusion, adsorption-desorption and condensation-evaporation. Drying can be analysed through the resolution of liquid water, vapor and dry air mass balance equations. The use of several hypotheses **[6,7]** allows for considering only the mass balance equation of liquid water:

$$\frac{dS_l}{dP_c}\frac{dP_c}{dt} = div\left(k_{rl}(S_l)\frac{K}{\mu_l \phi}grad(P_c)\right) \tag{1}$$

Where S_l, P_c, ϕ, K, k_{rl} and μ_l are, respectively, the saturation degree, the capillary pressure, the porosity, the intrinsic permeability, the relative permeability and the viscosity of the liquid water.

It is shown [6,7] that this equation is sufficient for an accurate prediction of the drying of ordinary and high-performance concretes at 20°C with a relative humidity greater than 50%. The capillary pressure and the relative permeability are related to the degree of saturation through van Genuchten's relation [8]:

$$S_l = \left(1 + \frac{P_c}{P_0}\right)^{1-\gamma} \tag{2}$$

$$k_{rl}(S_l) = \sqrt{S_l}\left(1 - \left(1 - S_l^{\frac{1}{\beta}}\right)^{\beta}\right)^2 \tag{3}$$

Where P_0 and β are materials parameters.

3.1.1 Drying shrinkage modelling

There are different ways to model drying shrinkage. Some of these are based on pore mechanic problem. The development of this kind of modelling could be easily found in [Biot] or [Thierry]. Others models are based on phenomenological observations. Indeed, following experimental results, [5,20] found a proportional relation between water content variation and drying shrinkage rate:

$$\dot{\epsilon}_{ds} = k_{ds}\,\dot{w}\underline{\underline{1}} \tag{4}$$

Where k_{ds} is a hydrous compressibility factor and $\underline{\underline{1}}$ is the unit matrix.

It is possible to find alternative approach but in this present work this modelling was chosen.

3.2 Mechanical modelling

This study, based on 3D modelling and meshing of all samples, uses a non-explicit modelling of concrete cracking by the way of damage theory. The variable D, a scalar damage variable ranging from 0 to 1, is considered in the stress-strain relation:

$$\sigma_{ij} = (1 - D)C_{ijkl}\epsilon_{kl}^{elas} \tag{5}$$

Where σ_{ij}, C_{ijkl}, ϵ_{kl}^{elas}, are respectively stress, elastic stiffness and elastic components.

The evolution of the damage relies on an equivalent strain criterion, calculated from the equivalent strain ϵ_{eq} introduced by [Ref Mazars]. It was shown [Feenstra] that the evolution of damage in tension could be taken as exponentially decreasing:

$$D = 1 - \frac{\epsilon_{d0}}{\epsilon_{eq}}. \exp\left(-B_t\left(\epsilon_{eq} - \epsilon_{d0}\right)\right) \tag{6}$$

Where $\epsilon_{d0} = f_t/E_c$, with f_t the tensile strength and E_c the Young modulus, and B_t a parameter controlling the softening behaviour of the concrete.

Softening behaviour of concrete may lead to non-unity of solutions and mesh dependency. Energetic regularization prevents these difficulties [**Hillerborg**]. Regularization is based on the parameter B_t, which is a function of the size of finite element h, tensile strength f_t, fracture energy G_f and a parameter for the initiation of the damage ϵ_{d0}.

$$B_t = \frac{h.f_t}{G_f - \frac{h.\epsilon_{d0}.f_t}{2}} \tag{7}$$

Finally, a random field on the tensile strength generated by the Turning Band Method [**Matheron**] is used. The parameters are:

- The coefficient of variation equals to 10 per cent;
- The correlation length taken as three times the size of the biggest aggregate.

4. Results

4.1 Experimental results

4.1.1 Drying test

4.2 Numerical results

5. Conclusion and perspectives

References

Below are examples of references to a conference contribution [1], a journal paper [2], a standard test method [3], and a thesis [4], respectively.

[1] Laustsen, S. et al, CT measurements of SAP voids in concrete, RILEM Proceedings PRO 74 from the International RILEM Conference on Use of Superabsorbent Polymers and Other New Additives, Denmark (2010), 153-162

[2] Jensen, O. M. and Hansen, P. F., Water-entrained cement-based materials. I. Principles and theoretical background, Cem Concr Res 31 (2001), 647-654

[3] ASTM C457, Standard test method for microscopical determination of parameters of the air-void system in hardened concrete, American Society for Testing and Materials, USA (2009)

[4] Laustsen, S., Engineered air-entrainment of concrete, PhD thesis, Technical University of Denmark (2011)

---

[5] Goltermann P. Mechanical predictions of concrete deterioration – Part 2: classification of crack patterns, ACI Materials Journals 92(1) (1995), 58-63

[6] Bažant ZP, Sener S, Kim JK. Effect of cracking on drying permeability and diffusivity of concrete. ACI Materials Journal 84 (1986), 351-357

[7] Hansen TC. Creep of concrete: the influence of variations in the humidity of ambient atmosphere, Proceedings 6th Congress of the International Association of Bridge and Structural Engineering, Stockholm (1960), 57-65

[8] Lassabatère T, Torrenti J-M, Granger L. Sur le couplage entre séchage du béton et contrainte appliqué, Proceedings Actes du Symposium Saint-Venant, Paris (1997), 331-338 (in french)

[20] Baroghel-Bouny V, Mainguy M, Lassabatere T, Coussy O. Characterization and identification of equilibrium and transfer moisture properties for ordinary and high-performance cementitious materials, Cement and Concrete Research 29 (1999), 1225-1238

[26] Mazars J. A description of micro-and macro scale damage of concrete structures. Eng Fract Mech 25(5) (1986), 729–37

[27] Feenstra PH. Computational aspects of biaxial stress in plain and reinforced concrete, PhD thesis Technical University of Delft (1993)

[28] Hillerborg A, Modéer M, Petersson P-E. Analysis of crack formation and crack growth in concrete by means of fracture mechanics and finite elements. Cem Concr Res 6(6) (1976), 773–81