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Application of Eurocode 2, ACI, and RILEM model in predicting shrinkage of 3D-printed concretes: Challenges and model optimization

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Abstract. 3D-printed concrete (3DPC) cures under nonstandard conditions due to the absence of formwork and external curing, which leads to rapid moisture evaporation. Combined with a unique mix design – characterized by high binder content and reduced water-to-cement ratio – this results in significantly different shrinkage behavior compared to conventional concrete, particularly at early ages. Measuring shrinkage in 3D-printed elements is technically challenging and often technically challenging, which emphasizes the need for reliable predictive models. Since well-established models exist for traditional concrete, this study focuses on estimating updated coefficient values for three widely used models – Eurocode 2 (EC2), RILEM B4, and ACI 209-92 – to enable their application to 3DPC. Experimental shrinkage measurements were performed on multi-layer printed specimens consisting of six layers, each with a 40 × 10 mm cross-section and a total length of 500 mm. Both noncontact laser sensors and LVDT devices were used. Model parameters were estimated using nonlinear regression techniques. The results show that all three models can accurately describe the shrinkage behavior of 3DPC after recalibration, with coefficients of determination exceeding 0.94. This confirms the potential of adapting existing shrinkage models – originally developed for conventional concrete – to the specific characteristics of 3D-printed materials.

Keywords: 3D printed concrete; shrinkage prediction; Eurocode 2 model; ACI 209; RILEM B4.

1. INTRODUCTION

3D printing using cementitious mixtures is currently one of the most rapidly developing fields in concrete technology [1–3]. This technology can improve safety on construction sites, economic efficiency, and freedom of design [4, 5]. Additive manufacturing enables greater freedom in shaping geometries, eliminates the need for traditional formwork, and automates the construction process. Despite its numerous advantages, this technology presents challenges that must be addressed, including the development of appropriate reinforcement strategies and effective curing methods during the hardening phase [6–8].

The elimination of formwork from the technological process and the lack of traditional external curing methods result in significant moisture evaporation from the concrete. The loss of free water from the mixture leads to drying shrinkage. The necessity of studying and analyzing shrinkage in 3D-printed concretes is emphasized by numerous researchers, e.g., Federowicz *et al*. [9].

Using digital image correlation (DIC) techniques, Moelich *et al*. [10] investigated shrinkage deformations in a multi-layered printed element. Within 40 minutes of printing, the surface was sufficiently dry to allow the application of paint and the preparation of an appropriate pattern. Deformations were recorded over the following 3 h. During this period, the upper layers exhibited free shrinkage of approximately 2400 μm/m and up to 1400 μm/m under laboratory conditions and under reduced relative humidity conditions, respectively.

Van Der Putten *et al*. [11] also researched shrinkage in 3D-printed concrete elements. Using the DIC method and the GOM Correlate software, they recorded the deformations of a cementitious composite composed of cement, sand, and water, with a water-to-cement ratio (w/c) of 0.36. After 24 h of curing, the specimens exhibited approximately 1500 μm/m deformations, increasing to around 3500 μm/m after five days.

Zhang and Xiao [12] investigated shrinkage in nine-layer 3D-printed specimens. The samples were not subjected to curing procedures, and deformation measurements commenced immediately after printing. Similarly, the DIC method was applied, embedding specialized reference points into the fresh mixture. The maximum recorded deformation for a mixture of cement and sand in a 1:1 ratio, with a w/c ratio of 0.35, reached 4000 μm/m after 3 h of testing.

Markin and Mechtcherine [13] also implemented the 2D DIC method to record deformations of 3D-printed concrete. This approach required a time-consuming calibration procedure before each measurement. The total recorded free shrinkage exceeded −9000 μm/m after 3 h. It is worth mentioning that, prior to

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measurement, samples were sprayed with paint to create the black-and-white pattern required for DIC.

An alternative to digital image analysis may be the use of fiber optic sensors. One of the first studies on this subject was presented by Zhang *et al*. [14], who fabricated multilayer specimens with embedded sensors placed in the interfacial zones. During the first few hours of measurement, the sensors recorded plastic shrinkage at a level of 1200 μm/m.

Due to technical challenges associated with measuring shrinkage in printed elements, some researchers opt to use standard measurement methods. Shahmirzadi *et al*. [15] conducted tests based on the EN 12617-4 standard [16], obtaining strains of approximately 1600 μm/m after 28 days, which noticeably deviates from the values measured using DIC. Le *et al*. [17] also investigated shrinkage on specimens with dimensions of $75 \times 75 \times 229$ mm, recording over 700 μm/m after 28 days.

A significant challenge in measuring the total shrinkage of 3D-printed concrete elements is the need to employ advanced measurement techniques based on digital image analysis or distributed optic fiber sensors (DOFS). Therefore, researchers are exploring the possibility of analytically determining the shrinkage of printed mixtures using empirical formulas, drawing analogies from existing shrinkage prediction models developed for conventional concrete, as suggested by Federowicz [18].

Some researchers, such as Ma *et al*. [19], attempted to develop completely novel analytical models. Deriving such models is highly labor-intensive and requires extensive measurements across multiple mixtures to obtain reliable data. However, even large-scale studies typically achieve only around 20% accuracy.

An alternative approach involves optimizing existing numerical models initially developed for conventional concrete. One of the most frequently used models, referenced in European standards, is the Eurocode 2 model, described in EN 1992-1-1:2004 [20] (referred to as Eurocode 2 or EC2). This model is based on the FIB Model Code 1990, which represents a modified version of the first 1978 model proposed by the Euro-International Committee for Concrete (CEB) and the International Federation for Prestressing (FIP), now operating under the *fib* organization. In the case of high-strength concretes, the B4 model [21], proposed and published by RILEM TC-242-MDC, is frequently used in research. Globally, the ACI 209-92 model [22] is also widely adopted as an alternative to the European standard.

Despite the growing body of work on shrinkage in printable cementitious materials, reported results remain difficult to compare directly because they depend strongly on the measurement technique (e.g., DIC, optical sensors, standardized linear shrinkage tests), specimen geometry, and exposure conditions. Consequently, there is a clear need for practical approaches that enable the use of well-established shrinkage models while accounting for the specific early-age behavior and boundary conditions of 3D-printed elements.

This paper compares shrinkage measurements in 3D-printed concrete elements with predicted values based on the Eurocode 2, B4, and ACI 209-92 model. These models were deliberately chosen to represent different geographic regions and varying levels of complexity – ACI being the simplest, followed by the standardized Eurocode 2, and then the highly advanced B4 model. Additionally, an attempt is made to optimize the model parameters for more accurate shrinkage predictions in 3D-printed concrete. It is also worth noting the existence of the B4s model, a simplified, design-oriented version of B4 that requires fewer input parameters and relies mainly on compressive strength; however, this model was not included in the present analysis.

2. MATERIALS AND METHODS

The reference mixture was a 3D-printed concrete with a binder composed of CEM I 42.5R cement, fly ash, and silica fume. Additionally, natural sand (< 2 mm), water, and a superplasticizer were used to achieve the desired consistency. The designed concrete mixture had a water-to-cement ratio (w/c) of 0.35, a water-to-binder ratio (w/b) of approximately 0.24, and an aggregate-to-cement ratio (a/c) of approximately 2.04. The mixture was thoroughly analyzed in terms of its rheological properties in a previous publication of Federowicz *et al*. [9]. The composition of the mixture is presented in Table 1.

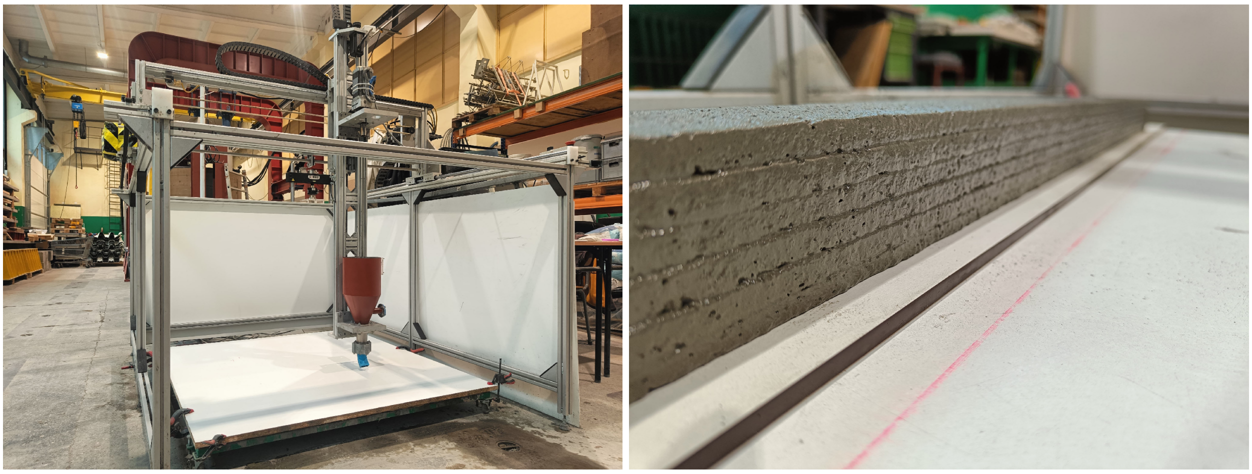

Fig. 1. Samples preparation: 3D printer (left); sample during printing process (right)

Table 1
3D printed concrete mixture composition [kg/m^3]

Cement	Fly ash	Silica fume	Fine sand	Superplasticizer	Water
600	180	90	1225	2.70	210

2.1. Shrinkage measurement

Shrinkage test specimens were printed using a Cartesian robot with parameters specified by Sikora *et al*. [23]. A rectangular nozzle with a 40×10 mm cross-section and a 45° outlet angle was used to print six-layer specimens, simulating the structure of a multi-layered wall. A photograph of the specimens during the printing process is shown in Fig. 1.

The shrinkage measurements were conducted using a specially designed and constructed measurement setup. The core of the measurement system was a noncontact optical measurement method utilizing laser displacement sensors (OMRON ZX1-LD50). These sensors have a measurement accuracy of 2 µm and continuously record deformations at a sampling rate of 0.02 Hz. A schematic drawing representing the measuring setup is presented in Fig. 2.

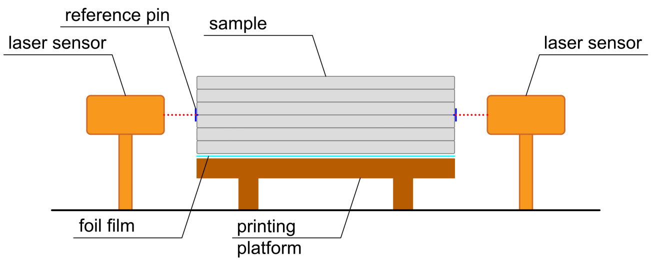

Fig. 2. Schematic drawing of the shrinkage measuring setup

As a control, the deformations of one specimen were also monitored using LVDT sensors and a specially designed holder, which was embedded in the specimen during printing. The measurement setup is shown in Fig. 3.

2.2. Shrinkage prediction models

The Eurocode 2 (EC2) shrinkage prediction model was first applied in this study. According to its assumptions, the model can be applied to all types of concrete within EC2 strength classes under thermal-humidity conditions.

In the EC2 analytical model, the total shrinkage-induced deformation of concrete should be determined using equation (1):

$$\varepsilon_{cs} = \varepsilon_{cd} + \varepsilon_{ca}, \tag{1}$$

where
ε_c – total shrinkage strain,
ε_{cd} – drying shrinkage strain,
ε_{ca} – autogenous shrinkage strain.
Drying shrinkage deformations as a function of time are given by equation (2):

$$\varepsilon_{cd}(t) = \varepsilon_{cd,0} \cdot \beta_{ds}(t, t_s) \cdot k_h, \tag{2}$$

in which

$$\varepsilon_{cd,0} = 0.85\,(220 + 110\alpha_{ds1}) \exp\left(-\alpha_{ds2}\frac{f_{cm}}{f_{cm0}}\right)\beta_{RH}, \tag{3}$$

$$\beta_{RH} = 1.55\left[1 - \left(\frac{RH}{RH_0}\right)^3\right], \tag{4}$$

where
$\varepsilon_{cd,0}$ – nominal value of drying shrinkage determined from (3) in µm/m,
$\beta_{ds}(t, t_s)$ – time-dependent shape coefficient,
k_h – coefficient dependent on the characteristic cross-sectional dimension,
α_{ds1} – coefficient dependent on the type of cement, for class R $\alpha_{ds1} = 6$,
α_{ds2} – coefficient dependent on the type of cement, for class R $\alpha_{ds2} = 0.11$,
f_{cm} – average compressive strength of concrete in MPa,
f_{cm0} – reference value equal to 10 MPa,
β_{RH} – relative humidity coefficient,

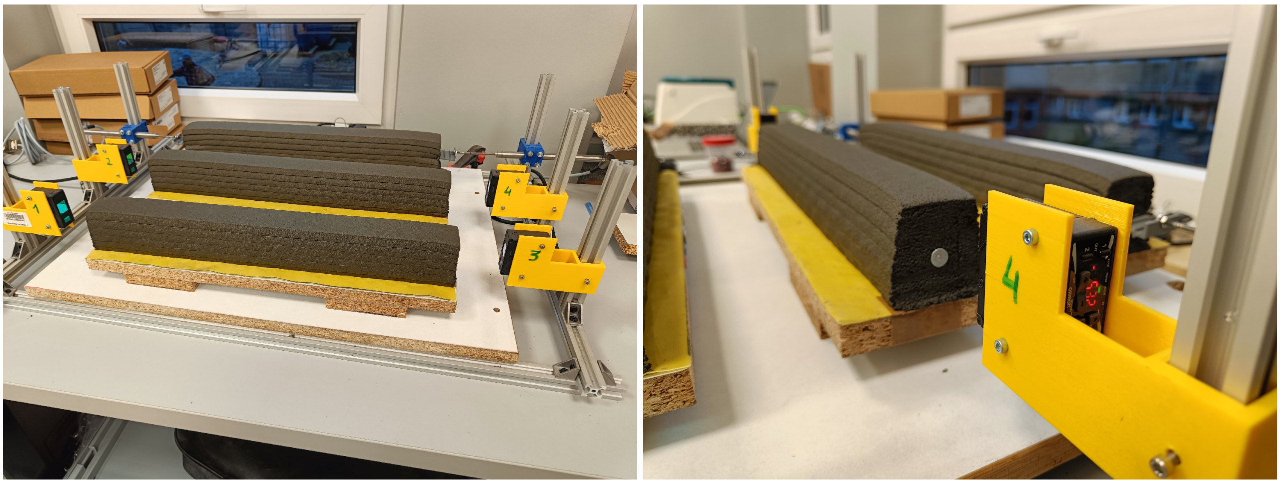

Fig. 3. Measuring shrinkage of 3D printed samples: measuring setup (left); sample with a reference point for laser measurement (right)

RH – relative humidity of the environment in %,
RH_0 – reference value equal to 100%.

$$\beta_{\text{ds}}(t,t_s) = \frac{(t-t_s)}{t-t_s+0.04\sqrt{h_0^3}}, \tag{5}$$

where
t – age of the concrete at the considered moment in days,
t_s – age of the concrete at the start of the drying process in days,
h_0 – characteristic cross-sectional dimension equal to $2A_c/u$,
A_c – cross-sectional area of the element in mm^2,
u – perimeter of the cross-section exposed to drying in mm.
Autogenous shrinkage strain is given by equation (6):

$$\varepsilon_{\text{ca}}(t) = \varepsilon_{\text{ca}}(\infty)\cdot\beta_{\text{as}}(t), \tag{6}$$

$$\varepsilon_{\text{ca}}(\infty) = 2.5\,(f_{\text{ck}}-10), \tag{7}$$

$$\beta_{\text{as}}(t) = 1-\exp\left(-0.2t^{0,5}\right), \tag{8}$$

where
$\varepsilon_{\text{ca}}(\infty)$ – nominal value of autogenous shrinkage in µm/m,
$\beta_{as}(t)$ – time-dependent shape coefficient,
f_{ck} – f_{cm}–8 MPa, where f_{cm} is the mean compressive strength,
t – age of concrete in a given time in days.
The B4 model, recommended by the RILEM organization, has minor limitations when used to estimate total shrinkage. The concrete should have a compressive strength, determined at 28 days on cylindrical specimens, in the range of 15 to 70 MPa. Additionally, the cement content should be between 200 and 1500 kg/m^3, w/c ranged 0.22 to 0.87, and a/c between 1.0 and 13.2. Importantly, the model authors allow its application to mixtures that fall outside these boundary conditions, while noting that this may negatively affect prediction accuracy. In the analytical model recommended by RILEM, the total strain of concrete should be determined according to the following equation:

$$\epsilon(t) = (t,t')\sigma + \epsilon_{\text{sh}}(t,t_0) + \epsilon_{\text{au}}(t,t_0) + \alpha_T\Delta T(t). \tag{9}$$

Since the printed specimens were not subjected to any external load during the measurements ($\sigma = 0$), and a constant temperature was maintained stable ($\Delta T(t) = 0$), equation (9) takes the following form:

$$\epsilon(t) = \epsilon_{\text{sh}}(t,t_0) + \epsilon_{\text{au}}(t,t_0), \tag{10}$$

where
$\epsilon(t)$ – total shrinkage,
$\epsilon_{\text{sh}}(t,t_0)$ – drying shrinkage at time t,
$\epsilon_{\text{au}}(t,t_0)$ – autogenous shrinkage at time t.
Drying shrinkage in the analyzed model should be determined according to the following equation:

$$\epsilon_{\text{sh}}(t,t_0) = \epsilon_{\text{sh},\infty}(t_0)k_h\tanh\left(\frac{t-t_0}{\tau_{\text{sh}}}\right)^p, \tag{11}$$

where
$\epsilon_{\text{sh},\infty}(t_0)$ – final drying shrinkage,
k_h – relative humidity factor,
p – fixed coefficient equal 0.5,
t – concrete age in days,
t_0 – concrete age in days at the beginning of drying,
τ_{sh} – shrinkage half-time.
Since the printed specimens were exposed to drying from the very beginning, $t_0 = 0$. The relative humidity coefficient should be determined according to (12):

$$k_h = \begin{cases} 1-h^3 & \text{for } h \le 0.98, \\ -0.2 & \text{for } h = 1, \\ 12.94(1-h)-0.2 & \text{for } 0.98 \le h \le 1.0, \end{cases} \tag{12}$$

where h – relative humidity of air [–].

The coefficient τ_{sh} accounts for the influence of the mixture composition and the specimen geometry on drying shrinkage, in accordance with (13):

$$\tau_{\text{sh}} = \tau_0 k_{\tau a}\left(k_s\frac{D}{1\text{ mm}}\right)^2, \tag{13}$$

where
τ_0 – the coefficient of the basic drying shrinkage value is defined by equation (14),
$k_{\tau a}$ – coefficient dependent on the type of aggregate,
k_s – shape coefficient, for prismatic specimens $k_s = 1.25$,
D – effective size of the specimen.

$$\tau_0 = \tau_{\text{cem}}\left(\frac{a/c}{6}\right)^{p_{\tau a}}\left(\frac{w/c}{0.38}\right)^{p_{\tau w}}\left(\frac{6.5c}{\rho}\right)^{p_{\tau c}}, \tag{14}$$

where
τ_{cem}, $p_{\tau a}$, $p_{\tau w}$, $p_{\tau c}$ – coefficients dependent on the type of cement used,
a – aggregate content in the mix, in kg/m^3,
c – cement content in the mix, in kg/m^3,
w – water content in the mix, in kg/m^3,
ρ – bulk density of concrete in kg/m^3.

The final drying shrinkage, $\varepsilon_{\text{sh},\infty}(t_0)$, considering the effect of aging on elastic stiffness, should be determined using equation (15):

$$\epsilon_{\text{sh},\infty}(t_0) = -\epsilon_0 k_{\epsilon a}\frac{E(7\beta_{Th}+600\beta_{Ts})}{E(t_0+\tau_{\text{sh}}\beta_{Ts})}, \tag{15}$$

where
ϵ_0 – basic shrinkage value,
$k_{\epsilon a}$ – aggregate factor, for natural sand $k_{\epsilon a} = 0.71$,
β_{Th}, β_{Ts} – correction coefficients accounting for ambient temperature variation, in the presented tests $\beta_{Th} = \beta_{Ts} = 1$,
$E(t)$ – modulus of elasticity of concrete at t days, calculated as $E(28)\left(\frac{t}{4+0.85t}\right)^{0.5}$.

The basic shrinkage value can be determined using (16):

$$\epsilon_0 = \epsilon_{\text{cem}}\left(\frac{a/c}{6}\right)^{p_{\epsilon a}}\left(\frac{w/c}{0.38}\right)^{p_{\epsilon w}}\left(\frac{6.5c}{\rho}\right)^{p_{\epsilon c}}, \tag{16}$$

where ϵ_{cem}, $p_{\epsilon a}$, $p_{\epsilon w}$, $p_{\epsilon c}$ – coefficients dependent on the type of cement used.

Autogenous shrinkage in the B4 model should be determined according to (17):

$$\epsilon_{\text{au}}(t,t_0) = \epsilon_{\text{au}\infty}\left[1+\left(\frac{\tau_{\text{au}}}{t+t_0}\right)^{\alpha}\right]^{r_t}, \tag{17}$$

where
$\epsilon_{\text{au}\infty}$ – final autogenous shrinkage,
τ_{au} – autogenous shrinkage halftime $\tau_{\text{au}} = \tau_{\text{au,cem}}\left(\frac{w/c}{0.38}\right)^{r_{\tau w}}$,
$\tau_{\text{au,cem}}$, $r_{\tau w}$ – coefficients dependent on the type of cement used,
α – auxiliary parameter $\alpha = r_\alpha\left(\frac{w/c}{0.38}\right)$,
r_α, r_t – coefficients dependent on the type of cement used, $r_\alpha = 1.4$ and $r_t = 4.5$.

The final autogenous shrinkage can be determined according to (18):

$$\epsilon_{\text{au}\infty} = \epsilon_{\text{au,cem}}\left(\frac{a/c}{6}\right)^{r_{\epsilon a}}\left(\frac{w/c}{0.38}\right)^{r_{\epsilon w}}, \tag{18}$$

where $\epsilon_{\text{au,cem}}$, $r_{\epsilon a}$, $r_{\epsilon w}$ – coefficients dependent on the type of cement used.

The ACI 209-92 model (ACI92) is widely used in North American and Asian countries. Its main advantages are the simplicity of calculations, the minimal amount of required input data, and its broad applicability. Its limitations are related to the cement content (between 279 kg/m^3 and 446 kg/m^3), the ambient relative humidity (above 40%), the type of cement used (type N or R), and a minimum curing period of 24 hours, similar to EC2. Additionally, the ACI model estimates shrinkage exclusively as a total strain, without distinguishing between drying and autogenous components, which limits its ability to reflect the complex early-age mechanisms governing shrinkage in 3D-printed concrete. Another important limitation is that the influence of specimen geometry is incorporated through a simplified surface-area-to-volume ratio, which was originally calibrated for conventional cast specimens and does not adequately capture the highly exposed and slender geometries typical of additively manufactured elements. Moreover, although the model formulation includes several correction factors, many of them are recommended to be taken as equal to unity in practical applications, which further restricts the model flexibility when applied outside its original range of validity. For the investigated printing mix, three out of the four main assumptions are not met, which inevitably affects the predictions. Nevertheless, the model was included in the analyses to quantify the extent of mismatch of the unmodified formulation and to assess the effectiveness of the parameter recalibration for this case.

In the analytical model recommended by the ACI organization, the total shrinkage-induced strain of concrete should be determined according to (19):

$$\varepsilon_{\text{sh}}(t,t_c) = \frac{(t-t_c)^{\alpha}}{f+(t-t_c)^{\alpha}}\varepsilon_{\text{shu}}, \tag{19}$$

where
$\varepsilon_{\text{sh}}(t,t_c)$ – total concrete shrinkage,
t – concrete age,
t_c – concrete age at the onset of drying,
α – specimen size coefficient, recommended value $\alpha = 1.0$,
f – specimen shape coefficient,
ε_{shu} – final concrete shrinkage.

The specimen shape coefficient f, when using the SI metric system, should be determined according to the following equation:

$$f = 26\exp\left(1.42\cdot 10^{-2}\left(\frac{V}{S}\right)\right), \tag{20}$$

where
V – sample volume,
S – drying surface of the sample.

The final shrinkage value ε_{shu} should be determined according to (21):

$$\varepsilon_{\text{shu}} = 780\gamma_{\text{sh}}\cdot 10^{-6}, \tag{21}$$

where γ_{sh} – the combined correction coefficient determined according to (22).

$$\gamma_{\text{sh}} = \gamma_{\text{sh,tc}}\gamma_{\text{sh,RH}}\gamma_{\text{sh,vs}}\gamma_{\text{sh,s}}\gamma_{\text{sh},\psi}\gamma_{\text{sh,c}}\gamma_{\text{sh},\alpha}, \tag{22}$$

where
$\gamma_{\text{sh,tc}}$ – coefficient accounting for the duration of curing,
$\gamma_{\text{sh,RH}}$ – coefficient accounting for the ambient relative humidity,
$\gamma_{\text{sh,vs}}$ – effective specimen size coefficient,
$\gamma_{\text{sh,s}}$ – coefficient accounting for the concrete consistency,
$\gamma_{\text{sh},\psi}$ – coefficient accounting for the percentage content of fine aggregate in the total aggregate,
$\gamma_{\text{sh,c}}$ – coefficient accounting for the cement content in the mix,
$\gamma_{\text{sh},\alpha}$ – coefficient accounting for the air entrainment of the mix.

In this study, the coefficients for the nonlinear concrete shrinkage models were estimated based on measurements of total and autogenous shrinkage. The estimation was performed using MATLAB (Curve Fitting Toolbox) with the Levenberg-Marquardt method. This method is a hybrid of the Gauss-Newton and steepest descent methods.

2.3. Regression model

The model fitting procedure operates iteratively using a nonlinear least squares method:

- It computes the model function values for the current parameters.
- It calculates the fitting error.
- It adjusts the parameters to minimize this error.

As a stopping criterion, the procedure terminates when either the change in parameter values or the objective function is less than 10[207B?]^3, or when the maximum number of iterations, set to 100, is reached. Physically meaningful constraints were applied to the estimated parameters (e.g., nonnegative time constants), and the search space was restricted to a maximum of 15 times the nominal parameter values.

For the equation describing drying shrinkage in the EC2 model, two coefficients were adopted for estimation. In equations (3) and (5), the following coefficients were introduced for estimation: $b1$ and $b2$. Additionally, in equations (7) and (8), which describe autogenous shrinkage, two coefficients were adopted for estimation: $b3$ and $b4$.

$$\varepsilon_{\mathrm{cd},0} = b1\,(220+110\alpha_{ds1})\exp\left(-\alpha_{ds2}\frac{f_{cm}}{f_{cm0}}\right)\beta_{RH}\cdot 10^{-6}, \quad (3b)$$

$$\beta_{\mathrm{ds}}(t,t_s) = \frac{(t-t_s)}{t-t_s+b2h_0^{1.5}}, \quad (5b)$$

$$\varepsilon_{\mathrm{ca}}(\infty) = b3\,(f_{\mathrm{ck}}-10)\cdot 10^{-6}, \quad (7b)$$

$$\beta_{\mathrm{as}}(t) = 1-\exp\left(-b4t^{0.5}\right). \quad (8b)$$

The coefficients $b1$ and $b3$ define the nominal value for drying and autogenous shrinkage, respectively. Meanwhile, $b2$ and $b4$ shape the shrinkage progression as a function of time.

For the RILEM B4 model, four coefficients were adopted for estimation. In (11), which describes drying shrinkage, two coefficients were estimated: $c1$ and $c2$. Additionally, in (17), which describes autogenous shrinkage, two coefficients were estimated: $c3$ and $c4$.

$$\epsilon_{\mathrm{sh}}(t,t_0) = c1\tan h\left(\frac{t-t_0}{c2}\right)^{0.5}, \quad (23b)$$

$$c1 = \epsilon_{\mathrm{sh},\infty}(t_0)k_h,$$

$$c2 = \tau_{\mathrm{sh}},$$

$$\epsilon_{\mathrm{au}}(t,t_0) = c3\left[1+\left(\frac{c4}{t+t_0}\right)^{\alpha}\right]^{r_t}, \quad (24b)$$

$$c3 = \epsilon_{\mathrm{au}\infty},$$

$$c4 = \tau_{\mathrm{au}}.$$

For the ACI model, two coefficients were adopted for estimation. In [19], which describes total shrinkage, the coefficients estimated were $d1$ and $d2$.

$$\varepsilon_{\mathrm{sh}}(t,t_c) = \frac{(t-t_c)^{\alpha}}{d1+(t-t_c)^{\alpha}}d2, \quad (25b)$$

$$d1 = f,$$

$$d2 = \varepsilon_{\mathrm{shu}}.$$

After performing the estimation, the quality of the model fit to the measurement data was evaluated based on the coefficient of determination, R^2:

$$R^2 = 1-\frac{\sum\left(\varepsilon_{\mathrm{cs}}(t_i)_m-\varepsilon_{\mathrm{cs}}(t_i)_{\mathrm{reg}}\right)^2}{\sum\left(\varepsilon_{\mathrm{cs}}(t_i)_m-\overline{\varepsilon_{\mathrm{cs}}}(t_i)_m\right)^2}, \quad (23)$$

where
$\varepsilon_{\mathrm{cs}}(t_i)_m$ – total shrinkage values obtained from measurements for successive times t_i,
$\overline{\varepsilon_{\mathrm{cs}}}(t_i)_m$ – average total shrinkage value for the measurements,
$\varepsilon_{\mathrm{cs}}(t_i)_{\mathrm{reg}}$ – total shrinkage values obtained from the regression model for times t_i.

3. RESULTS

3.1. Shrinkage measurement and concrete properties

As a control test, shrinkage measurements were conducted using the linear shrinkage test (LST), based on the EN 12390-16 method [24], which serves as the basis for the currently applicable standardized measurement procedures. Traditionally cast specimens with dimensions of $40\times 40\times 160$ mm were used in the test. The testing setup and the corresponding results are presented in Fig. 4, which shows three prediction models along with the LST results labeled as "Standard". The measurement of total shrinkage (TS) of 3D-printed samples was conducted continuously for seven days, starting approximately 40 min after mixing with water. The results are presented in Fig. 5 (left). Independently, autogenous shrinkage (AS) measurements were performed; for this purpose, with the sample isolated to minimize evaporation. However, since it was necessary to install measurement points and avoid deforming the plastic samples, perfect isolation was impossible. This effect can be observed in Fig. 5 (right) between the 6th and 12th hour of measure-

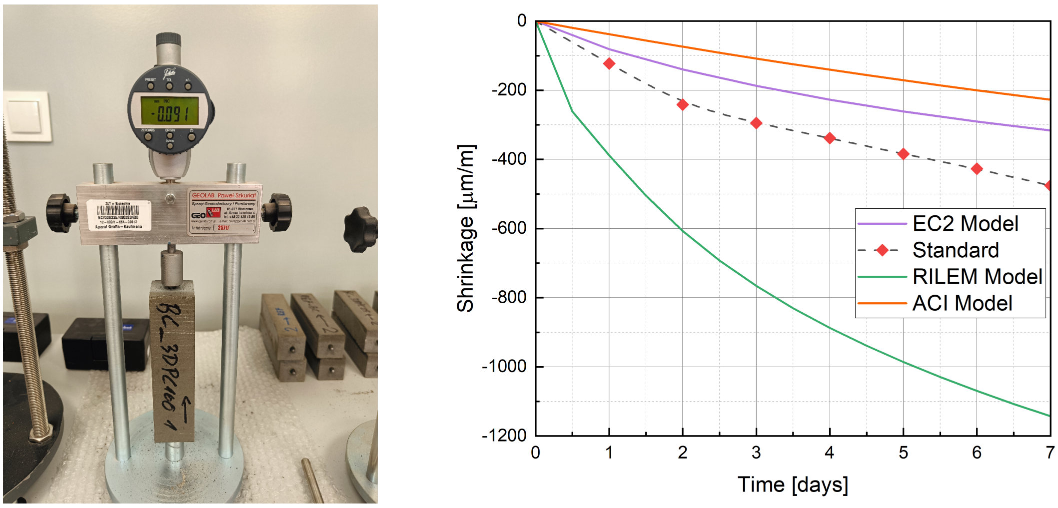

Fig. 4. Standard linear shrinkage test (LST): measuring setup (left); shrinkage evolution and comparison with model predictions (right)

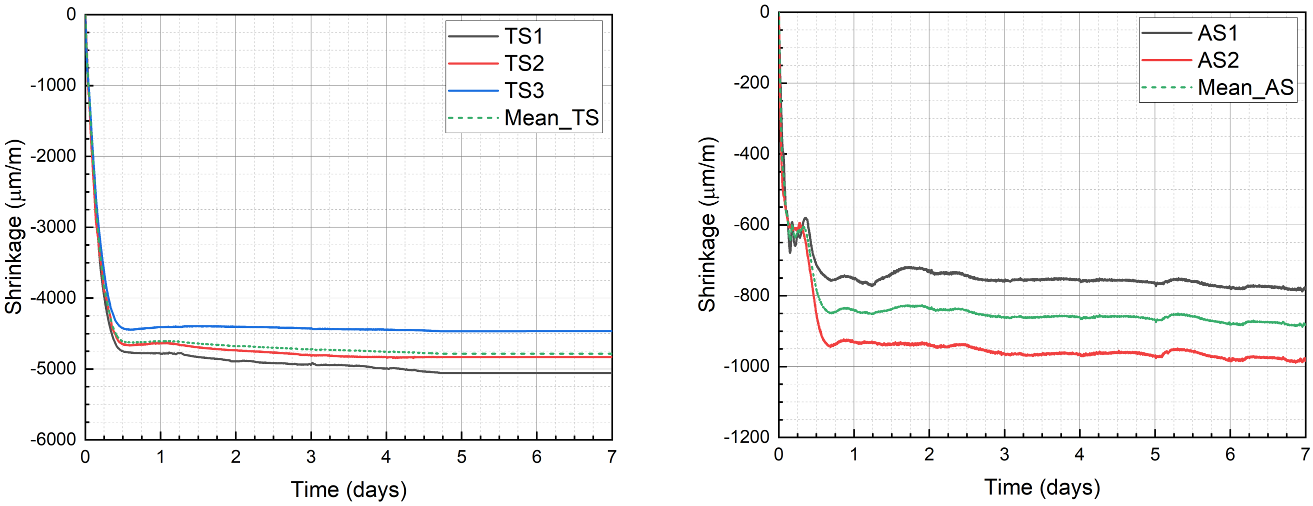

Fig. 5. Shrinkage measurement of 3D printed samples under ambient laboratory conditions ($T = 20°C$; $RH = 35\%$): total shrinkage – TS (left); autogenous shrinkage – AS (right)

ment, where deformation stabilized due to the condensation of evaporated water. All samples for shrinkage measurements were placed in one laboratory under ambient conditions of $T = 20°C$ and $RH = 35\%$. The figure highlights the rapid development of shrinkage within the first 24 h, which is not captured by standard shrinkage measurement methods.

The mean and characteristic compressive strength were also measured to determine all necessary parameters for the shrinkage estimation model. Cylindrical specimens with a diameter of 150 mm and a height of 300 mm were used for this purpose. The tested concrete exhibited a mean compressive strength of $f_{cm} = 53$ MPa after 28 days and a characteristic compressive strength of $f_{ck} = 45$ MPa, classifying it as C45/55 concrete. The modulus of elasticity, determined on 150×300 mm cylindrical specimens after 28 days, was 32.3 GPa. The characteristic cross-section was determined based on Fig. 6, which illustrates the cut specimens after testing, with markings of their cross-sectional area and perimeter exposed to drying.

3.2. Shrinkage prediction model fit

The estimated coefficient values for the EC2 model are presented in Table 2. The table includes the coefficient names and their values, the 95% confidence interval limits, standard deviations (σ), and Student's t statistics (t_{stat}). The p-values for the test verifying the significance of the coefficients in all the equations were below 0.05. Similarly, Table 3 and Table 4 present the estimation results for the RILEM and ACI models, respectively.

Table 2
Estimated coefficient values for the EC2 model

Coefficient	Mean	Confidence interval 95%		σ	t-stat
		Lower	Upper		
b1	6.16	5.66	6.66	0.25	24.21
b2	0.0004	0.0003	0.0005	0.0001	7.90
b3	11.75	2.60	20.89	4.65	2.53
b4	3.93	0.47	7.40	1.76	2.23

The p-values for all coefficients are lower than the significance level $\alpha = 0.05$ indicating that all coefficients are statistically significant. The predicted total shrinkage, determined based on the estimated parameters, is compared with the measurement data in Fig. 7 to Fig. 9. The coefficients of determination (R^2) are 0.9435, 0.9662, and 0.9447 for the EC2, RILEM, and ACI models, respectively, indicating an excellent fit of each model to the experimental data.

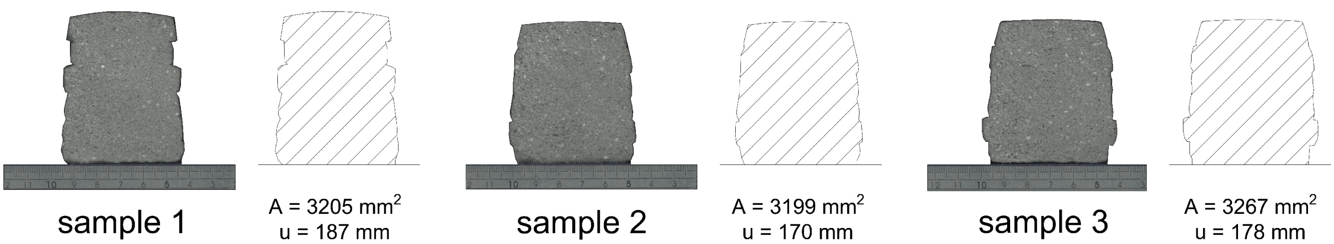

Fig. 6. Cross-section of the printed specimen after testing and definition of the exposed perimeter and area used to determine the characteristic cross-sectional dimension

Table 3
Estimated coefficient values for the RILEM model

Coefficient	Mean	Confidence interval 95%		σ	t-stat
		Lower	Upper		
c1	3850.4	3240.7	4460.1	309.97	12.42
c2	0.21	0.130	0.281	0.038	5.36
c3	899.99	295.57	1504.4	307.28	2.93
c4	0.054	0.012	0.097	0.022	2.52

Table 4
Estimated coefficient values for the ACI model

Coefficient	Mean	Confidence interval 95%		σ	t-stat
		Lower	Upper		
d1	0.083	0.082	0.083	3.26e-05	2529.62
d2	−4903.4	−4932.4	−4874.5	14.72	−333.11

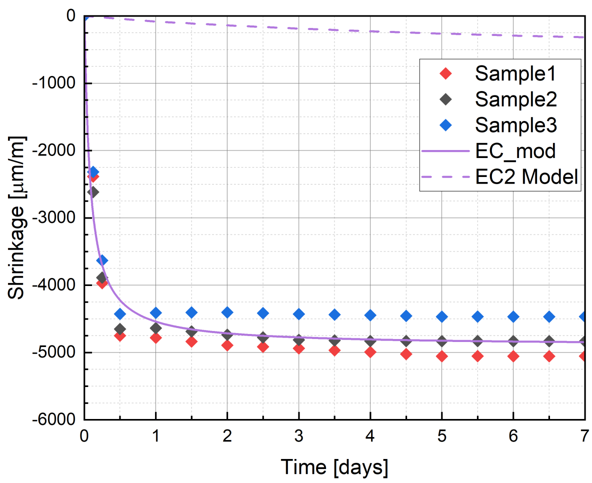

Fig. 7. Total shrinkage of 3D-printed concrete: measured data (markers) vs EC2 prediction (dashed) and recalibrated EC2 prediction (solid)

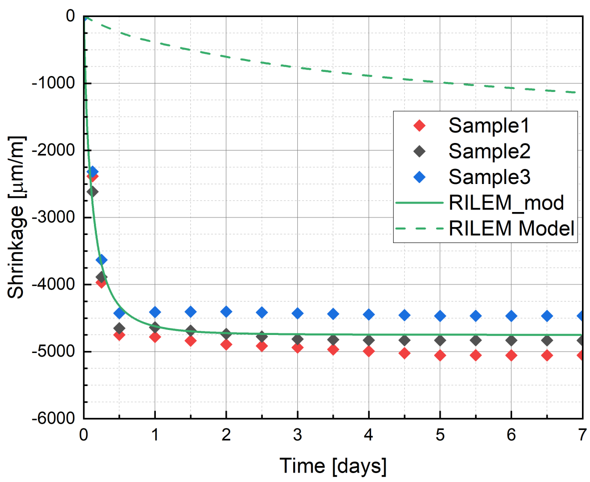

Fig. 8. Total shrinkage of 3D-printed concrete: measured data (markers) vs RILEM B4 prediction (dashed) and recalibrated RILEM B4 prediction (solid)

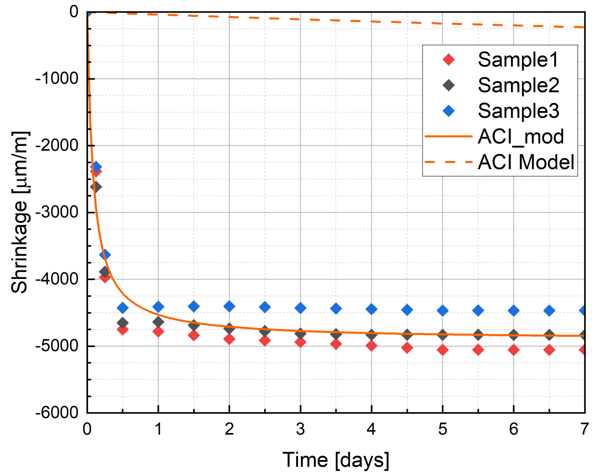

Fig. 9. Total shrinkage of 3D-printed concrete: measured data (markers) vs ACI 209-92 prediction (dashed) and recalibrated ACI 209-92 prediction (solid)

4. DISCUSSION AND CONCLUSIONS

The measurements and analyses indicate the feasibility of adapting the models for predicting shrinkage, as outlined in Eurocode 2, RILEM recommendation or ACI 209-92, to the specific characteristics of 3D-printed concrete. The coefficients of determination (R^2) of around 0.94 demonstrate that modifying the coefficients (Table 5) developed for conventional concrete can achieve remarkably high prediction accuracy. A key aspect is the adjustment of the shrinkage measurement methodology for printed elements, as standard methods such as the LST approach fail to capture the most critical changes occurring during the hardening process of 3D-printed concrete within the first 24 hours.

Table 5
Comparison of the model coefficients and their estimated values

EC2		b1	b2	b3	b4
	Model	0.85	0.04	2.5	0.2
	Estimation	6.16	0.0004	11.75	3.93
RILEM B4		c1	c2	c3	c4
	Model	−1657	20.32	−214.9	0.78
	Estimation	−3850.4	0.206	−899.99	0.055
ACI		d1	d2		
	Model	33.61	−1321		
	Estimation	0.083	−4903.4		

The coefficient estimation process for all three models demonstrated the necessity of modifying the function coefficients governing the time-dependent development of drying shrinkage (coef. $b2$, $b4$, $c2$, $c4$, and $d1$) and its nominal value, $\varepsilon_{\mathrm{cd},0}$ ($b1$, $c1$). It aligns with observations in the literature, as numerous studies (e.g., Ma *et al.* [19]) highlight significant differences in shrinkage deformations between printable and conventional concretes. Similarly, for autogenous shrinkage, the nominal value $\varepsilon_{ca}(\infty)$ (coef. $b3$ and $c3$) required estimation. It is expected to result primarily from the different binder compositions in 3D-printed concrete compared to traditional concretes, as mentioned by Zhang *et. al.* [25].

When analyzing changes in model parameters, attention should be paid to their physical significance. In the case of the EC2 model, coefficient $b1$ determines the final value of drying shrinkage. For 3D-printed concrete, many researchers have emphasized that the absence of traditional formwork leads to significantly higher evaporation rates – an effect also confirmed by parameter estimation [19, 26–28]. The value of b1 had to be increased several times, which reflects the accelerated moisture loss in printed elements.

On the other hand, a significant reduction in coefficient $b2$ can be interpreted as a necessary adjustment to the rate at which drying-induced shrinkage strains develop. The majority of these deformations occur within the first 24 hours of curing, which makes the impact of any model modification particularly noticeable. Future developments may require introducing additional coefficients that describe the evolution rate of shrinkage or more substantial revisions to the existing equation (5). However, such changes would require a broader and more diverse experimental dataset.

Quantitatively, the early-age shrinkage magnitudes reported in the literature underscore the rapid kinetics addressed by the recalibrations. DIC- and optical-sensor-based studies reported free shrinkage of approximately 2400 μm/m within 3 h [10], 1500 μm/m after 24 h, and ~ 3500 μm/m after 5 days [11], and up to 4000 μm/m after 3 h under noncuring conditions [12]. Markin and Mechtcherine reported values exceeding −9000 μm/m within 3 h [13]. In contrast, standardized measurements on cast specimens typically report markedly lower 28-day values (e.g., ~ 1600 μm/m in EN 12617-4-based testing [15] and > 700 μm/m in Le *et al*. [17]), highlighting the strong dependence of measured shrinkage on method, geometry, and exposure.

The authors of the EC2 model also recommend limiting model calibration to no more than two parameters: one controlling the final shrinkage value, and the other modifying its time-dependent evolution. This same approach was applied when modifying the autogenous shrinkage component. As previously mentioned, 3D-printed concrete differs significantly from conventional structural concrete in terms of mix proportions – particularly binder content and water-to-cement ratio [29–32]. Increased binder content combined with reduced mixing water results in substantially higher autogenous shrinkage and altered kinetics, as confirmed by the estimated b3 and b4 coefficients.

A similar interpretation applies to the B4 model, which – like EC2 – separately accounts for drying and autogenous shrinkage. The main difference lies in the role of coefficients $c2$ and $c4$, representing shrinkage half-times. As shown in Fig. 5, for 3D-printed elements, this threshold is reached within the first 8–12 hours after printing. Coefficients $c1$ and $c3$, which define the ultimate shrinkage magnitude, are affected similarly to EC2: the absence of formwork and high binder content necessitate adjustments to the nominal values.

In contrast, the ACI model does not distinguish between shrinkage components and instead estimates total shrinkage as a single value. This makes it more difficult to isolate the impact of individual parameters. In this study, attention was focused on the final shrinkage value and the geometry-related coefficient. Since d1 appears in the denominator, reducing its value increases predicted shrinkage – reflecting the pronounced effect of drying surface exposure. For 3D-printed elements, the drying surface is much larger due to the lack of formwork and slender geometries (40–50 mm print paths) [15, 19]. Because key applicability assumptions of ACI 209-92 are violated, the recalibrated coefficients should be considered case-specific.

However, it should be emphasized that the presented studies are preliminary and primarily assess the applicability of baseline formulations for additively manufactured concrete. The calibration is based on a single mixture, geometry, and ambient condition ($T = 20$°C, $RH = 35$%), with measurements up to 7 days. To achieve repeatable and universal solutions, a comprehensive database covering different geometries, compositions, and environmental conditions is required. Accordingly, further tests and supporting calculations are necessary to generalize the recommended coefficient sets and define their range of applicability.

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