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# MACROSCOPIC HYGRO-MECHANICAL MODELING OF RESTRAINED RING TEST - RESULTS FROM COST TU1404 BENCHMARK

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## Abstract

The restrained ring test under constant temperature is used for estimating cracking tendency of pastes, mortar or concrete. This test induces hygro-mechanical interactions, with intricate interplay of several phenomena such as autogenous shrinkage, drying shrinkage, basic and drying creep, as well as evolution of tensile strength and fracture energy. The benchmark described in this paper relies on extensive experimental data sets obtained through the extended Round Robin Testing programme (RRT+) of COST Action TU1404. Five teams took part with their simulation models. A series of outputs were produced, starting from mass loss of a prism through its axial deformation up to stress/strain evolution in the ring. Three teams quantified also damage due to drying and stress concentration around a ring's notch. All models showed excellent performance on mass loss while strain validation showed higher scatter and influence of several other factors. The benchmark demonstrated high capability of used models and emphasized strong role of calibration with regards to available experimental data.

## 1. INTRODUCTION

The restraint ring shrinkage test is a well-established method for testing cementitious binders for crack resistance during early ages, adopted further in e.g. ASTM C1581 or AASHTO T334. R. Carlson used the test already in 1942 [1] and a strong correlation with concrete surface cracking after 53 years was found. Several papers were published afterwards for optimizing binders and models using the ring, as shown in the review of reference [2].
COST Action TU1404 "Towards the next generation of standards for service life of cement-based materials and structures" has set up this benchmark to simulate experimental results on a reference concrete (labelled as 'OC') and to test different modelling approaches. Interested participants received input experimental data and they knew experimental results in advance in order to calibrate further their models if needed. The participants were free to use their

modelling approaches and models, however, several intermediate steps were required to validate their partial data. Five participants took part in the benchmark:

1. Arup+University of Minho, (ARUP+UMinho)
2. CTU in Prague (CTU)
3. KTH Royal Institute of Technology, Stockholm (KTH)
4. LafargeHolcim Research Center, Isle d'Abeau (LafargeHolcim)
5. Chair Pereniti-3SR Lab, Grenoble (Pereniti)

Experimental methods were defined in the documentation of the Extended Round Robin testing programme (RRT+) of COST TU1404 [3], including the restrained ring shrinkage test. Since deformation of the ring is driven dominantly by drying, the benchmark had two consecutive stages: hygro-mechanical simulation of drying prims 100×100×400 mm and hygro-mechanical simulation of the ring. Fig. 1 shows ring geometry, whereas Table 1 presents the composition of OC concrete mix used in the experiment.

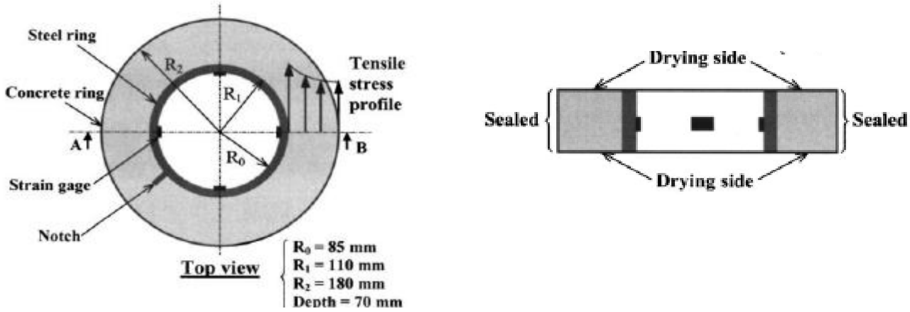

Figure 1: Geometry of the ring test

Table 1: Composition of OC concrete mix [3].

| **Basic Material** | **Type of the material** | **Amount [kg/m$^3$]** |
|---|---|---|
| **Cement** | CEM I 52.5 N-SR3 CE PM-CP2 NF HRC Gaurain | 320 |
| **Dry sand** | 0-4 mm, REC GSM LGP1 (13 % of CaO and 72 % of SiO2) | 830 |
| **Fully saturated gravel** | 4-11mm, R GSM LGP1 (rounded, containing silicate and limestone) | 449 |
| | 8-16 mm, R Balloy (rounded, containing silicate and limestone) | 564 |
| **Admixtures** | Plasticizer SIKAPLAST Techno 80 | 1.44 |
| **Added water** | Water that needs to be added to the mixer | 172.4 |
| **$w_{eff}$/c** | | 0.52 |

## 2. DESCRIPTION OF MODELS USED BY PARTICIPANTS

Participants used different governing equations and constitutive models for hygro-mechanical coupled simulations, as shown in Table 2. Four models for moisture transport were based on single-phase balance equations with humidity or moisture field as the unknowns. The KTH model used mass balance of a gas-phase and a liquid-phase based on the thermodynamically constrained averaging theory. All moisture models used non-constant diffusivity, decreasing with lowering relative humidity. Some participants took advantage of desorption isotherm

which was known from a similar mature Vercors concrete [4] with calibrated saturation from TU1404 data. Total water content at the full saturation of mature concrete was found as 165.3 kg/m$^3$. Only KTH model considered water consumption during hydration and its effect on decreasing evaporable water content during hydration.
All participants used small strain decomposition and incremental stress-strain relationship to account for creep. The most advanced models used the following incremental constitutive law

$$\Delta\varepsilon = E''\left(\Delta\varepsilon - \Delta\varepsilon'' - \Delta\varepsilon_{as} - \Delta\varepsilon_{ds} - \Delta\varepsilon_{f}\right) \tag{1}$$

where $\varepsilon_{as}$ is the autogenous shrinkage strain, $\varepsilon_{ds}$ is the drying shrinkage strain and $\varepsilon_f$ stands for fracturing strain. Except KTH, the participants assumed linear relation between drying shrinkage strain rate and relative humidity/moisture rate using a shrinkage factor. Four participants used fracture material model for crack initiation and propagation, usually in the framework of isotropic damage model.

Table 2: Summary of used equations, material models, software and computation times.

| | **Arup+UMinho** | **CTU** | **KTH** | **LafargeHolcim** | **Pereniti** |
|---|---|---|---|---|---|
| Equation for moisture transport | Humidity balance, h | Humidity balance, h | Gas-phase and liquid-phase, water, dry air | Water balance, w | Water balance, w |
| Material model for creep | Double-power law | Calibrated B3/B4 | Calibrated B3 with MPS theory | Two ageing Kelvin units | Burger model |
| Material model for fracture | Multidirectional fixed crack model | Isotropic damage model | Isotropic damage model | - | Stochastic isotropic damage model |
| Software | iDiana, Diana, Matlab | OOFEM | COMSOL | Aster | Aster |
| Computation time - prism | 20 min | 8 min | 3.5 min | 2 min | 3.5 min |
| Computation time - ring | 20 min | 20 min | 10 min | 5 min | 21 min |

## 3. RESULTS AND DISCUSSION

### 3.1 PRISM

The first part considered simulation of a prism 100×100×400 mm which started drying at 50 % RH after 1 day of sealed hydration. For this test, the mass loss in Fig. 2 and the total strain in Fig. 4 were measured in RRT+. Total strain is used for the identification of the parameter managing the moisture transport (through the measurement of mass loss) and for the shrinkage coefficient in models using linear relation between the moisture rate and the drying strain.
Drying shrinkage tests were held for 22 days and the asymptotic value at very long time was deduced from tests performed on smaller 70×70×280 mm specimens for which the hydric

equilibrium is reached faster (-450 με and 89.2 kg/m$^3$ of water loss for drying shrinkage at 50%RH and –50 με for autogenous shrinkage) [3].

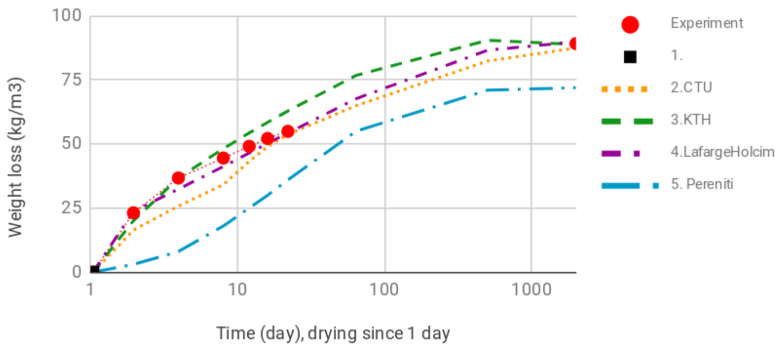

Figure 2: Weight loss of a prism 100×100×400 mm.

Fig. 3 shows models calibration to E-modulus and basic creep at t'=1 day. It is noted that the team of Arup+UMinho have used data for E-modulus from a distinct source within the RRT (data from EMM-ARM method measured at UMinho on the same concrete). Fig. 4 then provides the simulated total shrinkage (autogenous and drying) on the axis of the prism. It can be seen that the identification of the shrinkage models allows a good reproduction of the results.  Criteria for fracture initiation used splitting tensile strength 1.4 MPa at 2 days, 3.5 MPa at 7 days and 4.5 MPa at 28 days.

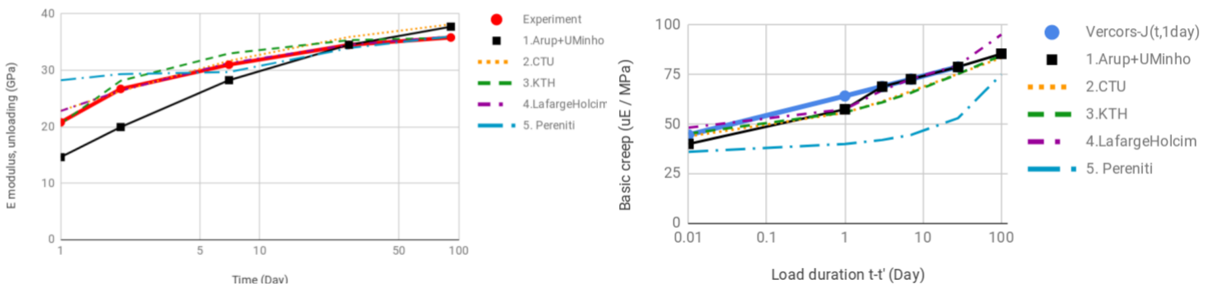

Figure 3: Calibration for E modulus and basic creep at t'=1 day.

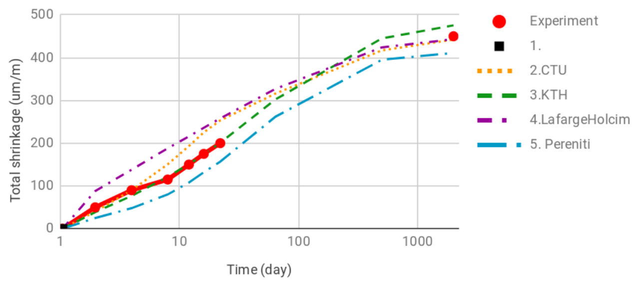

Figure 4: Total shrinkage on prism's axis.

### 3.2 RING

Once the drying kinetics were validated on the prism, simulation of ring test took place using the same constitutive laws for moisture transport. All participants used a 3D model except

LafargeHolcim who used axisymmetric model without any damage. Fig. 5 shows meshes in hygro-mechanical models.

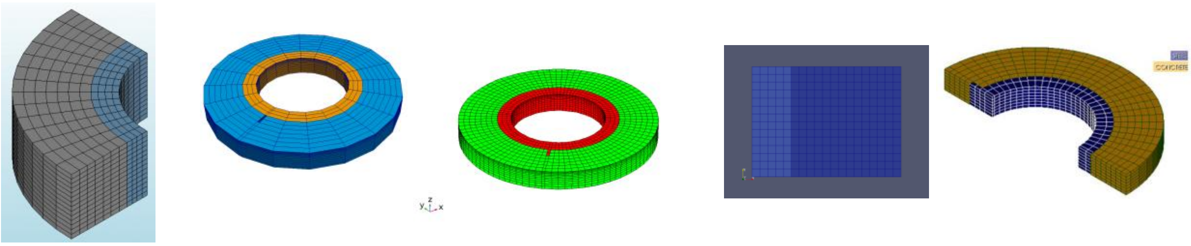

Figure 5: Meshes used in hygro-mechanical simulations of the ring.

First, the models validated steel strain, as shown Fig. 6. Except for the results from Pereniti, where strain localization occurs earlier than observed in the selected reference ring test, the participants have all simulated the experimentally measured strain rather well up to the maximum strain. Damage occurs immediately after the drying on dried horizontal surfaces up to a few mm, further damage occurs after approximately 10 days around steel, breaking up standard linear creep law. This is probably the main cause of slow strain decrease after the strain peak at 70 με at 50 days.

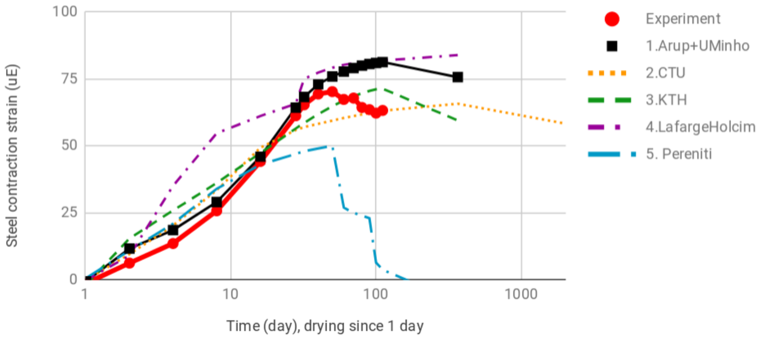


Figure 6: Validation of hoop steel strain.

Two material points are interesting for stress evolution; proximal point close to steel ring and distal point close to vertical exterior. Hoop stresses testify non-constant stress distribution across the ring as known even from analytical elastic solution [2]. Models provided blind prediction which is summarized in Fig. 7. The notch in the ring created small stress concentration but, due to stress gradient, it did not propagate to a visible crack even after experimental 111 days (except in the case of Pereniti team where visible cracks are obtained within 51 days). Fig. 8 shows non-validated and blind weight loss predictions of the ring.

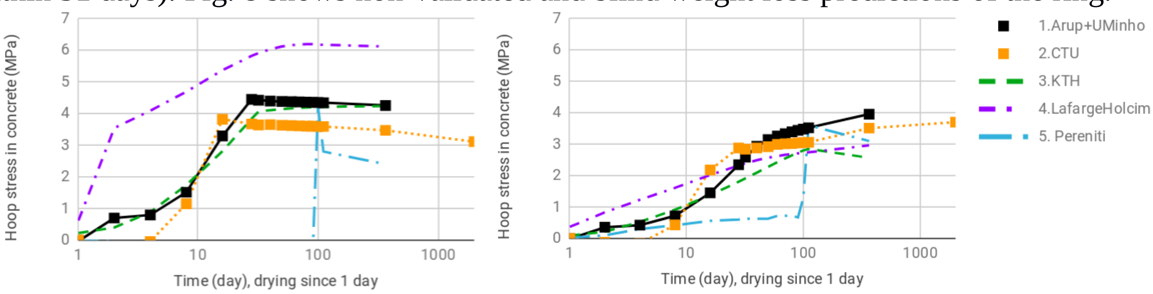


Figure 7: Proximal and distal hoop stress in concrete, blind prediction.

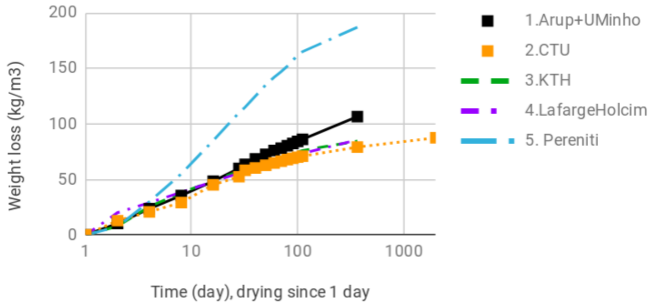


Figure 8: Blind prediction of ring's weight loss.

## 4. CONCLUSIONS

This benchmark extensively used available experimental data generated in the RRT+ programme of COST Action TU1404. Selection of feasible and reasonable data was a prerequisite for successful macroscopic validation of the ring test. The results from five participants showed:

- Drying shrinkage presents the main driving strain and mass loss needs validation. Data on prisms 100×100×400 mm with asymptotic values served for this purpose.
- Ageing creep with correct evolution of E-modulus represents sensitive constitutive law for stress evolution, damage and potential macro-crack formation.
- Hygro-mechanical models performed generally well. Nonlinear creep occurring close to tensile strength would likely improve strain evolution after its maximum. The variability of results is both due to calibration on limited data sets and models' limitations.

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