CONCRETE BEHAVIOR UNDER TRIAXIAL LOAD: EXPERIMENTATION AND IMPROVEMENT OF A DAMAGE AND PLASTICITY CONSTITUTIVE MODEL FOR CONCRETE

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Abstract: The upcoming need of concrete structures designed against impulsive and extreme load due to natural hazards, industrial accidents or terrorists attack requires analytical modeling capable of reproducing material behavior in this range of loading. When a concrete structure is submitted to an impact or an explosion loading, material may be submitted to high triaxial compression stresses as well as tensile stresses due to reflection of compressive waves on free surfaces. Furthermore, the water saturation degree in massive concrete structures may be nearly 100% at core whereas the material is dry on the skin. Thus, the impact response of a massive concrete wall may depend on the water saturation state in the material. This paper first presents some triaxial tests performed at a maximum confining pressure of 100 MPa on a concrete representative of a containment building of a nuclear power plant. Experimental results show the constitutive behavior and its dependence to the water saturation ratio of concrete specimens. The second part of this study aims at modeling these tests by means of the coupled PRM constitutive model. Although its robustness and effectiveness, this constitutive model did not allow to accurately reproduce the response of concrete specimens observed during the tests. The differences between experimental and numerical results can be explained by both the influence of the saturation state of concrete and the effect of deviatoric stresses which are not well taken into account into the PRM model. Some modifications of the PRM model were carried out; they allow improving the numerical prediction of concrete behavior under high triaxial stresses and various saturation states.

1 INTRODUCTION

Concrete is the most used material for the construction of civil engineering structures and buildings, including sensitive infrastructures. The concrete protection structures, such as the containment walls of nuclear reactors, are generally massive and remain saturated at core several years after the casting, while their skin surfaces in contact with air dry quickly. When these concrete structures are submitted to a missile impact, for instance due to the fall of an aircraft turbine, triaxial stresses characterized by a high mean stress are generated in the impact zone. The high loading capacity triaxial press GIGA allows testing concrete samples under various loading paths and various concrete compositions [1-6]. The behavior of wet concrete under this kind of loading may be very different from dry one [4]. Quantifying the influence of water content on the behavior of concrete is therefore essential to analyze the vulnerability of the massive concrete structures.

In this paper, triaxial tests up to 100 MPa of confinement will be presented and analyzed. Some results of test carried out at very high confinement (600 MPa) will also be presented for clarifying the effect of saturation ratio. These tests were simulated with the coupled damage plasticity model PRM [7]. Necessary changes of this model to obtain a better prediction will be presented and the influence of these changes will be highlighted by comparing the two versions of the model and experimental results.

2 TRIAXIAL TESTS

2.1 Experimental device

The GIGA press (figure 1) was designed to study the behavior of concrete under high confinement in a partnership between the 3SR laboratory and the CEA Gramat. It allows testing cylindrical concrete specimens under triaxial compression at a maximum confining pressure of 0.85 GPa and a maximum axial stress of 2.3 GPa [1-6].

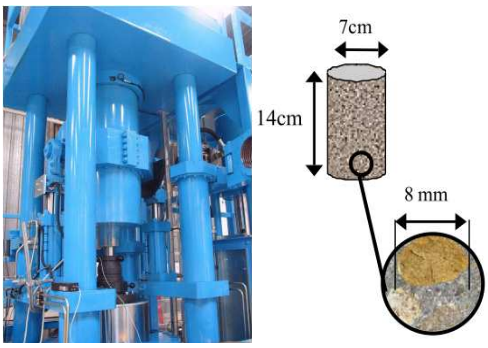

Figure 1: GIGA device and specimen dimensions

2.2 Composition of concrete

The studied high performance concrete was used in the benchmark project “Improving the Robustness of Assessment Methodologies for Structures Impacted by Missiles (IRIS)” of the Nuclear Energy Agency (NEA) of OECD [8]. Concrete samples were manufactured by VTT Finnish laboratory for the IRIS project. The composition and properties of VTT concrete are given in Table 1.

Table 1: Composition and properties of VTT concrete

Gravel (0.5/8) (kg/m^3)	925.9
Sand (kg/m^3)	646.1
Water (kg/m^3)	215
Cement (CEM II B 42.5) (kg/m^3)	489
Fly ash (kg/m^3)	88
Water-reducing agent (kg/m^3)	6.33
Cement paste volume (m^3)	0.375
Density (kg/m^3)	2370
Compressive strength (MPa)	67
Porosity accessible to water (%)	12%
Cement paste volume (m^3)	0.375
E/C ratio	0.44

2.3 Experimental results

The concrete used in this study is representative of the containment of a nuclear power plant. Its strengths under unconfined compression and tension are about 67 MPa and 4.5 MPa respectively. The samples were tested under triaxial confining pressure varying from 15 MPa to 100 MPa. The porosity and the degree of saturation were measured prior to testing. The degree of saturation of concrete in the first series of tests is about 60%.

The performed triaxial tests consist in applying a hydrostatic pressure all around the specimen at 0.5 MPa/s up to pressure value p_{conf}. A constant displacement rate of 14 µm/s of the axial jack and a constant confining pressure p_{conf} on the lateral face are then imposed.

Figure 2 shows the evolutions of the axial stress in function of the axial and circumferential strains for different confining pressures p_{conf}, the circumferential strain is the average measure of two gauges. The axial strain is obtained by means of an axial gauge and compared to the strain given by a LVDT sensor. These two measurements of the axial strain gave similar results indicating that the samples deform homogeneously. Figure 3 shows the volumetric behavior of concrete during the triaxial tests.

The analysis of tests highlights that stiffness and strength increase with confinement. This phenomenon is explained by the irreversible closure of porosity (compaction) with the mean stress increase. It is worth noting that with a confinement pressure less than 50 MPa, there is a stress peak in the axial behavior, while this phenomenon is not observed for the test at 100 MPa of confinement. At this confinement level, the reached limit state corresponds to a transition from contraction to dilatancy with no softening (figure 3).

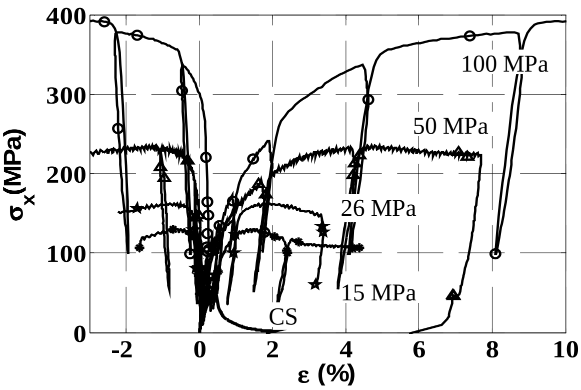

Figure 2: Axial stress vs. axial and circumferential strains for various confining pressures

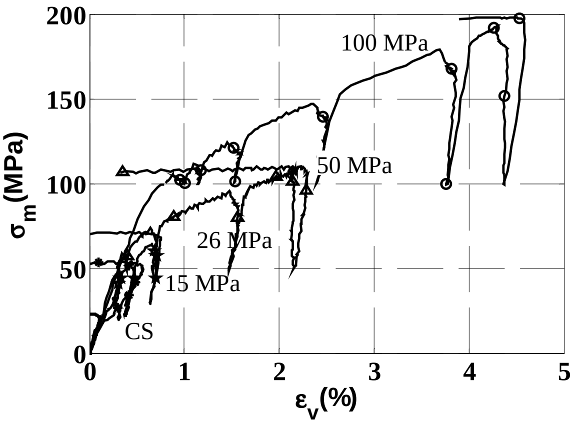

Figure 3. Mean stress vs. volumetric strain for various confining pressures

2.4 Influence of saturation ratio on concrete behavior at moderate and high confining pressures

A second triaxial test at 50 MPa of confinement has been performed on a saturated concrete specimen to study the influence of the saturation ratio (*Sr*). The procedure for testing saturated samples is described in [4]. The axial strain is measured by the LVDT sensor only. Figure 4 shows a comparison between the evolution of the axial stress as a function of axial strain obtained in this second test (*Sr* = 100%) and the one obtained on a wet concrete (*Sr* = 60%) at 50 MPa of confinement. The maximum axial stress is about 240 MPa in the two tests. This result is in agreement with the one obtained on a standard concrete [4]. Thus, the saturation ratio seems to have a low influence on the triaxial behavior of the tested high performance concrete at moderate confining pressures.

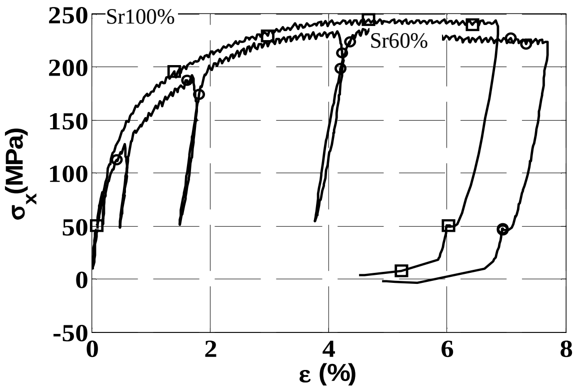

Figure 4: Comparison of axial behavior at 50 MPa of confining pressure for two different saturation ratios of concrete specimens

Because concrete may be submitted to very high triaxial stresses in case of impact, some additional triaxial tests were performed at high confining pressure.

Figure 5 shows the comparison between two hydrostatic tests at high confinement with different saturation ratios.

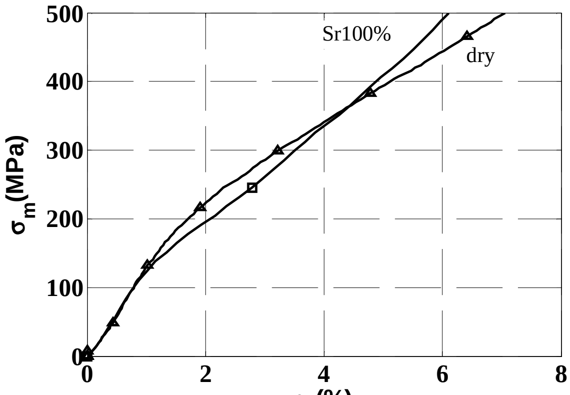

Figure 5. Hydrostatic behavior of concrete for two different degrees of saturation

The two curves on figure 5 are confounded at a mean stress lower than 100 MPa, this zone corresponds to the elastic behavior of VTT concrete. Beyond this zone, the closure of porosity of concrete begins. Due to the important volume of paste cement (Table 1), the influence of creep may be important and strongly dependent on the saturation ratio [9]. That explains why the volumetric deformation of saturated concrete is higher than one of dried concrete when the porosity of concrete begins to be enclosed. But at high mean stress, water is compressed and because the compressibility of water is higher than the one of air, the volumetric deformation of saturated concrete is lower than the one of dried concrete (figure 5) at high mean stress.

2.5 Limit state of VTT concrete under triaxial compression

The material limit state is defined as the maximum volumetric strain reached during a test; it corresponds to a transition from a contraction behavior to a dilatancy one. At moderate confinement, this transition also corresponds to the peak stress. Figure 6 shows the limit states in the deviatoric stress / mean stress plane for the various tests described earlier.

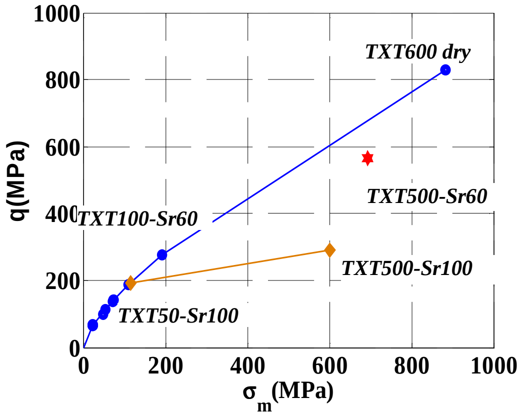

Figure 6. Limit states of concrete for the different tests: maximal deviatoric stress vs. mean stress.

On figure 6, it can be noted that, for a given mean stress, the maximum deviatoric stress reached during the test strongly depends on the saturation ratio of the concrete specimen. The presence of free water limits the admissible shear stress of concrete under confinement.

Figure 7 shows a zoom of the limit state curve of wet concrete at moderate confinement.

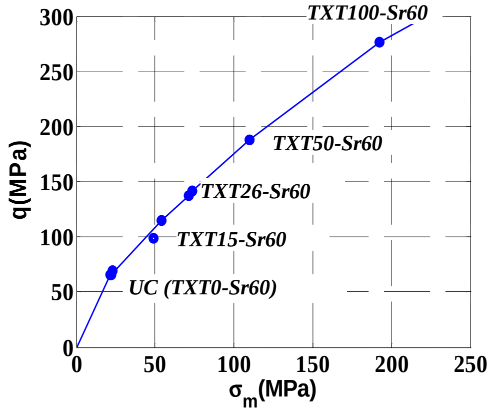

Figure 7. Zoom of figure 6 at low mean stress

For a moderate confining pressure (lower than 50MPa), the influence of free water on concrete behavior seems to be low, whereas the influence of the saturation degree is significant for a confinement pressure of the order of 500MPa. This difference may have an important effect on the response of a concrete structure submitted to an impact and should be taken into account in simulations.

3 MODELING TRIAXIAL BEHAVIOR OF CONCRETE

3.1 General description of PRM coupled model

PRM coupled model was developed by Pontiroli, Rouquand and Mazars [7], in order to simulate computational problems of structures subjected to impact or blast effects. This model is the result of a coupling between an elastic-damageable model [10] and a model of plasticity initially developed for soils [11]. It includes the calculation of the effective stress defined in [12] for a wet concrete to take into account the influence of water saturation on the response of concrete. The damage model is based on two damage variables, respectively in compression and tension, in order to simulate the unilateral feature of concrete behavior at low confinement. The plasticity model can correctly reproduce the mechanism of irreversible closure of pores during the compaction. The yield limit is defined in deviatoric stress (q) / mean stress (σ_m), it is supposed to correspond to the limit state of the material discussed in the previous section.

3.2 Improvement of the model

Although the model coupled PRM allows obtaining a good prediction of concrete behavior under various load paths, some shortcomings exist and this study aims at fixing them.

Influence of the deviatoric stress into the volumetric behavior

The plasticity model assumes that inelastic volumetric and shear strains are obtained independently. The volumetric strain (ε_v) is assumed to depend on the mean stress (σ_m) only and the strain deviator tensor is obtained by means of a perfectly plastic model.

One of the shortcomings of the present PRM coupled model is that it does not take into account the effect of the deviatoric stress q on the volumetric behavior of the concrete. The present model assumes that the compaction curve, i.e. the volumetric strain (ε_v) vs. the mean stress (σ_m), as material data independent on the load path. Figure 3 shows that the inelastic volumetric strain depends on both q and σ_m. It is then necessary to include the influence of q into the compaction curve of the material (ε_v = function (σ_m, q)).

To improve the PRM model, the original idea of two models of plasticity to calculate the inelastic strains is conserved. According to the test results [1-6], it is assumed that the maximum compaction is obtained under oedometric loading path, i.e. in uniaxial strain condition. The compaction curve of an oedometric test is then added as a second input data. The interest is on the one hand, this data is easily accessible to measurement and, on the other hand, that the oedometric test is the one which maximizes the compaction of concrete because the dilatancy is prevented.

The construction of the modified model is based on the following assumptions:

The curve of volumetric behavior of concrete is not supposed to be bijective. It is instead assumed bounded by the hydrostatic curve (figure 8 - opaque upper curve) and the oedometric curve (figure 8 - dotted lower curve).

The variation of the mean stress σ_m, between the bounded curves is given by:

$$d\sigma_m = \alpha\, d\varepsilon_v \qquad (1)$$

With:

$$\alpha = \alpha_H + (\alpha_o - \alpha_H)\, Min\left[\left(\frac{\left(\frac{dq}{d\sigma_m}\right)}{\left(\frac{dq}{d\sigma_m}\right)_o}\right);1\right] \qquad (2)$$

Where (figure 8):

$\alpha_H = d\sigma_m/d\varepsilon_V$ for a hydrostatic path ;
$\alpha_O = (d\sigma_m/d\varepsilon_V)_O$ for un oedometric path ;
$dq\,/\,d\sigma_m$ = load path direction ;
$(dq/d\sigma_m)_O$ = oedometric load path direction.

With formulae (1) and (2), the volumetric strain ε_v depends on both the mean stress σ_m and the deviatoric shear stress q, the compaction is then increased in presence of shear compared with volumetric strain obtained with the initial model.

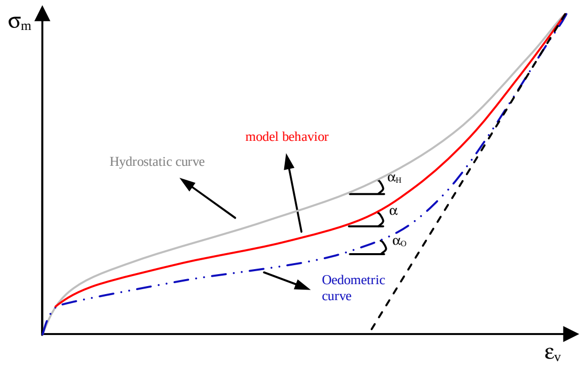

Figure 8. Hydrostatic behavior, oedometric behavior and consolidated behavior of concrete: mean stress in function of volumetric strain.

Influence of the water saturation ratio into the volumetric behavior

Two kind of approaches exist to characterize the behavior of a porous medium scale homogenized according to its properties at the microscopic level. The “mixing law” approaches take into account, at the microscopic level, the interaction between the two phases (liquid + solid) by means of simple rheological models for each phase associated in series or in parallel. Poromechanical approaches [13] assume that the concepts of mechanics in continuous media are valid at the macroscopic scale when the two phases (liquid + solid) overlap.

In the present PRM coupled model, the concept of effective stress is used to take into account the presence of water in confined concrete using the first approach. The drawback of this approach is that the behavior of the material becomes elastic after reaching the consolidation point (closure of all open pores), which is not observed experimentally. In the improved model, the second poro-mechanical approach is used to take into account the effect of free water.

The studied porous medium is assumed to be composed of a solid phase (skeleton) and a fluid phase occupying the voids [13]. The concept of the effective stress is introduced to separate the fluid pressure in the calculation of the total pressure

$$\sigma_{tot} = \sigma_M + bp \tag{3}$$

With σ_{tot} the total stress, σ_M transmitted by the matrix at a macroscopic scale, p the pore pressure, and b the Biot coefficient which depends on the nature of the porosity.

The calculation of pore pressure p is based on the Mie Gruneisen equation of state:

$$P = \frac{\rho_0 C_0^2 (\varepsilon_V - \varepsilon_{Vps})}{(1 - s(\varepsilon_V - \varepsilon_{Vps}))^2}\left[1 - \frac{\Gamma_0(\varepsilon_V - \varepsilon_{Vps})}{2}\right] + \Gamma_0 \rho_0 E_M \tag{4}$$

Where C_0 is the sound celerity (C_0 = 1500m/s), φ_0 is the density (φ_0 = 1000 kg/m^3 for water), s and Γ_0 are two Mie Gruneisen coefficients (s = 1.75 and Γ_0 = 0.28 for water). E_M is the internal energy per unit mass. This energy is considered negligible for water temperature and ambient pressure.

σ_M and b can be obtained by the following formulae [13]:

$$\sigma_M = K_0\, \varepsilon_v \tag{5}$$

$$b = 1 - \frac{K_0}{K_S} \tag{6}$$

K_0 is the modulus of the material drained ε_V is the volumetric strain at homogenized scale, K_S the compressibility modulus of the skeleton. From equation (6), in the particular case where $K_0 << K_s$, b is close to 1, which simplifies the equation (3) and becomes $\sigma_{tot} = \sigma_M + p$ (Terzaghi formula). In contrast, when $K_0 \approx K_S$ (dry concrete case), b tends to 0. In the end, thanks to the technical of homogenization of the drained porous medium [13] the ratio K_0/K_S can be estimated as follows:

$$\frac{K_0}{K_S} = (1 - \phi)^3 \tag{7}$$

Where ϕ is the porosity of the porous medium at the current state.

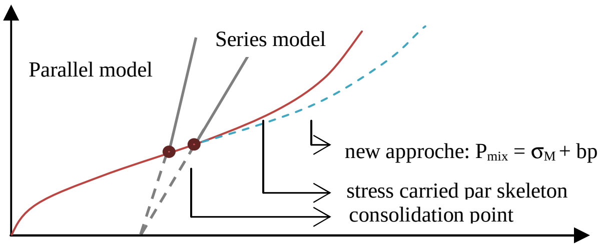

Figure 9. Diagram of stress calculation according to the poromechanical approach as concrete gets consolidated

With this new hypothesis, as the material reaches the point of consolidation (void pores are closed), the volumetric behavior remains nonlinear due to the fact that the voids filled with water continue to be compressed under compaction. Another advantage of this improvement is the unique point of consolidation instead of two points in the original model (figure 9).

3.3 Comparison between experimental results and simulations of tests.

The simulation results obtained with the original PRM coupled model and the modified model are compared to experimental results on figures 10 to 13.

Wet concrete

Figures 10 and 11 show results for a

concrete specimen with a saturation degree of 60% and submitted to triaxial compression with confining pressures varying from 15 to 100 MPa. At this saturation ratio and because of a moderate confining pressure, there is not the effect of free water on concrete behavior. The initial PRM coupled model allows a good prediction of the maximum stress but strains are significantly underestimated. Taking into account the influence of the deviatoric stress on the volumetric behavior of concrete significantly improves the prediction of the volumetric strain.

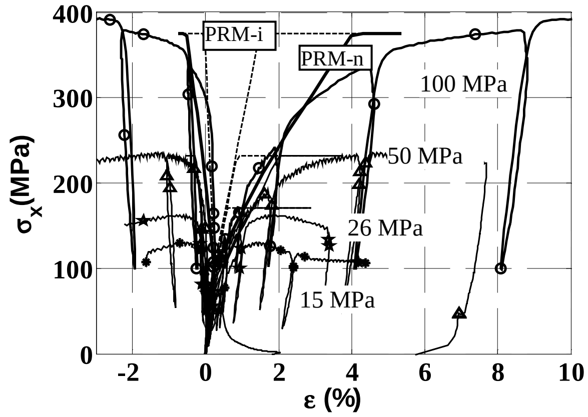

Figure 10. Axial stress vs. axial and circumferential strains: Comparisons of experimental results with simulation results obtained with the initial (PRM-i) and new model (PRM-n) for a wet concrete specimen under moderate confinement.

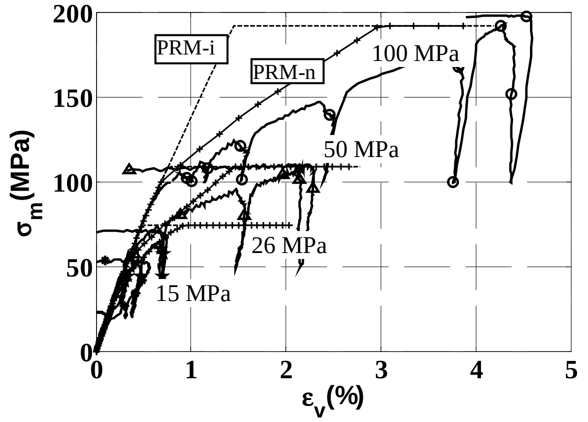

Figure 11. Mean stress vs. volumetric strain: Comparisons of experimental results with simulation results obtained with the initial (PRM-i) and new model (PRM-n) for a wet concrete specimen under moderate confinement.

Saturated concrete

Figure 12 shows experimental volumetric behavior of saturated and dry concrete and their comparison with simulation results obtained by both the initial and modified PRM coupled model. The initial model considers an elastic behavior after consolidation (closure of voids); while the modified model gives a simulation result closer to the experimental one.

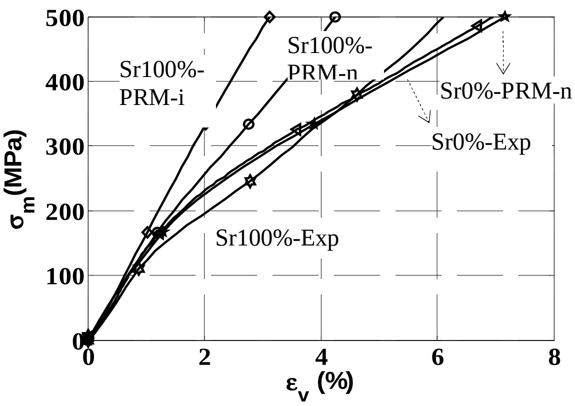

Figure 12. Mean stress vs. volumetric strain: Comparisons of experimental results with simulation results obtained with the initial (PRM-i) and new model (PRM-n) for saturated and dry concrete under high confinement.

4 CONCLUSION

This paper has presented new experimental results performed on a high performance concrete tested in the IRIS tests performed by VTT and the simulation of these tests with the PRM coupled model that was improved to better fit with experimental results.

Triaxial compression tests were performed at moderate and high confinement on concrete specimens with different saturation ratios. Significant differences in the maximum reached stresses can be highlighted. They can be attributed to the influence of the confining pressure but also to the saturation ratio at high confinement.

This paper has also presented the main features of the PRM model and its proposed improvement. The modified PRM model takes into account the influence of deviatoric stress on the volumetric behavior. The influence of the saturation ratio on the behavior of concrete under triaxial compression is also modified thanks to new approach. Therefore, the consolidation point is updated. These changes improve significantly the prediction of concrete behavior under triaxial compression with the PRM coupled model. The modified PRM model was then used to simulate the tests of the IRIS benchmark of the Nuclear Energy Agency (NEA) of OECD.

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