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BETON_RAG Summarized

: This

document presents behavior BETON_RAG the model , used to consider the behavior long-term of structures affected by the reaction alkali-aggregate. One
also details there the writing and the digital processing of the model. Contents

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Contents

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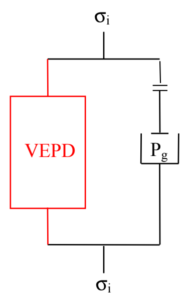
civil engineer works of the park of production of EDF, mainly of the stoppings, present pathologies of expansion of concretes due to the reaction (RAG) alkali-aggregates. In order to evaluate and the operation safety margins of these installations, and to control the costs of maintenance, EDF and the Laboratory Materials and Durability of Constructions (LMDC) of the university Paul Sabatier (Toulouse III) developed a digital model, [Grimal , 2007], allowing to simulate the structural mechanics behavior of structures affected by the RAG. The goal of this model is to evaluate the strains and the anisotropic damage (cracking) of the works reached. Indeed, recent experimental searches confirm that swelling due to the RAG becomes strongly anisotropic when the stress state becomes deviatoric. Moreover, the kinetics and the amplitude of the reaction strongly depending on the water content and the temperature of the concrete, the model take account of these environmental phenomena. In addition, creeps of compression and tension play a significant part in the behavior of the works, they were thus treated in a specific way. In

Code_Aster *, the model* is used under the name of BETON_RAG . Description

3 of the model [grimal, 2007] general

3.1 Principle

the reaction alkali-aggregates and its effects are modelled by means of a phenomenologic approach. This approach keeps account of the various important phenomena evolving within the concrete and influencing the chemical reaction. The principal developments suggested in this model relate to the interactions between the chemical pressure of origin and, the strains differed on the one hand and the anisotropic strains induced by the presence from directed cracks on the other hand.
The effects of moisture on the development of the alkali-reaction as on the capillary pressure inducing the shrinking of the matrix are also considered. The dependence between the evolution of swellings and the stress state is then a consequence of all these elementary phenomena; the mechanical effects of the alkali-reaction are thus the consequences of an internal loading "long run" due to the evolution of the chemical pressure (in P_g the Figure 2.1 3.1-a combined with the external loading. σ_i Figure



2.1 3.1-a Principle of the model of behavior of the concrete subjected to a pressure of swelling,

P_g in addition with the external stress requests σ_i the cementing matrix. The latter is regarded as a medium visco-élasto-plastic endommageable (modulus VEPD on the Figure 2.1 3.1-aThe next paragraph presents how the pressure due to the formation of gel is evaluated, in agreement with the environmental conditions and the strain state. Then, the model mechanical is exposed in the frame of the thermodynamics of the irreversible processes. Law

3.2 of evolution of the pressure interns

the pressure formulates P_g to the formation of gel in porosity is evaluated by making the assumption that the stress state does not modify the chemical advance of the reaction alkali-aggregate. In agreement with the various modelizations available, studied in the bibliographical part [Ulm and al.; Lemarchand and al.; Coussy, 2002], the concrete is regarded as a porous environment made up of a solid matrix and freezing occupying part of connected porosity. This porosity is made of two types of

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pores, those initially connected to the sites of reaction and those generated by the voluminal strain modifying porosity (in $b^g\, tr(\varepsilon)$ Equation2.2 - 1:1

The porosity connected to the sites of reaction is written in the form, $\varphi_0 = A_0 V^g$ in which, is A_0 the advance from which initial connected porosity is filled. Thus, as long as the volume of freezing created (formula AV^g lower than, $A_0 V^g$ freezing is placed in connected porosity and remains P_g null. P_g will increase only as from the moment when all porosity will be filled (). $AV^g \geq \langle A_0 V^g + b^g\, tr(\varepsilon)\rangle$ By taking account of these remarks, a statement connecting the pressure of freezing and the volume of freezing created () AV^g is proposed: Equation

2.2 - 1:1 Relation pressure - volume created - strain In

$$P_g = M^g \langle AV^g - \langle A_0 V^g + b^g \left(tr(\varepsilon) \right) \rangle \rangle$$

this statement: is

- V^g the maximum volume of freezing which can be created by the chemical reaction; it corresponds to the theoretical volume of freezing created by unit volume of concrete maintained under conditions saturated during an infinite time. formula
- A the advance of the chemical reaction, increasing by 0 for the healthy concrete with 1 when the reaction is completed. is
- M^g comparable to an elasticity modulus of freezing and can b^g be comparable to a coefficient of Biot for freezing. indicate $\langle\ \rangle$ the positive part of a quantity.
- The various positive parts allow:
- a taking into account of the influence of the voluminal strain induced by an external loading on a variation of connected porosity,
- an increase in the chemical pressure of origin if and only if freezing manages to fill connected porosity. Advance

3.3 of the reaction

the advance of the reaction “” A evoked previously is a function of the temperature and water content of the concrete.
The law of evolution used to evaluate chemical advance is inspired by works of S. Poyet [Poyet, 2003]. It shows that the freezing created during time () and t its kinetics of creation are proportional to the degree of saturation () of Sr the concrete, the degree of saturation being defined by: In

$$Sr = \frac{C}{C_{sat}}$$

this statement, is C the free water concentration contained per unit of volume of the concrete and is C_{sat} the value of formula C the concrete is completely saturated. In order to
take into account the effect of the temperature, the model of Arrhenius is used to model the thermic action [Capra, 1997]. Finally, the following model is proposed: Equation

2.3 - 2:2 Chemical advance In

$$\frac{\partial A}{\partial t} = \alpha_0 . \exp\left[\frac{E_a}{R}\left(\frac{1}{T_{ref}} - \frac{1}{T}\right)\right] \frac{\langle Sr - Sr^0 \rangle}{\left(1 - Sr^0\right)} \langle Sr - A \rangle$$

this model,. is α_0 a parameter of kinetics, is E_a the energy of activation of the reaction alkali-aggregates (usually of a value close to [Lombardi $47000\, J/mol/°K$ and al., 1995]), is R the constant of perfect gases (), $8.31\, J/mol$ (in T_{ref} Kelvin) is the absolute temperature of the test allowing the identification of, α_0 is T the temperature of the material point. The term means $\langle Sr - A \rangle$ that the chemical affinity of the reaction is conditioned by the degree of saturation of the concrete, Poyet having shown in its thesis that the advance formulates A is a standardized variable)

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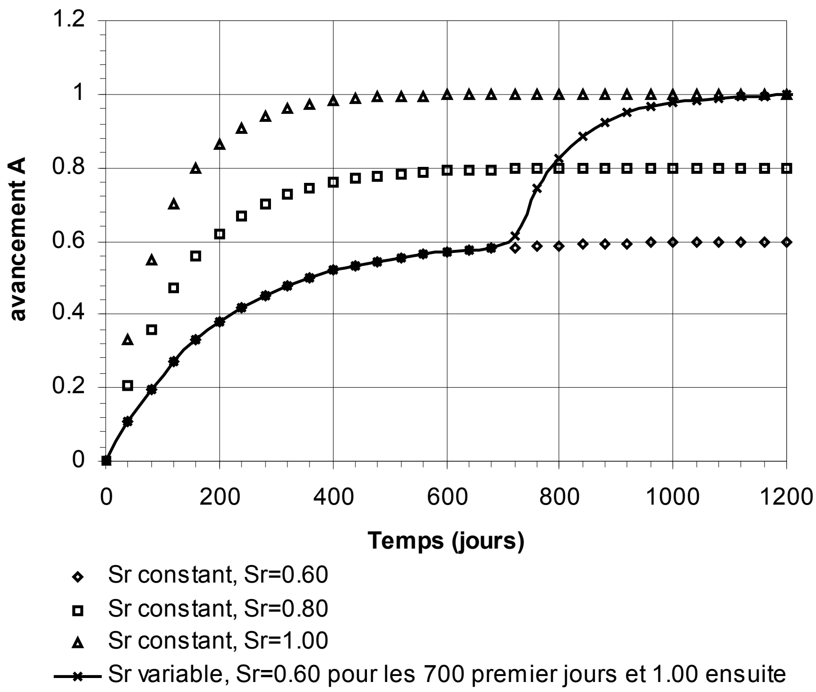
cannot exceed a value limits very near to the degree of saturation, it explains that by the fact that only the fraction of aggregate in contact with water can lead to the reaction. Consequently the amplitude of the reaction is proportional to the degree of saturation “”. Sr
Same way, the path traversed by the ions to reach silica reactive is all the more large as the degree of saturation is weak, which involves a reduction in the kinetics. This kinetic effect of the degree of saturation is taken into account via the term, $\frac{\langle Sr-Sr^0\rangle}{(1-Sr^0)}$ in which represents Sr^0 the threshold of saturation from which the evolution of the chemical reaction becomes possible.
The Figure 2.3 3.3-a some examples of variations of advance “” A for various states of moisture: the more important Sr is, the more is A large, being A maximum () when $A=1$ the concrete is saturated (). $Sr=1$ If the concrete remains in a state unsaturated (), $Sr<1$ the reaction is never complete (). $A<1$ On the other hand, if the state of saturation changes and passes for example from 0.6 to 1.0, the curve of advance is modified to join the state of maximum advance. Figure



2.3 3.3-a Evolution of the advance of the RAG under various degrees of saturation for $\alpha_0=0.0012$ **,** $T_{ref}=20°C$ **Dependence** $Sr^0=0.2$

3.4 between the damage and swelling

the alkali-reaction produces important swellings which should be accompanied by an important damage of structure. But, various experiments [Larive, 1997; Multon, 2003; Gravel, 2001] showed that the reduction in the mechanical properties remained weak compared to the strains reached.
A reduction of 20% of the mechanical characteristics is observed for a voluminal swelling of 0.1% (Figure2.4 - b: A test of direct tension leading to a comparable strain state would produce a complete damage of the cementing matrix. The particular behavior of the concrete reached by the reaction alkali-aggregates can be explained by two complementary phenomena: initially a phenomenon of cracking located around the reactive aggregate and then a viscoplastic adaptation for the long run of the cement paste. Cracking leads to large deformations because of the cumulative effect of the opening of the microscopic cracks. The viscoplastic behavior of the cement paste (in particular thanks to the HSC, to see [Grimal 2007]) can limit the stress concentration and thus the propagation of microscopic cracks and the associated damage is also restricted. Figure

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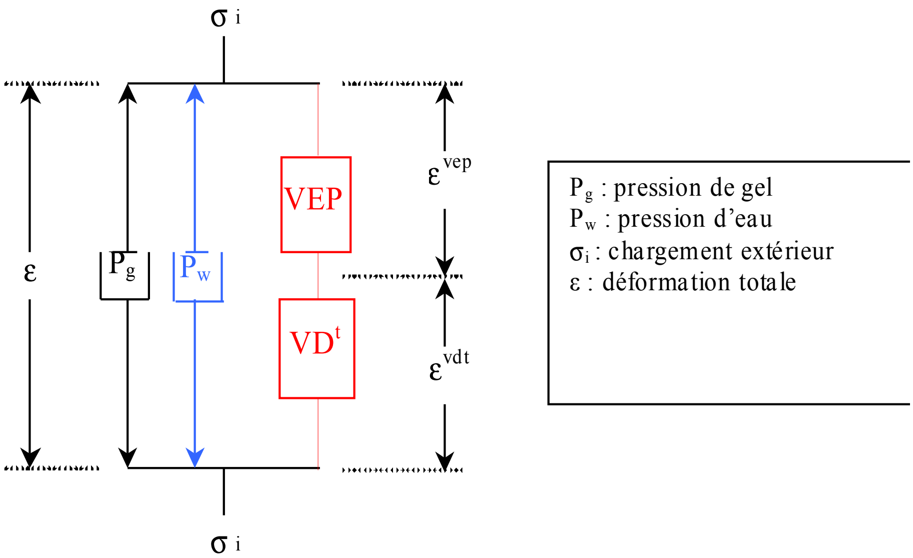
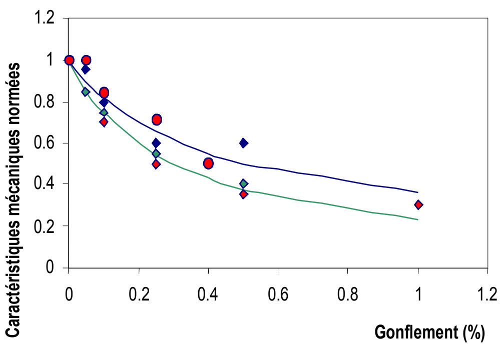


2.4 - a: Model viscoelastoplastic

compatibility between important swelling due to the RAG and the associated moderate damage is modelled by means of a plastic strain related to the damage of tension [Grimal and al., 2005; 2006]. This plastic strain limits the damage by allowing a stress relaxation caused by the pressure of freezing on the cement paste. Although necessary to model the swelling of alkali-reaction, this one is naturally insufficient to explain other long-term strains such as the multiaxial creep of the concrete not damaged. Thus, in order to obtain reliable forecasts of the strains induced in the long run by the pressure due to the presence of freezing and the effects of loading, a strain of creep was integrated into the model. Consequently
, the modulus visco-élasto-plastic endommageable (VEPD on the Figure 2.1 3.1-a was divided into two complementary levels (Figure2.4 - a::

1) a modulus (), VD^t dedicated to the modelization of the strain (Figure ε^{vdt} 2.4 - a: respecting the empirical relation existing between swelling due to the RAG and damage (Figure2.4 - b:
2) a modulus visco-élasto-plastic (VEP), corresponding to the strain on ε^{vep} the Figure 2.4 - a: allowing to model other aspects of the behavior of the concrete such as elasticity and creep. Figure



2.4 - b: Evolution of the mechanical characteristics in tension and compression [Saddler, 1999] Modelization

3.5 of the unelastic behavior of the concrete We

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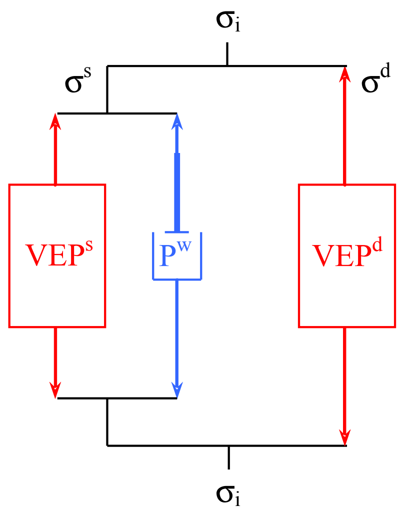
now will describe successively the moduli VEP and Vdt. Rheological

3.5.1 modulus simulating the creep and the shrinking of concrete (VEP) Acker

[Acker, 2003] proposes to explain the origins of creep by the particular behavior of the HSC, only component to have a viscous behavior. According to him, taking into account particular structure of the HSC, two mechanisms of strains are possible:

- Slidings between the averages of the HSC Of
- collapses in the stacking of the averages and a consolidation of the HSC.

The first mechanism is done with constant volume and suggests a behavior nonasymptotic long run. The second mechanism implies a water departure of the HSC towards capillary porosity, with an in the long run asymptotic behavior. In order to
model the difference in behavior, modulus VEP is divided into two parts, a “spherical” part and a “deviatoric” part. The spherical part (noted VEPs on the Figure .1-a 3.5.1-a the evolution of structure of the HSC subjected to a hydrostatic stress related to the water beginning like to viscoplastic compressing by “random” slidings overall isotropic. The deviatoric part translates the sliding of the averages subjected to a shearing stress. The Pw pressure present on the Figure .1-a 3.5.1-a to the hydrous pressure. It generates a shrinkage if it is negative and a swelling if it is positive. :



P_w pressure of water will intra porous:

VEP^s spherical part of modulus VEP:

VEP^d deviatoric part of modulus VEP Appears

.1-a 3.5.1-a Decomposition in parts spherical and deviatoric of modulus VEP Taking into account

the heterogeneous character of the porous distribution, we propose to model the phenomenon of creep like a hydraulic problem of consolidation in the following way: when a loading is applied to representative ground volume (V.E.R), of interstitial overpressures appear in the hydrous network, the first overpressures to disappear are those present in the water of the connected macroporosity, the loading initially taken again by these overpressures is transferred towards the solid squelette (Figure 2.5.1-b2.5.1-b 3.5.1-b part thus concerns the classical hydromechanics. The solid squelette itself is consisted, if one observes it with a finer scale, of a connected microporosity and a solid squelette which will be overloaded in its turn when overpressures present in its microporosity are evacuated towards the macroporosity. Creep then seems a succession of consolidation to increasingly fine scales, thus calling on transfers of less and less free water. This interpretation of the phenomenon of creep reveals a “fractal” character of the mechanism of consolidation, since the transfer of the stresses towards the solid squelette is made in a way similar to increasingly fine scales (2.5.1.1 Figure2.5.1.1 3.5.1.1-a assumption is also emitted by Acker [Acker, 2003]. For the finest scale, an irreversible character of creep can be present; the interfoliaceous water molecules are driven out in an irreversible way by compressing of the hydrates. Appear

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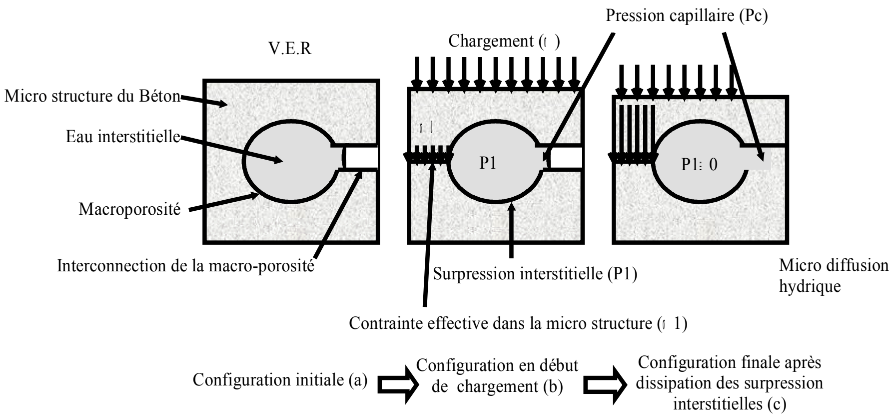
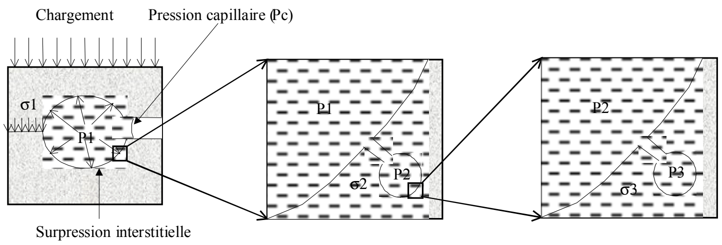


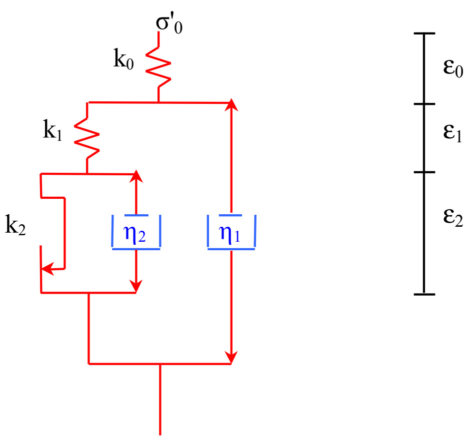
2.5.1-b 3.5.1-b mechanisms associated with the macro porosity spherical

3.5.1.1 Creep Appears



2.5.1.1 3.5.1.1-a Fractal" decomposition of the spherical viscoelastic mechanisms One proposes

to model these mechanisms of spherical creep by 3 levels (2.5.1.1 Figure2.5.1.1 3.5.1.1-b level representing a clean behavior. Appear



2.5.1.1 3.5.1.1-b spherical visco-élasto-plastic modelling spherical creep VEPs Level

- 0: Level
  0 is associated with the macroporosity subjected to the capillary pressure () if $P_w = P_c < 0$ the medium is not saturated, or with the pore water pressure () so the model $P_w > 0$ is used in a classical hydraulic approach. is thus σ_0^s the effective stress on the solid squelette. This level utilizes a purely elastic component of the concrete. It can thus be schematized and put in equation in the following way: Equation

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2.5 - 3 : stress3 on the level 0 Level

$$\sigma_0^s = k_0 \varepsilon_0^s$$

- <u>1: Level</u>
  1 corresponds to part of the microporosity slightly connected to the macroporosity open and prone to reversible hydrous motions. Associated viscoelasticity is modelled by a solid of Kelvin (2.5.1.1 Figure2.5.1.1 3.5.1.1-b

  2.5 - 4 : stress4 on level 1 Level

$$\sigma_1^s = k_1 \varepsilon_1^s + \eta_1 \dot{\varepsilon}_1^s$$

- <u>2: Equation</u>

  2.5 - 5 : forced5 on level 2 level

$$\sigma_2^s = k_2 \varepsilon_2^s + \eta_2 \dot{\varepsilon}_2^s$$

2 corresponds here to the interfoliaceous nanoporosity of the HSC. This level ensures the irreversible character of the viscous strains of the HSC. In this last statement, is k_2 a kinematical hardening modulus and is ε_2^s an unrecoverable deformation. The rheological
diagram makes it possible to establish the following system of equations: Equation

2.5 - 6 : System6 managing the strains of the spherical rheological model Creep

$$\begin{cases} \sigma_0^s = k_0 \varepsilon_0^s \\ k_1 \varepsilon_1^s = k_2 \varepsilon_2^s + \eta_2 \dot{\varepsilon}_2^s \\ \varepsilon^s = \varepsilon_0^s + \varepsilon_1^s + \varepsilon_2^s \\ \eta_0^s = k_1 \varepsilon_1^s + \eta_1 \left(\dot{\varepsilon}_1^s + \dot{\varepsilon}_2^s \right) \end{cases}$$

3.5.1.2 deviatoric In accordance with

the observations of Acker and al. [Acker and al., 2003], Acker [Acker, 2001], Bernard and al. [Bernard and al., 2003], the viscoelastic aspect of the behavior deviatoric is allotted to the interfoliaceous shears of the averages of HSC. These shears occur with two scales: A viscoelastic

- nanoscopic scale corresponding to water slightly related to the averages, a microscopic
- scale corresponding to free water slightly adsorbed between the averages and prone to desiccation. Lastly,

the part of the cement paste made up of better crystallized hydrates (portlandite and of hydrated calcium aluminate) has a quasi elastic behavior. Deviatoric
viscosity thus keeps a character multi scales, one then proposes to represent it in a way similar to the spherical branch, which moreover simplifies the placement of the model (rheological equations similar to those of the deviatoric branch). Appear

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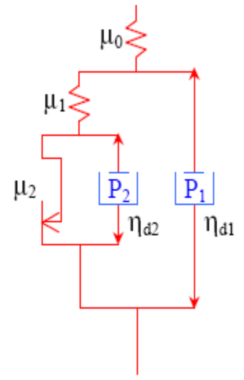

2.5.1.2 3.5.1.2-a viscoelastoplastic representation (VEPd) Equation

2.5 - 7 : System7 managing the strains of the rheological model deviatoric with One

$$\begin{cases} \sigma^d = \mu_0 \gamma_0^d \\ \sigma_0^d = \mu_1 \gamma_1^d + \eta_1^s (\dot{\gamma}_1^d + \dot{\gamma}_2^d) \\ \mu_1 \gamma_1^d = \mu_2 \gamma_2^d + \eta_2^s \dot{\gamma}_2^d \\ \gamma^d = \gamma_0^d + \gamma_1^d + \gamma_2^d \end{cases} \quad \text{can } \gamma_i^j = 2\varepsilon_i^j$$

specify at this stage of the modelization which the rheological systems of equations admit an analytical solution for a loading in linear total deflection according to time. We will draw part of this solution in the numeric work implementation. Modulate

3.5.2 dedicated to the modelization of the anisotropic swelling of RAG (VDt) the modulus

of VDt (Figure 2.4-a2.4 - a: an increase in the unelastic strain when the concrete is subjected to a tensile stress induced by RAG leading to the damage . We know
that in the presence of the RAG, the relation strain – damage following must be respected (Figure 2.4-a2.4 - b:

2.5 - 8 : Viscoplastic8 strain due to the RAG In this

$$\varepsilon_i^{vdt} = \varepsilon_0 \frac{d_i^{RO}}{1 - d_i^{R0}}$$

equation, is ε_0 a parameter identified on a large number of tests and of the concretes of various natures [Saddler, 1999]. Usually, its value is close to 0,35%. is
d_i^{R0} a principal value of the tensor of the damages due to the tensile stresses induced by the RAG. Here, it will be evaluated in the following way: In this

$$d_i^{R0} = \min \left(d_i^{R0} ; 1 - \exp \left(-\frac{1}{m^t} \left(\frac{b_g P_g}{\sigma^{ut}} \right)^{m^t} \right) \right)$$

statement, formula d_i^{R0} a principal value of the tensor of the damages of tension; and are m^t σ^{ut} parameters of the law of evolution of the damage. We will reconsider the choice of the variables of damages and their law of evolution in the following chapter. Assessment relating

3.5.3 to the partition of the strains The modelization

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proposed for creep was tested on multiaxial tests. The confrontation of simulations with the experimental results shows the capacity of the model of creep to reproduce the characteristics of the long-term behavior of the concrete. The next stage of modelization, consists in setting up a model of damage able to represent the behavior of the fissured concrete. This model will be then coupled with the model of clean creep and the model of swelling by the RAG describes up to now. Model

3.6 damage After

having given the great principles of the model, we initially will point out the concepts thermodynamics on which we must support our formulation. In the second time, we propose the free potential energy and the complementary models defining the model. This presentation makes it possible to check the conditions of dissipation imposed by the thermodynamics of the irreversible processes necessary to convergence of computations. Principle

3.6.1 of the modelization the reaction

alkali-aggregates causes swellings of structure. These swellings can be very different according to the loadings from damaged structures. The expansion considered isotropic in swelling not prevented becomes a strongly anisotropic expansion as soon as the concrete is subjected in a stress state deviatoric [Multon, 2003; 2006]. The microfissuring generated by the intra-porous pressure is then prevented in the direction of loading and swelling appears systematically associated with the directions where the compressive stresses are weakest. This phenomenon is particularly visible in the beams where the cracks are directed reinforcements parallel to. A mechanism of macro-cracking, due to the opening of cracks in the direction where the material is damaged the most, amplifies this anisotropy. The microphone and generated macro-crackings lead to a fall of the elastic modulus of the concrete, this fall is usually modelled by the theory of the damage. We present below the principles of the model of damage which we will apply to the stresses resulting from the rheological diagram presented in the preceding chapter. In order to
simulate the behavior of the concrete degraded by the reaction alkali-aggregates, an anisotropic model of damage, based on a realistic criterion of cracking, must be used. This model of damage must be formulated in the frame of the thermodynamics [Lemaitre, 2001]. The thermodynamic frame allows to avoid possible inconsistencies of formulation which would lead to problems of physical representation and numerical convergence. A this end, a thermodynamic potential of free energy from which the constitutive laws derive from the material must be proposed. If mechanical dissipation can be decoupled of other dissipations (thermal, hydrous or chemical), the condition of dissipation is given by the equation of Clausius-Duhem (Equation2.6 - 9 : Equation9 relation expresses the fact that the power of the “external forces” is at every moment higher than the restorable power stored by the material; part of the power of the “external forces” being dissipated mechanically by decoherence, friction etc Equation

2.6 - 9 : Equation9 of Clausius-Duhem for an isothermal mechanical transformation In this

$$\sigma : \dot{\varepsilon} - \rho \, \dot{\psi} \geq 0$$

statement, is σ the tensor of the stresses, that of ε the total deflections and the voluminal $\rho \, \psi$ free potential energy. This last is selected so that dissipation is null in the case of the perfectly elastic loading. This restriction
implies that the stresses derive σ from the free potential energy by the elastic strain, that is to say ε^e : Equation

2.6 - 10 : Dependence10 force-potential of free energy With:

$$\sigma = \rho \frac{\partial \phi}{\partial \varepsilon^e}$$

Equation

2.6 - 11 : Partition11 of the total deflection Where is

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$$\varepsilon^{e}=\varepsilon-\varepsilon^{an}$$

ε^{an} the unelastic strain . Two local variables, bound by this equation of partition, are thus defined: the unelastic strain formulates ε^{an} strain formulates ε^{e} model, formula ε^{e} the strain on level 0 of the rheological diagram; formula ε^{an} the strains and presented ε_{vdt} ε_{vep} on the Figure 2.4 - a: the thermal strain if it is necessary. The microphone
and macro crackings generated by the stresses lead to a fall of the elastic modulus of the concrete, this fall is usually modelled by the theory of the damage. We present below the principles of a model of damage The model
suggested is based on a tensorial representation of the damage. This representation is formulated so that the unilateral aspect of the behavior can be treated simply and independently in each of the three principal directions of the effective stresses. The tensor
of the effective stresses is estimated starting from the principle of equivalence in elastic strain, on level 0 of the rheological diagram (Figure 2.4-a2.4 - a:

2.6 - 12 : Estimate12 of the effective stresses starting from the principle of equivalence in strain With

$$\tilde{\sigma}=R^{0}:\varepsilon^{e}$$

the elasticity tensor R^{0} of the 4th order of the healthy concrete, calculated starting from Young and the Poisson's ratio modulus of the concrete not fissured. The apparent
stresses are connected to the effective stresses by the tensor of the damages: Equation D

2.6 - 13 : apparent13 stresses function of the effective stresses In this

$$\sigma=(I-D):\tilde{\sigma}$$

statements, () a tensor $I-D$ of integrity, also of the 4th order made up on the one hand matrix identity () and on the other hand I tensor of damage. By treating
the phenomenon of cracking starting from the tensor of damage of the 4th order , the free D potential energy takes the following general shape: Equation

2.6 - 14 : Potential14 of an elastic material endommageable In indicielle

$$\rho\psi=\frac{1}{2}(I-D):R^{0}:\varepsilon^{e}:\varepsilon^{e}$$

notation this last relation is written: Equation

2.6 - 15 : Potential15 in indicielle notation Thus,

$$\rho\psi=\frac{1}{2}(I-D)_{ijkl}R^{0}_{klmn}\varepsilon_{mn}\varepsilon_{ij}$$

Equation 2.6 - 9 : Equation9 2.6 - 10 : Dependence10 2.6 - 11 : Partition11 2.6 - 12 : Estimate12 2.6 - 13 : apparent13 in writing the relation of Clausius - Duhem in the following form: Equation

2.6 - 16 : Dissipation16 for a material endommageable Where are

$$\sigma:\dot{\varepsilon}^{an}-\rho\frac{\partial\psi}{\partial D}::\dot{D}-\rho\frac{\partial\psi}{\partial V^{an}}:\dot{V}^{an}\geq 0$$

to them V^{an} the local variables associated with the unelastic strains. That is to say still

with the indicielle notation: Equation

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$$\underbrace{\sigma_{ij}\dot{\varepsilon}_{ij}^{an}-\rho\frac{\partial\psi}{\partial V_{ij}^{an}}\dot{V}_{ij}^{an}}_{\phi^{an}}\underbrace{-\underbrace{\rho\left(\frac{\partial\psi}{\partial D}\right)_{ijkl}}_{Y_{ijkl}}\dot{D}_{ijkl}}_{\phi^{D}}\geq 0$$

2.6 - 17 : Dissipation17 in indicielle notation This last

relation makes it possible to define dissipation by unelastic strain as well as ϕ^{an} dissipation by mechanical damage. It ϕ^{D} also makes it possible to define the thermodynamic forces called Y_{ijkl} rate of energy restitution. A way
simple to ensure the positive character of dissipation whatever the state of the material and loading is to apply the decoupling of dissipations by unelastic strains and by damage, one must then check separately and is $\phi^{an}\geq 0$ still $\phi^{D}\geq 0$: Equation

2.6 - 18 : Decoupling18 of dissipations In viscoelasticity

$$\begin{cases}\sigma_{ij}\dot{\varepsilon}_{ij}^{an}-\rho\dfrac{\partial\psi}{\partial V_{ij}^{an}}\dot{V}_{ij}^{an}\geq 0\\ -Y_{ijkl}\dot{D}_{ijkl}\geq 0\end{cases}$$

, the condition of dissipation by unelastic strain results in choosing, for the models of viscosity, of the plus coefficients. In plasticity
, one applies the existence of a potential pseudonym of dissipation (). This last ϕ^{*an} being a positive convex function within the space of stresses and null in the beginning, so that the positivity of dissipation is automatically checked. The flow model of the unelastic strains can be written in the form: Equation

2.6 - 19 : Flow19 of the unelastic strains Where is

$$\dot{\varepsilon}_{ij}^{an}=\dot{\lambda}\frac{\partial\phi^{*an}}{\partial\sigma_{ij}}$$

$\dot{\lambda}$ a positive scalar called plastic multiplier. This last is calculated so that the increase in the unelastic strain leads to a relaxation of the stresses, this making it possible to check the plasticity criterion, also expressed within the space of stresses. Remain
to check the condition of positivity of dissipation by damage. One can for that take as a starting point the formalism briefly described previously for plasticity. I.e. to give a potential pseudonym of convex and null dissipation at the origin within the space of rate of energy restitution from which the increments derive of the components from the tensor of damage. One has then: Equation

2.6 - 20 : Laws20 of evolution of the damage the "

$$\dot{D}_{ijkl}=-\dot{\lambda}\frac{\partial\phi^{*D}}{\partial Y_{ijkl}}$$

multiplier of damage" having $\dot{\lambda}$ to be calculated in order to check the criterion of damage. The construction of the potential pseudonym being difficult; the use of a more rational layer, making it possible to ensure the coherent shape of the tensor of damage with the physical phenomena at the origin of the damage, is regularly used. For that, one calls on the theory of the homogenization. The tensor of damage is estimated there D from the constitutive law of the operational material () and from R^{0} that of a ground volume representative (WORM) of fissured material (), it comes R^{D} then: Equation

2.6 - 21 : Computation21 of the damage starting from the matrixes of the behavior homogenized the representativeness

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$$D_{ijkl}=\delta_{ik}\delta_{jl}-R^0_{ijmn}R^{D^{-1}}_{mnkl}$$

of the constitutive law, on the damaged equivalent material will depend on the quality of the homogenization of the WORM. The unilateral character of the behavior of the concrete is induced by the restoration of stiffness related to Re-closings of cracks. In the case of a cyclic uniaxial loading with change of the sign of the stress, one can note in experiments the creation of tension cracks perpendicular to the axis of loading and cracks of compression parallel with the axis of loading. The losses of stiffness in tension and compression are thus allotted to at least two orthogonal crack networks. When the stress passes from the tension to compression, the tension cracks are closed and the cracks of compression are activated. When the stress passes from compression to the tension, the tension cracks open and are activated in their turn. To model
"physically" the unilateral behavior of the concrete, it is convenient to reason from a tensorial description of the crack network. The losses of stiffness in tension or compression can thus be treated in each direction of space according to the sign of the stresses and the directional sense of cracks: if a principal stress is positive, the most active cracks will be those whose directional sense is overall perpendicular to the stress, whereas if the principal stress is negative, the most active cracks will be parallel to the stress. Anisotropic

3.6.1.1 damage by tension the various

reasons briefly stated previously lead us to propose a model of damage based on a representation of the cracking of tension by a tensor of the second order estimated starting from the tensor of the effective stresses of tension and not $\tilde{\sigma}^t$ on the extensions. They is here the effective stresses within the meaning of the damage, they should not be confused with the effective stresses within the meaning of mechanics of porous media which affect all the solid squelette whereas the effective stresses within the meaning of the damage affect only the not damaged part of the solid squelette. The tensor
of the effective stresses of tension is obtained starting from the effective stresses principal, themselves resulting from the application of the principle of equivalence in strain to the rheological model used for the solid squelette. Equation

2.6 - 22 : Definition22 of the effective stresses of tension Where is

$$\tilde{\sigma}^t=\langle\tilde{\sigma}_i\rangle.\left(\vec{e}^i\otimes\vec{e}^i\right)$$

$\vec{e}^i$ the eigenvector associated with which is $\langle\tilde{\sigma}_i\rangle$ the positive part of the effective principal stress. By means of $\tilde{\sigma}_i$
the principle of equivalence in strain stated by Lemaître, the effective stresses of tension make it possible to define the tensor of the associated elastic strain: Equation ε^{et}

2.6 - 23 : Elastic strain23 associated with the effective stresses of tension the criterion

$$\varepsilon^{et}=\frac{1+\nu^0}{E^0}\tilde{\sigma}^t-\frac{\nu^0}{E^0}tr(\tilde{\sigma}^t)I$$

of cracking retained for the damage of tension is that of Rankine, the tensor of the stresses thresholds is noted, the criterion σ^R translated in each principal direction of the tensor $\vec{e}^i$ of the effective stresses nonthe going beyond the normal component of the stress threshold: Equation

2.6 - 24 : Anisotropic24 criterion of cracking in a principal direction the actualization

$$f_i=\langle\tilde{\sigma}_i\rangle-\sigma^R:\left(\vec{e}^i\otimes\vec{e}^i\right)$$

of the tensor of the stresses thresholds is in conformity with the condition of consistency which is written simply: Equation

2.6 - 25 : Laws25 of evolution of the stress threshold where

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$$\sigma_{ii}^R = \sup\left(\langle \tilde{\sigma}_i \rangle, \sigma_{ii}^R\right)$$

are σ_{ii}^R the terms of the diagonal of the tensor expressed σ^R in the principal base of the effective stresses. By admitting
that the "equivalent" cracks, and thus the damages have the same principal directions that the stresses thresholds, one can define the tensor of the damages in the base of the principal stresses of: Equation σ^R

2.6 - 26 : Definition26 of the tensor of damage of the second order by spectral decomposition the damage

$$d^t = d_i^t . \left(\vec{v}^i \otimes \vec{v}^i\right)$$

"" represents d^t a set of three orthogonal plane crack networks coexistent within the same representative ground volume. The terms are $\vec{v}^i$ the eigenvectors of and the σ^R eigenvalues d_i^t of the tensor of damage estimated starting from the eigenvalues of, and σ_i^R σ^R the law of following evolution inspired by the model of Weibull [Saddler, 1995]: Equation

2.6 - 27 : Laws27 of evolution of the damage In this

$$d_i^t = 1 - \exp\left(\underbrace{-\frac{1}{m^t}\left(\frac{\sigma_i^R}{\sigma^{ut}}\right)^{m^t}}_{\beta_i}\right)$$

statement is m^t a all the more large parameter as the material is brittle, formula σ^{ut} a parameter "material", it is comparable to a cohesion, in practice formula m^t identified from the experimental damage measured starting from the peak of the constitutive law, σ^{ut} is directly connected to strength. We will and the give the relations between the parameters of the model measurable quantities in the following paragraphs. By introducing
the index of cracking defined by: Equation

2.6 - 28 : Definition28 of the index of cracking it comes

$$\beta_i = \frac{1}{m^t}\left(\frac{\sigma_i^R}{\sigma^{ut}}\right)^{m^t}$$

: Equation

2.6 - 29 : Relation29 damage - index of cracking This last

$$\frac{1}{1 - d_i^t} = e^{\beta_i}$$

relation will be practical for the construction of the free potential energy. The local variables introduced on this level will also make it possible to memorize the state of cracking. It is also necessary, accordingly, to note that the damage is an increasing and continuous function of the index of cracking which is itself an increasing function of the stress threshold. As the latter can only increase, the principal values of the tensor of damage can only grow. With regard to
the normal strain-forced relations, the transition of the tensor of damage to the constitutive law of the damaged material must translate on the one hand a reduction in the Young modulus in the normal direction with crack and on the other hand an attenuation of the effect Fish between the direction orthogonal to plane of crack and the directions contained in its plane. To observe these conditions, we propose to use the following constitutive law: Equation

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2.6 - 30 : Relation30 normal stress - normal strain according to the damage of tension Is still

$$\varepsilon_{ii}^{e}=\frac{\sigma_{ii}}{E^{0}(1-d_{i}^{t})}-\frac{\nu^{0}}{E^{0}}\left(\sigma_{jj}+\sigma_{kk}\right)$$

according to the indices of cracking: Equation

2.6 - 31 : Relation31 normal stress – normal strain according to the index of cracking In this

$$\varepsilon_{ii}^{e}=\frac{\sigma_{ii}}{E^{0}}e^{\beta_{i}}-\frac{\nu^{0}}{E^{0}}\left(\sigma_{jj}+\sigma_{kk}\right)$$

statement is E^0 the Young modulus of the operational material and its Poisson's ratio ν^0 . The relation is written in the principal base of the damages. It should be noted that this model is expressed here according to the apparent stresses and not effective stresses, it is this particular writing which makes it possible to profit simply from an attenuation of the effect Fish according to cracking in the directions and as well as j k symmetry of the tensor of flexibility of the constitutive law. The sliding-forced
relations of shears are also written in the principal base of damage, the relation suggested is the following one: Equation

2.6 - 32 : Relation32 stress-strain in shears expressed according to the damages Which one

$$\varepsilon_{ij}^{e}=\frac{\sigma_{ij}}{G^{O}(1-d_{i}^{t})(1-d_{j}^{t})}$$

can also express according to the indices of cracking: Equation

2.6 - 33 : Relation33 stress-strain in shears expressed according to the indices of cracking Where is

$$\varepsilon_{ij}^{e}=\frac{\sigma_{ij}}{G^{O}}e^{\beta_{i}+\beta_{j}}$$

G^0 the shear coefficient of the operational material. Equation

2.6 - 34 : Elastic modulus34 of shears the sliding-forced

$$G^{0}=\frac{E^{0}}{2(1+\nu^{0})}$$

relation of shears utilizes the damages on the two principal directions of cracking requested in shears, the combination of the damages is of the standard weakest link. In addition to the interaction between damages which this writing gets, one can allot a statistical meaning to him by considering that the damages are comparable to probabilities of meeting surface discontinuities on the facets [Saddler, 1995]. On this assumption, the theory of the weakest link indicates that the probability so that a shearing stress forwards on two orthogonal facets is equal to the probability of having simultaneously two not broken orthogonal surfaces. By neglecting the statistical dependences between the two planes of cracking, this probability is equal to the product of the probabilities of having on each one of these two facets a continuity of the material, one from of deduced the denominator from Equation2.6 - 32 : Relation32 the last reason for which we adopted this form for the damage of the shear coefficient is that the resulting constitutive law presents the expected response with the test of rotation of the principal directions (known as test of Willam [Willam and al., 1987]). To express
the free potential energy according to the elastic strain, it is necessary to make sure of the invertibility of the relations stress-strains suggested previously. For that, let us express the apparent normal stresses according to the elastic strain: Equation

2.6 - 35 : Statement35 of the normal stresses according to the normal strains with formula

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$$\sigma_{ii}=\frac{E^0}{D^n}\left[\left(e^{\beta_j+\beta_k}-\nu^{0^2}\right)\varepsilon_{ii}^{et}+\nu^0\left(\varepsilon_{jj}^{et}\left(\nu+e^{\beta_k}\right)+\varepsilon_{kk}^{et}\left(\nu+e^{\beta_j}\right)\right)\right]$$

D^n of the linear system expressing the normal strains according to the apparent normal stresses: Equation

2.6 - 36 : Determinant36 of the matrix of flexibility reduced to the normal stresses and strains One shows

$$D^n=e^{\beta_i+\beta_j+\beta_k}-\nu^{0^2}\left(e^{\beta_i}+e^{\beta_j}+e^{\beta_k}+2\nu^0\right)$$

that is always D^n positive if the two following conditions are checked: Equation

2.6 - 37 : Condition37 of invertibility of the matrix of flexibility the condition

$$\begin{cases}\beta_i\geq 0\,\forall i\in\{1,2,3\}\\ \nu\leq 0.5\end{cases}$$

on the Poisson's ratio is checked, it is the same for the condition on, taking into account β_i the law of evolution of the damages suggested previously. The invertibility of the relation normal strain - normal stress is thus assured some is the level of damage. With regard to
the relations between rates of shears and the shearing stresses, the inversion is immediate and it comes: Equation

2.6 - 38 : Statement38 of the shearing stress according to the strain As

$$\tau_{ij}=\frac{G^0}{e^{\beta_i+\beta_j}}\,\varepsilon_{ij}^e$$

the denominator of this statement is understood in the interval invertibility $[1,+\infty[$ is there too assured. By integrating
the relations stress-strains compared to the elastic strain associated with the effective stresses of tension, one obtains the elastic free potential energy associated with the effective stresses of tension. This potential noted thereafter $\rho\,\Psi^t$ is expressed here in the principal base of the damages: Equation

2.6 - 39 : Free39 potential energy associated with the effective stresses of tension With

$$\rho\,\Psi^t=\rho\,\Psi^{t(n)}+\rho\,\Psi^{t(s)}$$

the potential $\rho\psi^{t(n)}$ of the free energies associated with the extensions: Equation

2.6 - 40 : Free40 potential energy associated with the normal stresses with the principal planes of cracking And that

$$\rho\psi^{t(n)}=\frac{1}{2}\frac{E^0}{D^n}\left(\begin{array}{l}\left(e^{\beta_j+\beta_k}-\upsilon^{0^2}\right)\varepsilon_{ii}^{et^2}+\left(e^{\beta_i+\beta_k}-\upsilon^{0^2}\right)\varepsilon_{jj}^{et^2}+\left(e^{\beta_j+\beta_i}-\upsilon^{0^2}\right)\varepsilon_{kk}^{et^2}\\+2\upsilon^0\left(\varepsilon_{jj}^{et}\varepsilon_{ii}^{et}\left(\upsilon^0+e^{\beta_k}\right)+\varepsilon_{kk}^{et}\varepsilon_{ii}^{et}\left(\upsilon^0+e^{\beta_j}\right)+\varepsilon_{jj}^{et}\varepsilon_{kk}^{et}\left(\upsilon^0+e^{\beta_i}\right)\right)\end{array}\right)$$

associated $\rho\psi^{t(s)}$ with the elastic strain of shears: Equation

2.6 - 41 : Free41 potential energy associated with the tangent stresses with the principal planes of cracking the potential

$$\rho\psi^{t(s)}=\frac{1}{2}G^0\left(e^{-(\beta_i+\beta_j)}\varepsilon_{ij}^{et^2}+e^{-(\beta_i+\beta_k)}\varepsilon_{ik}^{et^2}e^{-(\beta_j+\beta_k)}\varepsilon_{jk}^{et^2}\right)$$

can be also expressed simply according to the apparent stresses associated σ^t with the effective stresses with tension. Maybe with regard to the potential associated with the extensions: Equation

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2.6 - 42 : Potential42 in apparent normal stresses being to Them

$$\rho\psi^{t(n)}=\frac{1}{2}\left(\frac{\sigma_{ii}^{t^2}}{E_i}+\frac{\sigma_{jj}^{t^2}}{E_j}+\frac{\sigma_{ii}^{t^2}}{E_i}+2\frac{\upsilon^0}{E^0}\left(\sigma_{ii}^t\sigma_{jj}^t+\sigma_{ii}^t\sigma_{kk}^t+\sigma_{kk}^t\sigma_{jj}^t\right)\right)$$

$E_i=E^0(1-d_i^t)$ Young moduli of the damaged material. And for

the potential associated with the shears: Equation

2.6 - 43 : Potential43 in apparent tangent stresses the indices

$$\rho\psi^{t(s)}=\left(1+\upsilon^0\right)E^0\left(\frac{\sigma_{ij}^{t^2}}{E_iE_j}+\frac{\sigma_{ik}^{t^2}}{E_iE_k}+\frac{\sigma_{kj}^{t^2}}{E_kE_j}\right)$$

of cracking which can β_i be connected in a bijective way to the principal damages of tension, the statement d_i^t of Clausius-Duhem can be expressed according to the indices of cracking. For more clearness we disregard here temporarily role of the unelastic strains, by supposing an elastic transformation endommageable utilizing only the effective stresses of tension: Equation

2.6 - 44 : Equation44 of Clausius-Duhem for a damage of tension In this

$$\sigma:\dot{\varepsilon}_{ij}^{et}-\left(\underbrace{\rho\frac{\partial\psi^{t(n)}}{\partial\beta_i}\dot{\beta}_i}_{-\varphi^{Dt(n)}}+\rho\frac{\partial\psi^{t(n)}}{\partial R}:\dot{R}+\underbrace{\rho\frac{\partial\psi^{t(s)}}{\partial\beta_i}\dot{\beta}_i}_{-\varphi^{Ft(s)}}+\frac{\partial\psi^{t(s)}}{\partial R}:\dot{R}+\rho\frac{\partial\psi^t}{\partial\varepsilon_I^{et}}\varepsilon_I^{et}\right)\geq 0$$

statement, is ε_I^{et} a principal value of the tensor of the strains associated with the effective stresses with tension, is $\varphi^{Dt(n)}$ dissipation associated with the normal strains and that associated $\varphi^{Dt(s)}$ with the shears. is R the transition matrix of the principal base of the elastic strain at the principal base of the damages, can be $\dot{R}$ interpreted as a rate of rotation of the tensor of damage if the principal directions of strain do not turn. The taking into account of the form of the free potential energy associated with the shears then makes it possible to calculate dissipation due to the damage associated with the shears. It comes: Equation

2.6 - 45 : Dissipation45 associated with the tangent strains with cracks This statement

$$\phi^{Dt(s)\dot{\beta}}=\dot{\beta}_i\underbrace{\left(\frac{1}{2}G^0\left(e^{-(\beta_i+\beta_j)}\varepsilon_{ij}^{et^2}+e^{-(\beta_i+\beta_k)}\varepsilon_{ik}^{et^2}\right)\right)}_{\geq 0}$$

is always positive since is positive $\dot{\beta}_i$, the positivity of dissipation associated with the shears is thus checked. With regard to
dissipation associated with the normal strains, one can notice that by means of the statements in stress of and of $\psi^{t(n)}$ in ε^{et} the equation of Clausius-Duhem, it comes : Equation

2.6 - 46 : Dissipation46 associated with the normal strains with cracks What

$$\sigma:\dot{\varepsilon}^{et}-\rho\,\dot{\psi}^{t(n)}=\left(\underbrace{\sigma:\frac{\partial\varepsilon^{et}}{\partial E_i}}_{-\frac{\sigma_i^{t^2}}{E_{i^2}}}-\underbrace{\rho\frac{\partial\, spi^{t(n)}}{\partial E_i}}_{-\frac{1}{2}\frac{\sigma_i^{t^2}}{E_{i^2}}}\right)\dot{E}_i=\underbrace{-\frac{1}{2}\frac{\sigma_i^{t^2}}{E_{i^2}}}_{\leq 0}\cdot\dot{E}_i\geq 0$$

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implies that, gold and $\dot{E}_i \leq 0$ being $\dot{E}_i = -E^0 \dot{d}_i^t$ $\dot{d}_i^t$ positive, the second principle is also checked for the damage associated with the normal strains. In the case of
the nonradial loading, the relation of Clausius-Duhem contains the terms due to the evolutions of the principal damages, which are always positive as we have just seen it, as well as terms due to rotations of the directions of damage. The latter translate a bringing together of the directions of orthotropy of the material and those of the loading. From an analytical point of view, this second transformation is similar to a rotation of the principal directions of strain without damage. It is thus done without dissipation, the following relation must thus be respected at every moment: Equation

2.6 - 47 : Equation47 of nondissipation during the rotation of the loading what

$$\left(\sigma : \frac{\partial \varepsilon^{et}}{\partial R} - \rho \frac{\partial \Psi^t}{\partial R} \right) \dot{R} = 0$$

implies: Equation

2.6 - 48 : Condition48 of nondissipation during the rotation of the loading But, by

$$\sigma : \frac{\partial \varepsilon^{et}}{\partial R} = \rho \frac{\partial \Psi^t}{\partial \varepsilon^{et}} : \frac{\partial \varepsilon^{et}}{\partial R}$$

construction, therefore this $\sigma = \rho \dfrac{\partial \Psi^t}{\partial \varepsilon^{et}}$ condition is identically observed and the rotation of the directions of damage does not involve complementary but induced dissipation a variation of the free potential energy compatible with the evolution of the loading. We

have just presented the principles of an orthotropic model of damage in effective stress, this last enters the thermodynamic frame and profits moreover from a method of direct numerical resolution conformément (not of under iteration at the Gauss point). Indeed, the computation of the damage according to the effective stress is direct, like that of the apparent stress according to the effective stress and the damage. Isotropic

3.6.1.2 damage by compression Under request

of tension, the criterion usually used is that of Rankine (principal stress of tension), this criterion gives an account of a crack propagation in mode. In compression I, the criteria of Mazars [Mazars, 1994] or of Drücker-Prager are usually employed; the criterion of Mazars utilizes the notion of extension of the WORM, the criterion of Drücker-Prager gives an account of the unfavourable effect of the deviator of the stresses. In practice, the fracture in compression is induced by elastic heterogeneities leading to the appearance of local fields of auto--balanced stresses of which the positive part involves the starting and the propagation of cracks (2.6.1.2 Figure2.6.1.2 3.6.1.2-a their origins, these induced positive stresses can exist only in the orthogonal directions with the compressive stresses which generate them. When these auto-contraintes reaches the tensile strength a crack starts and the damage of compression appears. In the ordinary concretes, this damage appears in a progressive way and it is possible to observe multiple vertical cracks distributed on broad band localised and inclined of shears (2.6.1.2 Figure2.6.1.2 3.6.1.2-b

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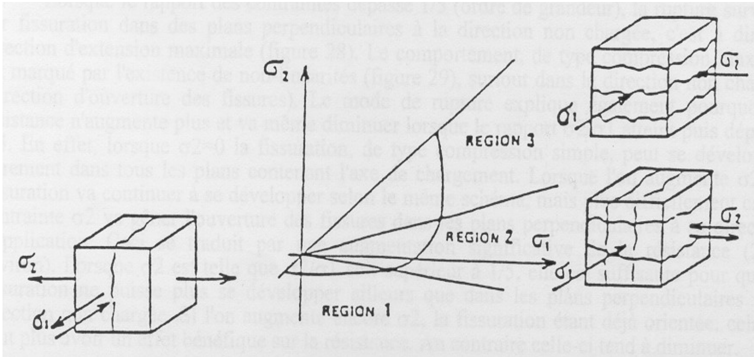
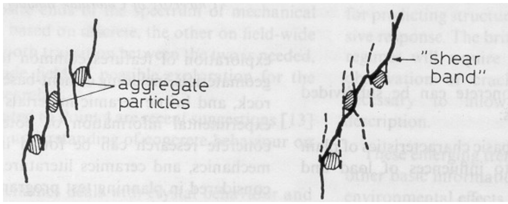


2.6.1.2 3.6.1.2-a of cracking according to the loading path [Torrenti , 1987] the cracks

parallel with free edges are started in the vicinity of the aggregates by the induced self stresses, they fissure the forming concrete of small "columns " which perish by side instability as shown in the figure 2.6.1.2 3.6.1.2-b



2.6.1.2 3.6.1.2-b of "columns" in the vicinity of the aggregates [Torrenti, 1987] Thus,

the propagation of cracks of compression can be comparable to a phenomenon of multiple instabilities in compression along a tape of shears. However the phenomena of mechanical instability are very closely related to the conditions of side maintenance of the compressed element. The instability always occurring in the direction of weaker maintenance, this explains cracks parallel with edges noncharged on the 2.6.1.2 2.6.1.2 3.6.1.2-a
the mode of fracture describes above, it is important to recall how much the compressive strength is sensitive to containment as the various biaxial and triaxial tests of the literature show it. Taking into account a share of the complexity of the mode of fracture in compression and in addition of the sensitivity to containment, it is usual to model the damage of the concrete in compression to adopt an isotropic macroscopic criterion of Drücker-Prager if one reasons in terms of stresses, or a criterion of Mazars if one reasons in term of strains. We chose here to adopt the criterion of Drücker-Prager to be coherent with the formalism in effective stresses introduces at the time of the presentation of the model of damage of tension. The stresses at the origin of the damage of compression are thus supposed to be the negative effective stresses, these last $\tilde{\sigma}^c$ are defined in the principal base of the effective stresses by: Equation

2.6 - 49 : Definition49 of the effective stresses of compression Where is

$$\tilde{\sigma}^c = \tilde{\sigma} - \tilde{\sigma}^t$$

$\tilde{\sigma}$ the effective stress from the rheological model and the effective stress $\tilde{\sigma}^t$ of tension defined by Equation2.6 - 22 : Definition22 of Drücker-Prager is written then: Equation

2.6 - 50 : Equivalent stress50 of Drücker-Prager Where and

$$\sigma^{ceq} = \sqrt{J_2} + \delta_{\text{hom}} \frac{I_1}{3}$$

are I_1 J_2 the first 2 invariants of the tensor of the effective stresses of compression: Equation

2.6 - 51 : Definition51 of the invariants (expressed here according to the principal effective stresses) flow

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$$\begin{cases} J_2=\frac{1}{6}\left(\left(\tilde{\sigma}_1^c-\tilde{\sigma}_2^c\right)^2+\left(\tilde{\sigma}_1^c-\tilde{\sigma}_3^c\right)^2+\left(\tilde{\sigma}_2^c-\tilde{\sigma}_3^c\right)^2\right) \\ I_1=\tilde{\sigma}_1^c+\tilde{\sigma}_2^c+\tilde{\sigma}_3^c \end{cases}$$

is carried out by considering that the stress threshold of damage memorizes the maximum value of the stress of Drücker-Prager: Equation

2.6 - 52 : Law52 evolution of the stress threshold L" damage

$$\sigma^{DP}=\sup\left(\sigma^{DP},\sigma^{ceq}\right)$$

evolves then not linearly according to the stress threshold: Equation

2.6 - 53 : Law53 evolution of the isotropic damage of compression the potential

$$d^c=1-\exp\left(-\frac{1}{m^c}\left(\frac{\sigma^{DP}}{\sigma^{uc}}\right)^{m^c}\right)$$

D" free energy associated with the effective stresses of compression is written very simply because of assumption of isotropy of the damage of compression: Equation

2.6 - 54 : Free54 potential energy associated with the effective stresses of compression dissipation

$$\rho\,\psi^c=\left(1-d^c\right)\frac{1}{2}\left[\lambda^0\left(tr\left(\varepsilon^{ec}\right)\right)^2+2\mu^0\,tr\left(\left(\varepsilon^{ec}\right)^2\right)\right]$$

associated with the damage with compression is written: Equation

2.6 - 55 : Dissipation55 by damage of compression rate of energy restitution

$$\phi^{dc}=\underbrace{-\rho\frac{\partial\psi^c}{\partial d^c}}_{Y^c}\dot{d}^c$$

being Y^c negative and the damage strictly growing, the positivity of dissipation by damage of compression is assured. Coupling

3.6.1.3 of the damages of tension and compression the isotropic

character prevailing of the damage of compression is related to the complexity "quasi random and thus statistically isotropic" of the paths of cracking generated during the process of degradation. It is obvious that the cracks created will affect behavior in tension. A way simple to give an account of the reduction in the elastic moduli in tension according to the damage of compression is to consider that the isotropic damage of compression also comes to reduce the free potential energy of tension which becomes: Equation

2.6 - 56 : Deterioration56 of the free potential energy in tension by the damage of compression the term

$$\rho\,\psi^{t*}=\left(\left(1-d^c\right)\underbrace{\left(\rho\,\psi^{t(n)}+\rho\,\psi^{t(n)}\right)}_{\rho\,\psi^t}\right.$$

being $\rho\,\psi^t$ positive, the positivity of dissipation by damage of compression remains assured: Equation

2.6 - 57 : Positivity57 of dissipation by damage of compression formulates

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$$-\rho(\frac{\partial\psi^c}{\partial d^c}+\frac{\partial\psi^{t*}}{\partial d^c})\dot{d}^c\geqslant 0$$

being $(1-d^c)$ also positive, dissipation by damage of tension remains positive. Free

3.6.1.4 potential energy associated with the macroscopic elastic strain the partition

of the strains according to the sign of the effective stresses being made Equation 2.6 - 22 : Definition22 2.6 - 49 : Definition49 potential energy is the sum of the free energies associated with the effective stresses of tension on the one hand and the effective stresses of compression on the other hand: Equation

2.6 - 58 : Potential energy58 of the concrete squelette only free

$$\rho\,\psi=\left(1-d^c\right)\underbrace{\left(\rho\,\psi^{t(n)}+\rho\,\psi^{t(s)}\right)}_{\rho\psi^t}+\rho\,\psi^c$$

3.6.1.5 Potential energy associated with an expansive internal chemical reaction However the model

integrates a pressure () created P_g by the expansive chemical reaction of advance, the free A potential energy, with imposed temperature and at a given time, becomes a function of formula A

2.6 - 59 : Free59 potential energy in the presence of an expansive internal reaction In this

$$\rho\,\psi\left(\varepsilon^{ec},\varepsilon^{et},A,d^t,d^c,V^{an}\right)$$

statement represents V^{an} the local variables associated with the unelastic phenomena. The inequality
of Clausius-Duhem thus becomes: Equation

2.6 - 60 : Dissipation60 in the presence of an expansive phase with the pressure In this P_g

$$\sigma:(\dot{\varepsilon}^e+\dot{\varepsilon}^{an})+P_g(\dot{A}\,V^g)-\rho\frac{\partial\psi}{\partial\varepsilon^e}\dot{\varepsilon}^e-\rho\frac{\partial\psi}{\partial d^t}:\dot{d}^t-\rho\frac{\partial\psi}{\partial d^c}\dot{d}^c-\rho\frac{\partial\psi}{\partial A}\dot{A}-\rho\frac{\partial\psi}{\partial V^{an}}\dot{V}^{an}\geq 0$$

statement the term is $P_g\left(\dot{A}\,V^g\right)$ the mechanical power brought to the solid squelette by the chemical reaction. If one considers a physical transformation of the WORM without damage nor unelastic strain, therefore without mechanical dissipation, this energy must be completely regained in the free potential energy, which is written: Equation

2.6 - 61 : Relation61 thermodynamic connecting the free potential energy to the pressure On the other hand

$$P_g(\dot{A}\,V^g)=\rho\frac{\partial\Psi}{\partial A}\dot{A}$$

the physical considerations lead us to express the pressure of freezing according to the voluminal fraction of matter in excess compared to the volume of the vacuums connected to the reactive site on the one hand and of the total deflections in addition (Equation2.2 - 1:1
of the two preceding relations results in proposing for the share of the potential due to freezing the following form: Equation

2.6 - 62 : Free62 potential energy associated with the expansive chemical reaction This form

$$\Psi^g=\frac{1}{2}M^g b^{g^2}\left(\frac{A-A^0}{b^g}V^g-tr(\varepsilon^e+\varepsilon^{an})\right)^2$$

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of potential is close to that proposed by Ulm et al. [Ulm and al., 2002]. The derivative of this potential compared to the elastic strain gives the share of the macroscopic stress induced by the internal pressure of freezing in the solid squelette: Equation

2.6 - 63 : Isotropic63 stress generated by the expansive reaction free

$$\pi^g = -b^g P_g = \rho \frac{\partial \Psi^g}{\partial \varepsilon^e}$$

3.6.1.6 Potential energy associated with the hydrous pressures In saturated

medium, the pressures will intra porous act on the solid squelette by deforming the walls of the porous network; the equation of Clausius-Duhem is written, in the absence of damage and of unelastic phenomena: Equation

2.6 - 64 : variation64 of the free potential energy per fluid contribution of mass In this

$$-\left(P_w - P_{w0}\right)\dot{\varphi}^w - \rho \frac{\partial \Psi}{\partial \varphi^w}\dot{\varphi}^w = 0$$

statement is $\varphi^w = \frac{m^w}{\rho^{w0}}$ the standardized contribution of mass of water, being m^w the contribution of mass and the density ρ^{w0} of the water defined in the pressure of reference. In addition P_{w0} the physical considerations result in expressing the water pressure in the form [Coussy, 2002]: Equation

2.6 - 65 : Hydrous65 of pressure in medium saturated an acceptable

$$P_w - P_{w0} = M^w\left(\varphi^w - b^w tr(\varepsilon)\right)$$

form for the free potential energy associated with these equations is then: Equation

2.6 - 66 : Free66 potential energy associated with the hydrous pressure the derivative

$$\rho\,\psi^w = \frac{1}{2} M^w b^{w^2}\left(\frac{\varphi^w}{b^w} - tr(\varepsilon)\right)^2$$

of this potential compared to the elastic strain gives the share of the macroscopic stress induced by the pressure of water: Equation

2.6 - 67 : Stress67 induced by the hydrous pressure If

$$\pi^w = \rho \frac{\partial \psi^w}{\partial \varepsilon^e} = -b^w\left(P_w - P_{w0}\right)$$

the state of reference is defined for the material saturated with the atmospheric pressure, then $\left(P_{w0} = 0\right)$ the preceding statement is valid only if the fluid contribution of mass is positive. In the contrary case, the concrete die-is saturated and the hydrous pressure is not managed any more by relative compressibilities of the various phases but by the capillary phenomena. The average hydrous pressure is thus P_w a function of the capillary pressure and degree of saturation. In addition to S^w the variation of pressure in the water induced by the capillary phenomena, it is also necessary to consider the action of the interfaces of the fluid with the gaseous medium and solid. Indeed, these interfaces are prone to the phenomena of capillary tension which act they-also directly on the solid squelette. If the gas pressure intra porous is in equilibrium with the atmospheric pressure [Coussy, 2002], the share of the macroscopic stress induced by these two phenomena can be put in the following general form: Equation

2.6 - 68 : Hydrous68 stress in the concrete unsaturated Where taking into account

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$$\pi^w = b^w f^{w(S^w)} P^c$$

on the one hand f^w the reduction in the volume of water is a function and on the other hand increase amongst solid sites subjected to the surface tension with interface. In the present modelization, we are interested in the works located in partially saturated zone, in this case we propose to use a function formulates f^w form, the contribution $k^w \cdot S^w$ of the hydrous effects in the macroscopic stress has the following form then: Equation

2.6 - 69 : Particular69 statement of the hydrous stress in medium unsaturated with By

$$\pi^w = -b^w S^w k^w P^c = \rho \frac{\partial \psi^w}{\partial \varepsilon^e}$$

considering $S^w = \frac{\varphi \rho^{w0} + m^w}{\rho^{w0}} = \varphi + \varphi^w$

that the variation of porosity due to φ the strain remains small compared to, one can φ^w admit that for the medium unsaturated. If in addition $\varphi \approx \varphi^0$, it is admitted that the capillary curve of pressure is almost $P^c(S^w)$ insensitive with the strain state of the solid squelette, then: If the capillary

$$\pi^w \approx b^w (\varphi^0 + \varphi^w) k^w P^{c(\varphi^0 + \varphi^w)} = \rho \frac{\partial \psi^w}{\partial \varepsilon^e}$$

curve of pressure admits an equation of the type "Van Genuchten" then takes π^w the following shape: Equation

2.6 - 70 : Form70 hydrous pressure in unsaturated with the capillary curve with Van Genuchten Where has and

$$\pi^w = -b^w (\varphi^0 + \varphi^w) \left(a \left((\varphi^0 + \varphi^w)^{-b} - 1 \right)^{\left(1 - \frac{1}{b}\right)} \right)$$

B are two constants of chock. The free
potential energy can then be put in the form: Equation

2.6 - 71 : Free71 potential energy associated with the capillary pressure the thermodynamic

$$\rho \psi^w = -b^w (\varphi^0 + \varphi^w) \left(a \left((\varphi^0 + \varphi^w)^{-b} - 1 \right)^{\left(1 - \frac{1}{b}\right)} \right) tr(\varepsilon)$$

force associated with the variation of the mass of water is obtained by derivative of this potential compared to. Dissipation φ^w

3.6.1.7 due to the unelastic strains the equation

of Clausius-Duhem reveals the unelastic strains in ε^{an} the term. It $\sigma : \dot{\varepsilon}^{an}$ is the power of the external forces of the unelastic strain field, the evolution of these strains induces an evolution of the local variables associated possibly V^{an} causing a variation with the free potential energy: Equation

2.6 - 72 : Variation72 of the free potential energy by unelastic strains This last

$$\rho \frac{\partial \phi}{\partial V^{an}} \dot{V}^{an}$$

term represents the elastic strain energy blocked in the solid squelette by the unelastic strain. In our model the unelastic strains have a viscoelastic or viscoplastic origin and can directly be used as local variables: . Thus $V^{an} = \varepsilon^{an}$,
in the typical case of a purely unelastic transformation, dissipation is summarized with: Equation

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2.6 - 73 : Dissipation73 by unelastic transformation In the model

$$\phi^{an}=\sigma:\dot{\varepsilon}^{an}-\rho\frac{\partial\psi}{\partial\varepsilon^{an}}\dot{\varepsilon}^{an}\geq 0$$

proposed here we adopted the principle of partition of the partly elastic deflection total and unelastic part (Equation2.6 - 11 : Partition11 makes it possible to express the elastic strain according to the unelastic strains and to conclude that the thermodynamic force associated with the unelastic strain is the stress: Equation

2.6 - 74 : Force74 thermodynamic associated with the unelastic strain the second

$$\rho\frac{\partial\psi}{\partial\varepsilon^{e}}=-\rho\frac{\partial\psi}{\partial\varepsilon^{an}}=\sigma$$

principle is thus checked if. In the model $\sigma:\dot{\varepsilon}^{an}\geq 0$ studied here, the unelastic strain associated with long-term creep or the expansive chemical reaction is proportional to the stress, which one can write in shortened form, where is $\dot{\varepsilon}^{an}=k\,\sigma$ k a plus coefficient depend on the local variables for each component of the tensor of the strains. Thus unelastic dissipation due to the long-term strains is a viscous dissipation of the form. Concerning $k\,\sigma^{2}\geq 0$ the strain of RAG, we authorize his evolution only if the dissipation calculated numerically on time step is indeed positive. Total

3.6.1.8 potential of free energy and state models the free

potential energy of the solid squelette is obtained by adding the energy contributions of the various phenomena studied previously: Equation

2.6 - 75 : Free75 potential energy of the concrete the state models

$$\psi=\psi^{t^*}+\psi^{c}+\psi^{g}+\psi^{w}$$

are obtained by derivative of the total potential: If one

$$\sigma=\rho\frac{\partial\psi}{\partial\varepsilon^{e}}$$

expresses the stresses in the principal base of the damages of tension, it comes for the diagonal terms from the tensor from the stresses: Equation

2.6 - 76 : Statement76 of the normal stresses in principal base of damage and for

$$\sigma_{ii}=\left(1-d^{c}\right)\left(\begin{array}{c}\frac{E^{0}}{D^{n}}\left[\left(e^{\beta_j+\beta_k}-\nu^{0^2}\right)\varepsilon^{et}_{ii}+\nu^{0}\left(\varepsilon^{et}_{jj}\left(\nu+e^{\beta_k}\right)+\varepsilon^{et}_{kk}\left(\nu+e^{\beta_j}\right)\right)\right]\\+\left(1-d^{c}\right)\left[\lambda^{0}tr\left(\varepsilon^{ec}\right)+2G^{0}\varepsilon^{ec}_{ii}\right]-b^{g}P_{g}-b^{w}P_{w}\end{array}\right)$$

the terms except diagonal: Equation

2.6 - 77 : Statement77 of the tangent stresses in principal base of damage with

$$\tau_{ij}=\left(1-d^{c}\right)G^{0}\left(\frac{\varepsilon^{et}_{ij}}{e^{\beta_i+\beta_j}}+\left(1-d^{c}\right)\varepsilon^{ec}_{ij}\right)$$

and Let us recall $D^{n}=e^{\beta_i+\beta_j+\beta_k}-\nu^{0^2}\left(e^{\beta_i}+e^{\beta_j}+e^{\beta_k}+2\nu^{0}\right)$ $e^{\beta_i}=\frac{1}{1-d^{t}_{i}}$

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that the elastic strain of tension and compression ε^{et} result ε^{ec} from two successive decompositions, the partition of the total deflection on the one hand: Equation
2.6 - 78 : Partition78 of the total deflection and in addition

$$\varepsilon=\varepsilon^{e}+\varepsilon^{an}+\varepsilon^{th}+\varepsilon^{0}$$

of the partition function of the sign of the effective stress within the meaning of the damage: Equation

2.6 - 79 : Partition79 of the elastic strain according to the sign of the principal effective stresses Equation

$$\varepsilon^{e}=\varepsilon^{et}+\varepsilon^{ec}$$

2.6 - 80 : Thermal strain80 In

$$\varepsilon^{th}=\alpha^{\theta}\left(T-T_{0}\right)I$$

Equation2.6 - 78 : Partition78 ε^{th} the strain due to classically definite thermal thermal expansion by the Equation2.6 - 80 : Thermal strain80 α^{θ} the thermal coefficient of thermal expansion, the temperature T and the reference temperature T_0 . Let us note that in Equation2.6 - 78 : Partition78 of reference is also ε^{0} present, it acts of a strain of non-zero reference corresponding in a free state of stress. It can be associated only with one voluminal variation with the solid squelette of chemical origin (chemical shrinkage dependant of the hydration for example). Indeed, the strains of hydrous shrinkage or swelling by internal expansive products are manifestations of the pressures will intra porous appearing via the elastic strain and unelastic, they should not thus be confused with this "imposed chemical strain of reference" which is not accompanied by internal pressures and cannot thus create damage in free strain. The elastic strain
and unelastic are obtained by resolution of the system of the rheological equations presented to the preceding chapter. If the resolution of the system of equations of the rheological model is direct (without nonlinearity requiring of under numerical iterations at the Gauss point in the implementation finite elements), then the resolution of the group of the model is direct for the total data of the strain field. Let us recall that this aspect of the model answers the purpose of facility of implementation and reduction of the computing time that we initially fixed ourselves. 2.6.1.8 table 3.6.1.8-1 recapitulates the variables. 2.6.1.8

table 3.6.1.8-1 variables Processing

Variables d'état		Variables associés
Observables	Internes	
ε		σ
T		s
	ε^{e}	σ
	ε^{an}	$-\sigma$
	d^{t}	Y^{t}
	d^{c}	Y^{c}
	AV_{g}	P_{g}
	ϕ^{w}	P_{w}

3.6.2 of the problem of localization the localization

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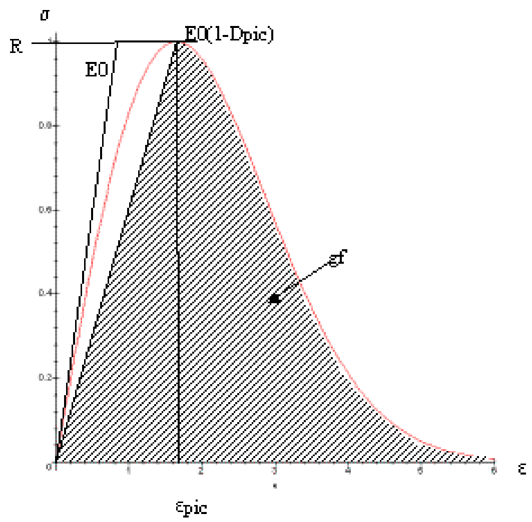
of the strain results in experiments in the creation of a macro located crack, surface energy necessary to the creation of this crack, noted formula Gf_t direct tension cracks, must then be dissipated in the finite element undergoing the localization. As the classical shape functions suppose a homogeneous behavior of the finite elements, the modelization of the localization of the strain is not assumption of responsibility by the computer code, one chooses here to carry out this assumption of responsibility on the level of the constitutive law by adapting the part post peak of the damage model in order to respect dissipation. A layer Gf_t to reach that point is to modify the slope of the downward branch of the damage model. One must then check the equation of following dissipation: Equation

2.6 - 81 : Energy81 dissipated in phase of localization of the strains the term

$$Gf_i^r = l_i \underbrace{\int_{D=D_{pic}}^{D=1} \sigma_i^r(\epsilon) \frac{\partial \epsilon}{\partial D_i^r} dD_i^r}_{gf_i^r} \Leftrightarrow gf_i^r = \frac{Gf_i^r}{l_i} \quad r=\{t,c\}$$

indicates Gf^r voluminal energy to dissipate by the constitutive law to satisfy the condition with dissipation on the finite element, one notes that this voluminal energy depends on the size of the finite element () in l_i the principal direction (). In addition i formula Gf^r to the integral under the constitutive law as shown in the figure 2.6.2-a 3.6.2-a



2.6.2-a 3.6.2-a voluminal energy As

localised dissipation is done starting from the peak of the constitutive law (starts localization in direct tension), a layer to control is Gf to modify the pace of the downward branch of the constitutive law. We implement this solution by making a homothety of the strains post peak. Indeed, for a uniaxial loading, the energy dissipated for a Gauss point integrating a dimension “” is written l_i : Equation

2.6 - 82 : Dissipation82 of localization in an element of size What l_i

$$Gf_i^r = l_i \left(\int_0^{\epsilon_{pic}} \sigma_i^r(\epsilon) d\epsilon + \int_{\epsilon_{pic}}^{\infty} \sigma_i^r(\epsilon) d\epsilon \right) = l_i \left(\frac{(R_i^r)^2}{E_0(1-D_{i\ pic}^r)} + \int_{\epsilon_{pic}}^{\infty} \sigma_i^r(\epsilon) d\epsilon \right)$$

can be also written: Equation

2.6 - 83 : Definition83 of homothety for the control of dissipation in phase of localization the parameter

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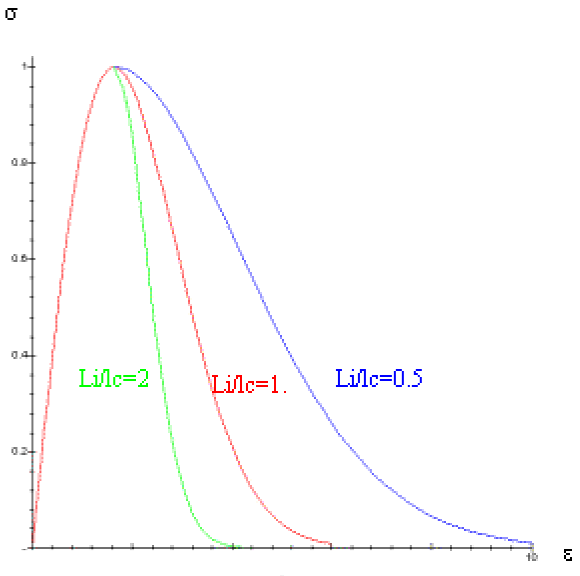
$$\begin{cases} Gf_i^r - l_i \dfrac{(R_i^r)^2}{E_0(1-D_{i\ pic}^r)} = l_i \displaystyle\int_{\epsilon_{pic}}^{\infty} \sigma_i^r(\epsilon)\, d\epsilon = lc_i^r \displaystyle\int_{\epsilon^*_{pic}}^{\infty} \sigma_i^r(\epsilon^*)\, d\epsilon^* \\ si \quad \epsilon^* = \dfrac{l_i}{lc_i^r}(\epsilon - \epsilon_{pic}) + \epsilon_{pic} \quad et \quad \epsilon^* \geqslant \epsilon_{pic} \end{cases}$$

characterizing lc_i homothety to be carried out must then be estimated from the energy of cracking in the following way: Equation

2.6 - 84 : Estimate84 of the parameter of homothety We give

$$lc_i^r = \frac{Gf_i^r - l_i \dfrac{(R_i^r)^2}{E_0(1-D_{i\ pic}^r)}}{\displaystyle\int_{\epsilon_{pic}}^{\infty} \sigma_i^r(\epsilon)\, d\epsilon}$$

on the following figure, as illustration, the effect of the homothety described by Equation 2.6 - 83 : Definition83 the pace of the constitutive law (normalized). Appear



2.6.2-b 3.6.2-b dissipation by adaptation of the damage model in keeping with the finite element In the case of

a triaxial loading, homothety can be done directly on the effective stresses, it comes for the tension: and For

$$\tilde{\sigma}_i^* = \frac{l_i}{lc_i^t}(\tilde{\sigma}_i - \tilde{\sigma}^{ut}) + \tilde{\sigma}^{ut} \quad \tilde{\sigma}_i^* \geqslant \tilde{\sigma}^{ut}$$

compression, one defines the ratio of homothety from h^c the equivalent stress defined by Equation2.6 - 50 : Equivalent stress50 this ratio in an isotropic way to the effective stresses of compression: Equation

2.6 - 85 : Homothety85 on the effective stresses for the control of dissipation post peak the size

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$$\sigma^{eqc^*}=\frac{l_m}{lc^c}(\sigma^{eqc}-\tilde{\sigma}^{uc})+\tilde{\sigma}^u \quad et \quad \sigma^{eqc^*}\geqslant\tilde{\sigma}^{uc}$$

$$h^c=\frac{\sigma^{eqc^*}}{\sigma^{eqc}}$$

$$\tilde{\sigma}_i^{c^*}=h^c\tilde{\sigma}_i^c$$

is l_m an isotropic measurement of the "dimension" associated with the Gauss point taken on equalizes with: Equation

2.6 - 86 : Isotropic86 measurement of the size of the finite element Coupling

$$l_m=\left(\prod_{i=1}^{3} l_i\right)^{1/3}$$

3.6.3 of the model of damage and the rheological model The model

rheological and the model of damage having individually been described in the preceding paragraphs, they must now be connected. As we mentioned in the preceding paragraph, the effective stresses and the strains to which it is refers in the chapter devoted to the model of damage result from the rheological diagram. The coupling between the viscoelastic phenomena and the damage thus consists in defining on the rheological diagram the effective stresses and the strains to use the damage to compute:. Currently, the effective stresses used in the model of damage are directly from the rheological model for which the integration of Equation 2.6 - 12 : Estimate12 2.6 - 13 : apparent13 with the viscoelastic characteristics of the operational material. The coupling between the damage and rheology is thus immediate. Indeed, if the damage increases a creep test during, then the effective stresses will increase in the model rheological, leading to an increase the velocity of creep. Description

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4 of the local variables the following

table gives the correspondence between the number of the local variables accessible by Code_Aster *and their* description: Number

of the variable Description	Strain
viscous spherical 1st 2	
EIS	deviatoric
viscous Strains 3 ERD1	
4	EID1
5	ERD2
6	EID2
7	ERD3
8	EID3
9	ERD4
10	EID4
11	ERD5
12	EID5
13	ERD6
14	EID6
intrinsic	
Damages of tension 15 DT1	
16	DT2
17	DT3
18	DT4
19	DT5
20	DT6
intrinsic	
Damage of compression 21 Forced	
DC0	
thresholds of tension 22 SUT1	
23	SUT2
24	SUT3
25	SUT4
26	SUT5
27	Forced
SUT6	
thresholds of compression 28 JUICE	
hydrous	
Pressure 29 PW chemical	
Pression 30 PCH	
Advance	
of the reaction 31 ARAG	
spherical	
Strains viscoplastic thresholds 32 ESI	
33	ES
Strains	
viscoplastic thresholds deviatoric 34 EDI1	
35	EDS1
36	EDI2
37	EDS2

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38	EDI3
39	EDS3
40	EDI4
41	EDS4
42	EDI5
43	EDS5
44	EDI6
45	EDS6
Effective stresses	
in the model rheological 46 SEF	
1 47	SEF
2 48	SEF
3 49	SEF
4 50	SEF
5 51	SEF
6 Strains	
viscoplastic 52 EVP	
1 53	EVP
2 54	EVP
3 55	EVP
4 56	EVP
5 57	EVP
6 macroscopic	
Damage (indicating of cracking) 58 BT	
1 59	BT
2 60	BT
3 61	BT
4 62	BT
5 63	BT
6 64	BC effective
Pressure due have the RAG 65 bch	
*pch	indices

1,2,3 , 4,5,6 correspond respectively to the components: 11,22,33,12,13,23 of the tensors. Presentation

5 of the algorithm of resolution Let us place

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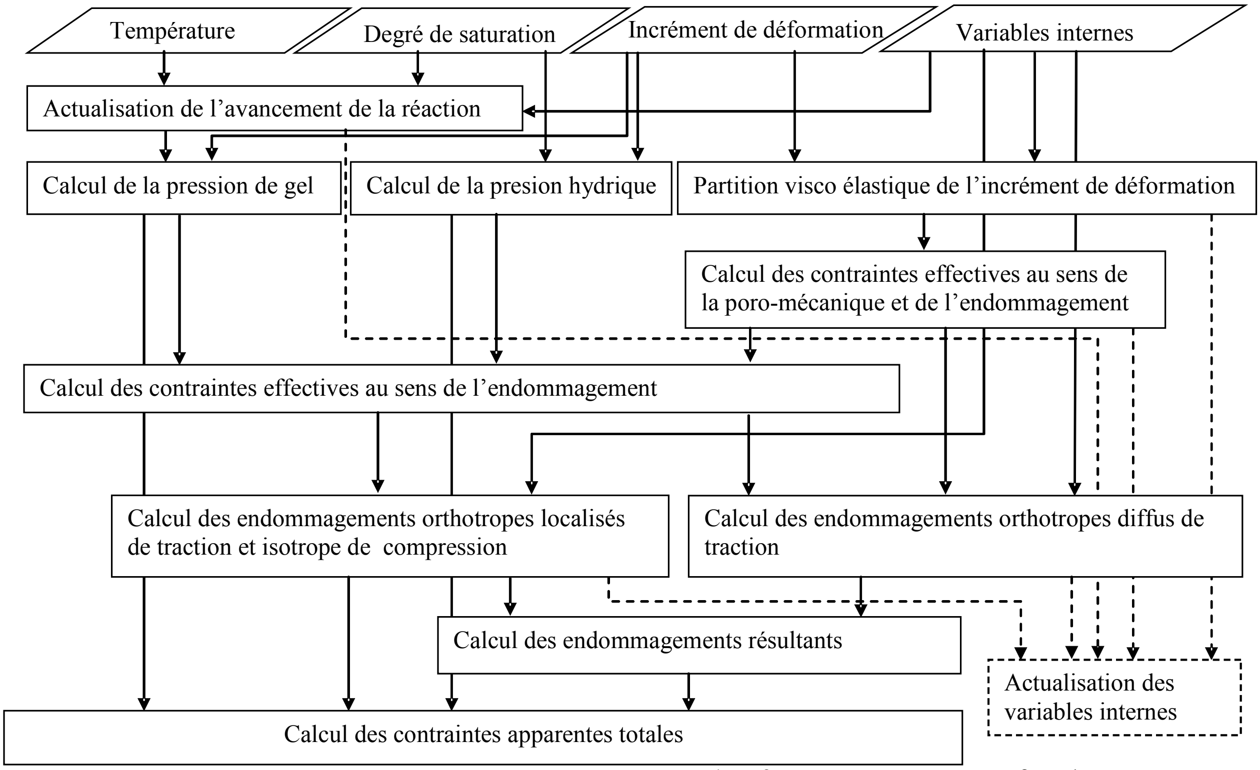

on a Gauss point between times and such as t^1 t^2 . That is to say $t^2-t^1=\Delta t$ the increment $\Delta\varepsilon=\dot{\varepsilon}\Delta t$ of strain between these two time step. In addition one notes the advance A of the reaction of RAG. The first

stage consists in calculating the new advance of the reaction Where

$$A^2=A^1+\Delta A(Sr,\theta)$$

is estimated ΔA in accordance with the integration of the differential model of advance by adopting the temperature and the average degree of saturation on the step (in the middle of time step) One can deduce the pressure from it from freezing at the end of time step from the strain state of the solid squelette the hydrous

$$Pg=Kg\left(A^1 Vg-\left(A^0 Vg+bgtr\left(\varepsilon^1-\varepsilon^{th}\right)\right)^+\right)^+$$

pressure when P_w with it is calculated from the state of saturation and strain according to Equation2.6 - 65 : Hydrous65

one breaks up the following increment of total deflection the model rheological: With L

$$\dot{\varepsilon}=\dot{\varepsilon}^e+\dot{\varepsilon}^{anr}+\dot{\varepsilon}^{ani}+\dot{\varepsilon}^{anth}$$

"increment $\dot{\varepsilon}^e$ of elastic strain of the solid squelette, the reversible $\dot{\varepsilon}^{anr}$ share of creep, the irreversible $\dot{\varepsilon}^{ani}$ share of creep including the contribution of the pressure of RAG and L" increment $\dot{\varepsilon}^{anth}$ of thermal strain. The realization of this partition is carried out by solving the system of equations differentials of creep for the which imposed initial conditions relate to each stage of the rheological model, one recalls that the coupling between these equations is obtained by writing the continuity of the stress in the model rheological and that the solution must check the preceding equation what results in solving a system of 4 differential equations coupled to 4 unknowns 7 times, once for the increment of spherical strain and 1 time for each deviatoric component of the tensor strainrates. The strains
obtained are stored as local variables to initiate the resolutions similar to the following computation step… is 28 local variables. Knowing

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the increments of strain on the various stages of the rheological model one from of deduced the increments from effective stresses, by applying the law of elasticity of the operational material on the elastic floor. The apostrophe

$$\tilde{\sigma}' = C^0 : \dot{\varepsilon}$$

means that the stress is effective within the meaning of the poro-mechanics and the tilde means that it is also effective within the meaning of the damage mechanics. One can

then estimate the effective stresses in the solid squelette (by cumulating with the effective stress of the preceding step the increment previously calculated, which implies that this stress either stored in the local variables , or 6 complementary local variables), as well as the effective stresses within the meaning of the damage but total within the meaning of the mechanical poro: This last

$$\tilde{\sigma} = \tilde{\sigma}' - b_g P_g - b_w P_w$$

stress then is used for built the functions thresholds corresponding to the orthotropic criteria of Rankine (for the damage of tension) and to the criterion of isotropic Drucker Pragger (for the damage of compression). If

the functions thresholds requires it an evolution of the stress threshold of Rankine and Drucker $\tilde{\sigma}^R$ Pragger is carried out $\tilde{\sigma}^{DP}$ (flow) to ensure the conditions of Kuhn Tucker. The new

functions thresholds are then stored in local variables (6 in tension and 1 in compression is 7 complementary local variables). Knowing

the new tensor of the stresses threshold of Rankine, one it diagonalized to obtain the principal directions of damage and the values of the damages (by application of the damage model on the principal stresses thresholds). In addition

one reiterates the process on the level of the effective stress to obtain $\tilde{\sigma}'$ the diffuse damage of with the pressures intra-porous. One adopts then like damage resulting the maximum value between the diffuse damage and the damage localised. One then

applies the orthotropic damage model to the effective stresses of tension within the meaning of the damage. This operation proceeds in the base of the principal damages, bases in which the form of the tensor of damage is simplest . One applies

then the damage of compression to the stresses resulting from the operation preceding and increased effective stresses of compression and effects of the pressures will intra porous. One obtains

finally the total apparent stresses which are result of integration at the Gauss point . Complementary

remarks: In

the local variables are also memorized the pressures intraporeuse and the diffuse damages (equivalents with the damages due to the RAG because here the pressure is quite P_g higher than) and locality P_w (damage of Rankine or Drucker Pragger). These variables are actually only statements of the stresses thresholds of cracking already memorized in addition, they are not thus essential of these last but facilitates the post processing by authorizing a direct display of the damage to resulting from computation. To limit the obstruction in memory related to these variables one could remove them list of the local variables and carry out this computation in post processing . When

the user the model engages the use of the tangent matrixes (on the level of the total iterative resolution) with BETON_RAG , `actually` only a secant operator is used for the total resolution; the damages are then reappraised and the secant matrix passed in total fixed base for built the secant stiffness matrixes of the elements. The nonlinear procedure is pressed then on each under iteration on the secant operator. Bibliography

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7 and checking constitutive law

BETON_RAG (key word COMP_INCR of STAT_NON_LINE) and its associated material (command DEFI_MATERIAU) is checked by the following tests: COMP003

Test of	behaviors specific to the concretes. Simulation in a material point [V6.07.103	] SSNV212
Constitutive law	BETON_RAG : free swelling on test-tube [V6.04.212	] SSNV213
Constitutive law	BETON_RAG : swelling prevented on test-tube [V6.04.213	] SSNV214
Constitutive law	BETON_RAG : cyclic loading of a concrete test-tube [V6.04.214	] SSNV215
Constitutive law	BETON_RAG : test of rotation of the principal directions [V6.04.215	] SSNV216
Constitutive law	BETON_RAG : biaxial creep of a cube [V6.04.216	] Description

8 of the versions of the document Index

document Version	**Aster Author (**	**S) Organization (S) Description**	**of the modifications A 10.2**
E.	Grimal	EDF-DPIH A. Sellier LMDC Toulouse P. of Bonnières EDF-R&D /AMA initial Text	

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