Mechanical behavior of concrete cold joints

Comportamiento mecánico de juntas frías lisas de concreto

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Abstract

A smooth cold joint of concrete is an untreated weak plane caused by an interruption of the casting process, which can significantly affect the performance of a structural system. In this paper, the problem of the generation of cold joints is approached from two complementary perspectives. a) The loss of resistance due to the occurrence of cold joints is quantified through an extensive experimental program of concrete cylinders and b) a constitutive model is proposed and its performance is analyzed to simulate the time-dependent behavior of concrete under load (viscosity) and no load (setting). A loss of resistance over 30% for cold concrete cylinders with diagonal joints was found, while concrete cylinders with horizontal cold joints had no loss of resistance. Thus, the loss of resistance depends on the orientation of the cold joint with respect to the direction of the main stresses. This aspect is explained by the proposed constitutive model of viscous–reactive type, which is able to simulate the results of the experimental program. This work opens the possibility of numerical modeling of boundary value problems of structures with a cold joint and to study their influence on the structure's overall stability.

Keywords: *Cold joint, constitutive model, stress, strain, finite element*

Resumen

Una junta fría lisa en el concreto es un plano débil no tratado causado por la interrupción de suministro de mezcla en el vaciado que puede afectar de manera considerable el desempeño de un sistema estructural. En este trabajo se aborda el problema de la generación de juntas frías lisas desde dos perspectivas complementarias a. se cuantifica la disminución de la resistencia debido a la aparición de juntas frías en concreto por medio de un extensivo diseño experimental de cilindros de concreto y b. se propone un modelo constitutivo y se analiza su desempeño para simular el comportamiento esfuerzo – deformación dependiente del tiempo del concreto en condiciones de carga (viscosidad) y no carga (fraguado). Se encuentran pérdidas de resistencia máxima de más del 30% para cilindros de concreto con juntas frías diagonales comparadas con cilindros sanos en tanto que los cilindros de concreto con junta fría horizontal no presentan disminución de resistencia por lo que la disminución de la resistencia depende de la orientación de la junta fría con relación a la dirección de los esfuerzos principales. Este aspecto tiene su explicación en la propuesta del modelo constitutivo de tipo viscoso –reactivo capaz de simular los resultados de la campaña experimental. Este trabajo abre la posibilidad de hacer modelación numérica de problemas de valor de contorno de estructuras que presenten una junta fría y de esta manera estudiar su influencia en la estabilidad global

Palabras clave: Junta fría, modelo constitutivo, esfuerzo, deformación, elementos finitos

1. Introduction

A smooth cold joint of concrete is a weak plane caused by an interruption in the casting process. It is widely recognized that difficulties in the constructive method of concrete structures can entail cold joints that evidently impair the structural performance, since it reduces the system's stress-strain characteristics (Harsem, 2005). The reduction of the system's maximum resistance depends on factors such as the inclination of the cold joint, the cold joint formation time, and the relationship between the inclination of the cold joint and the direction of the state of the stresses (Wall and Shrive, 1988; Rathi and Kolase, 2013; Tapkire and Kumavat, 2015). The loss of mechanical properties caused by the presence of cold joints can compromise the structural integrity of the building (Volz and Olson, 2008). Although the aspects involved in the cold joint issue are quite clear, it is not yet as clear in what proportion the peak resistance of concrete is reduced when there is a cold joint, and neither its evolution during the setting time. Regulations in several countries indicate that if a structural element with a cold joint has to be built, it should be performed in such a way that the interruption will not interfere with the mechanical behavior nor the stability. The treatment of a cold joint is made during a controlled process in the construction. However, if a cold joint is found and it is unknown whether it was improved with adequate techniques, an unfavorable scenario is presented due to the uncertainty regarding its mechanical behavior.

This work addresses the problem of smooth cold joints from two complementary perspectives:

1. The loss of resistance due to the occurrence of cold joints in concrete is quantified through an extensive experimental program with concrete cylinders.

2. A constitutive model is proposed and its performance is analyzed in relation to the capacity to simulate the viscous behavior of concrete that allows generating modelling bases for boundary value problems in real structures and, consequently, its future use in the design of concrete structures.

This paper shows a lower limit of the mechanical behavior of the interruption, since both the experiments and the numerical analysis are made with smooth cold joint. The

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smooth cold joint is the worst scenario and, therefore, it establishes minimum values that must be considered when facing the analysis of a cold joint and when the fact of being treated or not is unknown.

2. Experimental tests

Ultimate uniaxial compressive strength tests and indirect tensile strength tests were performed in standardized concrete cylindrical specimens of 15cm diameter and 30cm long, on which smooth flat cold joints were induced horizontally, diagonally and vertically. These cold joints had formation times of 2, 4, 6 and 8 hours and metallic molds were used to give each inclination; therefore, the resulting plane was flat. Likewise, the ultimate strength tests were carried out on the samples at the ages of 3, 7 and 28 days. Cylinders with horizontal and diagonal cold joint were subjected to uniaxial compressive strength tests and cylinders with vertical cold joints were subjected to indirect tensile strength tests. Figure 1 shows a summary of these experimental tests.

The process for making these cylinders consisted in preparing a fresh concrete mix for the first halves of cylinders with cold joints; some complete cylinders were also made in order to rely on intact core samples. Before the formation time of cold joints was completed (2, 4, 6 and 8 hours), a second batch of fresh concrete was prepared in order to complete the missing halves and thus form the specimens with cold joints, and some intact cylinders of this second mix were also cast. Intact cylinders with cold joints were stripped once they had the proper consistency, they were taken to a curing pool at constant temperature and were taken out at the preassigned ages of 3, 7 and 28 days in order to be subjected to the uniaxial compressive strength or indirect tensile strength tests, depending on the case. In every tested cylinder with cold joint, two core samples without joint of the same batch were loaded up to failure so as to establish the percentage of the loss of resistance. For the uniaxial compressive strength test in cylinders with diagonal and horizontal joint, once the samples were withdrawn from the curing pool, a retainer with a neoprene pad was put on both ends, the cylinder was put vertically and aligned with the hinge joint of the upper plate of the testing machine. The press applied the load at a speed of 0.25 MPa/s until the cylinder failed and the strength was obtained at the moment of cracking. For the indirect tensile strength test of the sample with vertical cold joint, the cylinder was put with the axis oriented horizontally and the load was applied all along the height of the cylinder and parallel to the joint's plane. Figure 2 illustrates how the load was applied to the cylinders with cold joint during the tests.

Once the failure data from the different cylinders with cold joint were available, they were compared with those obtained from the cylinders without cold joint and the percentage of loss of resistance was calculated as shown in Figure 3, 4 and 5.

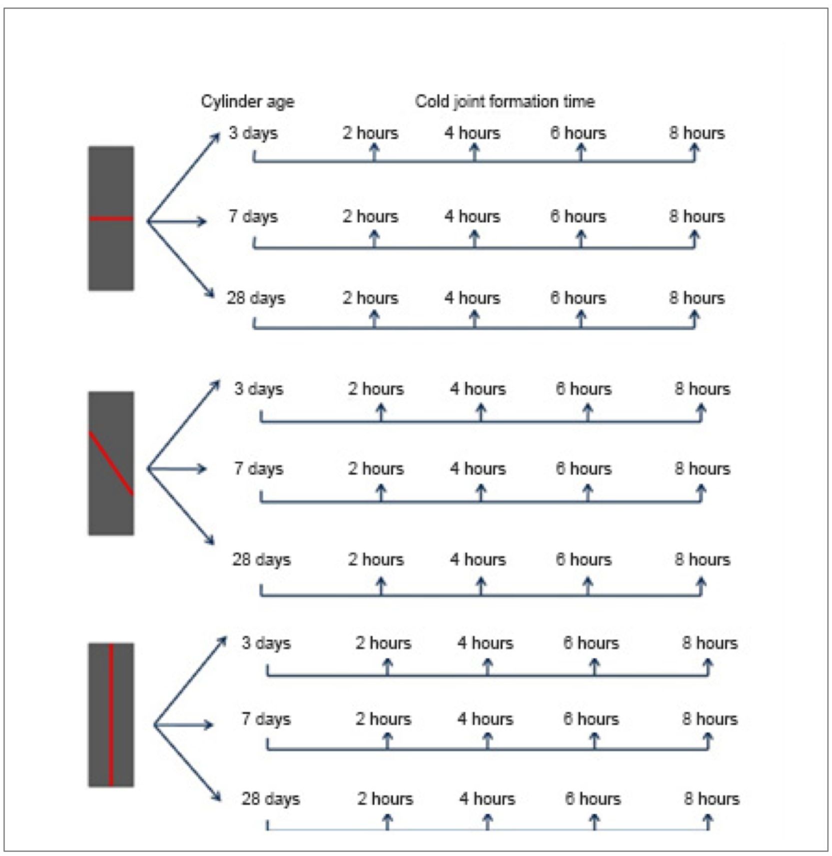

Figure 1. *Experiments of concrete cylinders with cold joint*

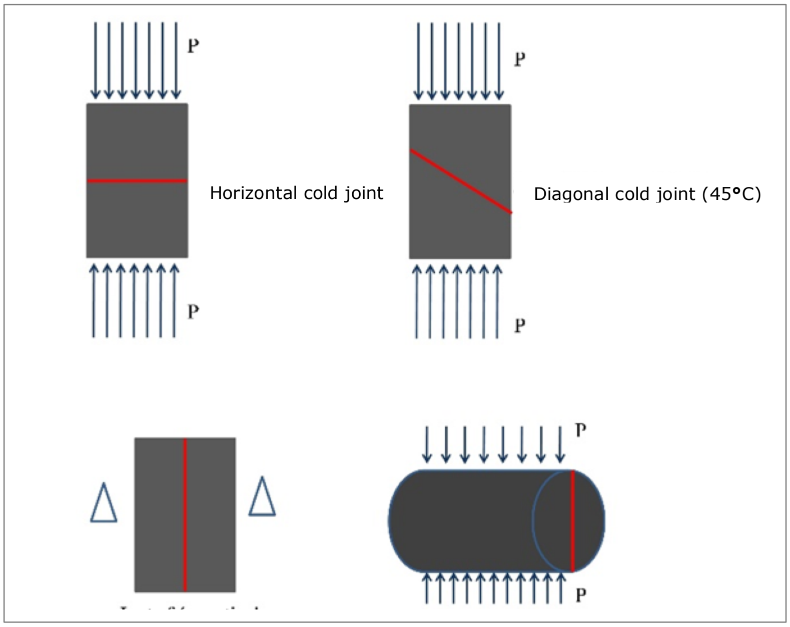

Figure 2. *Loading of cylinders with cold joint*

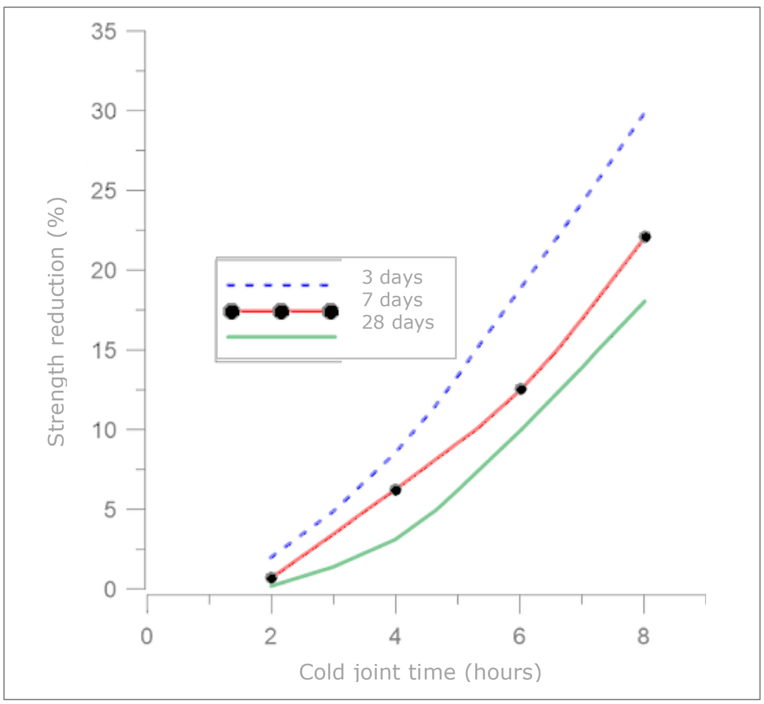

Figure 3. *Compressive strength reduction due to diagonal cold joint in standardized concrete cylinders*

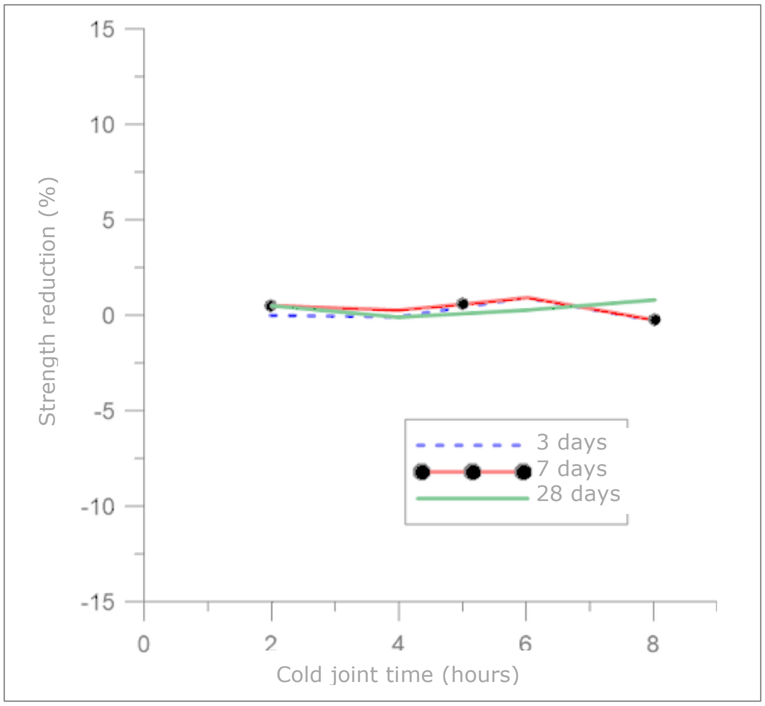

Figure 4. *Compressive strength reduction due to horizontal cold joint in standardized concrete cylinders*

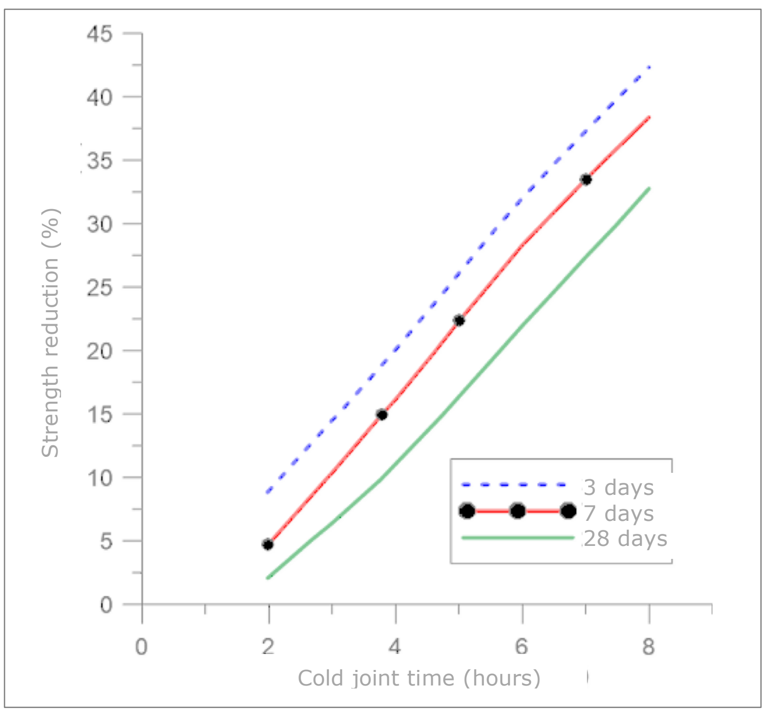

Figure 5. *Indirect tensile strength reduction due to vertical cold joint in standardized concrete cylinders*

A significant loss of resistance is observed regarding the compressive strength of cylinders with diagonal joint, where failure is reported along the cold joint. Cylinders with horizontal joint do not lose resistance and the way they fail is the same as in the intact cylinder. Cylinders with vertical joint report the highest loss of resistance and failure also occurs along the plane of the joint. The previous results are qualitatively similar to those reported by Rathi and Kolase (2013) and Tapkire and Parihar (2014), based on the different inclinations of the cold joint; however, the percentages of loss of resistance are different since the materials' conditions are different and the treatment given to the surface of the cold joint in this work produces low-roughness surfaces in relation to the treatment used by Rathi and Kolase (2013) and Tapkire and Parihar (2014). The percentages of loss of resistance reported by Rathi and Kolase (2013) and Tapkire and Parihar (2014) are maximum 17%, while those reported in this work are maximum 45%.

3. Proposed constitutive model

This section proposes a constitutive model for concrete with the potential of including the variation of the stress-strain behavior that varies over time. The results shown in the experimental section were useful to calibrate the proposed constitutive model and thus evaluate their performance in order to model the mechanical behavior of concrete with the occurrence of a cold joint in a boundary value problem.

Many mathematical models have been proposed that relate the stresses and deformations of concrete (Kunieda and Srisoros, 2007; Asamoto and Ishida 2006; Babu and Benipal 2005). The problem with those models is that they have been proposed for the uniaxial condition only, so their applicability in boundary value problems, as simulation of structures with multiaxial stress fields, is limited for their implementation in a finite element program. In order to overcome this limitation, this work proposes a combined constitutive model, which includes the usual viscoelastic behavior plus a reactive one (Suter and Benipal, 2007) that aims at simulating the variation of the mechanical properties as concrete sets.

(Suter and Benipal, 2007) developed a time-dependent viscoelastic model using a Maxwell material parallel to the so-called "reactive" model. This model allows varying the concrete's properties over time and phenomena can be simulated where there is loss or gain of stiffness due to the existence of a chemical reaction inside the material causing physical changes. Several phenomena can make concrete to lose or gain mechanical properties as time goes by, such as the chemical attack of harmful substances and the cement's hydration process, which derives in the stiffening of concrete. Whatever the reaction causing physical changes in the concrete has a variable speed over time, which is ruled by an equation α *that determines the percentage of the completed reaction, also called volume function (Suter and Benipal, 2006). In this particular research, the "reactive" element represents the part of concrete that is in a plastic state and which stiffens by parts over time, according to a specific volume function.*

The viscoelastic model is defined by the Young's modulus E*, the Poisson ratio* ν *and the parameters* $\bar{g}_i^P$, $\bar{k}_i^P$ *and* τ_i *that indicate how the stiffness modulus changes over time while loads are applied (Simulia, 2015). This modulus is able to simulate time-dependent phenomena such as creep or stress relaxation of concrete. The model considers that if the material is subjected to a time-dependent shear deformation* $\gamma(t)$*, the response will be a time-dependent shear stress* $\tau(t)$ *according to Equation 1:*

$$\tau(t) = \int_0^t G_R(t-s)\dot{\gamma}(s)ds \tag{1}$$

Where G_R *is the time-dependent shear relaxation modulus.*

If the shear deformation $\gamma(t)$ *is applied instantaneously and is held constant for some time* t*, Equation 1 is reduced to 2:*

$$\tau(t) = G_R(t)\gamma, \text{con } \dot{\gamma} = 0 \; y \; t > 0 \tag{2}$$

The variation over time of the shear relaxation modulus can be defined in a more simple way, as in 3:

$$g_R(t) = G_R(t)/G_0 \tag{3}$$

Where $G_0 = G_R(0)$*, that is, the instantaneous shear relaxation modulus. Equations that define the volumetric behavior of the material have the same explanation, thus the hydrostatic pressure ρ is given by 4:*

$$\rho(t) = -K_0 \int_0^t K_R(t-s)\,\dot{\varepsilon}^{vol}(s)ds \tag{4}$$

Where K_0 *is the instantaneous elastic bulk modulus,* $K_R(t)$ *is the dimensionless instantaneous bulk relaxation modulus and* $\dot{\varepsilon}^{vol}$ *is the volumetric deformation. The following expressions are the same as those for the shear behavior applied to the volumetric case.*

The numerical implementation of the proposed constitutive model was made with the ABAQUS software, where the dimensionless relaxation modulus $g_R(t)$ *and* $k_R(t)$ *are approximated as a Prony series expansion when defining the above mentioned parameters* $\bar{g}_i^P$, $\bar{k}_i^P$ *and* τ_i*. The expansion of the shear relaxation modulus is given by 5:*

$$g_R(t) = 1 - \sum_{i=1}^N \bar{g}_i^P \left(1 - e^{-t/\tau_i^G}\right) \tag{5}$$

Additionally, the expansion for the volumetric behavior is given by 6:

$$\rho = -K_0\left(\varepsilon^{vol} - \sum_{i=1}^N \varepsilon_i^{vol}\right) \tag{6}$$

Where:

$$\varepsilon_i^{vol} = \frac{\bar{k}_i^P}{\tau_i^K}\int_0^t e^{-s/\tau_i^K}\varepsilon^{vol}(t-s)ds \qquad (7)$$

The ABAQUS software assumes that $\tau_i^G = \tau_i^K = \tau_i$ *. When entering parameters* $\bar{g}_i^P$ *,* $\bar{k}_i^P$ *and* τ_i *plus the Young's modulus and the Poisson ratio, the viscoelastic behavior of the material is defined. It is important to highlight that the viscoelastic model presented herein is able to change the material's mechanical properties over time, while load is applied. Therefore, it is necessary to improve the viscoelastic model aimed at simulating the stiffening of concrete where there is a change of mechanical properties over time without the application of forces. The Suter and Benipal model allows simulating the stiffness of the material from its fresh state until it becomes a material whose mechanical characteristics have a better performance, by incorporating the variation of concrete elastic properties (*E *and* ν*) over time, in order to include it in the viscoelastic model later on. The mathematical function for the evolution of the elastic modulus (Equation 8) included in the model was calibrated based on the experimental results of the previous section.*

$$E(t) = 6375t^{1/3} \qquad (8)$$

With E *in MPa and* t *in seconds.*

This ratio was used to calculate the Young's modulus of each one of the two layers of concrete of the cylinders with cold joint at failure.

The Poisson ratio that concrete should have over time is also known, according to the Equation 9 proposed by Reinhardt and Hilsdorf (2001):

$$\nu(t) = \nu_0 - (\nu_0 - \nu_{28})\beta(t), \qquad (9)$$

$$\beta(t) = \sqrt{e^{s\left(1-\sqrt{28\frac{t_1}{t}}\right)}} \qquad (10)$$

Where t_1=86400 s, s=0.38, ν_0=0.4999 and ν_{28}=0.20

Figure 6 shows the curve representing the variation of the elasticity modulus and the Poisson ratio of the concrete used in the present work.

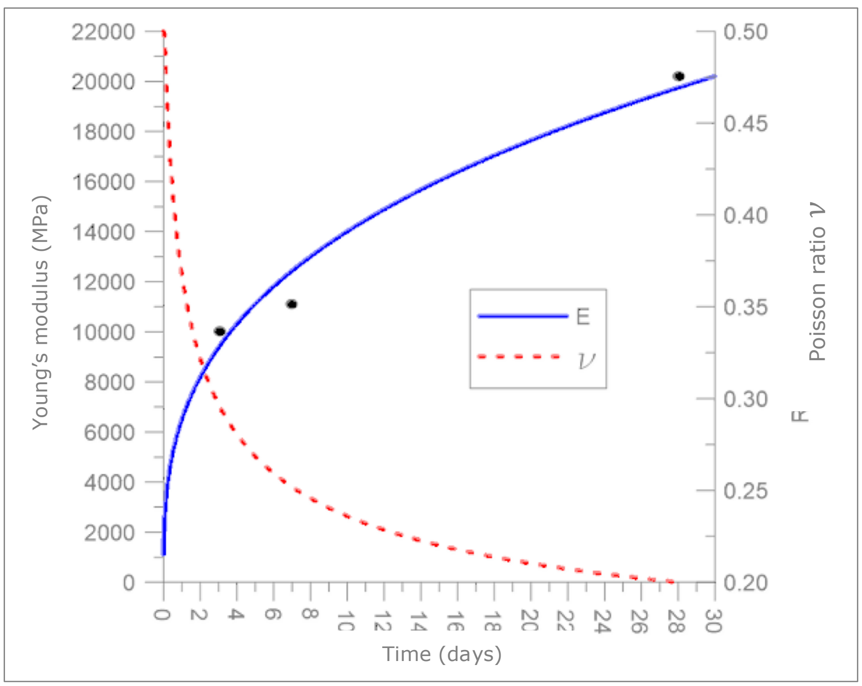

Figure 6. *Variation of the Young's modulus and the Poisson ratio over time for the proposed constitutive model*

The material's parameters at different ages of concrete according to the theory proposed by Suter and Benipal can be included within the viscoelastic model and thus a new combined constitutive model is proposed, which includes, on the one hand, the viscous behavior of concrete and the dependence on the load speed and, on the other hand, it allows including the variation of the elasticity modulus E and the Poisson ratio t over time. This does not only allow to consider the concrete's stiffening process but also the stiffness differences between two volumes of materials forming a cylinder, which have been cast at different times and subjected to loads at different ages.

In order to observe the behavior of the proposed constitutive model in cold joint conditions, the calibration of experimental uniaxial compressive tests with concrete cylinders at 3 days of age was undertaken (Figure 7). Figure 7 shows an acceptable performance of the constitutive model under elemental test conditions, both for deformability and ultimate resistance. After obtaining the parameters of the models that best represent the properties of the concrete used in the laboratory, the same experimental tests were run in cylinders with cold joint using the ABAQUS finite element method.

The cylinder models with cold joint are formed by two volumes of different materials having the characteristics according to their age, and obtained from the variation curve for the elasticity modulus and the Poisson ratio over time (Figure 6). In a cylinder with cold joint formation time of 2 hours and subjected to the load test at 3 days of age, one of the layers is assigned the properties of concrete at 3 days and the other layer, the properties of concrete at 3.08 days, that is, with a difference of 2 hours; and so, properties are assigned in the same way to each cylinder with cold joint. These models are subjected to a load of 0.25 MPa/s until they reach a maximum unit strain of 0.002. In these simulations, intact cylinders were also loaded with the aim of observing how the behavior changes when the cold joint is induced.

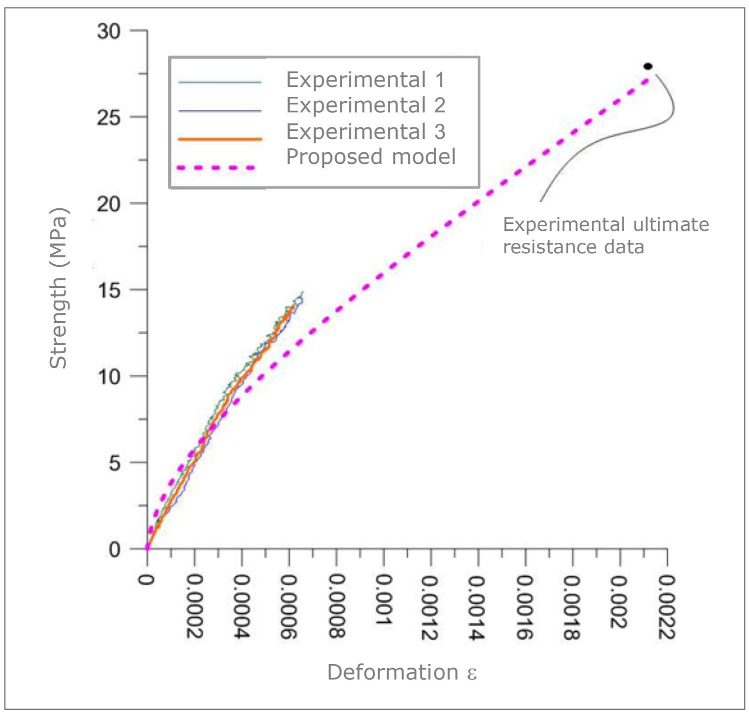

***Figure 7.** Axial stress-axial deformation ratio at 3 days. Results from 3 tests under the same conditions and the proposed model*

4. Numerical simulations – comparison with experiments and discussion

Cylinders without cold joint subjected to uniaxial compressive strength show stresses only in the direction of the force applied and, additionally, they are equal along the height of the specimen for any load magnitude applied. Since the cylinder is not laterally restrained, no stresses in these directions are generated and there is free deformation due to the Poisson's effect. Therefore, there are no stresses or strains in the shear components. When the same load is applied to a cylinder with diagonal cold joint, a concentration of stresses and strains is observed, typically in certain areas close to the joint. Figure 8 shows typical diagrams of axial stresses for an intact cylinder with diagonal and horizontal cold joint.

These stress concentrations are observed in a lesser degree as the joint formation time is lower. This situation is illustrated in Figure 9, which shows the behavior of the axial stresses and strains along the height of the cylinders with different times of formation for a diagonal cold joint located at approximately 10cm on the specimen's height. All these curves correspond to a 3-days concrete. It can be appreciated that the horizontal line corresponds to an intact specimen where there is no stress variation along the cylinder, but when there is a cold joint and its formation time is higher, curves go increasingly farther away from the horizontal line in the interface zone of the two concretes.

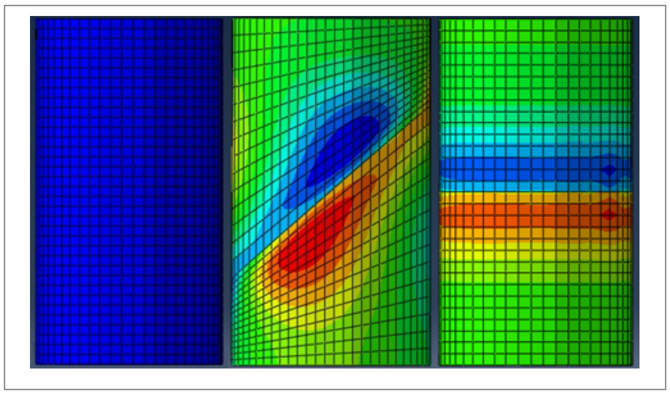

Figure 8. *Diagram of axial stresses on an intact cylinder (left), with diagonal cold joint (center) and horizontal cold joint (right)*

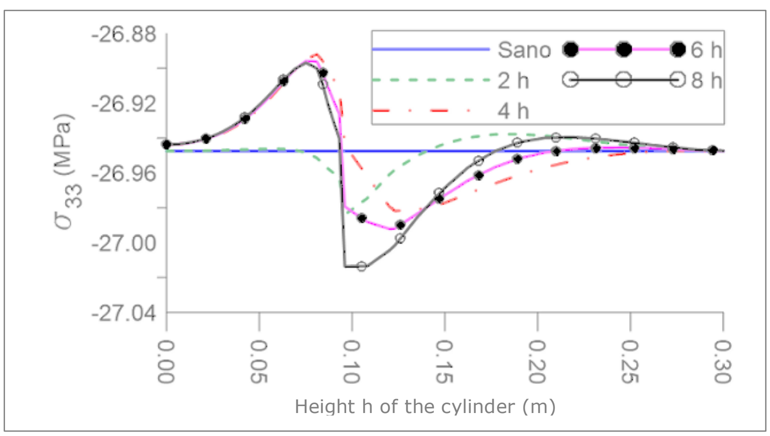

Figure 9. *Axial stresses along the height of the cylinders for different cold joint formation times*

A significant fact in the models is that when subjecting the specimens with cold joint to uniaxial compressive strength, shear stress components are evidenced that reduce their resistance; these are greater when the age of concrete is lower and the joint formation time is higher, as illustrated in Figure 10. This shear stress trends are consistent with the experimental data of the cylinders with diagonal cold joint, where a higher loss of resistance is evidenced for specimens tested at early ages with long joint formation time (Figure 3).

At the end of the loading stage it is possible to obtain the stress tensors in the higher concentration areas for diagonal and horizontal joints. The stress tensors can change the base in relation to the horizontal plane of the ABAQUS model, with the aim of analyzing the variation of the shear components based on the base angle change. Figure 11 shows the maximum shear stress in the joint area of a cylinder in relation to the base angle change of the stress tensor. It is important to note that this is presented only for the case of the diagonal joint, since the result for the horizontal cold joint is very close.

It is evidenced that the highest shear stress component is produced when rotating 45° the base of the stress tensor with respect to the horizontal; in fact, this angle coincides with the orientation of the studied diagonal cold joint. This explains the loss of resistance to the uniaxial compressive strength of cylinders with 45°diagonal joint of the experimental tests (Figure 3). In the case of cylinders with horizontal cold joint there was no loss of compressive strength, since the higher shear stresses are also present at 45°, but this angle does not coincide with the plane of the joint and, therefore, the behavior of the sample subjected to compressive strength is similar to an intact cylinder without joint.

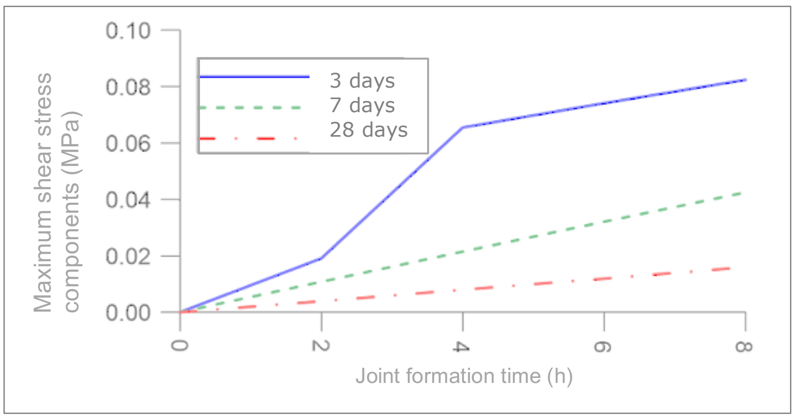

Figure 10. *Shear stresses on cylinders depending on joint formation time and concrete age*

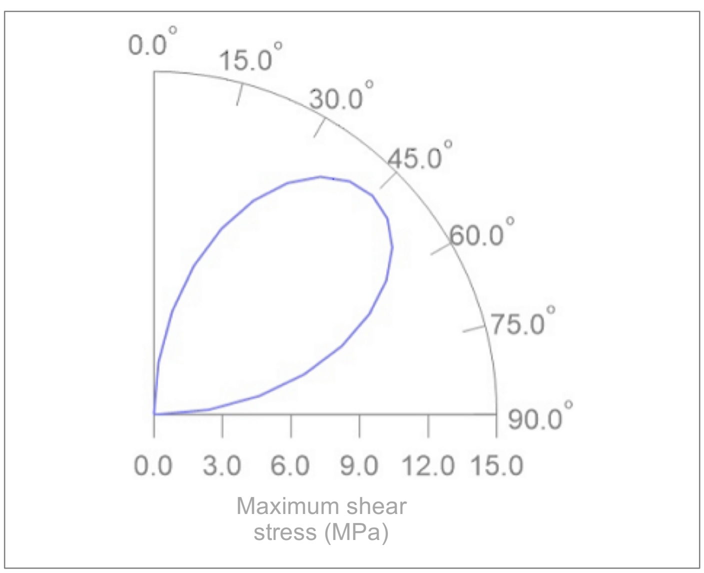

Figure 11. *Maximum shear stress component with respect to the rotating angle of the base*

The stress concentration is due to the fact that in the cylinder with cold joints there are differences between the elasticity modulus of the materials forming the first and second concrete volume; because there is a time gap between each placement, their ages and stiffness are also different. In the case of cylinders with cold joint, there are shear stresses as a consequence of the difference in stiffness in both concrete volumes, being higher at early ages and longer joint formation times. In turn, this is explained by the setting speed of concrete, which is very fast during the first days but at further ages the process becomes much slower tending almost to its standstill. This is why there will be a greater difference between the elasticity modulus of concretes forming a cylinder at early ages and longer pouring times, between one and the other, and the case of two older concretes with shorter joint formation time. A larger stiffness difference leads to a greater amount of shear stress and, therefore, more loss of resistance in the sample. It is important to highlight that this behavior is very similar in the cylinders with horizontal and diagonal joints.

Figure 12 illustrates the difference in the elasticity modulus of two layers of concrete forming the cylinder with cold joint, which depends on the joint formation time and the age of concrete. It can be seen that there are greater stiffness differences in early age concrete cylinders than in older ones, but it is also evidenced how these differences change with the joint formation time. The increase speed of the stiffness difference with respect to the joint formation time is higher for early age cylinders than for older age cylinders, and the same occurs with the shear stresses, as shown in Figure 10.

Furthermore, an analysis of Von Mises' stress invariant is made in relation to the shear inclination on a sample with cold joint. The cylinder models can be cut at different angles and on the resulting surfaces we find the stress invariant of Von Mises over the lines along the generated plane, as shown in Figure 13. The average stress results of Von Mises over these lines were the following:

* $\sigma_{Von\ Mises}$ in a 35° inclined shear plane = 26.95 MPa

* $\sigma_{Von\ Mises}$ in a 45° inclined shear plane = 27.05 Mpa

* $\sigma_{Von\ Mises}$ in a 55° inclined shear plane = 26.95 MPa

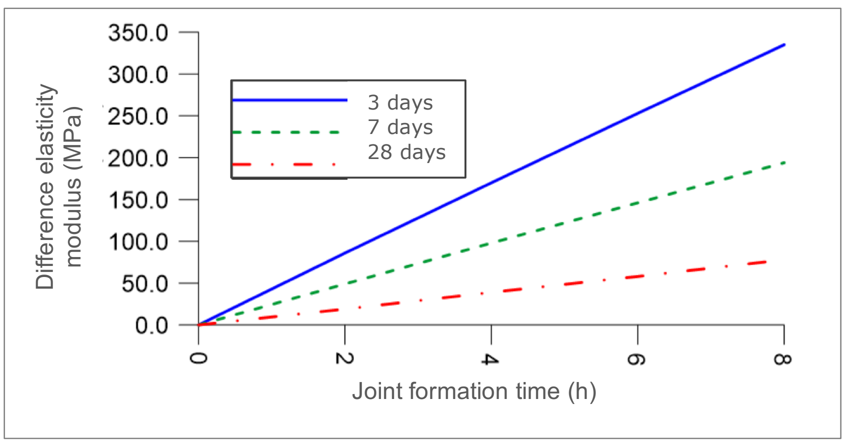

Figure 12. *Evolution of the difference in the elasticity modulus of concrete volumes in cylinders with cold joints*

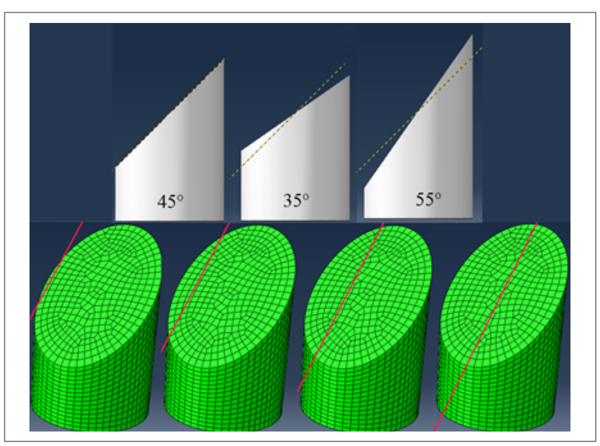

Figure 13. *Lines over planes with different inclinations on which there are Von Mises stresses in cylinders with cold joint*

The highest Von Mises stresses are reached on a plane that cuts the cylinder with a 45° inclination in relation to the horizontal, which means that this surface has the highest deviatoric stresses that cause the materials to fail. The plane on which the highest deviatoric stresses are reached is consistent with the plane of the diagonal cold joint of the experiments, which reinforces the explanation given to a greater loss of resistance in samples with diagonal joints than in samples with horizontal joints.

Furthermore, the stress concentration in a cylinder with diagonal cold joint is given in this interface and towards the sample's surface or shaft, where there is more probability of finding voids due to the concrete's compacting difficulties in this area. This situation enables the material's rupture with lower compressive stresses than in an intact cylinder made with the same mixture. In cylinders with horizontal cold joint, the maximum stress concentrations are found inside the cylinder, where there is a better compaction and placement of the fresh mixture; this condition helps the sample to behave in a similar way than in one without interruptions. Figure 14 illustrates the areas with highest stress concentrations in cylinders with diagonal (left) and horizontal (right) cold joints, cutting through the plane of the interface of both concretes.

The results are not consistent with those obtained experimentally, because the constitutive model used considers that the behavior of the material is the same when subjected to tensile or compressive strength, although concrete has actually a different behavior in both directions. In this sense, it is worth noting that the simulation of concrete with cold joints, using a viscoelastic model to relate the material's stresses and strains, only shows congruent results when the material is subjected to compressive strength.

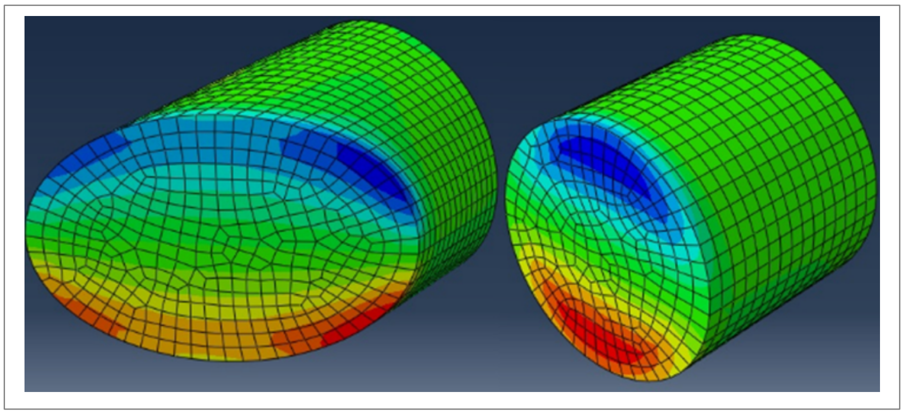

Figure 14. *Areas with highest stress concentrations on cold joints. Diagonal joint (left) and horizontal joint (right)*

5. Conclusions

The experimental tests demonstrated that cylinders with horizontal cold joint subjected to compressive strength do not show a loss of resistance in any case. Cylinders with diagonal joint subjected to compressive strength and with vertical joint subjected to indirect tensile strength did present a great loss of resistance (up to 30% and 42% respectively), which was higher with long joint formation times and early ages of the sample.

Concrete cylinders with cold joint subjected to uniaxial compressive strength present stress and strain concentrations in the proximity of the joint. The magnitudes of the concentrated stresses are higher as the stiffness differences between the concrete volumes forming the cylinder are higher. The biggest stiffness differences are given in early age cylinders with long joint formation times, and they are smaller in mature cylinders with shorter joint formation times, due to the concrete's decreasing setting speed. This explains why a cylinder with a specific joint formation time loses a higher percentage of compressive strength at an earlier age rather than at an older age.

The highest loss of the percentage of compressive strength in a cylinder with diagonal cold joint rather than in a cylinder with horizontal joint can be explained because the greatest components of shear stress and Von Mises stress are presented in a 45°angle, which is consistent with the surface inclination of the diagonal joint.

6. Acknowledgements

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