THOUGHTS UPON SHRINKAGE INDUCED CRACKING OF CONCRETE. A STRUCTURAL DESIGNER PERSPECTIVE

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Abstract

Shrinkage of concrete is a natural phenomenon, with several well known mechanisms. However, restrained shrinkage is the challenging problem both to design and construction practice. External and/or internal restraint to shrinkage generates tensile stresses that may easily result in time-dependent excessive cracking states, compromising the durability of the structures. After a brief introduction, the paper presents aspects concerning cracking states induced by restrained shrinkage of concrete, met in the last decade in Romania. Consequently, a new design guide was released, as part of the Romanian technical regulations system. Next, the paper presents a synthetic critical review of the guide.

Résumé

Le retrait du béton est un phénomène naturel, issu de plusieurs mécanismes bien connus. Pourtant, le retrait généré reste un défi à la fois pour la conception et les méthodes constructives. Les entraves au retrait, d’origine externe ou interne, génèrent des contraintes de traction qui produisent facilement des états de fissuration évolutifs inacceptables, compromettant la durabilité des ouvrages. Après une brève introduction, l’article présente des exemples caractéristiques de fissuration due au retrait généré du béton observés en Roumanie depuis dix ans. En conséquence, un nouveau guide de conception a été publié au sein du corpus Roumain de règles techniques. Une synthèse critique de ce guide est présentée.

1. INTRODUCTION

Durability design is often neglected in current design practice, even if it is a major component of the holistic sustainable design approach. The primary interest in design is to meet the safety performance indicators and compliance criteria by specific Ultimate Limit States structural analyses. Because direct calculations to Serviceability Limit States are relatively complicated by the non-linear behaviour of concrete, cracking, tension stiffening, creep and shrinkage, the indirect design by simply applying the codes provisions is preferred. However, often this approach does not cover the entire range of phenomena that can be met to a specific work. Shrinkage of concrete is a natural phenomenon, with several well known mechanisms (Fig. 1). External and/or internal restraint to shrinkage generates tensile stresses that may easily result in time-dependent excessive cracking states, compromising the durability of the structures.
As shown hereafter, many excessive cracking cases were noticed during the last decade due to restrained shrinkage of concrete. Besides poor design, poor construction practice and inadequate maintenance have been critical issues which prevented to ensure the durability and reliability of the reinforced concrete structures. The background of such a reality was found in the educational system and the lack of specific technical information.

The authors hope that starting with 2011, the new design guide, integrated in the national technical regulation system, fully compatible and complementary to the Eurocodes series, will generate effects that will be noticeable on medium and long term.

2. SOME CASE STUDIES ABOUT EARLY AGE CRACKING OF CONCRETE DUE TO RESTRAINED SHRINKAGE

Almost instant cracking (e.g., within a couple of hours after formwork removal) was found at the mass concrete elements from a motorway works (Fig. 2). Figure 3 shows the typical cracking patterns registered at the abutments and piers. The largest cracks were registered around the middle of the elements height, and their width was well above the admissible limit of 0.3 mm (i.e., the maximum crack width reached 0.43 mm after a week). Six months later, the cracks width was reduced up to 30 % due to creep of concrete.

As shown by Mircea et al. [1], the main cause of the cracking was the restrained volume change caused by thermal shrinkage of concrete. The heat generated by the hydration of the Portland cement led to a thermal shock, with temperature drops up to 40 °C at 4 days age of concrete. Thermal shrinkage was not considered in design and the shear reinforcement (i.e., the reinforcing ratio was 0.0026) was not enough to ensure the distribution of the cracking to many smaller cracks. Mix design was also inappropriate (e.g., 460 kg/m³ of cement II 32.5R, w/c=0.38 and maximum aggregate size 31 mm). Moreover, early formwork removal was not supplemented by an adequate concrete treatment, and the elements lost very fast the excess water. The analysis showed that the cracking states will became stable after 6 months, and routing and sealing of the cracks exceeding the allowable limit restored the durability of the elements.
Another case refers to the basement walls of an industrial building (Fig. 4 and 5). Built during a hot summer, a cracking state, apparently chaotic, installed in the basement reinforced concrete walls when concrete reached the age of about one month. In two years, apparently on the ground given by the vibration induced by nearby heavy traffic, the cracking state became severe, as shown in Fig. 6. Besides, underground water ingress also occurred in the basement.
Atypical horizontal cracks developed in the 40 cm thick boundary walls, 0.3 mm to 0.5 mm in width. Vertical cracks occurred in both the boundary and inside 25 thick walls, crack spacing varying between 2.0 m and 3.0 m. The maximum crack width was 3.5 mm. The investigation revealed that the main responsible factor is the restrained drying shrinkage. Even if the length of the building is about 60.0 m, no expansion/contraction joint was considered and no attention was given in design to the restrained shrinkage of concrete. The careless
construction emphasized the problem at an early age of concrete. The horizontal cracks proved to in fact poor treated technological joints. After two more years of monitoring, while the underground water problem was resolved, the cracks with the width less than 0.05 mm were just sealed with an extensible gypsum based coating (52 % of the total number), the cracks opened between 0.05 mm and 2.0 mm were injected with epoxy resin (28 % of total), and the larger cracks were injected with cement paste (20 % of total cracks). Areas with cracks width more than 1.0 mm were also strengthened with bidirectional glass fibre sheets.

![Cracking pattern in the most cracked walls (maximum crack width in mm)](image)

Figure 6: Cracking pattern in the most cracked walls (maximum crack width in mm)

Restrained shrinkage cracking occurred also at the technical floor of a cash & carry shopping centre (Fig. 7). The prefabricated structure has a length of about 80 m, and the intermediate slab of the technical floor was made by prefabricated units and a 15 cm top layer of cast in situ concrete. The maximum global restraint to shrinkage occurred in the middle of the structure. The lack of contraction joint led to its natural creation in the middle of the slab system (Fig. 8 and 9.a). The precast units were disarranged (Fig. 8) and the drywalls cracked too (Fig. 9.b). The discrete restraint provided by the columns induced parasite stress states in the main structure.

![Cash & carry shopping centre](image)

Figure 7: Cash & carry shopping centre
Besides many other defects, restrained shrinkage cracking are common at slabs on ground. Fig. 10 shows typical cracks caused by drying shrinkage restrained by the base layer. Poor concrete mix design (e.g., high water-cementitious materials ratio, wrong dosage of the aggregates, use of inappropriate aggregates like shale and siltstone, with considerable expanding potential) are very often met in the pavements current practice. Fig. 11 shows another type of shrinkage cracking specific to slabs on ground. Crazeing is a network of fine cracks on the concrete surface that enclose small (12 to 20 mm) and irregular polygonal areas. Shallow, often only 3 mm deep cracks occur throughout the panel surface due to restrained drying shrinkage of the surface layer after set (usually apparent the day after placement or by the end of the first week). It is often associated with the following poor practices: over finishing the new surface or finishing while there is bleed water on the surface, mixes with high water-cementitious materials ratios (mixes that are too wet), late or inadequate curing, spraying water on the surface during finishing and sprinkling cement on the surface to dry bleed water. Map cracks permit water and chemicals to enter the concrete surface, so extensive map cracking results in short durability due to the freeze-thaw cycles. Given the Romanian specific conditions, with large temperature gradients over a year, cracking due to restrained volume change is very likely to occur in pavements. Wrong maintenance strategies are also often met. Instead of injecting and sealing the excessive cracks, these are allowed to
extend. When the condition state becomes unsatisfactory, pavement panels are simply replaced, and the cycle continues with considerable costs.

![Figure 10: Cracking of slabs on ground due to restrained drying shrinkage](image1)

![Figure 11: Map cracking due to restrained drying shrinkage of the top concrete layer](image2)

3. CRITICAL REVIEW OF THE NEW DESIGN GUIDE

The guide establishes the operational rules for application of the principles and general rules provided by the Eurocodes, mentioned as reference norms, with regard to the control of cracks generated by restrained shrinkage in mass elements, shear walls and bridge superstructures. The first part of the guide presents the mechanisms of free shrinkage of concrete. Even if restraint generates tensile stresses only due to thermal contraction, autogenous and drying shrinkage, for informative purpose the mechanisms of chemical shrinkage, plastic and aggregate settlement contraction, and carbonation shrinkage are also mentioned.

The next chapter presents in a synthetic manner the factors that influence the free shrinkage of concrete. Some of graphs, tables and equations are used for the preliminary design of concrete and estimation of maximum temperature of concrete, procedures pointed
out by two applications, introducing two design scenarios (i.e., with and without cooling of the concrete ingredients). The dosage of Portland cement influence upon the hydration heat is considered linearly proportional. Reference graphs are given in relation with the influence of the primary mineral compounds of Portland cement upon the adiabatic temperature rise in concrete, and the rate of hydration related to the fineness of cement. In this respect, more research should be done in order to certify the conformity of the common Portland cement mentioned by EN 197-1 [2] with regard to its mineralogical composition. Mineral additions are considered on the ground of the k value concept. The influences of the water content, the aggregates, the relative humidity and the ratio between the volume of the element (V) and the surface exposed to drying (S) are also revealed by synthetic graphs and tables. Curing of concrete, in general is related to EN 206-1 [3]. Supplementary recommendations are given for the cooling of the concrete ingredients and cooling of concrete after casting, in order to reduce the thermal shock at mass concrete elements. Concrete mix design ends the chapter, a step by step procedure being emphasized for the preliminary mix design by the absolute volume method. For the concrete specification, recommendations are given to the following aspects to be considered in design:
- The control of the cement type to be used and its strength properties and hydration heat generation properties;
- Cooling of the concrete ingredients and of the fresh concrete;
- A longer curing period after concrete casting (e.g., a period of at least 3 weeks is recommended) and cooling of the concrete surface.

The time dependent free concrete shrinkage models are introduced in the chapter. The total shrinkage strain to be considered in design of mass concrete elements is

\[ \varepsilon_{ct}(t) = \varepsilon_{ca}(t) + \varepsilon_{cn}(t) + \varepsilon_{cd}(t) \]  

(1)

where \( \varepsilon_{ct}(t) \) is the thermal contraction strain, \( \varepsilon_{ca}(t) \) is the strain caused by autogenous shrinkage and \( \varepsilon_{cd}(t) \) is the drying shrinkage strain. The effective modulus of elasticity of concrete includes the creep effects.

The autogenous and drying shrinkage analytical models are the ones given by EN 1992-1-1 [4] for ordinary concrete and by EN 1992-2 [5] for high strength concrete. The same norms are considered for the creep models. The thermal strain is estimated in a four steps procedure, considering the concrete temperature at casting, the minimum concrete temperature of concrete after casting and in service, and the temperature rise in the concrete mass due to cement hydration. Following variables are taken into account: the type of cement, the V/S ratio, the type of formwork, the climatic zone according to EN 1991-1-5/NA [6], the cement content and the fineness of cement and the bedrock temperature. The maximum temperature drop is recommended to be considered at the age of concrete of one week. For various further applications are continuing the design process started with the concrete mix design for a specific element, up to the associated shrinkage strains specific to each scenario.

Cracking control by structural analysis refers to mass elements (i.e., wall type and mat foundation), shear walls and bridge superstructures. For walls, unless a numerical analysis is performed, a shear base restraint is recommended, as emphasized in Fig. 12. Internal restraint given by the steel rebars is considered only against autogenous and drying shrinkage. As mentioned by Mircea et al. [1], the base restraining factor considered at the time by ACI 207.2R-95 [7] was too conservative (Fig. 14). Tests and numerical simulations performed by Mircea [8] (Fig. 13) showed reasonable results considering a pure shear transfer.
a. base restraint through a shear mechanism

b. redistribution of the base restraint with cracking sequences

Figure 12: Basic assumption for wall type elements restrained at the base

While for bridge superstructures the global control is ensured by bearings and expansion joints devices, for the deck restraint the axial model is assumed (Fig. 14). As shown in Fig. 15, mat foundations are restrained only by the friction with the base. Details, explicit
formulas, drawings and applications are introduced in order to make the documentation very accessible.

\[ \sigma_{\text{residual}} = 0 \]

\[ \Delta L_{\text{free}} \]

\[ \sigma_{\text{residual}} > 0 \]

\[ \sigma_{\text{residual}} < 0 \]

Figure 14: Axially restrained shrinkage

\[ \Delta L_{\text{restrained}} \]

\[ L/4 \quad L/4 \quad L/4 \quad L/4 \]

Figure 15: Friction base restraint and cracking sequences at mat foundations

4. CONCLUSIONS

Restrained volume contraction of concrete structure is not yet fully regarded as a major component of a holistic design. However, in the last decade, many research efforts were noticed on the subject. A design guide was released in Romania, in compliance with the Eurocodes series, in order to ensure a technical background for the current design practice. However, further research is needed, both at national and European level, in order to improve the knowledge and to ensure the parameters database necessary for a more efficient control of the restrained shrinkage cracking states.

REFERENCES


