Evaluation of the techniques to mitigate early shrinkage cracking through an image analysis methodology

Techniques to mitigate early shrinkage cracking

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ABSTRACT

Nowadays, new products are introduced in concrete mixes to reduce the effects of shrinkage, which are the main reason of most of early-age cracking phenomena, especially when curing is not done in accordance to best practices. The lack of a standardized methodology to quantify concrete cracking complicates the determination of the effectiveness of different solutions and comparison between them.

This research presents an evaluation through images of the suitability of fibres and shrinkage reducing admixtures (SRA) to control early shrinkage cracking in slab-type concrete elements. The use of this technique has permitted **quantifying** the typical cracking parameters objectively, and **analyse probabilistically** the average crack width.

Results show a delay and reduction of cracking after adding SRAs and fibres in concrete, especially 1 kg/m^3 of polymeric micro-fibres. The incorporation of these components directly into the mix modified the behaviour of concrete, reducing shrinkage cracking from the beginning of moisture losses.

KEYWORDS: *admixture, concrete, fibre reinforcement, image analysis, shrinkage.*

1. Introduction

Shrinkage is the main reason of the large majority of early-age cracking in concrete, especially in **the** case of restrained structures. In these cases, strain is usually limited by supports, adjacent structures and bonded reinforcements, among others. Consequently, the mix design and curing conditions become a very important part of good concrete technology practice [1]. However, there are applications where curing is not enough to prevent cracking, e.g. when severe environmental conditions are combined with large surface-to-volume ratios and restraints. One usual case where this takes place is in bi-dimensional elements such as slabs. Therefore, other recommendations and mitigation techniques have been introduced by modern concrete technology in order to limit and reduce shrinkage effects, as shrinkage cracking is practically unavoidable so far.

These recommendations focus on limiting moisture losses in properly designed concrete mixes. The most accepted way to do it is to cure concrete carefully, especially in structures with high **surface-to-volume** ratio, rather than **using** methods which only prevent moisture loss, as protecting from wind or sunshine by plastic sheeting, mono-molecular films, windbreaks and/or shades [2-3]. Also re-vibration and re-finishing of the fresh concrete tends to close early shrinkage cracking, due to the destruction of the growing tensile stress and the fill of cavities under horizontal reinforcing bars. Likewise, the use of screeding when concrete is still workable should be limited because its excessive use creates cracking patterns parallel to the screeding [4].

Other possible **way of minimizing** shrinkage cracking **is** the incorporation of admixtures or fibres. While fibres work like millions of bridges that uniformly **distribute tensile** stresses, intercepting and stopping the growth and evolution of cracks by reinforcing the mix in all directions, admixtures act like internal curing agents providing a slow and uniform curing. The use of both additives has increased progressively over the past years, specifically in the field of pavements, bridge decks, industrial floors, tunnel linings and precast elements. On the one hand, fibres can be added to reduce the shrinkage cracking pattern at later ages through a mechanical action, as well as to improve ductility, strength, and toughness [5-6]. In this case, in order to ensure that cracks remain small and in accordance with design assumptions [7], it is essential that the quantity and distribution of reinforcement are adequate. From this point of view, several researchers have studied and demonstrated the benefits of adding fibres in the concrete mix [8-13], especially polymeric micro-fibres. Whereas steel reinforcement is less effective in controlling plastic shrinkage cracks, as the bond between the plastic concrete and the reinforcement has not been yet developed, the dimensions and large numbers of fibres permits a strong mitigation of plastic shrinkage cracking. On the other hand, the incorporation of **curing compounds [14], such as superabsorbent polymers [15] or saturated lightweight aggregates [16-18],** may decrease shrinkage by means of a reduction of the **evaporation rate. This measure is even more effective if it also reduces settlement and capillary pressure of pores, as the use of shrinkage reducing admixtures (SRA) [19-23] has been demonstrated.** Another solution to control shrinkage cracking is by means of expansive cements or admixtures like calcium oxide or calcium sulfoaluminate, which act during wet setting phase. These last alternatives, leading to the so-called shrinkage compensating concrete, are not a widespread solution so far, partially because of the difficulty to accurately control the final expansion. **For this, most of current research trend to use such products with SRA, as this combination shows a synergetic effect on shrinkage reducing. The negative retarding effect of the chemical admixtures turns into an advantage for the efficiency of the expansive products [24-25].**

Some related works in literature also study the cracking problem due to different types of shrinkage. However, it has not yet been found any widely and reliable solution to reduce this crucial problem. Because of this, it is absolutely essential to use an objective methodology to reflect clearly the effects of the different solutions introduced to minimize **shrinkage cracking**. The lack of a simple standardized methodology nowadays complicates the determination of the effectiveness of the different products added to concrete to decrease early shrinkage cracking, and the comparison between them. In fact, most of the techniques used for estimating the shrinkage cracking pattern are subjective and labour-intensive because they are based on visual and manual measurements. **Only very few methodologies based on image analysis are considered objective. Relevant cracking information can be extracted rapidly and systematically from the photographs of the cracked specimen. Some of these methods are based on the elimination iteratively of the residual noise [26], which can only measure the crack width. Others lead to approximate results due to the specification of an appropriate threshold value for creating binary images, and a uniformly spaced grid for quantifying the cracking pattern [27-29]. Although it has been proved that**

minor variations in threshold and mask values generally do not affect the measurement results [27, 30], this study is based on a new technique. It provides more precise and automatic results, avoiding the possible errors derived from the comparison between cracking patterns obtained with slightly different threshold values and/or not perpendicular grid to stress riser along all the cracks. The **great** results obtained with conventional concrete, and the capacity **of identifying and characterizing** any shrinkage cracking pattern due to any cause in an uncomplicated and fast way, with common equipment and software, leads to the experimental methodology proposed by Ruiz-Ripoll et al. **[31] as one of the best options. It** consists in photographing the entire cracking pattern and stitching all pictures together. Afterwards, the image is filtered to correct lens defects and the contrast between lights and shadows, **then** the cracks are isolated, **and, finally,** the cracking patterns are quantified by means of geometric figures, which **adapt to the shape of all cracks. As a result, the methodology provides easily** parameters such as cracked area, crack length, and maximum and average crack width.

From this literature review, it appears that no objective methodical studies about the influence and comparison of admixtures and fibres individually, as possibilities for the mitigation of early age shrinkage cracking, have been published so far. Most of works are focused on the synergetic effect which may provide the combination of different additives [25, 32]. However, a further investigation is required to quantify the effectiveness of the different strategies applied separately, as some researchers noted [13, 34]. This situation motivated the present research, in which some different products are incorporated directly into a conventional mix in order to modify the behaviour of concrete, and to control and/or reduce shrinkage cracking from the beginning. The suitability of these products are evaluated through the analysis of the cracking patterns, obtained with the same base mix design in order to reflect only their influence [25, 27], following the aforementioned imaging

methodology proposed by Ruiz-Ripoll et al. [31]. Between the effective solutions to limit early age cracking, which is measured here through a test of 20 hours [31], this paper is focused on the use of synthetic fibres and a SRA to mitigate shrinkage cracking of conventional concrete. Most of the other mentioned actions would not affect early shrinkage cracking (plastic sheeting, mono-molecular films, re-vibration, re-finishing, shrinkage compensating concrete…) due to the limitation of time. **The aim is that these test results guarantee the effects of the additives incorporated, and serve as a good basis to apply them to other special concretes (with very low water-to-binder ratio and high fineness admixtures), which mechanical properties can be more affected.**

2. Experimental programme

The evaluation of the effectiveness of different methods to reduce early shrinkage cracking in concrete was based on the methodology developed by Ruiz-Ripoll in **[31]**. An experimental programme was designed**, based on Kraai [9], Yokoyama [34], Mora [35] and ASTM C1579 tests [36]. It consisted** in highly restrained square slabs of 800x800x100 mm, with lateral surfaces anchored by bolts and a roughened wood panel at the bottom. The slab was placed in a wind tunnel and subjected to controlled environmental conditions (45^{o}C, 75% relative humidity and 7 km/h wind speed) achieved by usual devices (fan, heaters, temperature sensors…), during approximately 20 hours (Figure 1). This time was considered enough to account for most of early shrinkage to take place, and also adequately represents the time in practice during which the slab could be left without proper curing after execution; finishing of concrete works at the end of the day to continue activities the following day. The slab restraints maximize a two-dimensional cracking pattern. The large **surface-to-volume** ratio of the slab and the demanding environmental conditions speed up the water evaporation process creating greater internal stresses. The high degree of restriction provided by anchor bolts and bottom increased the cracking pattern through friction and adherence between the concrete and mould (no release agent was applied, of course).

Seven different types of concrete were tested: one plain conventional concrete, five with different types and contents of **monofilament polypropylene** fibres and one with a glycolether SRA. The same base mix design (constant type and proportions of components) was used in each case, to which the different additives were incorporated. In this way, the results reflect surely only the influence of the additives in the behaviour of concrete. The mix proportions corresponded to those widely used in pavement applications. Concrete for pavement/flooring applications usually avoids excessive cement and sand contents and uses the most favourable granular skeleton from the point of view of shape, maximum aggregate size, and particle size distribution. The reference base mix design (control concrete, CC) was a plain C30 strength class and S5 consistency class concrete **[37]**. The different slabs were achieved adding to the reference mix macro-fibres of 0.075 mm of diameter and 40 mm of length (FRC1), micro-fibres of 0.031-0.035 mm of diameter and 12 mm of length (FRC2, FRC4 and FRC5), a combination of macro-fibres and micro-fibres (FRC3) and a SRA (SC). The dosages of the additives were based on the recommendations given by **suppliers.** Note that only in the case of SC, the common base mix design was slightly modified (0.4% less superplasticizer) because the SRA introduces and additional plasticizing effect that could lead to segregation in this S5 consistency class concrete. Concrete mix proportions are summarized in Table 1. Following the recommendations given in ASTM C1579 **[36]**, two slab specimens of each concrete were tested in the same conditions for each case, in order to obtain a more reliable and homogeneous comparison among different cracking patterns.

The concrete was mixed in a 50-litre forced action mixer with rotating drum and blades, and agitator. As each slab needed a concrete volume of about 56 litres, two identical batches of 30 litres were made following the same mixing sequence, which is important for fibre reinforced concrete (FRC). Mixing is a critical phase of FRC because of the risk of fibre entanglement, which might generate fibre clusters or balls. For this reason, it was visually checked that the fibre distribution was homogeneous in all batches. Before placing the concrete, the workability of the mix was evaluated for each slab; the slump of the first batch was determined in accordance with EN 12350-2 **[38]**, while the second batch was not measured because the followed production process was identical and took place just after the first batch **[39]**. The slabs were finished by troweling, avoiding the tips of the fibres coming out of the surface, as would be done in practice.

Once the specimen was cast and the pan used to measure the evaporation rate was filled with concrete, the elements were placed in the environmental tunnel downstream from the fan. Note that the evaporation rate gives also an idea of the capillary pressure, which is related to the shrinkage strains. When the rate of evaporation exceeds the rate of bleeding, the concrete surface dries out, causing the formation of meniscus which tends to contract the paste by negative pressure. The evaluation of cracking started when all the instrumentation was positioned and the fan turned on, which corresponded to an age of the concrete of 30 minutes. This was the time needed to cast the two batches of each slab and prepare the test. The air and concrete temperatures, speed of the air flow, and evaporation rate, were recorded since the beginning of the test by means of three thermocouples, an anemometer, and a 1-g precision scale (Figure 2), respectively. The precision scale was positioned under the pan. One thermocouple was located on the upper part of the wind tunnel, at the middle of its length. Other two thermocouples were placed close to the surface of the concrete slab, at the beginning and at the end of the tunnel. This location responded to the study of the homogeneity of the temperature inside the tunnel and its influence in the distribution of the early cracking pattern. The thermal behaviour of concrete was only analysed in CC as all concrete had the same matrix composition. In this case, the thermocouple located close to the surface at the end of the tunnel was inserted into the concrete at the beginning of the tunnel. Except the wind speed, the measurements of temperature and evaporation rate were repeated and recorded until the end of the test (20 hours later) as they not only help to control of environmental conditions but also gives an idea of the evolution of early shrinkage cracking. Temperatures were registered automatically every 10 minutes through a data logger, the evaporation rate was determined every hour during the first 6 hours, approximately. At the end of the test, the last measurement was recorded and after removing the mould, the specimen was subjected to the crack image analysis process **[31].**

3. Analysis of results

In order to analyse the effectiveness of the different additions used, early shrinkage cracking results obtained from the beginning of the test have to be taken into account. Parameters measured during the test as well as measurements obtained through digital imaging methodology (the total cracked area, the total crack length, the maximum and average crack width and the crack reduction ratio) are very important to achieve clear understanding on the real applicability of fibres and SRA to decrease early shrinkage cracking.

3.1. Results of the control measures

As it can be observed in Table 2, the addition of relatively high dosages of micro-fibres decreases the slump, as it is the case for FRC2 containing 2 kg/m^3 of polypropylene micro-fibres. Due to the larger dimensions and lower number of fibres per unit weight of the used polypropylene macro-fibres, the effect on workability is less significant. The plasticizing effect of the SRA was clear, as the same workability was achieved while introducing 0.4% less superplasticizer. Even if all mixes could have been taken to an equal consistency (for example, by higher superplasticizer and/or paste content in case of FRCs), it was decided to work in these conditions **as they** better represent usual practice, i.e. just introducing the addition into a given mix.

The thermal behaviour of concrete is presented in Figure 3, showing the influence of the evolution of the hydration process and the tunnel temperature, which practically does not vary. On the surface, temperature is approximately constant with a very small trend to increase due to the heat released by the chemical reactions during the formation of the hydration products of the concrete. On the bottom, temperature rises almost at a stable rate to reach the surface temperature. As Figure 4 reflects, there is a difference of temperature between the beginning and the end of the environmental tunnel at the surface of the slab, but this variability is closely linked to the position of the two sensors (one at the beginning and one at the end of the tunnel). **Both sensors register the increment of temperature caused by the contribution of the heat of hydration, which eventually becomes higher than the tunnel temperature. Considering the surface temperature at the beginning of the tunnel, this fact is recorded at about 10-12 hours for concrete with fibres, and at about 7-8 hours for concrete with SRA.** On the contrary, the tunnel temperature, evaluated at the central point of the cover, is always around 33ºC (±1ºC). Thus, these results prove that the conditions imposed inside the tunnel are fairly homogeneous.

With respect to evaporation rate, the values registered indicate that this parameter has a significant effect on early shrinkage cracking as its evolution reflects the development of the cracking pattern with time, as expected. The visual control of the slab performed during the development of each test allowed to detect the formation of the first crack at two hours after the start of the tests on CC and SC **(as SRA has little influence on the evaporation rate for the first few hours [40])**, and after three hours after the start of the FRC1, FRC3 and FRC5 tests. However, the early cracking pattern could not be distinguished at a glance in concrete with micro-fibres FRC2 and FRC4. As mentioned earlier, the weight loss of the pan filled with concrete exposed placed at the end of the tunnel was measured approximately each hour. This frequency was decreased after the first crack appeared. From the weights recorded, the evaporation rate was determined dividing the mass loss by the surface area of the pan and the time interval between successive weightings **[36]**. Figure 5 shows the results obtained. Figure 5a represents the evolution of the evaporation rate along the time whereas Figure 5b represents the evolution of the evaporation rate in each time interval. It is noted that the evolution of the slope of each curve of Figure 5a corresponds to the evaporation rate plotted in Figure 5b. As it can be observed, the initial evaporation rate is in the range of 0.30 to 0.54 kg/m^2·h, which is slightly higher than 0.23 kg/m^2·h, the average evaporation rate. This phenomenon responds to the loss of the free water of capillary pores and bleeding **[41]. A specific case to highlight is the distinct behaviour which show the concretes with micro-fibres. The evaporation rate of FRC2 is higher compared with FRC4 and FRC5 although its slump is the lowest. This may be due to the fibre content incorporated, which dosage exceeds the range recommended by suppliers (0.6-1 kg/m^3). Even when a denser grid redistributes more uniformly loads and efforts, it has been noted that an excessive amount of fibres tend to induce workability and homogeneity mixture issues, which are reflected in the porous microstructure.** After one hour, the rate is reduced significantly until it becomes negligible from the sixth hour onward. This reduction can be attributed to the decrease in both bleed water and water transported by capillary action to the surface.

3.2. Results of the test

When the test has already finished, the early shrinkage cracking patterns obtained are analysed and quantified by means of image analysis. As expected, the distribution of cracks responds to a two-dimensional cracking pattern, sign of the effectiveness of the restraints. In general, the most important cracks are concentrated at the centre of the slab, and the rest of cracks distributed towards the edges. In fact, it can be **stated** that there is some symmetry in the cracking within the randomness. Moreover, it can be observed that the wider cracks are result of the cracking during the plastic state since they present no constant width and their paths cross the aggregate grains. But there are also other smaller cracks of different origins, in all these cases the plastic cracks predominate. All these results can be observed more clearly after the application of the digital imaging methodology **[31]**. This enables not only a numerical characterization of shrinkage effects, but also sorting cracks by colour code according to their widths, among other classifications (Figure 6). The images of the different crack patterns and the cracking parameters calculated are summarized in Table 3, in terms of average values. As it can be seen, the reference CC experiences the largest cracking conditions. It shows the highest cracked area, which is distributed in many width cracks (Figure 6a). The crack length registered in the SC, which contains SRA, is longer than the CC. It is due to the fact that SC cracking pattern is formed by finer and longer cracks (Figure 6b)**, as a consequence of the increment of temperature that occurs when the evaporation rate is reduced. As some researchers noted [18, 40, 42], this fact leads to have higher water content and, therefore, lower tensile stresses at the surface, promoting a possible expansion of concrete [42], which might contribute to the closing of part of the cracks.**

The parameter that affects the durability and structural integrity most adversely is the crack width. The maximum and average crack widths of the different concretes can be observed in Table 3 and Figure 7. They also indicate how all concretes incorporating shrinkage reducing additives have similar average crack widths, around 0.35 mm (± 0.10 mm). In fact, most of the crack widths measured at 10 mm intervals along the length of each crack, are concentrated in this range, as it can be seen in Figure 7 by means of an overlap between curves. However, they differ in their maximum crack widths, especially FRC5 and SC mixes. The higher maximum crack widths in these two cases could be due to a low micro-fibre content and the use of the same base mix design for all types of concrete, respectively. As **recommended** by suppliers, the dosage of polypropylene micro-fibres should be between 0.6 and 1 kg/m^3. On the other hand, the contents of superplasticizer and/or water should be less when this SRA is added.

Anyway, in spite of using a common mix design, the values of characteristic crack width shown in Table 4 (parameter defined as the crack width **with a** probability of being exceeded **of** 95%) reveal the beneficial effects of incorporating SRA. Table 4 also summarizes the main one-dimensional statistical parameters that determine the distribution of crack widths and its best probabilistic **adjustment**. As the shape of curves of Figure 7 points out, the distribution of crack widths fits almost perfectly a lognormal distribution (Figure 8). Indeed, the differences between the average and typical deviation calculated with original data and lognormal distribution are practically negligible (Table 4) and are due to the random character of values measured. This probabilistic analysis is really useful to predict, according to the type of concrete, the probability that a critical crack width can develop and can affect durability of a concrete element.

From the analysis of the studied parameters, and especially the characteristic crack width and crack reduction ratio (Table 3) that are the parameters that **represent** the efficacy of the product added to the CC mix for reducing the average crack width caused by early shrinkage, **concretes** with enough content of micro-fibres (FRC2 and FRC4), are the ones that present the best performance. This **is the expected result**, since well dispersed micro-fibres lead to a homogeneous and effective three-dimensional reinforcement network. In spite of the fact that a higher content induces a reduction of the maximum crack width, the values of the cracked area of FRC2 and FRC4 are very similar (Table 3). Such performance can be justified by the recorded evaporation rate. As it can be observed in Figure 5a, FRC4 shows a lower evaporation than FRC2, which implies lower strains. Therefore, the highest crack reduction is reached with the addition of 1 kg/m^3 of micro-fibres.

4. Conclusions

This work presents an objective comparison between different methods to control concrete cracking due to early shrinkage, in order to evaluate their respective effectiveness. The research is focused on two early shrinkage cracking mitigation methods comprising products that are incorporated in the concrete mix; fibres and **SRA**. As there is currently no standard technique to estimate early shrinkage cracking, the quantification of the cracked area, crack length, and maximum and average crack width has been performed through image analysis, specifically by means of the digital imaging methodology developed by Ruiz-Ripoll et al. **[31].** This simple, objective, economical and quick technique consists of photographing the cracking pattern obtained after subjecting a biaxial restrained square slab to controlled environmental conditions during approximately 20 hours **(initial restrictions which can be adjusted according to the needs)**, processing the pictures, and isolating and highlighting**, by means of adaptable geometric figures,** the cracks. The experimental configuration **permits the analysis of** the final cracking patterns, but does not track the shrinkage cracking evolution.

A conventional plain concrete mix typically used in flooring applications was selected to evaluate the performance of the two early shrinkage cracking mitigation techniques; fibres (micro and macro) and a **SRA**. **The use of a common base design for all types of concrete allows comparing only their reducing effects and their implications in the workability of the concrete. Moreover, the application of the aforementioned imaging methodology reflects their**

effectiveness with numerical and graphic results, providing a global and precise vision of the geometry and distribution of each of the shrinkage cracking patterns. This leads to other way of proving the coherence of the test results obtained. Fibres, and especially micro-fibres, significantly reduce early shrinkage cracking, though the effectiveness depends on the dosage. The effect of the **SRA** was found similar from the point of view of the crack reduction ratio and characteristic crack width. The considerable differences found with respect to the cracked area, crack length, and maximum crack width, were probably due to the rather high superplasticizer **and/or water** content of the base mix design if a **SRA** was to be used. In spite of the common proportions, its first beneficial effects are reflected in the cumulative evaporation rate through a practically constant curve from the fifth hour. This admixture acts in long-term becoming shrinkage independent from the age progress, meaning that the evolution of the cracking pattern is negligible **[43].**

The fibre and SRA content have a direct influence on reducing the restrained early shrinkage cracking and its control. **These good results show that the use of one or other will be governed by the requirements of the casting and execution of the structural element.** From the alternatives considered in this study (2 micro-fibres dosages, 1 macro-fibre dosage, 1 micro+macro-fibres dosage, and a SRA), the best option to control early shrinkage cracking in the selected 30 MPa concrete, was the addition of 1 kg/m^3 of polymeric micro-fibres. **This fact proves that** higher addition rates may not always involve better results. **It can be optimized to enhance the workability and, thus, the costs.**

Even if early-age cracking on site is hardly relatable to laboratory test results (different restrain conditions, size effects, environmental factors, execution, etc.) this evaluation method can clearly help on the selection and cost-performance optimization of available alternatives for the control of early-age shrinkage cracking. **Nevertheless, it would be necessary to complement the test with an investigation of the hardened properties for its application to special concretes.**

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