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# Assessment of behaviour and cracking susceptibility of cementitious systems under restrained conditions through ring tests: A critical review

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## Abstract

Cracking occurrence due to shrinkage related effects is a widely recognised issue which is frequently evaluated with the shrinkage restraining ring test. This paper provides a state-of-the-art review of the ring test method, which has been used for the last four decades. The last review on such matter was conducted only in early 2000s; however, a significant amount of studies has been conducted since then and considerable advancements or modifications in this testing method have taken place over the last decade. Studies on the traditional ring test, i.e. a circular concrete ring cast around a steel ring, are identified and the history, tendencies, practices and quantitative methods are analysed thoroughly. Furthermore, any modifications/advancements in the testing method with respect to their purpose, applications and capabilities based on current knowledge, are addressed. Finally, an insight on the challenges that the developers of testing methods for restrained shrinkage are facing with is given together with perspectives for their future potential improvement.

## Keywords

Ring test, restrained shrinkage, cracking risk, cracking sensitivity, drying shrinkage, cementitious materials

# 1 Introduction

Cracking due to restrained volumetric changes has been a well-known and ongoing problem in concrete structures as it may allow deleterious substances to penetrate concrete [1-4]. Such volumetric changes may correspond to different mechanisms, such as plastic, chemical, autogenous, drying or carbonation shrinkage. Autogenous and drying shrinkage have always been of particular interest for researchers and engineers as almost irrespectively of the composition of the cementitious material considered, they will occur and may potentially be detrimental for the service life of concrete structures. It is, therefore, particularly beneficial to enable a characterisation of a cementitious material in terms of its cracking risk under restrained autogenous/drying shrinkage, prior to using it on site or on order to investigate potential mitigation strategies.

The ring test is perhaps the most frequently employed experimental method for the determination of the likelihood of cracking of a cementitious system subjected to restrained, mainly drying, shrinkage. As it has been used for several decades, in this paper, the available in the literature information is collected and an up-to-date systematic review of this experimental method is presented. Previously published reviews include [1] and [5] in 2003 and 1998, respectively, in which ring tests were not addressed in great detail. Furthermore, a considerable amount of studies has been conducted since then and also significant advancements/modifications in this experimental technique have been witnessed, especially over the last decade. The above, in addition to the fact that there not seems to be a comprehensive, detailed review on the restrained ring test method, highlight the need for such study to be conducted.

Traditionally, the ring test is a passive test in nature as there is no control or induction of concrete strain in the setup, i.e. a concrete ring cast around a restraining core (usually a steel ring) with the latter proving restraint to concrete shrinkage. However, recent advancements enabled an active control of the restraining core (in terms of temperature or controlled deformation) and hence, ring tests can be differentiated into two types, i.e. passive and active.

Cracking sensitivity, tendency, susceptibility, propensity, proneness and potential have all been used to describe the likelihood of cracking of a cementitious system, albeit rather inconsistently. Therefore, in this document and in order to improve consistency thereafter, whenever they are mentioned they correspond to the risk of a particular cementitious system to crack under explicit restraint of volumetric changes and environmental conditions, i.e. a system having low cracking sensitivity is less likely to crack than a system having high cracking sensitivity with the same boundary conditions.

This paper is structured in four main sections (apart from the present introduction), concerning respectively: passive ring tests (Section 2), active ring tests (Section 3), challenges and perspectives (Section 4), as well as the conclusions (Section 5). The largest development and depth of discussion is devoted to the most widely used passive ring test setup (circular) in Section 2, with thorough discussion of several experimental aspects involved, as well as methods for evaluation of induced stresses and degree of restraint.

## 2 Passive ring tests

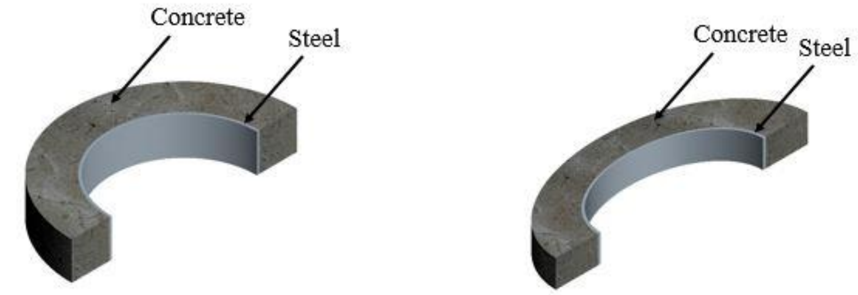
Passive ring tests are those that have been extensively adopted in numerous studies that investigated cracking sensitivity, restrained shrinkage, creep and stress relaxation of cement-based materials. The original test setup, which has been predominantly used over the last five decades with applications dating back to late 1930s [6-8], includes an outer concrete ring cast around a steel ring; however, recent efforts from researchers to improve or extend the capabilities of this testing method has resulted in modifications of traditional geometric characteristics of the ring test. Therefore, the passive ring tests can be subdivided into the following proposed four categories, which are also shown in Figure 1:

(a) Traditional-circular ring tests, where a concrete, mortar or paste ring is cast around a restraining core, most frequently, an instrumented steel ring.

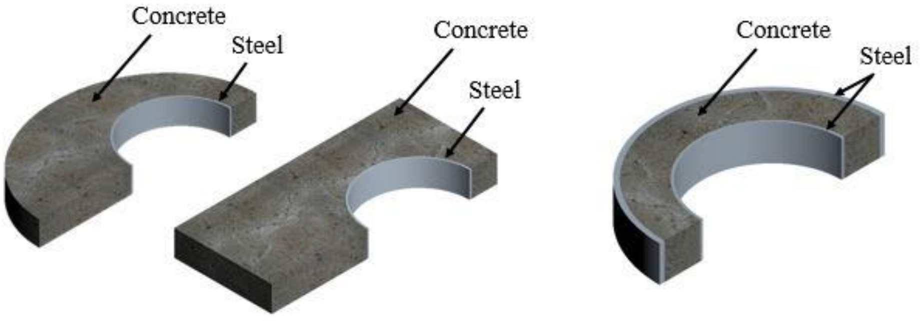
(b) Elliptical ring tests, where the testing principle follows that of the traditional-circular ring tests; however, concrete and steel rings are of elliptical geometry.

(c) Eccentric or square-eccentric ring tests, where the position of the restraining steel ring is eccentric relative to centre of the concrete specimen. In this case, the concrete specimen can be either of circular of square geometry.

(d) Dual ring tests, where a concrete ring is cast in-between two steel rings resulting in restraint of both contraction and expansion of concrete. Restraint strains are monitored in both inner and outer steel rings.



**(a)** Traditional-circular **(b)** Elliptical



**(c)** Eccentric and square-eccentric **(d)** Dual

**Figure 1:** *Types/categories of passive ring tests*

## 2.1 Traditional-circular ring tests

### *2.1.1 General characteristics, practices and applications*

The traditional-circular ring can be regarded as the most common method that can be used to assess the likelihood of cracking of cementitious materials subjected to restrained shrinkage, probably due to the simplicity associated with the test setup, see Figure 2 (RIS = internal radius of steel, ROS = outer radius of steel and ROC = outer radius of concrete) and the principles governing it. In this test, the volumetric changes of concrete and steel can be measured with various ways, however, the most common is that resistive strain gauges are adhered on the inner circumference of the restraining ring so that obtained steel strains can be utilised to study stresses in concrete. Due to the traditional ring test having been used for many years, there is a wealth of studies available in the literature [9-96,99], in which researchers have used different geometric characteristics, curing conditions and cementitious systems. All of these parameters affect the results that can be obtained from the tests, thus, as an efficient method to differentiate studied ring tests based on their characteristics; key features are identified and presented in Table 1. It is worth mentioning that the majority of the studies performed on traditional ring tests dates after 2003 (the last time when a corresponding review was published [1]), which highlights the need for an up-to-date review.

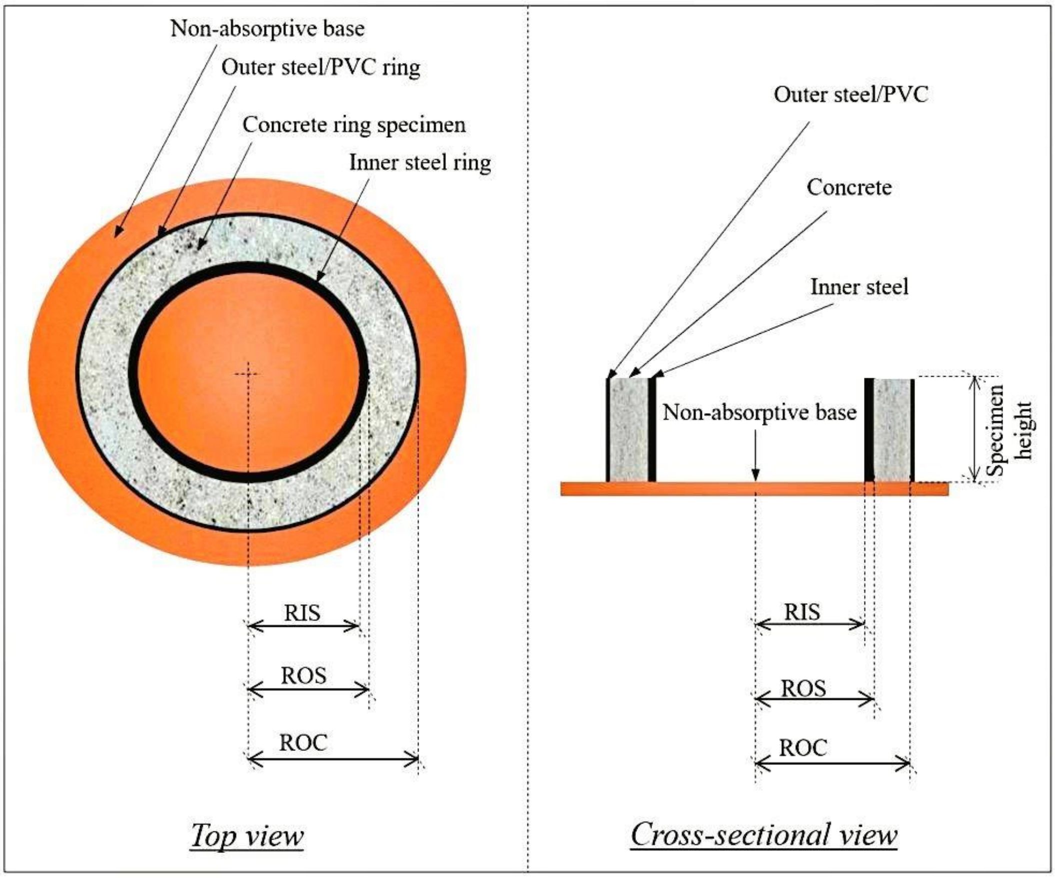


**Figure 2:** *Typical testing arrangement of the traditional-circular ring test*

The primary parameters that are of interest in the ring tests are the geometric characteristics, i.e. diameter of rings, steel and concrete ring thickness and specimen height, as well as the drying direction. To begin with the former, the selected geometry of the ring specimens will dictate the resulting degree of restraint (DR), which can be calculated from the following formula [24]:

$$DR = \frac{A_{rc}E_{rc}}{A_{rc}E_{rc}+A_{cm}E_{cm}} * 100\% \qquad \textbf{Equation 1}$$

where:

DR = degree of restraint [%]

$A_{rc}$ = cross-sectional area of restraining core (usually a steel ring) [$mm^2$]

$E_{rc}$ = modulus of elasticity of restraining core (usually steel) [GPa]

$A_{cm}$ = cross-sectional area of cementitious material (usually concrete) [$mm^2$]

$E_{cm}$ = modulus of elasticity of cementitious material (usually concrete) [GPa]

The degree of restraint concept allows a realistic experimental simulation of the interplay that exists between the potential free shrinkage (were the specimen unrestrained) and the creep/stress relaxation the occurs due to actual restraint to deformation. This interplay is complex and highly influenced by the extent of restraint, thereby, playing a fundamental role in the stress development. Hence, the concept of "degree of restraint", which is applied in many simplified approaches to design of concrete under restrained shrinkage stresses. Typical values seen in the field depend on the application, for example: a) DR ≈ 60-80% for a base of a wall cast on to a massive base, b) DR ≈ 80% for an edge element cast onto a slab, c) DR ≈ 20-40% for suspended slabs or 80-100% for infill bays [100].

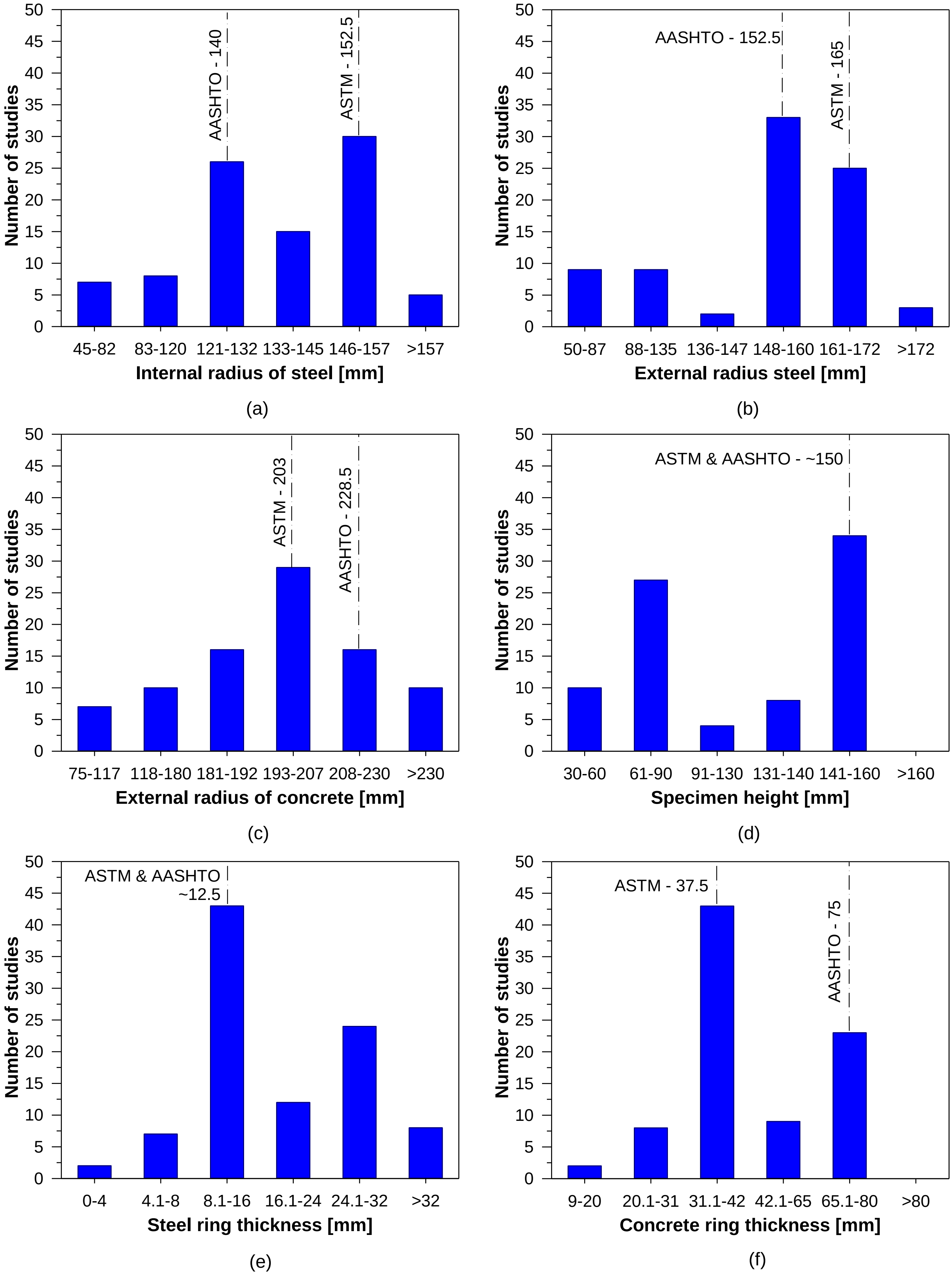
Equation 1 was used to calculate the degree of restraint based on the geometries selected by different authors, as shown in Table 1, assuming a steel restraining ring with an elastic modulus of 200 GPa and a concrete ring with an elastic modulus of 30 GPa (reference/typical values for steel and concrete). It is worth pointing out, however, that the selection of elastic modulus and calculation of degree of restraint will not be necessarily representative of concrete's behaviour because creep effects are disregarded. Although a reference value of elastic modulus is used in the majority of the conducted studies, few authors adopted a decrease in the elastic modulus of concrete by 40% in calculations or simulations, in order to account for the effects of creep [33-35,82,89-96]. It is also worth to remark that concrete E-modulus endures significant changes during the actual experiment (as well as creep behaviour), which even adds more complexity to this analysis.

As it can be seen from Equation 1, the degree of restraint depends on the height and thickness of the restraining steel and concrete. In principle, the greater the thickness of the steel ring, the higher the degree of restraint; however, the selection of very thick inner rings may reduce the magnitude of measurable strain in the steel rings resulting from the concrete shrinkage strains not being significant enough. This can be compensated by increasing the concrete ring thickness (depending on drying direction) which will in return reduce the degree of restraint in the system and prolong the test duration. Hence, a dilemma around the selection of specimen geometry is generated. It should be noted that although the selection of a solid restraining core (steel) will result in a considerable increase in the degree of restraint provided, such arrangement is not normally preferred as it inhibits the adhesion of strain gauges on the inner circumference of the core and increases specimen weight. Generally, experience dictates that using an inner steel ring of thickness greater than 20-25 mm may inhibit the measurability of real induced compressive strains in the steel ring. Taking into consideration that typical strain gauge accuracy is ± 5 $\mu\varepsilon$ [101,102] and that additional nuisance may be induced by even small temperature changes, vibrations and electrical disturbances from adjunct/nearby appliances operating simultaneously with monitoring [45,89], one should chose such geometric characteristics that steel strains will ultimately exceed the value of at least 20 $\mu\varepsilon$.

The ring test method has been standardized through a course of years and updates by AASHTO [103-105] and ASTM [106-108] standards, with the latest releases dating in 2008 and 2016 respectively. AASHTO [105] suggests a setup with 140, 152.5, 228.5 and 152 mm internal and external radius of steel, external radius of concrete and specimen height respectively, which results in a degree of restraint of approximately 52%. On the other hand, as an attempt to reduce testing duration, ASTM standard [108] based on the works [24, 25] suggested a setup with 152.5, 165, 203 and 150 mm as internal and external radius of steel, external radius of concrete and specimen height, respectively, which results in a degree of restraint of approximately 69%. The recommended steel ring thickness by both standards is the same, i.e. 12.5 mm, however, the AASHTO setup allows the use of greater maximum size of aggregate than ASTM (25 mm instead of 12.5 mm), by increasing the concrete wall thickness (75 mm instead of 37.5 mm). This selection compromises the degree of restraint in the system which implies that specimens investigated with the AASTHO setup may take longer to crack (or not crack at all), which makes the ASTM setup more preferable according to conducted studies, as shown in Table 1.

Tendencies regarding geometrical characteristics of the ring test in the literature become more apparent when studied geometries are plotted in the form of histograms, as shown in Figure 3. To begin with the selection of the internal radius of the restraining steel ring (RIS), it appears that the in the majority of the studies, a similar RIS with that suggested by AASHTO (approximately 140 mm) or ASTM (approximately 152.5 mm) is preferred, with particular preference to the latter. However, in a considerable amount of studies a smaller RIS is selected (approximately 127 mm) due to such geometry having been selected by S. P. Shah and colleagues in the numerous studies that they have conducted, as well as in other studies influenced by their work (see Table 1 for references). Other RIS have also been reported but are not normally preferred. Similarly, with RIS, the outer radius of the restraining steel ring (ROS) selected in the majority of the studies coincides with those suggested by AASHTO (approximately 152.5 mm) and ASTM (approximately 165 mm). In this case, the number of studies in which the AASHTO ROS was preferred is greater than that of ASTM, also because such ROS was selected in the influential works of the previously mentioned investigators, on which the development of AASHTO standard was based. Similar trends are also observed for adopted outer radius of concrete (ROC), with the majority of the studies reporting ROC similar to that suggested by ASTM standards (approximately 203 mm). Nevertheless, in a considerable number of studies, ROC was selected to equal to approximately 228.5 and 187.5/202.5, which is that suggested by AASHTO and reported in works of S. P. Shah, respectively.

As far as the selection of specimen height is concerned, two distinct trends are apparent from Figure 2(d). In the vast majority of the studies, a specimen height of approximately 150 mm is reported as such geometrical feature is suggested by both standards. In a less but still considerable extent, a specimen height between 61-90 mm was preferred, whilst this is mainly attributed to the research efforts by J. W. Weiss and co-workers, where a 75 mm height was selected, as part of their investigations on the role of specimen geometry and boundary conditions on the results obtained in the ring test. Few studies also report a specimen height of approximately 140 mm, which is also close to that suggested by current standards, while other specimen heights have occasionally and rather irregularly been reported. Finally, as per the selection of steel and concrete ring thicknesses, in the greater number of studies, the selected dimensions were in accordance with the standards' recommendations. A resultant steel ring thickness of approximately 12.5 mm is usually preferred, as also recommended by both standards. Greater steel ring thicknesses are also reported, especially in the region of 24.2-32 mm, but, excessively thick or thin steel rings are not normally preferred. Concrete ring selection tendency is in the same region with the ASTM recommendations (approximately 37.5 mm), whilst in a fewer but still considerable number of studies, the AASHTO recommended concrete ring thickness is adopted (approximately 75 mm), mainly due to the potentially longer test duration associated with the ring geometries in the latter.


Number of studies
0
5
10
15
20
25
30
35
40
45
50
AASHTO - 140
ASTM - 152.5
45-82
83-120
121-132
133-145
146-157
>157
Internal radius of steel [mm]
AASHTO - 152.5
ASTM - 165
50-87
88-135
136-147
148-160
161-172
>172
External radius steel [mm]
ASTM - 203
AASHTO - 228.5
75-117
118-180
181-192
193-207
208-230
>230
External radius of concrete [mm]
ASTM & AASHTO - ~150
30-60
61-90
91-130
131-140
141-160
>160
Specimen height [mm]
ASTM & AASHTO
~12.5
0-4
4.1-8
8.1-16
16.1-24
24.1-32
>32
Steel ring thickness [mm]
ASTM - 37.5
AASHTO - 75
9-20
20.1-31
31.1-42
42.1-65
65.1-80
>80
Concrete ring thickness [mm]

(a)

(b)

(c)

(d)

(e)

(f)

**Figure 3:** *Histograms of selected geometric characteristics of ring test in the literature*

The drying direction also plays a significant role in the expected outcomes of the ring test. Both of the standards, suggest sealing the top and bottom surfaces and allow drying only from the outer circumference, thus in the majority of the studies this drying method is adopted. This is suggested on the basis that if specimen height is four times the concrete wall thickness, the shrinkage is assumed to be uniform through the height of the specimen (but not in the radial direction) [24]. Yet, others attempted to allow drying from top and bottom ring surfaces (see Table 1) suggesting that this boundary condition results in uniform unhindered shrinkage strain in the radial direction, which simplifies the calculation of the maximum tensile stress in concrete. Exposing all three surfaces to drying, although it would result in potentially quicker cracking, is not normally preferred as it produces non-uniform shrinkage and stress distributions.

Generally, the ring test has been used to evaluate the cracking characteristics of cement-based materials under restrained drying shrinkage cracking at standard curing temperature (as also suggested by the current standards). Furthermore, the relative humidity selection upon drying initiation is in consonance with the current standards, i.e. predominantly adjusted at 50% ± 10% with very few studies reporting a deviation from this range. At the same time, in a few studies, all the faces of concrete ring were sealed in order to study restrained autogenous shrinkage, sometimes at various (mainly elevated) curing temperatures.

Conventionally, the ring test has been considered as a qualitative test from a materials science perspective, i.e. different cementitious systems are tested and cracking age is obtained as an indication of their cracking sensitivity. However, from the point where strains developed in the inner ring can be recorded, a form of structural monitoring commences and quantitative information with respect to stresses generated in concrete can be obtained. In this sense and considering the simple geometry of the test, analytical solutions based on Timoshenko’s theory of elasticity and thin cylinder behaviour

[109] have made possible the calculation of elastic hoop stress in concrete, defined from strains in the steel ring (solutions may not be applied directly to concrete due to creep effects). Studies applying such approaches are listed in Table 1. Due to the potential calculation complexity of such models and also the fact that such calculations may not necessarily provide explicit information regarding the cracking sensitivity of a cementitious system, a classification method is recommended by ASTM standard (firstly published in 2004) [106-108]. More specifically, cracking sensitivity in this standard is calculated using a special procedure suggested by See, Attiogbe and Miltenberger [24-26] by taking into account the stress rate and cracking age of the specimen and is classified accordingly from low to high, depending on the results. It is worth noting that as an attempt to avoid inconsistencies inherent in this approach, Kovler and Bentur [44] suggested an improvement in the calculation procedure of the classification basis for cracking sensitivity through combining the stress rate and cracking age to derive an integrated criterion.

As mentioned earlier, analytical solutions have been developed that can be used to convert the recorded strains in the steel ring into tensile stresses in concrete (refer to Table 1 for corresponding studies). However, the stress distribution is strongly dependent on the shrinkage condition, as illustrated in Figure 4. The simplest case that can be considered is when shrinkage is uniformly distributed over the radial direction and over the height of the specimen. Such behaviour may only be observed when moisture exchange between concrete and surrounding environment is avoided, i.e. under autogenous (sealed) conditions.

Another possible boundary condition regards to the possibility of allowing top and bottom surface drying, which results in uniform unhindered shrinkage along the radial direction, but not along the height of the specimen. As such, the maximum tensile stress develops in the inner radius of the concrete ring.

Finally, the case of circumferential drying (which is also suggested by the current standards) results in shrinkage being uniform across the height of the specimen, but not in the radial direction. Under such boundary conditions the majority of the water loss takes place at the circumference of the specimen, hence maximum stresses develop at the drying face resulting in complex stress distribution that changes shape over time [23,27,31,33-36]. Yet, such drying direction is normally preferred due to potentially faster cracking times compared to top and bottom drying. This is associated with the exposed surface area of concrete being larger in circumferential drying rather than in top and bottom drying (based on the geometries provided by the two standards).

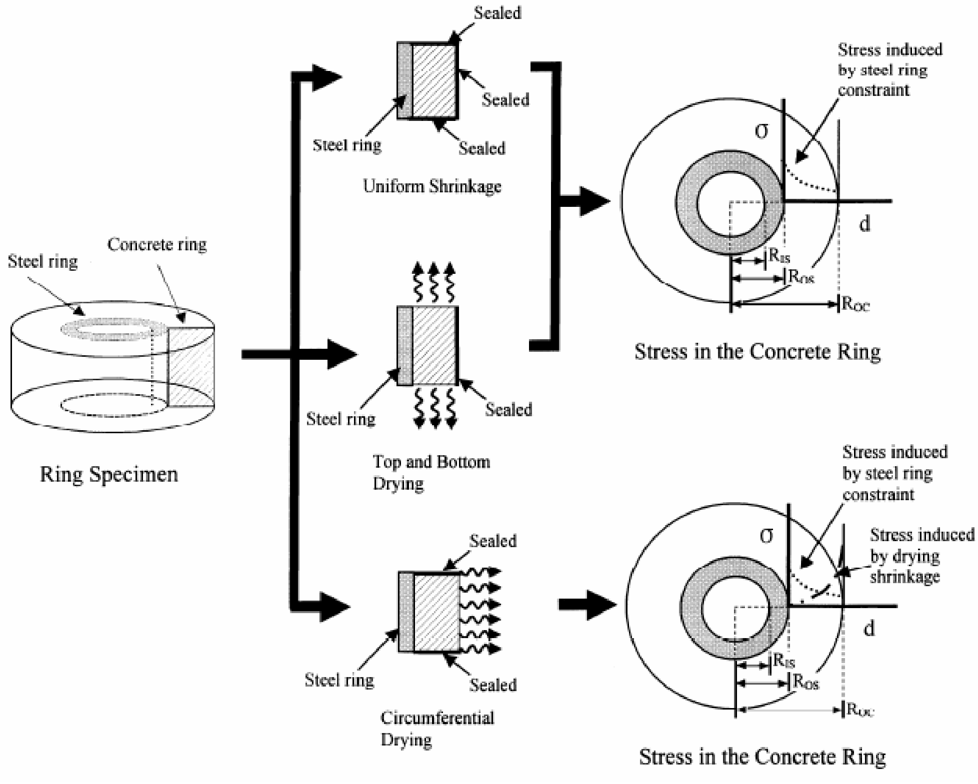


**Figure 4:** *Resulting stress development in the restrained concrete ring as affected by drying direction [33,34]*

Simulations of the ring tests have also been performed by several authors who investigated the restrained shrinkage behaviour of concrete whilst in-depth discussion and summarisation of their characteristics is provided later on section 2.1.3 and Table 2, respectively. Generally, different strategies have been adopted by various researchers to reproduce the shrinkage behaviour of concrete and mortar in finite element modelling, such as using moisture controlled relationships and fictitious temperature drops (thermal loading) [33-35,38,45,90-96,134] or directly input of free shrinkage data [51,89,136,137]. These simulations were mainly conducted in order to determine the stress distribution, deformations, cracking age, location and propagation. Similar analyses further revealed that cracking initiates from the inner circumference and propagates towards the outer circumference of the concrete rings with a thin wall, whilst such behaviour is inversed when thick concrete walls are considered also due to self-restraint effects in the case of the latter [27,77,82,89-91,94,96]. With regards to the self-restrained effect, it should be mentioned that the competition between the gradient of stresses induced by steel ring restraint to concrete shrinkage (gradient A) and that of the unrestrained differential shrinkage (gradient B) is more complex for drying from the outer circumference. Under circumferential drying, the gradient A is parallel to gradient B, whilst under top and bottom drying gradient A is perpendicular to gradient B. Indeed, the added simplicity brought about by the perpendicularity of gradients A and B in the case of top and bottom drying, is probably the cause for this literature review not having found any reference to self-restrained effects in the analysis of rings with this boundary condition configuration.

As part of the requirements for a representative analytical and numerical modelling of the restrained shrinkage behaviour of concrete in the ring test, the knowledge of few fundamental material properties is needed. One of the important cases, if not the most, is that of free shrinkage under identical curing and boundary conditions with the restrained shrinkage specimens, due to the fact that in this test, (drying) shrinkage is the primary driving force which may consequently lead to cracking. Therefore, in several studies, the free (unrestrained) shrinkage of the material investigated under the same conditions with the restrained shrinkage tests is measured using companion specimens. The quantification of free shrinkage is most frequently made through measuring the change in length of prismatic specimens with surfaces sealed accordingly in order to obtain the same area-to-volume ratio with the restrained ring specimen, as described in [24,26,27,29,32,39,44-46,48,49,51,52,58,62,63,65,73,75,78-80,83,88-96]. However, it is believed that the most accurately representative free shrinkage measurement at this case, is achieved through the measurement of the volumetric changes on unrestrained ring specimens that have identical size and boundary conditions with the restrained ring specimen, as shown in [19,36,53,77,82,85]. Such methods require a careful selection of the inner ring mould material, i.e. polystyrene or silicon-based, in order to allow its removal after concrete setting without damaging the specimen, as well as special configurations to enable the measurement of the linear strain of the concrete ring.

The materials investigated in the vast majority of the studies are concrete mixes, while the effects of mix composition and curing condition are frequently considered, together with the evaluation of induced stresses, creep and stress relaxation effects. Mortar mixes have also been used in an albeit fewer number of studies whilst such mixes might be preferred as they exhibit higher shrinkage than concrete due to the absence of coarse aggregate (coarse aggregate provides additional restraint to shrinkage [111]) which can reduce the testing duration. However, the appropriateness of using mortar mixes to represent concrete is debatable [89,114], especially in such mechanisms where the presence of coarse aggregate has a significant effect [112,113].

Consideration needs to be also given to the preferred sealing type used in the literature. In the majority of the studies, adhesive aluminium-foil tape has been used to seal the desired surfaces of the concrete ring [27,31,32,36,41,39,45,48,51,55,63,73,75,77,78,81,82,83,88-96], which is suggested by the current standards. Paraffin wax [11,24,26,53,59,61,68,79], which is also recommended by ASTM and silicon rubber [14,16,21,30,37,46,58,71,76] has also been used as sealants, but in a rather less frequent manner when comparing to aluminium-foil tape. Other sealing types reported in the literature for ring specimens are epoxy raisins [19,57,72,74], plastic/polyethylene sheets [29,60], waterproof sealant [69,87], or even combinations of bituminous paint and aluminium-foil tape [45]. However, the efficiency of each sealing method, in terms of preventing moisture loss from the concrete surfaces, has not been mentioned or measured in the rings in any of the identified studies; nevertheless, it has been argued that the use of double layer aluminium-foil tape can be more effective than acrylic, latex or epoxy protection [73,81,115]. Yet, in other studies, not necessarily directly relevant to the ring test, the efficiency of sealant types was more thoroughly investigated. More specifically, an experiment was made in [116] by sealing 50 x 50 x 50 mm$^3$ cement paste specimens with several different materials/techniques (plastic foil wrapping, liquid paraffin application, epoxy resin, siloxanic resin, liquid rubber and bitumen). Weight loss was monitored on the specimens during exposure to drying in a climatic chamber (at constant 20ºC temperature and 30% humidity). Samples of the sealing materials themselves (when applicable) were also placed in independent cups as to monitor their own moisture losses. The best overall behaviour was obtained with paraffin sealing and with plastic wrapping (with zero or negligible weight losses in both experiments). The authors however recommend the advantageous use of paraffin, as opposed to plastic wrapping because the latter creates pockets of droplets in the surface that can be later reabsorbed by the sample, thus not reproducing a barrier to moisture loss from the surface (water is still lost to a very small surrounding environment, proportioning potential reabsorption).

As far as the outer ring (formwork) is concerned, the current standards recommend its removal at 1 day after casting, in order to initiate drying and prevent any potential restraint to concrete's movement from the outer ring. As it can also be seen from Table 1, such practice is accepted in most of the studies, while in few other ones the outer ring was removed earlier or even considerably later than the suggested time, depending on the aim of the research. It is worth noting that removing the outer mould at 1 day (or earlier after assuring that the specimen will not be damaged) does not necessarily mean that drying will commence at this time as the exposed concrete surfaces can be sealed and sealants can be removed in accordance with the desired curing period. One aspect, which also concerns the outer ring, is the selection of an appropriate material. The current standards suggest that a non-reactive and nonabsorptive material should be used for the outer ring, such as PVC or steel and provide guidance regarding its minimum thickness depending on the material used. In the majority of the studies there is no explicit description of the materials used for the outer rings, whilst indeed PVC [14,16,20,24,26,30,52,61,68,79] and steel [37,45,47,62,69,77,80,82,85-89] is reported in studies in which this matter is accounted for, with the exception of a few studies reporting a cardboard tube as an outer ring [46,57,72,74].

One aspect, which is not explicitly mentioned in the vast majority of the identified studies, is the type of the substrate material used and how are the authors addressing potential friction problems. Where mentioned, steel, plywood or PVC bases have been preferred and the only precaution against potential friction between the concrete ring and the base of the mould is the application of releasing agent. Furthermore, there is also limited information disclosed in the existing studies regarding experimental configurations for top and bottom drying with respect to ensuring drying from the bottom surface that is not inadvertently prevented. Since positioning the ring setup vertically would not be practical as this would result in self-weight problems, ribbed or partially hollow bases are preferred upon drying initiation, as those in [45].

Finally, from examining the place where the identified studies were conducted, it appears that there is a balanced cardinal of studies between America, Europe and Asia, whilst a considerably less frequent number of publications is observed Africa and Oceania. Through the early years of the research on ring tests, studies were predominantly originated from N. America, however; upon its standardisation from AASHTO and ASTM, researchers and engineers in other continents also used this method to a great extent, which demonstrates its worldwide adoption and application, especially over the last decade.

**Table 1:** *Characteristics of traditional-circular ring tests found in the literature*

| **Internal radius of steel [mm]** | | | | | |
|---|---|---|---|---|---|
| 45-82 | 83-120 | 121-132 | 133-145 | 146-157 | >157 |
| [11, 54,62,63,75,83,87] | [27,32,37,45,52,67,81,99] | [12-14,16-20,27,30,36,42,45-47,50,55,57,60,71,72,74,77,78,82,84] | [22,27,28,29,36, 45,49,55,58,60,65,80,85,91,95] | [24,26,28,31,36,39-41,43,44,48,53,59,61, 64,68-71,76,79,80,86,88-90,92,93,95,96] | [9,10,51,73,78] |
| **Outer radius of steel [mm]** | | | | | |
| 50-87 | 88-135 | 136-147 | 148-160 | 161-172 | >172 |
| [11,15,54,62,63, 66,75,83,87] | [15,32,37,52,67,77,81,82,99] | [22,84] | [12-14,16,17-21,27,29-31,36,41,42,45-47,49,50,55,57,58,60,65,72,74,76,78,80,85,91,94] | [24,26,28,39,40,43,44,48,53, 59,61,68-71,80, 86,88,89,90,92,93,95,96] | [9,10,51,73] |
| **Outer radius of concrete [mm]** | | | | | |
| 75-117 | 118-180 | 181-192 | 193-207 | 208-230 | >230 |
| [11,54,62,63,75, 83,87] | [15,21,32,37, 66,77,81,82,84,99] | [12-14,16,18-20,28,30,36,42,52,61, 65-68] | [17,24,26,28,39,40,43,44,46,48,53,55,57,59,60,64,69-72,74,76,80, 86,88-90,93,95,96] | [21,23,27,29,31,36,41,45,47, 50,58,78,80,85,91,94] | [9,10,21,22,36,49,51,73,92,96] |
| **Specimen height [mm]** | | | | | |
| 30-60 | 61-90 | 91-130 | 131-140 | 141-160 | >160 |
| [11,15,21,23,52, 65-67,87,92] | [22,27,31,32,36,41,45,49-51,55,62,63,71,77,78,81,82,84,90-96,99] | [9,10,47,73] | [12-14,16,19,30,37,42] | [17,20,23,24,26,29,39,40,43,46,48,53,57-61,64,68-72,74-76,79,80,83-89] | - |
| **Steel ring thickness (mm)** | | | | | |
| 0-4 | 4.1-8mm | 8.1-16mm | 16.1-24 | 24.1-32 | >32 |
| [36,87] | [22,45, 54,75,77,82,83] | [24-28,29,31,36,39-41,43-45,48,52-55,58-61,64-71,76,79,80,85-96] | [27,28,36,47,49-51,62,63,73,78,84] | [9-14,16-20,30,32,37,42,45,46, 57,60,63,72,74,78,81,99] | [9,10,15,21,23,27,55,78] |

| **Concrete ring thickness (mm)** | | | | | |
|---|---|---|---|---|---|
| 9-20 | 20.1-31 | 31.1-42 | 42.1-65 | 65.1-80 | >80 |
| [63,87] | [11,15,21,28, 54,61,68,75,83,84] | [12-14,16,18-20,24,26,28,30,36,37,39-44,48,52,53,59,60,64-67,69-71,76,77,79-82,84, 86,88-90,93,95,96] | [15,17,41,46,55, 57,64,72,74] | [9,10,21,23,27,29,31,32,36,45,49-51,58,78,80,81,85,91,92,94,96,99] | - |

| **Hollow/solid restraining core** | |
|---|---|
| Hollow | Solid |
| [ 9-14,16-20,22,24-95,99] | [15,21,23] |

| **Degree of restraint [%]** ***(calculated by the authors assuming an elastic modulus of 200 and 30 GPa for steel and concrete, respectively)*** | | | |
|---|---|---|---|
| <44 | 44-65 | 66-85 | >85 |
| [22,36,45] | [27,28,29,31,36,41,45,49-52,55,58,67,73,77,78,80,82,85,87,90-92,94,96] | [9,10,12-14,16,17,19-21,23-27,30,32,36,37,39-48,53,55,57,59,60,61,64-72,74-76,79-81,83-90,93,95,96,99] | [11,15,62,63,84] |

| **Drying direction** | | | | |
|---|---|---|---|---|
| Circumferential | Top & bottom | Top | All 3 sides exposed | All 3 sides sealed |
| [11-20,24,26,28-30,36,37-44,46-48,53,57-61,63,65-76,78-80,83,85-87,90,91,93-95] | [21,23,27,28,31,32,36,41,45,49,50,55,77,81,82,84,91,92,99] | [22] | [9,10] | [48,51,52,67,62,64,73,88,89] |

| **Relative humidity [%]** | | |
|---|---|---|
| 0-39 | 40-60 | >60 |
| [11] | [9-32,36-50,53-61, 63-65,68-85-87,90-95,99] | [11,19] |

<table>
<tr><th colspan="6">Curing temperature</th></tr>
<tr><td colspan="2">Standard (18-24 °C)</td><td colspan="2">Elevated</td><td colspan="2">Lower</td></tr>
<tr><td colspan="2">[11-22,24-28,32-69,72-95,99]</td><td colspan="2">[15,23,30,31,88,89] (30 °C), [88,89] (40 & 50 °C)</td><td colspan="2">[9,10] (16 °C), [71] (11 °C)</td></tr>
<tr><th colspan="6">Material investigated</th></tr>
<tr><td colspan="2">Concrete</td><td colspan="2">Mortar</td><td colspan="2">Paste</td></tr>
<tr><td colspan="2">[9-24,26,28-30,32,39,43-47,49,51,53,58-60,64,68-77, 80-83,85, 86,88-95,99]</td><td colspan="2">[27, 31,36,37,40,41,42,48,50,54,55,61-63,65,68,78,79,84,87]</td><td colspan="2">[52,67]</td></tr>
<tr><th colspan="6">Calculation of stresses, cracking age/width/sensitivity</th></tr>
<tr><td colspan="3">Analytical approach</td><td colspan="3">Numerical simulation</td></tr>
<tr><td colspan="3">[9,10,12,15,18,19,21,23-27,31-36,44,45,53-60,63,65,77,78,82]</td><td colspan="3">[21,33-35,38,45,51,89-96,134,136,137]</td></tr>
<tr><th colspan="6">Formwork removal age</th></tr>
<tr><td><1 day</td><td>1 day</td><td>2 days</td><td>3 days</td><td>4 days</td><td>>4 days</td></tr>
<tr><td>[10, 14-16,22]</td><td>[9-13,15,17-32,36,37,39-42,44-53-55,57-59,63,65,68,70,72-74,76-95,99]</td><td>[15,61,71,75]</td><td>[15,43,69,80]</td><td>[60]</td><td>[61,80]</td></tr>
<tr><th colspan="6">Place of study [continent of host institution of 1st author]</th></tr>
<tr><td>N. America</td><td>S. America</td><td>Europe</td><td>Asia</td><td>Africa</td><td>Oceania</td></tr>
<tr><td>[11-14,16-18,21,23-31,33-36,39-41,43,48,53-59,69,76,85-87]</td><td>-</td><td>[9,10,22,32,37,45,46, 49,51,52,57, 66,67,70,72-74,81,88-91,99]</td><td>[15,19,38,47,50,60,62-65,71,75,78,80,83,84,92-95]</td><td>[61,68,79]</td><td>[20,42, 77,82]</td></tr>
<tr><th colspan="6">Year of publication</th></tr>
<tr><td>1975-1985</td><td>1986-1995</td><td>1996-2005</td><td>2006-2015</td><td colspan="2">>2015</td></tr>
<tr><td>[9,10]</td><td>[11-15]</td><td>[16-30]</td><td>[31-72,90,91,94]</td><td colspan="2">[73-89,92,93,95,99]</td></tr>
</table>

### *2.1.2 Analytical approaches and comparisons*

Different calculation procedures have been proposed to enable the calculation of either induced restraint stresses in concrete or degree of restraint. This section focuses on the differences between methods that can be used to calculate stresses based on recorded steel strains, as well as on the differences between methods that can be used to calculate the degree of restraint in the ring test prior to conducting the experiment and the applicability and potential limitations of each approach are discussed.

#### 2.1.2.1 Comparisons between methods to estimate stresses in the concrete based on recorded steel ring strains

As mentioned earlier, analytical methods have been proposed that can be used to compute the induced tensile stresses in the concrete ring. These can be subdivided in two categories: i) Analytical approaches which require knowledge of the free shrinkage (and modulus of elasticity) of the investigated mix (as those described in [12,15,18,19,23,27,34,35,53,56]), preferably under the same drying conditions as the restrained specimen and ii) analytical approaches that only require the knowledge of the steel ring strains induced by concrete shrinkage (i.e. [9,10,24,27,34,35]). Analytical approaches as per (i) may be considered as more labour intensive, since additional experiments are required in order to determine the free shrinkage and elastic properties. Therefore, in this section, the most convenient/simplistic approaches will be compared, which are no other than (ii), provided also that shrinkage is deemed uniform across the radial direction, i.e. top and bottom drying or all surfaces sealed.

There are three analytical models that can be used to convert recorded steel (or any other linear-elastic material) ring strains into tensile stresses in concrete, all of them based on equilibrium of radial pressure between the concrete and steel rings [109]. The first one is that suggested by Swamy and Stavrides based on averaging the maximum and minimum circumferential stresses [9,10,110]:

$$\sigma_t(t) = \frac{-\varepsilon_{st}(t)E_{st}}{2}\frac{A_{st}}{A_c}\left(1 + \frac{R_{is}^2 + R_{os}^2}{2R_{os}^2}\right) \qquad \textbf{Equation 2}$$

where:

$\sigma_t(t)$ = average tensile stress in concrete at time t [MPa]

$\varepsilon_{st}(t)$ = average steel ring strain at time t

$E_{st}$ = modulus of elasticity of steel [GPa]

$A_{st}$ = cross-sectional area of steel ring [mm]

$A_c$ = cross-sectional area of concrete ring [mm]

$R_{is}$ = internal radius of steel ring [mm]

$R_{os}$ = outer radius of steel ring [mm]

The second solution for maximum tensile stress is that from See *et al.* [24] based on thin cylinder behaviour [109]:

$$\sigma_{max}(t) = -\varepsilon_{st}(t)E_{st}\frac{R_{os}W_{st}}{R_{is}W_c} \qquad \textbf{Equation 3}$$

where:

$\sigma_{max}(t)$ = maximum tensile stress in concrete at time t [MPa]

$W_c$ = wall thickness of the concrete ring [mm]

$W_{st}$ = wall thickness of the steel ring [mm]

The last one is the “thick-walled” [109] or general solution proposed by Hossain and Weiss [27]:

$$\sigma_{max}(t) = -\varepsilon_{st}(t)E_{st}\frac{R_{os}^2+R_{oc}^2}{R_{oc}^2-R_{os}^2}\frac{R_{os}^2-R_{is}^2}{2R_{os}^2} \qquad \textbf{Equation 4}$$

where:

$R_{oc}$ = outer radius of concrete ring [mm]

The calculation of stresses in concrete based on the above formulations requires knowledge of the steel ring strains. As an example and to satisfy the comparative purposes of this section, results obtained through a series of ring tests previously conducted by Azenha [45] will be considered herein. In this investigation, reported in [45], different steel ring wall thicknesses were also examined. The geometrical characteristics of the investigated ring specimens were as follows [45]: RIS = 145, 140 and 130 mm (resulting in 20, 10 and 5 mm steel wall thicknesses), ROS = 150 mm, ROC = 225 mm (achieving a concrete wall thickness of 75 mm) and a specimen height of 75 mm. The experiments were conducted under standard conditions, i.e. approximately 20 °C and 50% RH, whilst drying was only permitted to occur from the top and bottom concrete ring surfaces, hence, uniform shrinkage through the radial direction can be assumed. The elastic modulus of steel was taken as 195 GPa [45]. Typical results obtained from these series of ring tests are shown in Figure 5.

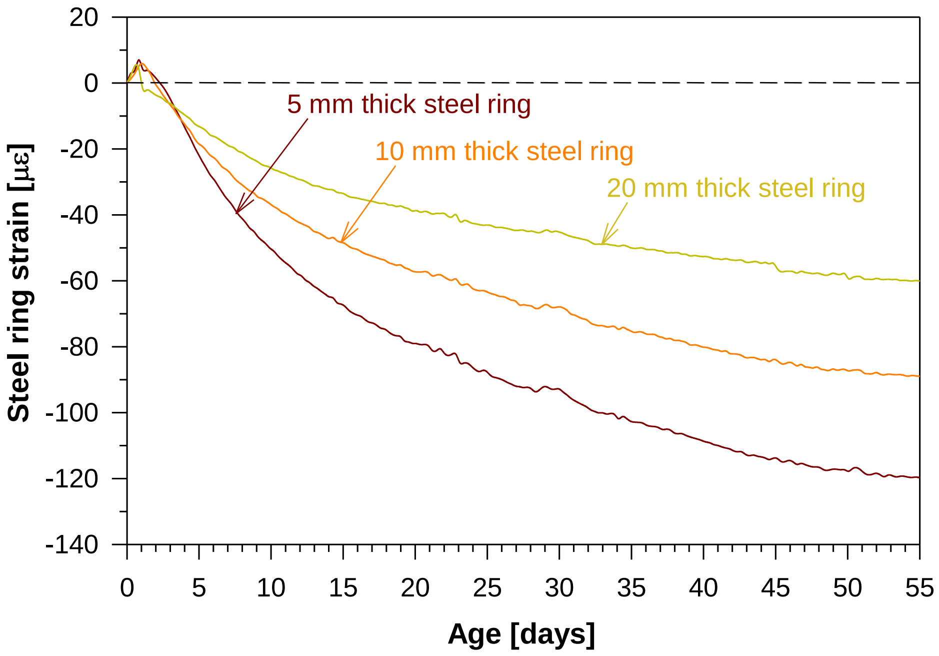


**Figure 5:** *Recorded steel ring strains in experiments conducted by Azenha [45]*

The steel ring strains shown in Figure 5 can be used to calculate stresses in concrete based on Equations 2, 3 and 4, and these are illustrated in Figure 6. In order to not only avoid data congestion but to also enable a distinct comparison of the methods, the experimental results from ring tests with 5 and 20 mm steel wall thickness are considered, i.e. the two extreme cases. It can be observed from Figure 6 that there are discrepancies in the calculated stresses based on different equations. Most notably, it appears that Equation 4 consistently yields greater values of induced tensile stresses in the concrete ring, which is followed by Equation 3. A possible explanation of this could be the fact that a "thick-walled" concrete ring (75 mm) was considered as an example, whilst Equation 3 was derived considering a thin wall approximation, as it has been observed that Equations 3 and 4 yield similar results for thinner rings (which are also the geometries that are commonly used) [25,130]. It should also be noted that Equation 2 calculates the average stresses in concrete, while Equations 3 and 4 provide the maximum stresses; hence, the stresses computed using Equation 2 have the lowest magnitude. It is also worth mentioning that whenever a thicker walled steel ring was considered, Equations 3 and 4 yielded somewhat similar results. This behaviour was altered for a thinner-walled steel ring with Equations 2 and 3 providing more similar stress estimations.

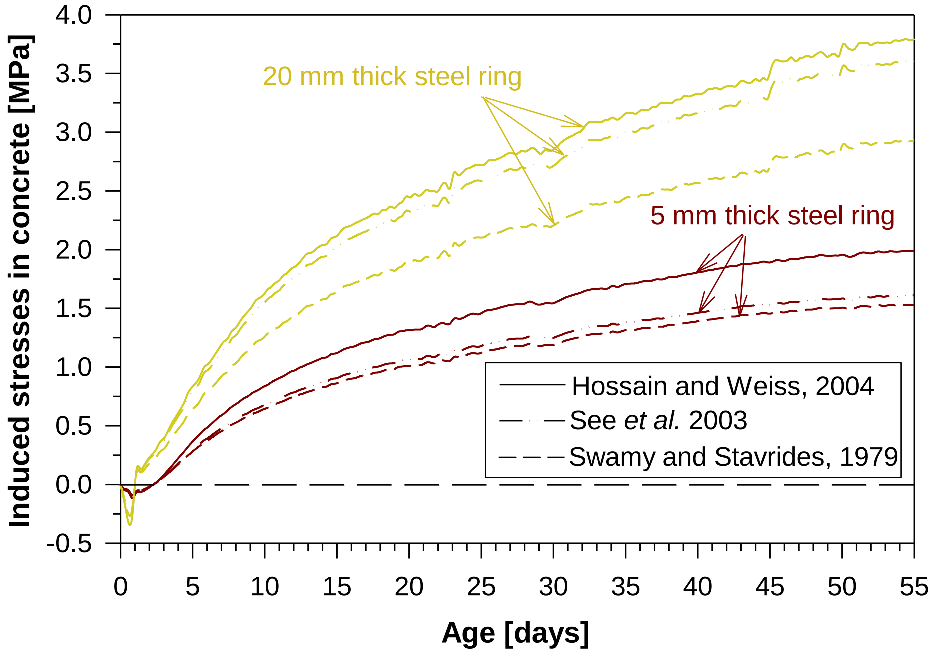
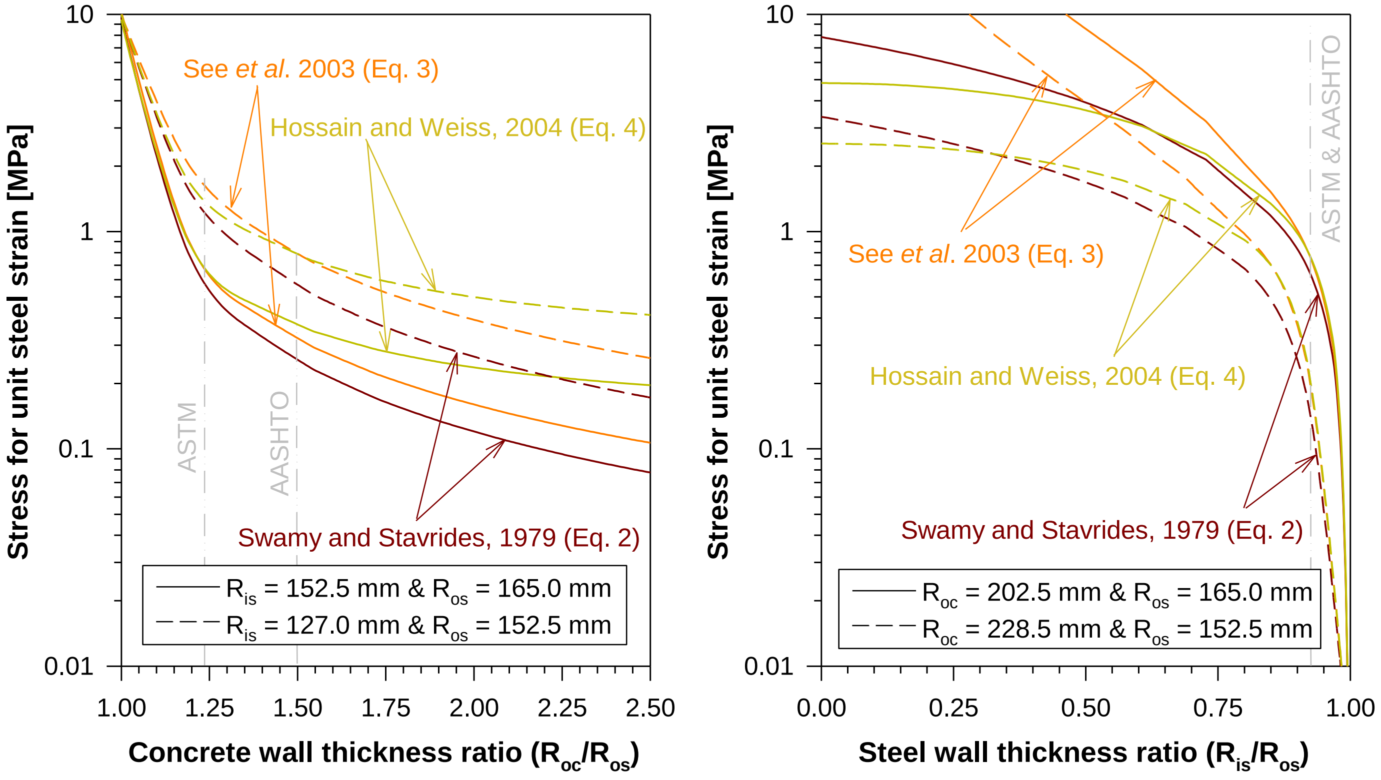


**Figure 6:** *Computed stresses using Equations 2, 3 and 4 based on data shown in Figure 5*

The differences between the investigated equations in estimating the stresses in the concrete rings can be elucidated by examining the calculated stress over a varying concrete or steel wall thickness, as shown in Figure 7. Constant steel wall thicknesses of 12.5 mm (ASTM and AASHTO) and 25.5 mm (found in the works of S. P. Shah and J. Weiss) and constant concrete wall thicknesses of 37.5 mm (ASTM) and 75 mm (AASHTO) are considered in Figure 7(a) and 7(b) respectively. Indeed, when a constant steel wall thickness of 12.5 mm is considered, the solutions from Equations 3 and 4 only converge for values of concrete wall thickness ratio below 1.3, indicating that for this range, a thin wall approximation can be appropriate. However, their convergence whenever the steel wall thickness is increased to 25.5 mm diminishes. It is worth mentioning that Equation 2 consistently yields lower stress values, apart from very low concrete wall thickness ratios. Similar behaviour is also observed when the steel wall thickness ratio is varied [Figure 7(b)]. As the steel wall thickness ratio decreases, the convergence of the investigated models is also decreasing; however, for steel wall thicknesses similar to those suggested by ASTM and AASHTO (approximately 12.5 mm) the equations yield similar results.



a) Varying concrete wall thickness

b) Varying steel wall thickness

**Figure 7:** *Comparing Equations 2, 3 and 4: a) Varying concrete wall thickness with two different steel wall thicknesses and b) Varying steel wall thickness with two different concrete wall thicknesses*

### 2.1.2.2 Comparisons between methods to estimate *a priori* degree of restraint

The determination of the *a priori* degree of restraint in the setup is of particular importance when adjustments of the specimen geometry are required in order to achieve a desired degree of restraint (for example, whenever a particular field application of concrete needs to be tested). Indeed, an *a posteriori* determination of the actual degree of restraint in the knowledge of free shrinkage and restrained shrinkage behaviour of the ring would be more accurate. However, this would require to first conduct the experiments, which is not practical, if decisions need to be made prior to it. Apart from the formula suggested by See *et al.* [24] (Equation 1) for the *a priori* determination of the degree of restraint in the ring test, Moon *et al.* [33] also proposed a formulation for its calculation, see Equation 5. This equation was developed for the calculation of the degree of restraint in ring specimens in particular (taking also into consideration the Poisson’s ratio of the investigated materials), as Equation 1 was proposed based on the behaviour of linear specimens.

$$DR = 100\% - \frac{E_c}{E_{st}} \frac{1}{\frac{E_c}{E_{st}} - \frac{\left[1-\left(\frac{R_{is}}{R_{os}}\right)^2\right]\left[(1+\nu_c)\left(\frac{R_{oc}}{R_{os}}\right)^2+(1-\nu_c)\right]}{\left[1-\left(\frac{R_{oc}}{R_{os}}\right)^2\right]\left[(1+\nu_{st})\left(\frac{R_{is}}{R_{os}}\right)^2+(1-\nu_{st})\right]}} * 100\% \qquad \textbf{Equation 5}$$

Where:

DR = degree of restraint [%]

$E_c$ = modulus of elasticity of concrete [GPa]

$E_{st}$ = modulus of elasticity of steel [GPa]

$\nu_c$ = Poisson’s ratio of concrete

$\nu_{st}$ = Poisson’s ratio of concrete steel

$R_{os}$ = outer radius of steel ring [mm]

$R_{oc}$ = outer radius of concrete ring [mm]

$R_{is}$ = internal radius of steel ring [mm]

To enable a comparison between these methods in regards to the calculation of the degree of restraint, four different ring geometries are considered: i) ASTM recommended geometry (152.5, 165, 202.5 and 150 for RIS, ROS, ROC and specimen height respectively), ii) AASHTO recommended geometry (140, 152.5, 228.5 and 152 for RIS, ROS, ROC and specimen height respectively), iii) the geometry found in the numerous studies of S. P. Shah and colleagues (127, 152.5, 187.5 and 140 for RIS, ROS, ROC and specimen height respectively) and iv) one of the geometries investigated by Hossain and Weiss [27] (140.5, 150, 225 and 75 for RIS, ROS, ROC and specimen height respectively). Typical values have been used for the required steel and concrete properties: $E_c$ = 30 GPa, $E_{st}$ = 200 GPa, $v_c$ = 0.18 and $v_{st}$ = 0.3. It should be noted that in [33] it was suggested that the elastic modulus of concrete in Equation 4 should be the "effective" elastic modulus, $E_{c,eff}$, which aims to account for creep effects; which is the static elastic modulus reduced to 60% [33-35,82,89-96]. In this comparison, both original and "effective" elastic moduli are considered in both equations in order to explore the differences between the calculated values of degrees of restraint.

The calculated values of degree of restraint achieved in rings with different geometries based on the aforementioned methods are shown in Figure 8. Overall, the calculated values of the degree of restraint of the ring specimens was somewhat similar to typical values considered for field applications. However, from the same figure, it is apparent that there are discrepancies in the obtained, theoretical, value of degree of restraint depending on the method used. Generally, the values calculated using the formula proposed by Moon *et al.* [33] (Equation 5) which takes into account the Poisson's ratio of steel and concrete in addition to the elastic moduli, were of greater magnitude than those estimated with the simple method in [24] (Equation 1). In both cases, the calculated degrees of restraint increased whenever an "effective" elastic modulus was considered, which was rather anticipated; however, such approximation/assumption, i.e. reduce the static elastic modulus down to 60% to account for creep effects, might not be necessarily realistic. Nevertheless, irrespective of the discrepancies in the estimated values of degree of restraint, in which a difference of ± 10% can be observed depending on the approach used, both equations showed that the highest, theoretical degree of restraint is achieved in the setup suggested in the works of S. P. Shah, which is then followed by the geometries found in ASTM, AASHTO and Hossain and Weiss [27].

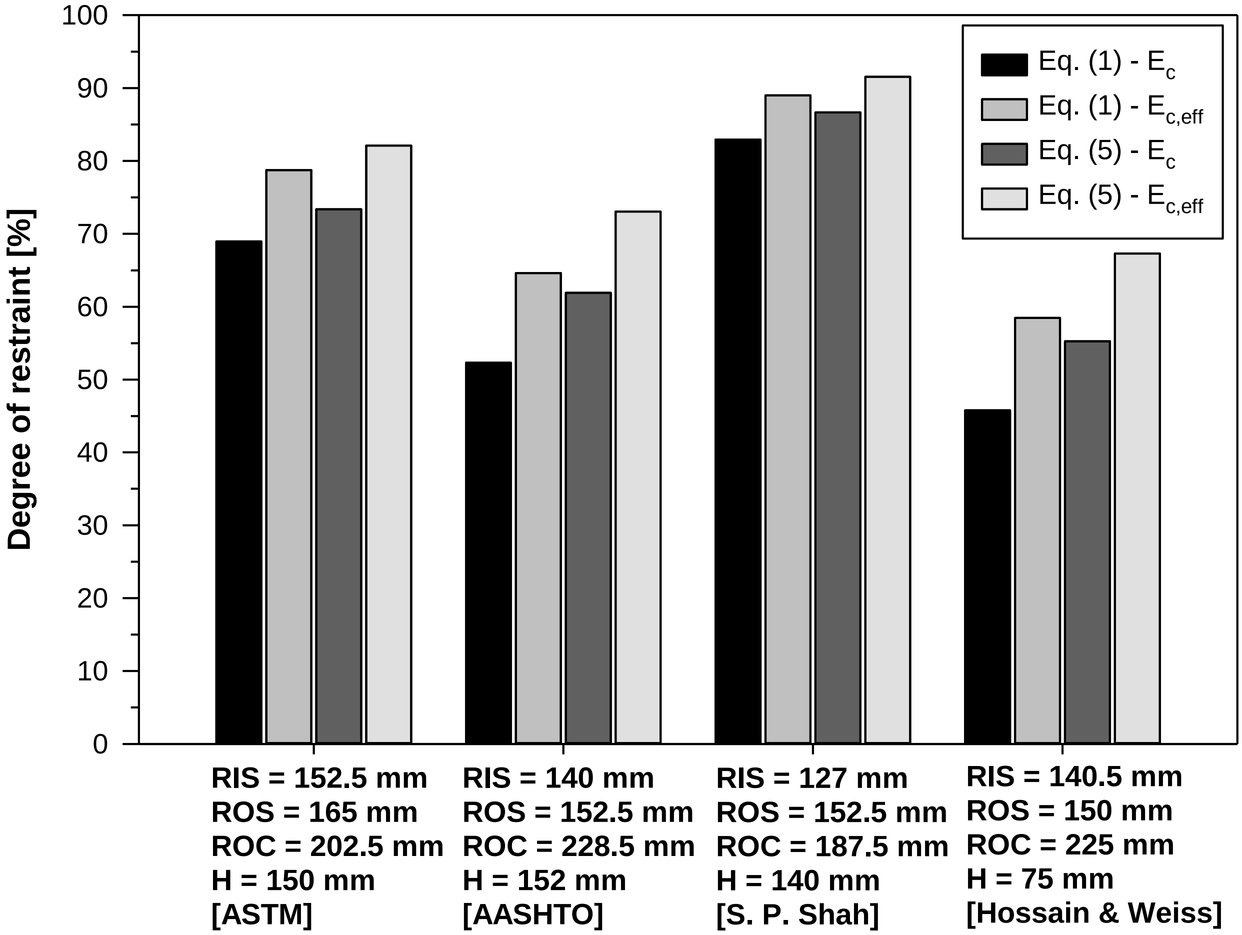


**Figure 8:** *Comparison between calculated values of degree of restraint based on different methods*

### *2.1.3 Numerical simulations of the ring test*

The topic of numerical simulations of the ring test, i.e. using finite element analysis (FEA), is of considerable importance due to fundamental information that can be obtained with respect to homogeneity of stresses, deformations, interactions with between the two materials and cracking initiation/propagation. Simulation efforts from researchers are collected and categorised in Table 2 depended on approaches adopted and boundary conditions considered. Generally, in the majority of the studies a 3D geometry is employed [89-96,136,137] or a 2D-axisymmetric [34,35,45,51] in the case where post cracking behaviour is not investigated whilst in a lesser extend a 2D-plan view [38,82] configuration is modelled. In all cases, shrinkage is the driving force: uniform autogenous for sealed conditions [51,89,134,136,137]; uniform drying shrinkage [82,90,91,93-95] if drying is allowed from top and bottom or from the outer circumference provided that the concrete wall thickness is small enough to assume uniform shrinkage; or non-uniform shrinkage [34,35,38,45,92,96], mainly for thicker concrete rings, which also enables the evaluation of the self-restraint effects due to moisture gradients. Generally, there was a similar distribution of studies where all surfaces were sealed [51,89,134,136,137] and top and bottom drying [45,82,91-93] was considered. However, the majority of studies investigated circumferential drying [34,35,38,90-93,94-96] which may be attributed to such drying conditions being suggested by the relevant standards [103-108]. In the cases where non-uniform drying was considered it is worth pointing out that in all studies, the moisture field was modelled using humidity-based relationships [34,35,38,45,92,96], rather than explicit modelling of water distribution in concrete. Perhaps a possible explanation for this is that shrinkage may be relatively easier to be related to changes in humidity rather than changes in water content/distribution [45,138]. Furthermore, as FEA packages may not always accommodate shrinkage input as a concrete property, a frequently employed approach is to calculate a fictitious temperature field. The fictitious temperature field to simulate shrinkage contraction is calculated with basis on a constant arbitrary coefficient of thermal expansion (CTE), as to ensure temperature driven contraction that matches the contraction due to shrinkage [34,35,45,82,90-96].

Viscoelasticity is also of paramount importance in modelling the restrained shrinkage behaviour of concrete and this is accounted for in all identified studies. However, as the incorporation of creep effects into the simulation may often be relatively complex, the method of effective modulus (reducing the age-dependent elastic modulus, usually by 40%) is often employed [34,35,82,89-96], which is considerably simpler and potentially less accurate than modelling creep with a constitutive law [38,45,51,134,136,137]. Additionally, heat of hydration analysis and temperature effects on concrete properties where mainly considered in studies where a temperature load was induced, as the temperature increase during the early stages of hydration at standard curing can be considered to have negligible effects to the overall behaviour, stress build-up and cracking age of the ring test. Thermo-mechanical simulations were performed in [51,89,134,136,137] due to thermal and autogenous deformations being the dominant driving forces in the models, whilst a multiphysics approach to the problem was described in [45] where a thermo-hygro-mechanical framework [117,118] was used for rings drying from top and bottom surfaces, also considering explicitly the moisture profiles in the specimens. It is also worth noting that authors usually validated their models (mostly against their own experimental results) on the basis of cracking age [89-91,94-96,136] whilst there are only a few studies where direct comparison between steel strains (or even crack widths [38]) from FEA and recorded ones was used for model validation [45,51,136,137], which may also be considered more reliable than the former. Next to this, drying from all three potentially exposed surfaces has not beet simulated yet.

One aspect of the simulation that is still debatable pertains to the contact characteristics considered between concrete and steel. In the majority of the studies in which such matter is mentioned, frictionless contact between steel and concrete was assumed [34,35,90-96,134]. Within the argument that bond will always be present between concrete and steel, others assumed a perfect bond between the two materials in their models [45,82,89,136,137] whilst a Coulomb friction model was used in [38] to explicitly describe friction characteristics in the concrete-steel interface. Generally, in the identified studies there is no justification as to why a particular steel-concrete interface was chosen (apart from when friction was considered) and a parametric study could possibly elucidate this debatable matter. However, it is noted that these interface properties are only likely to be of relevance for post-cracking behaviour.

With respect to this, particular consideration should be given in employing advanced computational techniques for optimising the ring geometry characteristics. This was first attempted in [21,23] where fracture mechanics were implemented to study the role of the ring specimen geometry on the restrained shrinkage behaviour of concrete and since then similar approaches were adopted by other researchers who further investigated the effects of different steel and concrete ring dimensions and boundary conditions [94-96]. Similar methods were employed in the identified studies, i.e. a smeared cracking model with a failure criterion based on the fracture resistance curve approach. In spite of such methods being deemed relatively complex, it could be said that if implemented, the efficiency of the experiment would be improved, i.e. using fracture mechanics and/or numerical simulations for the *a priori* optimisation of ring geometry based on the cementitious system and boundary conditions.

**Table 2:** *Assumptions, approaches and considerations associated with the numerical simulation of the ring test reported in the literature*

| **Model geometry** | | |
|---|---|---|
| 2D – plan view | 2D - axisymmetric | 3D |
| [38,82] | [34,35,45,51] | [89-96 136,137] |
| **Shrinkage** | | |
| Uniform autogenous | Uniform drying | Non-uniform shrinkage based on moisture field |
| [51,89,134,136,137] | [82,90,91,93-95] | [34,35,38,45,92,96] |
| **Moisture field consideration** | | |
| Not considered | Humidity field | Explicit water distribution field |
| [51,82,89-91,93-95,134,136, 137] | [34,35,38,45,92,96] | - |
| **Drying conditions** | | |
| All surfaces sealed | Top and bottom | Circumferential |
| [51,89,134,136,137] | [45,82,91-93] | [34,35,38,90-93,94-96] |
| **Viscoelasticity (creep effects)** | | |
| “Effective” elastic modulus adoption | Constitutive law | Not considered |
| [34,35,82,89-96] | [38,45,51,134,136,137] | - |
| **Thermal analysis and temperature effects** | | |
| Heat-transfer and heat of hydration | Temperature effects on concrete properties | |
| [45,51,89,134,136,137] | [45,51,89,134,136,137] | |
| **Steel-concrete interface** | | |
| Frictionless | Full bond | Consideration of friction |
| [34,35,90-96,134] | [45,82,89,136,137] | [38] |
| **Fracture mechanics and post cracking behaviour** | | |
| [18,21,23,38,92,94-96,134,136,137] | | |
| **Material considered** | | |
| Concrete | Mortar | Fibre reinforced concrete |

| | | |
|---|---|---|
| [45,82,89,90,91,92,93,94-96,134,136] | [34,35,134] | [38,51,137] |
| **Validation against experimental results** | | |
| Yes – conducted by the same research team | Yes – using results from literature | No – analysis or sensitivity study |
| [38,45,51,89-92,94-96,134,136,137] | - | [34,35,93,134] |
| **Validation method** | | |
| Based on cracking age | Based on steel strain measurements | Based on crack width measurements |
| [89-91,94-96,136] | [45,51,136,137] | [38] |

### *2.1.4 Minor modifications of the traditional ring test setup*

Minor modifications of the traditional ring test include these by Dahl (described in [119]), adopted for the evaluation of plastic shrinkage cracking. The setup of the test was similar to that of the traditional test; however, the outer steel ring accommodated flat ribs to act as stress risers while hot air was blowing on the top surface of the ring. This method, however, which has been also used in [22] and was slightly improved by Esping and colleagues [120-122], is of more relevance to plastic rather than drying shrinkage. Other minor modifications include that reported in [123] where a concrete ring was cast around a hardened cube and hot air was blown on the top, exposed surface of the specimen and through rapid evaporation cracking was induced close to the four corners of the cubic core.

## 2.2 Elliptical ring tests

Elliptical ring specimens (Figure 1) have been developed relatively recently in Dalian University and Brunel University of London by the collaborative work of Zhou, Dong and colleagues [90-97]. The aim of this development was mainly associated with overcoming two particular barriers of the traditional-circular ring tests: a) to shorten the time required for the specimen to crack and b) to eradicate the randomness of the crack initiation location. The above-mentioned authors performed numerous studies [90-97] in order to investigate the effects of steel and concrete ring thicknesses, minor and major radius of the ellipse, as well as drying direction to argue that depending on the geometry used, cracking initiation is reduced and its location can be well predicted. It should be mentioned that although this method has been proposed to replace the standardised ring test, it has only been used by its conceptors so far (with the exception of [98]) and therefore it may be considered that it is still under development.

## 2.3 Eccentric and square-eccentric ring tests

Eccentric ring tests (Figure 1) have been recently developed in China [124] as an attempt to overcome the disadvantage of crack initiation randomness in traditional-circular ring tests. The geometry of the specimens was designed based on numerical simulations for the determination of the effects of eccentricity and mould weight. Various specimen lengths (405-800 mm) and weights (44-148 kg) were investigated whilst the cracking age was claimed to be lower than in the traditional ring test due to stress concentrations in the narrow side.

## 2.4 Dual ring tests

Dual ring tests have been developed in several laboratories in order to assess the restrained expansive behaviour of concrete, in addition to restrained shrinkage [125-134]. These, have been initially developed by Weiss and colleagues [125], used also by others [128], in order to evaluate the restrained volumetric changes of expansive pastes, such as internally cured pastes or pastes containing super absorbent polymers. The geometry of the specimens was smaller for the investigation of pastes [125] and similar to AASHTO standard [105] for the investigation of mortar/concrete [128]. The primary feature was the consideration of Invar steel for the rings as an attempt to negate the influence of temperature effects, whilst drying from top and bottom surfaces was investigated. Further improvements of the dual ring to extend its applicability for assessment of thermal and autogenous shrinkage include those of Schlitter *et al*. [131-134]. Following the principle of the previously described dual ring tests, the geometrical characteristics adopted resulted in a degree of restraint of 72% (similar to that of ASTM [108]) whilst apparatus additions included that of a temperature coil to control temperature and considerable insulation. Artificial cooling to induce cracking in the specimen was also possible, whilst analytical formulations to calculate induced stresses in concrete based on strain recordings have been proposed.

# 3 Active ring tests

Active ring tests, similar to the other modifications in the traditional-circular ring test, have not been widely adopted, however, they consist recent modifications of the ring test and are therefore briefly explained herein. The active feature of these tests corresponds to a particular controlled condition of the restraining core and can be separated into two categories: a) thermally-active, where the temperature of the core is continuously controlled and b) expansive core tests, where the restraining core is expanding generating additional tensile stresses in concrete.

The only thermally-active ring test was recently developed in France as an attempt to study the effects of restrained thermal and autogenous deformations in massive concrete structures [135-137]. The setup consisting of a restraining brass ring with RIS and thickness of 190 and 30 mm respectively and a 100 mm thick-walled concrete ring which remained sealed throughout the test duration. The inner brass ring hollow at several locations to accommodate a temperature regulation system was designed and temperature increases were induced at a rate of 0.17-0.70 °C/h. In contrast the constant boundary in Schlitter's *et al*. [131-134] setup, this test generates a moving boundary, resulting from brass ring expansion due to induced temperature increase.

Ring specimens with an active-expansive core that were reported by Kovler *et al.* [15]. The investigators replaced the traditionally considered hollow steel core with a solid Perspex core (higher CTE than concrete) and were able to induce cracking as early as 30 minutes after casting through increasing the temperature from 20 °C to 30 °C. Other modifications include that by Lemour *et al.* [139,140], where a mortar ring with 40 mm x 40 mm cross-section and 300 mm outer diameter was cast around a pressurised brass cylinder and that of a similar system also developed in France, able to induce controlled tensile cracking in disk-shaped specimens in order to study gas transfer in cracked mortars [141,142].

Most recently, a different active ring test was developed for the investigation of the cracking behaviour of fibre-reinforced mortars subjected to restrained plastic shrinkage [143,144]. In this configuration, a mortar ring was cast around a quasi-incompressible polymer core and after exposing the top surface of mortar to drying, the setup was placed on a tensile-compression testing machine under which the core was loaded in compression for the same amount of force induced in it by shrinkage, whilst the load was measured using a loadcell.

# 4 Challenges and perspectives

Indeed, several challenges and limitations are associated with the ring tests. Firstly, the rings are limited by cross-sectional sizes. Many standards require sieving concrete; however, this would not be necessarily representative of the same material used *in-situ*. Conversely, although much larger cross-sections could be more realistic, such solution would not be practical or even feasible for laboratory investigations. Moreover, the traditional-circular passive ring test is still the most popular in terms of the methodology; however, the restraint depends on the intensity of processes causing shrinkage and on the interaction with the concrete and therefore, is not controlled precisely.

Additional aspects are the duration of test and boundary conditions applied. It is not so infrequently observed for a certain mix tested for cracking sensitivity using the ring test method to only crack after few months since casting. In several cases, like the one considered for the analytical calculations in Section 2.1.2, cracking does not occur at all. In order to mitigate this and enable a more convenient application for routine evaluation, cracking is forced to occur relatively fast after drying commencement (for instance by the use of "activators-catalysers", such as active rings or stress concentrators as mentioned earlier). However, whether such extreme cases represent a reality is rather debatable, as concrete structures are exposed to both loading and drying. Next to this, viscoelasticity is very much pronounced at early ages and, therefore, accelerated cracking tests might not be representative of the long-term performance of concrete.

Furthermore, a point which was recently raised by Kovler [145] is that regarding the curing duration for ring specimens made of concretes/mortars which contain cement replacement materials (CRMs). Both the ASTM and the AASHTO standards, which are very popular among researchers and engineers for the determination of the restrained shrinkage cracking risk of cementitious materials, recommend a curing duration of 1 day and hence formwork removal, irrespective of the binder used. However, it is well known that concretes containing CRMs have different kinetics of hardening, creep, heat of hydration, modulus of elasticity and tensile strength gain, which often results in contradictory conclusions regarding their cracking sensitivity depending on the method used. In the case of concretes with CRMs, only 1 day of curing would not suffice due to their slower setting and early age strength development and their need for prolonged moisture curing because of slower hydration. Thus, a direct comparison of their cracking sensitivity with neat Portland cement concrete under these conditions would not be necessarily realistic. It might therefore be recommendable to modify the existing AASHTO and ASTM standards by applying at least two different curing periods, i.e. 1 and 7 days, in the case that the aim of the testing is to evaluate the cracking sensitivity of concrete mixes having different kinetics of hardening (like concretes with and without CRMs).

Finally, another relevant aspect to take into account in the use of the ring test is related to the game-changing aspects related to technology. Strain measurement has not evolved much in the last couple of decades, and the challenges that existed in measuring strain in highly restrained ring tests may disappear in a relatively short term. The capability of measuring sub-microstrain deformations with standardly available technology will definitely bring researchers and practitioners to focus more towards higher restraint experimental setups.

# 5 Conclusions

In this article, a state-of-the-art review of the widely adopted ring test method for the evaluation of the risk of cracking of cementitious materials under restrained shrinkage has been presented. Based on the review of the literature, statistical analysis and discussions, the following conclusive observations can be made:

- It appears that the standardisation of the ring test as a method to examine cracking sensitivity of cement-based materials promoted significantly its use. Thanks to standardisation, in a considerable amount of studies over the last fifteen years, research on restrained shrinkage has been conducted using such experimental method.
- In the majority of the reported studies the test configuration adopted by the researchers aligns to that suggested by the available standards, in favour of the ASTM one, whilst some geometrical modifications were reported depending on material (paste, mortar or concrete) and boundary conditions investigated.
- From examining the differences in quantitative-analytical approaches on computing stresses based on steel strains recorded it appeared that although all three solutions investigated (Equations 2, 3 and 4) converge at thin concrete and steel ring thicknesses, the general solution (Equation 4) may be deemed most widely applicable.
- It is of significant importance to determine the geometrical characteristics of the ring depending on boundary conditions and cementitious material intended to be investigated prior to performing the experiment. While this can be achieved with few relatively simple formulations, such as the *a priori* calculation of degree of restraint (Equations 1 and 5), to improve the accuracy of the calculations, focus can be given to fracture mechanics and numerical simulations approaches, highlighting the need for further investigations of the ring behaviour using these methods as most of the studies deal with cracking risk and do not consider fracture mechanics or numerical modelling.
- Recent advancements/modifications in the ring test include (a) elliptical and eccentric rings which aim to reduce the testing duration and eliminate cracking randomness occurrence, (b) dual rings which aim to enable the measurement of expansive and thermal deformations and (c) active rings which enable an active control of the restraining core. Although the capabilities of the traditional-circular ring test can be extended with such adaptations, they may be

considered to be still in developmental stage, as there has been no unequivocal proof that they improve a set of relevant factors (e.g. cost/ease of implementation, efficiency, effectiveness or even repeatability) of the traditional methods.

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