

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

Kanavaris, F., Azenha, M., Soutsos, M., & Kovler, K. (2019). Assessment of behaviour and cracking susceptibility of cementitious systems under restrained conditions through ring tests: A critical review. Cement and Concrete Composites, 95, 137-153. https://doi.org/10.1016/j.cemconcomp.2018.10.016

Published in:

Cement and Concrete Composites

Document Version:

Peer reviewed version

Queen's University Belfast - Research Portal:

Link to publication record in Queen's University Belfast Research Portal

Publisher rights

Copyright 2019 Elsevier. This manuscript is distributed under a Creative Commons Attribution-NonCommercial-NoDerivs License (https://creativecommons.org/licenses/by-nc-nd/4.0/), which permits distribution and reproduction for non-commercial purposes, provided the author and source are cited.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Open Access

This research has been made openly available by Queen's academics and its Open Research team. We would love to hear how access to this research benefits you. - Share your feedback with us: http://go.qub.ac.uk/oa-feedback

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

Fragkoulis Kanavaris^{1,a}, Miguel Azenha^{2,b*}, Marios Soutsos^{3,c} and Konstantin Kovler^{4,d}

^a Formerly in University of Minho, currently in Advanced Technology & Research, Arup, London, W1T 4BQ, UK

^b ISISE, University of Minho, Department of Civil Engineering. Campus of Azurém, Guimarães, 4800-058, Portugal

^c School of Natural and Built Environment, Queen's University Belfast, Belfast, BT9 5AG, UK

^d Faculty of Civil and Environmental Engineering, Technion - Israel Institute of Technology, Haifa 3200003, Israel

¹ Frag.Kanavaris@arup.com

² miguel.azenha@civil.uminho.pt (* corresponding author)

³ m.soutsos@qub.ac.uk

⁴ cvrkost@technion.ac.il

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) <u>Traditional-circular ring tests</u>, where a concrete, mortar or paste ring is cast around a restraining core, most frequently, an instrumented steel ring.
- (b) <u>Elliptical ring tests</u>, where the testing principle follows that of the traditional-circular ring tests; however, concrete and steel rings are of elliptical geometry.
- (c) <u>Eccentric or square-eccentric ring tests</u>, 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) <u>Dual ring tests</u>, 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.



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]:

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

where:

DR = degree of restraint [%]

 A_{rc} = cross-sectional area of restraining core (usually a steel ring) [mm²]

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

- A_{cm} = cross-sectional area of cementitious material (usually concrete) [mm²]
- 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 \approx 60-80% for a base of a wall cast on to a massive base, b) DR \approx 80% for an edge element cast onto a slab, c) DR \approx 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 $\pm 5 \ \mu\epsilon [101,102]$ 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 $\mu\epsilon$.

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.



[12]

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 $50\% \pm 10\%$ 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 described [24,26,27,29,32,39,44ring specimen, as in 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 mm³ 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 20°C 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 non-

absorptive 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.

Internal radius of steel [mm]							
45-82	83-120	121-132	133-145	146-157	>157		
[11, 54,62,63,75,83,8 7]	[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 radi	ius 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]		
		Specime	n 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]	[17,20,23,24,26,29,39,40,43,4 6,48,53,57-61,64,68-72,74- 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]		

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

1

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- 51,58,78,80,81,85,91,92,94,9 6,99]	_
		Hollow/solid	l restraining core		
	Hollow			Solid	
	[9-14,16-20,22,24-95,99]			[15,21,23]	
De	gree of restraint [%] (calculated by t	he authors assuming an	elastic modulus of 200 and 30 GPa	a for steel and concrete, respectiv	ely)
	<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	4]
		Dryin	g direction		
Circumferential	Top & bottom	Тор	All 3 sides exposed	All 3 sides seal	ed
[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]	[48,51,52,67,62,64,7]	3,88,89]
	· · · · · · · · · · · · · ·	Relative	humidity [%]		-
	0-39		40-60	>60	
	[11]	[9-32,36-50,53-61	3-61, 63-65,68-85-87,90-95,99] [11,19]		

Curing temperature						
S	Standard (18-24 °C)		Elevated	Lower		
[11-2	2,24-28,32-69,72-95,99]	[15,23,30,31,88,89]	(30 °C), [88,89] (40 & 50 °C)	[9,10] (16 °C), [71]	(11 °C)	
		Materia	l investigated			
	Concrete		Mortar	Paste		
[9-24,26,28-30,32 80	2,39,43-47,49,51,53,58-60,64,68-77, -83,85, 86,88-95,99]	[27, 31,36,37, 63,65	40,41,42,48,50,54,55,61- ,68,78,79,84,87]	[52.67]		
		Calculation of stresses, o	cracking age/width/sensitivity			
	Analytical approach		Ν	Numerical simulation		
[9,10,12,	15,18,19,21,23-27,31-36,44,45,53-60,6	3,65,77,78,82]	[21,33-35	,38,45,51,89-96,134,136,137]		
		Formwoi	·k removal age			
<1 day	1 day	2 days	3 days	4 days	>4 days	
[10, 14-16,22]	[9-13,15,17-32,36,37,39-42,44-53- 55,57-59,63,65,68,70,72-74,76- 95,99]	[15,61,71,75] [15,43,69,80]		[60]	[61,80]	
	P	ace of study [continent	of host institution of 1 st author]			
N. America	S. America	Europe	Asia	Africa	Oceania	
[11-14,16- 18,21,23-31,33- 36,39- 41,43,48,53- 59,69,76,85-87]	_	[9,10,22,32,37,45,46, 49,51,52,57, 66,67,70,72-74,81,88- 91,99]	[15,19,38,47,50,60,62- 65,71,75,78,80,83,84,92-95]	[61,68,79]	[20,42, 77,82]	
	Year of publication					
1975-1985	1986-1995	1996-2005	2006-2015	>2015		
[9,10]	[11-15]	[16-30]	[31-72,90,91,94]	[73-89,92,93,95	5,99]	

2

- 3
- 4

2.1.2 Analytical approaches and comparisons

5

6 Different calculation procedures have been proposed to enable the calculation of either induced 7 restraint stresses in concrete or degree of restraint. This section focuses on the differences between 8 methods that can be used to calculate stresses based on recorded steel strains, as well as on the 9 differences between methods that can be used to calculate the degree of restraint in the ring test prior 10 to conducting the experiment and the applicability and potential limitations of each approach are 11 discussed.

12

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

15

16 As mentioned earlier, analytical methods have been proposed that can be used to compute the induced 17 tensile stresses in the concrete ring. These can be subdivided in two categories: i) Analytical 18 approaches which require knowledge of the free shrinkage (and modulus of elasticity) of the 19 investigated mix (as those described in [12,15,18,19,23,27,34,35,53,56]), preferably under the same 20 drying conditions as the restrained specimen and ii) analytical approaches that only require the 21 knowledge of the steel ring strains induced by concrete shrinkage (i.e. [9,10,24,27,34,35]). Analytical 22 approaches as per (i) may be considered as more labour intensive, since additional experiments are 23 required in order to determine the free shrinkage and elastic properties. Therefore, in this section, the 24 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]:

31
$$\sigma_t(t) = \frac{-\varepsilon_{st}(t)E_{st}}{2} \frac{A_{st}}{A_c} \left(1 + \frac{R_{is}^2 + R_{os}^2}{2R_{os}^2}\right)$$
 Equation 2

32 where:

33 $\sigma_t(t)$ = average tensile stress in concrete at time t	[MPa]
---	-------

- 34 $\epsilon_{st}(t)$ = average steel ring strain at time t
- 35 E_{st} = modulus of elasticity of steel [GPa]
- $A_{st} = cross-sectional area of steel ring [mm]$
- $A_c = cross-sectional area of concrete ring [mm]$
- $R_{is} = internal radius of steel ring [mm]$
- $R_{os} = outer radius of steel ring [mm]$

40

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

43
$$\sigma_{max}(t) = -\varepsilon_{st}(t)E_{st}\frac{R_{os}W_{st}}{R_{is}W_c}$$
 Equation 3

44 where:

45

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

[24]

46
$$W_c$$
 = wall thickness of the concrete ring [mm]

47
$$W_{st}$$
 = wall thickness of the steel ring [mm]

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

49
$$\sigma_{max}(t) = -\varepsilon_{st}(t)E_{st}\frac{R_{os}^2 + R_{oc}^2}{R_{oc}^2 - R_{os}^2}\frac{R_{os}^2 - R_{is}^2}{2R_{os}^2}$$
 Equation 4

50 where:

51
$$R_{oc}$$
 = outer radius of concrete ring [mm]

52 The calculation of stresses in concrete based on the above formulations requires knowledge of the steel 53 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 54 55 investigation, reported in [45], different steel ring wall thicknesses were also examined. The 56 geometrical characteristics of the investigated ring specimens were as follows [45]: RIS = 145, 140 57 and 130 mm (resulting in 20, 10 and 5 mm steel wall thicknesses), ROS = 150 mm, ROC = 225 mm 58 (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 59 60 only permitted to occur from the top and bottom concrete ring surfaces, hence, uniform shrinkage 61 through the radial direction can be assumed. The elastic modulus of steel was taken as 195 GPa [45]. 62 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]

65

66 The steel ring strains shown in Figure 5 can be used to calculate stresses in concrete based on Equations 67 2, 3 and 4, and these are illustrated in Figure 6. In order to not only avoid data congestion but to also 68 enable a distinct comparison of the methods, the experimental results from ring tests with 5 and 20 69 mm steel wall thickness are considered, i.e. the two extreme cases. It can be observed from Figure 6 70 that there are discrepancies in the calculated stresses based on different equations. Most notably, it 71 appears that Equation 4 consistently yields greater values of induced tensile stresses in the concrete 72 ring, which is followed by Equation 3. A possible explanation of this could be the fact that a "thick-73 walled" concrete ring (75 mm) was considered as an example, whilst Equation 3 was derived 74 considering a thin wall approximation, as it has been observed that Equations 3 and 4 yield similar 75 results for thinner rings (which are also the geometries that are commonly used) [25,130]. It should 76 also be noted that Equation 2 calculates the average stresses in concrete, while Equations 3 and 4 77 provide the maximum stresses; hence, the stresses computed using Equation 2 have the lowest 78 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.



81

Figure 6: Computed stresses using Equations 2, 3 and 4 based on data shown in Figure 5 82 The differences between the investigated equations in estimating the stresses in the concrete rings can 83 84 be elucidated by examining the calculated stress over a varying concrete or steel wall thickness, as 85 shown in Figure 7. Constant steel wall thicknesses of 12.5 mm (ASTM and AASHTO) and 25.5 mm 86 (found in the works of S. P. Shah and J. Weiss) and constant concrete wall thicknesses of 37.5 mm 87 (ASTM) and 75 mm (AASHTO) are considered in Figure 7(a) and 7(b) respectively. Indeed, when a 88 constant steel wall thickness of 12.5 mm is considered, the solutions from Equations 3 and 4 only 89 converge for values of concrete wall thickness ratio below 1.3, indicating that for this range, a thin 90 wall approximation can be appropriate. However, their convergence whenever the steel wall thickness 91 is increased to 25.5 mm diminishes. It is worth mentioning that Equation 2 consistently yields lower 92 stress values, apart from very low concrete wall thickness ratios. Similar behaviour is also observed 93 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 94

similar to those suggested by ASTM and AASHTO (approximately 12.5 mm) the equations yield
similar results.



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

100

97

- 101
- 102

103 2.1.2.2 Comparisons between methods to estimate *a priori* degree of restraint

104

105 The determination of the *a priori* degree of restraint in the setup is of particular importance when 106 adjustments of the specimen geometry are required in order to achieve a desired degree of restraint 107 (for example, whenever a particular field application of concrete needs to be tested). Indeed, an *a* 108 *posteriori* determination of the actual degree of restraint in the knowledge of free shrinkage and 109 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.

116
$$DR = 100\% - \frac{E_c}{E_{st}} \frac{1}{\left[1 - \left(\frac{R_{is}}{R_{os}}\right)^2\right] \left[(1 + v_c) \left(\frac{R_{oc}}{R_{os}}\right)^2 + (1 - v_c)\right]}{\left[1 - \left(\frac{R_{oc}}{R_{os}}\right)^2\right] \left[(1 + v_{st}) \left(\frac{R_{is}}{R_{os}}\right)^2 + (1 - v_{st})\right]}} * 100\%$$
Equation 5

117 Where:

118	DR	= degree of restraint [%]
119	Ec	= modulus of elasticity of concrete [GPa]
120	E_{st}	= modulus of elasticity of steel [GPa]
121	ν_c	= Poisson's ratio of concrete
122	ν_{st}	= Poisson's ratio of concrete steel
123	R _{os}	= outer radius of steel ring [mm]
124	R_{oc}	= outer radius of concrete ring [mm]
125	Ris	= internal radius of steel ring [mm]
126		

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

131 found in the numerous studies of S. P. Shah and colleagues (127, 152.5, 187.5 and 140 for RIS, ROS, 132 ROC and specimen height respectively) and iv) one of the geometries investigated by Hossain and 133 Weiss [27] (140.5, 150, 225 and 75 for RIS, ROS, ROC and specimen height respectively). Typical 134 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 135 136 in Equation 4 should be the "effective" elastic modulus, $E_{c,eff}$, which aims to account for creep effects; 137 which is the static elastic modulus reduced to 60% [33-35,82,89-96]. In this comparison, both original 138 and "effective" elastic moduli are considered in both equations in order to explore the differences 139 between the calculated values of degrees of restraint.

140 The calculated values of degree of restraint achieved in rings with different geometries based on the 141 aforementioned methods are shown in Figure 8. Overall, the calculated values of the degree of restraint 142 of the ring specimens was somewhat similar to typical values considered for field applications. 143 However, from the same figure, it is apparent that there are discrepancies in the obtained, theoretical, 144 value of degree of restraint depending on the method used. Generally, the values calculated using the 145 formula proposed by Moon et al. [33] (Equation 5) which takes into account the Poisson's ratio of 146 steel and concrete in addition to the elastic moduli, were of greater magnitude than those estimated 147 with the simple method in [24] (Equation 1). In both cases, the calculated degrees of restraint increased 148 whenever an "effective" elastic modulus was considered, which was rather anticipated; however, such 149 approximation/assumption, i.e. reduce the static elastic modulus down to 60% to account for creep 150 effects, might not be necessarily realistic. Nevertheless, irrespective of the discrepancies in the 151 estimated values of degree of restraint, in which a difference of $\pm 10\%$ can be observed depending on 152 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 153 154 ASTM, AASHTO and Hossain and Weiss [27].



156 Figure 8: Comparison between calculated values of degree of restraint based on different methods157

137

158 2.1.3 Numerical simulations of the ring test

159

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] 167 configuration is modelled. In all cases, shrinkage is the driving force: uniform autogenous for sealed 168 conditions [51,89,134,136,137]; uniform drying shrinkage [82,90,91,93-95] if drying is allowed from 169 top and bottom or from the outer circumference provided that the concrete wall thickness is small 170 enough to assume uniform shrinkage; or non-uniform shrinkage [34,35,38,45,92,96], mainly for 171 thicker concrete rings, which also enables the evaluation of the self-restraint effects due to moisture 172 gradients. Generally, there was a similar distribution of studies where all surfaces were sealed 173 [51,89,134,136,137] and top and bottom drying [45,82,91-93] was considered. However, the majority 174 of studies investigated circumferential drying [34,35,38,90-93,94-96] which may be attributed to such 175 drying conditions being suggested by the relevant standards [103-108]. In the cases where non-uniform 176 drying was considered it is worth pointing out that in all studies, the moisture field was modelled using 177 humidity-based relationships [34,35,38,45,92,96], rather than explicit modelling of water distribution 178 in concrete. Perhaps a possible explanation for this is that shrinkage may be relatively easier to be 179 related to changes in humidity rather than changes in water content/distribution [45,138]. Furthermore, 180 as FEA packages may not always accommodate shrinkage input as a concrete property, a frequently 181 employed approach is to calculate a fictitious temperature field. The fictitious temperature field to 182 simulate shrinkage contraction is calculated with basis on a constant arbitrary coefficient of thermal 183 expansion (CTE), as to ensure temperature driven contraction that matches the contraction due to 184 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

192 temperature increase during the early stages of hydration at standard curing can be considered to have 193 negligible effects to the overall behaviour, stress build-up and cracking age of the ring test. Thermo-194 mechanical simulations were performed in [51,89,134,136,137] due to thermal and autogenous 195 deformations being the dominant driving forces in the models, whilst a multiphysics approach to the 196 problem was described in [45] where a thermo-hygro-mechanical framework [117,118] was used for 197 rings drying from top and bottom surfaces, also considering explicitly the moisture profiles in the 198 specimens. It is also worth noting that authors usually validated their models (mostly against their own 199 experimental results) on the basis of cracking age [89-91,94-96,136] whilst there are only a few studies 200 where direct comparison between steel strains (or even crack widths [38]) from FEA and recorded 201 ones was used for model validation [45,51,136,137], which may also be considered more reliable than 202 the former. Next to this, drying from all three potentially exposed surfaces has not beet simulated yet. 203 One aspect of the simulation that is still debatable pertains to the contact characteristics considered 204 between concrete and steel. In the majority of the studies in which such matter is mentioned, 205 frictionless contact between steel and concrete was assumed [34,35,90-96,134]. Within the argument 206 that bond will always be present between concrete and steel, others assumed a perfect bond between 207 the two materials in their models [45,82,89,136,137] whilst a Coulomb friction model was used in 208 [38] to explicitly describe friction characteristics in the concrete-steel interface. Generally, in the 209 identified studies there is no justification as to why a particular steel-concrete interface was chosen 210 (apart from when friction was considered) and a parametric study could possibly elucidate this 211 debatable matter. However, it is noted that these interface properties are only likely to be of relevance for post-cracking behaviour. 212

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 - axisyn		mmetric	3D		3D	
[38,82]	[34,35,4	5,51]			[89-	96 136,137]
		Shrinkag	e			
Uniform au	togenous	Uniform dr	ying	Non-uni	form	shrinkage based on moisture field
[51,89,134,	136,137]	[82,90,91,93	3-95]			[34,35,38,45,92,96]
		Moisture field cons	sideration			
Not considered		Humidity field			I	Explicit water distribution field
[51,82,89-91,93-95,134,13 137]	36,	[34,35,38,45,92,96]]			-
		Drying condi	tions			
All surfaces sealed	Top and bo	ttom	Circumferential			cumferential
[51,89,134,136,137]	[45,82,91-	93]	[34,35,38,90-93,94-96]			
		Viscoelasticity (cre	ep effects)			
"Effective	e" elastic modulus adoptio	n	Constit	utive law		Not considered
	[34,35,82,89-96]		[38,45,51,2	134,136,13	37]	-
	Therm	al analysis and ten	nperature ef	fects		
Heat-trai	nsfer and heat of hydration	l	Te	emperature	e effe	cts on concrete properties
[45	5,51,89,134,136,137]			[45	5,51,8	39,134,136,137]
		Steel-concrete in	nterface			
Frictionless	Full bond		Consideration of friction			
[34,35,90-96,134]	[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			oncrete			

[45,82,89,90,91,92,93,94- 96,134,136]	[34,35,134]		[38,51,137]		
	Valid	ation against (experimental results		
Yes – conducted by the same research team	Yes – using results from literature		No – analysis or sensitiv	vity 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]	

225

226

227 2.1.4 Minor modifications of the traditional ring test setup

228

229 Minor modifications of the traditional ring test include these by Dahl (described in [119]), adopted for 230 the evaluation of plastic shrinkage cracking. The setup of the test was similar to that of the traditional 231 test; however, the outer steel ring accommodated flat ribs to act as stress risers while hot air was 232 blowing on the top surface of the ring. This method, however, which has been also used in [22] and 233 was slightly improved by Esping and colleagues [120-122], is of more relevance to plastic rather than 234 drying shrinkage. Other minor modifications include that reported in [123] where a concrete ring was 235 cast around a hardened cube and hot air was blown on the top, exposed surface of the specimen and 236 through rapid evaporation cracking was induced close to the four corners of the cubic core.

237

238 2.2 Elliptical ring tests

239

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

242 aim of this development was mainly associated with overcoming two particular barriers of the 243 traditional-circular ring tests: a) to shorten the time required for the specimen to crack and b) to 244 eradicate the randomness of the crack initiation location. The above-mentioned authors performed 245 numerous studies [90-97] in order to investigate the effects of steel and concrete ring thicknesses, 246 minor and major radius of the ellipse, as well as drying direction to argue that depending on the 247 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 248 249 only been used by its conceptors so far (with the exception of [98]) and therefore it may be considered 250 that it is still under development.

251

252 2.3 Eccentric and square-eccentric ring tests

253

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.

260

261 2.4 Dual ring tests

262

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

[36]

265 developed by Weiss and colleagues [125], used also by others [128], in order to evaluate the restrained 266 volumetric changes of expansive pastes, such as internally cured pastes or pastes containing super 267 absorbent polymers. The geometry of the specimens was smaller for the investigation of pastes [125] 268 and similar to AASHTO standard [105] for the investigation of mortar/concrete [128]. The primary 269 feature was the consideration of Invar steel for the rings as an attempt to negate the influence of 270 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 271 272 shrinkage include those of Schlitter et al. [131-134]. Following the principle of the previously 273 described dual ring tests, the geometrical characteristics adopted resulted in a degree of restraint of 274 72% (similar to that of ASTM [108]) whilst apparatus additions included that of a temperature coil to 275 control temperature and considerable insulation. Artificial cooling to induce cracking in the specimen 276 was also possible, whilst analytical formulations to calculate induced stresses in concrete based on 277 strain recordings have been proposed.

278

279 **3** Active ring tests

280

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. 287 The only thermally-active ring test was recently developed in France as an attempt to study the effects 288 of restrained thermal and autogenous deformations in massive concrete structures [135-137]. The setup 289 consisting of a restraining brass ring with RIS and thickness of 190 and 30 mm respectively and a 100 290 mm thick-walled concrete ring which remained sealed throughout the test duration. The inner brass 291 ring hollow at several locations to accommodate a temperature regulation system was designed and 292 temperature increases were induced at a rate of 0.17-0.70 °C/h. In contrast the constant boundary in 293 Schlitter's *et al.* [131-134] setup, this test generates a moving boundary, resulting from brass ring 294 expansion due to induced temperature increase.

295 Ring specimens with an active-expansive core that were reported by Kovler et al. [15]. The 296 investigators replaced the traditionally considered hollow steel core with a solid Perspex core (higher 297 CTE than concrete) and were able to induce cracking as early as 30 minutes after casting through 298 increasing the temperature from 20 °C to 30 °C. Other modifications include that by Lemour et al. 299 [139,140], where a mortar ring with 40 mm x 40 mm cross-section and 300 mm outer diameter was 300 cast around a pressurised brass cylinder and that of a similar system also developed in France, able to 301 induce controlled tensile cracking in disk-shaped specimens in order to study gas transfer in cracked 302 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.

309

310

4 Challenges and perspectives

311

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 crosssections 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.

319 Additional aspects are the duration of test and boundary conditions applied. It is not so infrequently 320 observed for a certain mix tested for cracking sensitivity using the ring test method to only crack after 321 few months since casting. In several cases, like the one considered for the analytical calculations in 322 Section 2.1.2, cracking does not occur at all. In order to mitigate this and enable a more convenient 323 application for routine evaluation, cracking is forced to occur relatively fast after drying 324 commencement (for instance by the use of "activators-catalysers", such as active rings or stress 325 concentrators as mentioned earlier). However, whether such extreme cases represent a reality is rather 326 debatable, as concrete structures are exposed to both loading and drying. Next to this, viscoelasticity 327 is very much pronounced at early ages and, therefore, accelerated cracking tests might not be 328 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 334 is well known that concretes containing CRMs have different kinetics of hardening, creep, heat of 335 hydration, modulus of elasticity and tensile strength gain, which often results in contradictory 336 conclusions regarding their cracking sensitivity depending on the method used. In the case of concretes 337 with CRMs, only 1 day of curing would not suffice due to their slower setting and early age strength 338 development and their need for prolonged moisture curing because of slower hydration. Thus, a direct 339 comparison of their cracking sensitivity with neat Portland cement concrete under these conditions 340 would not be necessarily realistic. It might therefore be recommendable to modify the existing 341 AASHTO and ASTM standards by applying at least two different curing periods, i.e. 1 and 7 days, in 342 the case that the aim of the testing is to evaluate the cracking sensitivity of concrete mixes having 343 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 gamechanging 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.

350

351 **5** Conclusions

352

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.
- 369 It is of significant importance to determine the geometrical characteristics of the ring depending 370 on boundary conditions and cementitious material intended to be investigated prior to 371 performing the experiment. While this can be achieved with few relatively simple formulations, 372 such as the *a priori* calculation of degree of restraint (Equations 1 and 5), to improve the 373 accuracy of the calculations, focus can be given to fracture mechanics and numerical 374 simulations approaches, highlighting the need for further investigations of the ring behaviour 375 using these methods as most of the studies deal with cracking risk and do not consider fracture 376 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.

385

386 Acknowledgements

387 This study was conducted during the "Short-term Scientific Mission" (STSM) fund awarded to the 388 first author and hosted by the second author. The authors are grateful for the financial support received by COST Action TU1404 "Towards the next generation of standards for service life of cement-based 389 390 materials and structures". This work was partially financially supported by project POCI-01-0145-391 FEDER-007633 (ISISE), funded by FEDER funds through COMPETE2020 - Programa Operacional 392 Competitividade e Internacionalização (POCI), and by national funds through FCT - Fundação para a 393 Ciência e a Tecnologia. FCT and FEDER (COMPETE2020) are also acknowledged for the funding of 394 the research project IntegraCrete PTDC/ECM-EST/1056/2014 (POCI-01-0145-FEDER-016841). The 395 contents of this paper reflect the views of the authors, who are responsible for the validity and accuracy 396 of presented data, and do not necessarily reflect the views of their affiliated organisations.

397

398 **References**

399	1.	Bentur, A. and Kovler, K. "Evaluation of early age cracking characteristics in cementitious
400		systems", Materials and Structures, 36, 2003, pp. 183-190.

401 2. Shah, S.P., Weiss, J., W. and Yang, W. "Shrinkage cracking – Can it be prevented?" *Concrete*402 *International*, **20**(4), 1998, pp. 51-55.

403	3.	Ingham, J. and McKibbings, L. "Briefing: Concrete structures affected by cracking",
404		Proceedings of the institution of Civil Engineers: Forensic Engineering, 166(FE1), 2013, pp.
405		3-8.
406	4.	Barre, F., Bisch P., Chauvel, D. et al. "Control of cracking in reinforced concrete structures:
407		Research project CEOS.fr", Wiley, August, 2016.
408	5.	Mangold, M. "Methods for experimental determination of thermal stresses and crack sensitivity
409		in the laboratory", in Prevention of thermal cracking in early ages, Springenschmid, R. (ed),
410		RILEM state-of-the-art report, E & FN SPON, 1998, pp. 26-39.
411	6.	Vaysburd, A.M., Emmons, P.H., Bissonnette, B. and Pigeon, M. "Some aspects of evaluating
412		cracking sensitivity of repair materials", in: Proceedings of the international RILEM
413		conference on early age cracking in cementitious systems EAC-01, Bentur, A. and Kovler, K.
414		(eds), Haifa, Israel, March, 2001, pp. 169-186.
415	7.	Mahlotra, V.M., Zoldners, N.G. and Woodroffe, H.M. "Ring test for tensile strength of
416		concrete", Materials Research and Standards, 6(1), 1966, pp. 2-12.
417	8.	Malhora, V.M. "Concrete rings for determining tensile strength of concrete – An ACI Digest
418		paper", ACI Journal Proceedings, 67(4), 1970, pp. 354-357.
419	9.	Swamy, R.N. and Stavrides, H. "Influence of fiber reinforcement on restraint shrinkage and
420		cracking", ACI Journal, 76(3), 1979, pp. 443-460.
421	10.	Swamy, R.N., Bandyopadhyay, A.K. and Stavrides, H. "The ring method of measuring
422		restrained shrinkage in mortar and concrete", Cement, Concrete and Aggregates, 1(1), 1979,
423		pp. 13-20.
424	11.	Carlson, R.W. and Reading, T.J. "Model study of shrinkage cracking in concrete building
425		walls", ACI Structural Journal, 85(4), 1988, pp. 395-404.

[43]

- 426 12. Grzybowski, M. and Shah, S.P. "Shrinkage cracking of fiber reinforced concrete", *ACI*427 *Materials Journal*, 87(2), 1990, pp. 138-148.
- 428 13. Shah, S.P., Karaguler, M.E. and Sarigaphuti, M. "Effects of shrinkage-reducing admixtures on
 429 restrained shrinkage cracking of concrete", *ACI Materials Journal*, **89**(3), 1992, pp. 291-95.
- 430 14. Sarigaphuti, M., Shah, S.P. and Vinson, K.D. "Shrinkage cracking and durability
 431 characteristics of cellulose fiber reinforced concrete", *ACI Materials Journal*, **90**(4), 1993, pp.
 432 309-318.
- 433 15. Kovler, K., Sikuler, J. and Bentur, A. "Restrained shrinkage tests of fibre-reinforced concrete
 434 ring specimens: effect of core thermal expansion", *Materials and Structures*, 26(4), 1993, pp.
 435 231-237.
- 436 16. Wiegrink, K., Marikunte, S. and Shah, S.P. "Shrinkage cracking of high-strength concrete",
 437 *ACI Materials Journal*, **93**(5), 1996, pp. 409-415.
- 438 17. Folliard, K.J. and Berke, N.S. "Properties of high-performance concrete containing shrinkage439 reducing admixtures", *Cement and Concrete Research*, 2(9), 1997, pp. 1357-1364.
- 18. Shah, S.P., Ouyang, C., Marikunte, S., Yang, W. and Becq-Giraudon, E. "A method to predict
 shrinkage cracking of concrete", *ACI Materials Journal*, 95(4), 1998. pp. 339-46.
- 442 19. Li, Z., Qi, M., Li, Z. and Ma, B. "Crack width of high-performance concrete due to restrained
 443 shrinkage", *Journal of Materials in Civil Engineering*, **11**(3), 1999, 214-223.
- 20. Collins, F. and Sanjayan, J.G. "Cracking tendency of alkali-activated slag concrete subjected
 to restrained shrinkage", *Cement and Concrete Research*, **30**(5), 2000, pp. 791-798.
- 446 21. Weiss, J.W., Yang, W. and Shah, S.P. "Influence of specimen size/geometry on shrinkage
 447 cracking of rings", *Journal of Engineering Mechanics*, **126**(1), 2000, pp. 94-101.

[44]

448	22. Branch, J., Rawling, A., Hannant, D.J. and Mulheron, M. "The effects of fibres on plastic
449	shrinkage cracking of high strength concrete", Materials and Structures, 35(3), 2002, pp. 189-
450	194.
451	23. Weiss, W.J. and Shah, S.P. "Restrained shrinkage cracking: the role of shrinkage reducing
452	admixtures and specimen geometry", Materials and Structures, 35(2), 2002, pp. 85-91.
453	24. See, H.T., Attiogbe, E.K. and Miltenberger, M.A. "Shrinkage cracking characteristics using
454	ring specimens", ACI Materials Journal, 100(3), 2003, pp. 239-245.
455	25. Attiogbe, E.K., Weiss, J.W. and See, H.T. "A look at the stress rate versus time of cracking
456	relationship observed in the restrained ring test", in: Proceedings of the international
457	symposium on concrete science and engineering: A tribute to Arnon Bentur, Kovler, K.,
458	Marchand, J., Mindness, S. and Weiss, J. (eds), RILEM Publications SARL, Evanston, IL, USA,
459	March, 2004.
460	26. See, H.T., Attiogbe, E.K. and Miltenberger, M.A. "Potential of restrained shrinkage cracking
461	of concrete and mortar", Cement, Concrete and Aggregates, 26(2), 2004, pp. 1-8.
462	27. Hossain, A.B. and Weiss, J.W. "Assessing the residual stress development and stress relaxation
463	in restrained concrete ring specimens", Cement and Concrete Composites, 26(5), 2004, pp.
464	531-540.
465	28. Tritsch, N., Darwin, D. and Browning, J. "Evaluating shrinkage and cracking behavior of
466	concrete using restrained ring and free shrinkage tests", Structural Engineering and
467	Engineering Materials, Report SM Report No. 77, The University of Kansas Center for

468 Research, Kansas, USA, 2005.

[45]

469	29. Mokarem, D.W., Weyers, R.E. and Lane, D.S. "Development of a shrinkage performance
470	specifications and prediction model analysis for supplemental cementitious material concrete
471	mixtures", Cement and Concrete Research, 35(5), 2005, pp. 918-925.
472	30. Subramanian, K.V., Gromotka, R., Shah, S.P., Obla, K. and Hill, R. "Influence of ultrafine fly
473	ash on the earlyage response and the shrinkage cracking potential of concrete", Journal of
474	Materials in Civil Engineering, 17(1), 2005, pp. 45-53.
475	31. Shah, H.R. and Weiss, J.W. "Quantifying shrinkage cracking in fiber reinforced concrete using
476	the ring test", Materials and Structures, 39, 2006, pp. 887-899.
477	32. Turcry, P., Loukili, A., Haidar, K., Pijaudier-Cabot, G. and Belarbi, A. "Cracking tendency of
478	self-compacting concrete subjected to restrained shrinkage: Experimental study and
479	modeling", Journal of Materials in Civil Engineering, 18(1), 2006, pp. 46-54.
480	33. Moon, J.H., Rajabipour, F., Pease, B. and Weiss, J. "Quantifying the influence of specimen
481	geometry on the results of the restrained ring test", Journal of ASTM International, 3(8), 2006,
482	14 p.
483	34. Moon, J.H. "Shrinkage, residual stress and cracking in heterogeneous materials", PhD Thesis,
484	Purdue University, West Lafayette, USA, 2006.
485	35. Moon, J.H. and Weiss, J. "Estimating residual stress in the restrained ring test under
486	circumferential drying", Cement and Concrete Composites, 28(5), 2006, pp.486-496.
487	36. Hossain, A.B. and Weiss, J.W. "The role of specimen geometry and boundary conditions on
488	stress development and cracking in the restrained ring test", Cement and Concrete Composites,
489	26 (1), 2006, pp. 189-199.

490	37. Turatsinze, A., Bonnet, S. and Granju, JL. "Potential of rubber aggregates to modify
491	properties of cement based-mortars: Improvement in cracking shrinkage resistance",
492	Construction and Building Materials, 21(1), 2007, pp. 176-181.
493	38. Kwon, S.H. and Shah, S.P. "Prediction of early-age cracking of fibre-reinforced concrete due
494	to restrained shrinkage", ACI Materials Journal, 105(4), 2008, pp. 381-389.
495	39. Hwang, SD. and Khayat, K.H. "Effect of mixture composition on restrained shrinkage
496	cracking of self-consolidating concrete used in repair", ACI Materials Journal, 105(5), 2008,
497	pp. 499-509.
498	40. Radlinska, A., Bucher, B. and Weiss, J. "Comments on the interpretation of results from the
499	restrained ring test", Journal of ASTM International, 5(10), 2008, pp. 1-12.
500	41. Hossain, A.B., Fonseka, A. and Bullock, H. "Early age stress development, relaxation and
501	cracking in restrained low W/B ultrafine fly ash mortars", Journal of Advanced Concrete
502	<i>Technology</i> , 6 (2), 2008, pp. 261-271.
503	42. Ahmed, S.F.U. and Mihashi, H. "Restrained shrinkage-induced cracking of lightweight high
504	performance fiber reinforced cementitious composites", American Journal of Engineering and
505	<i>Applied Sciences</i> , 2 (4), 2009, pp. 775-780.
506	43. VonFay, K.F., Morency, M., Bissonnette, M. and Vaysburd, A.M. "Development of test
507	methods to evaluate cracking tendency of repair materials – Field study Phase II", Reclamation
508	- Managing water in the west, Concrete Repair Engineering Experimental Programme, MERL
509	research report 2009-1, USA, May, 2009.
510	44. Kovler, K. and Bentur, A. "Cracking sensitivity of normal- and high-strength concrete", ACI
511	Materials Journal, 106(6), 2009, pp. 537-542.

[47]

- 45. Azenha, M. "Numerical simulation of the behaviour of concrete at since its early ages", PhD
 Thesis, Universidade to Porto, Portugal, 2009.
- 46. Passuello, A., Moriconi, G. and Shah, S.P. "Cracking behavior of concrete with shrinkage
 reducing admixtures and PVA fibers", *Cement and Concrete Composites*, **31**(10), 2009, pp.
 699-704.
- 517 47. Ji, T., Hu, C.-B. and Liang, Y.-N. "Preliminary study on a new evaluation method of concrete
 518 cracking resistant behaviour", *Key Engineering Materials*, **400-402**, 2009, pp. 459-463.
- 48. Henkensiefken, R., Bentz, D., Nantung, T. and Weiss, J. "Volume change and cracking in
 internally cured mixtures made with saturated lightweight aggregate under sealed and unsealed
 conditions", *Cement and Concrete Composites*, **31**(7), 2009, pp. 427-437.
- 49. Van Itterbeeck, P., Cauberg, N., Parmentier, B., Vandewalle, L., Lesage, K. "Evaluation of the
 cracking potential of young self compacting concrete", in: Proceedings of SCC 2010 design,
 production, and placement of SCC (Khayat, K. and Feys, D. (eds)), Vol. 2, Montreal Canada, *Springer*, September, 2010, pp. 991-1001.
- 526 50. Nguyen, Q.-P., Jiang, L.-H. and Zhu, Q. "Assessment of early-age cracking in high527 performance concrete in restrained ring specimens", *Water Science and Engineering*, 3(1),
 528 2010, pp. 113-120.
- 529 51. Zreiki, J., Bouchelaghem, F. and Chaouche, M. "Early-age behaviour of concrete in massive
 530 structures, experimentation and modelling", *Nuclear Engineering and Design*, 240(10), 2010,
 531 pp. 2643-2654.
- 532 52. Mounanga, P., Bouasker, M., Pertue, A., Perronnet, A. and Khelidj, A. "Early-age autogenous
 533 cracking of cementitious matrices: physico-chemical analysis and micro/macro
 534 investigations", *Materials and Structures*, 44(4), 2011, pp. 749-772.

535	53. Lomboy, G., Wang, K. and Ouyang, C. "Shrinkage and fracture properties of semiflowable
536	self-consolidating concrete", Journal of Materials in Civil Engineering, 23(11), 2011, pp.
537	1514-1524.

- 538 54. Pour-Ghaz, M. and Weiss, J. "Detecting the time and location of cracks using electrically
 539 conductive surfaces", *Cement and Concrete Composites*, 33(1), 2011, pp. 116-123.
- 540 55. Pour-Ghaz, M., Poursaee, A., Spragg, R. and Weiss, J. "Experimental methods to detect and
 quantify damage in restrained concrete ring specimens", *Journal of Advanced Concrete*542 *Technology*, 9(3), 2011, pp. 251-260.
- 543 56. Grasley, Z.C. and D'Ambrosia, M.D. "Viscoelastic properties and drying stress extracted from
 544 concrete ring tests", *Cement and Concrete Composites*, **33**(2), 2011, pp. 171-178.
- 545 57. Corinaldesi, V. and Moriconi, G. "Evaluation of recycled aggregate concrete cracking through
 546 ring test", *Applied Mechanics and Materials*, **174-177**, 2012, pp. 1475-1480.
- 547 58. Ray, I., Gong, Z., Davalos, J.F. and Kar, A. "Shrinkage and cracking studies of high
 548 performance concrete for bridge decks", *Construction and Building Materials*, 28(1), 2012, pp.
 549 244-254.
- 550 59. Wang, K., Schlorholtz, S.M., Sritharan, S., Seneviratne, H., Wang, X. and Hou, Q.
 551 "Investigation into shrinkage of high-performance concrete used for Iowa bridge decks and
 552 overlays", Final report, Institute for Transportation, Iowa State University, USA, 2013.
- 60. Gao, Y., Zhang, J. and Han, P. "Determination of stress relaxation parameters of concrete in
 tension at early-age using by ring test", *Construction and Building Materials*, **41**, 2013, pp.
 152-164.
- 556 61. Beushausen, H. and Chilwesa, M. "Assessment and prediction of drying shrinkage cracking in
 557 bonded mortar overlays", *Cement and Concrete Research*, 53, 2013, pp. 256-266.

558	62. Yoo, D.Y., Park, J.J., Kim, S.W. and Yoon, Y.S. "Early age setting, shrinkage and tensile
559	characteristics of ultra high performance fiber reinforced concrete", Construction and Building
560	<i>Materials</i> , 41 , 2013, pp. 427-438.

- 561 63. Yoo, D.Y., Park, J.J., Kim, S.W. and Yoon, Y.S. "Influence of ring size on the restrained
 562 shrinkage behavior of ultra high performance fiber reinforced concrete", *Materials and*563 *Structures*, **47**, 2014, pp. 1161-1174.
- 564 64. Ji, T., Zhang, B.-B., Chen, Y.-B. and Zhuang, Y.-Z. "Evaluation method of cracking resistance
 565 of lightweight aggregate concrete", *Journal of Central South University*, 21, 2014, pp. 1607566 1615.
- 567 65. Chen, K., Hu, H., Chen, K., Zhen, Z. and Wang, X. "Cracking tendency prediction of high568 performance cementitious materials", *Advances in Condensed Matter Physics*, 2014, 2014, 12
 569 p.
- 66. Bryne, L.E., Ansell, A. and Holmgren, J. "Investigation of restrained shrinkage cracking in
 partially fixed shotcrete linings", *Tunnelling and Underground Space Technology*, 42, 2014,
 pp. 136-143.
- 67. Bouasker, M., Khalifa, N.E.H., Mounanga, P. and Kahla, N.B. "Early-age deformation and
 cracking risk of slag-limestone filler-cement blended binders", *Construction and Building Materials*, 55, 2014, pp. 158-167.
- 576 68. Dittmer, T. and Beushausen, H. "The effect of coarse aggregate content and size on the age at
 577 cracking of bonding concrete overlays subjected to restrained deformation", *Construction and*578 *Building Materials*, **69**, 2014, pp. 73-82.
- 69. Ghezal, A.F. and Assaf, G.J. "Restrained shrinkage cracking of self-consolidating concrete", *Journal of Materials in Civil Engineering*, 27(10), 2015.

- 581 70. Kaszynska, M. and Zielinski, A. "Effect of lightweight aggregate on minimizing autogenous
 582 shrinkage in self-compacting concrete", *Procedia Engineering*, **108**, 2015, pp. 608-615.
- 583 71. Choi, K.-K., Truong, G.T. and Choi, S.-J. "Restrained shrinkage cracking of amorphous
 584 metallic fibre-reinforced concrete", *Proceedings of the Institution of Civil Engineers:*585 *Structures and Buildings*, **168**(SB12), 2015, pp. 902-914.
- 586 72. Corinaldesi, V. and Nardinocchi, A. "Experimental study on cracking behaviour of fiber
 587 reinforced concretes by ring test", *International Journal of Structural Analysis and Design*,
 588 2(1), 2015, pp. 37-43.
- 589 73. Briffaut, M., Bendoudjema, F. and D'Aloia, L. "Effect of fibres on early age cracking of
 590 concrete tunnel lining. Part I: Laboratory ring test", *Tunnelling and Underground Space*591 *Technology*, **59**, 2016, pp. 215-220.
- 592 74. Corinaldesi, V., Nardinocchi, A. and Donnini, J. "Study of physical and elasto-mechanical
 593 behaviour of fiber-reinforced concrete made of cement containing biomass ash", *European*594 *Journal of Environmental and Civil Engineering*, 20, 2016, pp. 152-168.
- 595 75. Shen, D., Shi, H., Tang, X., Ji, Y. and Jiang, G. "Effect of internal curing with super absorbent
 596 polymers on residual stress development and stress relaxation in restrained concrete ring
 597 specimens", *Construction and Building Materials*, **120**, 2016, pp. 309-320.
- 598 76. Adams, M.P., Fu, T., Cabrera, A.G., Morales, M., Ideker, J.H. and Isgor, O.B. "Cracking
 599 susceptibility of concrete made with coarse recycled aggregates", *Construction and Building*600 *Materials*, **102**, 2016, pp. 802-810.
- 77. Khan, I., Castel, A. and Gilbert, R.I. "Prediction of early-age creep and cracking age of
 concrete: a proposed modification for AS3600 provisions", *Australian Journal of Structural Engineering*, 17(2), 2016, pp. 151-166.

[51]

604	78. Choi, H. and Cho, B. "Calculation of constrained stress in expansive mortar with a composite
605	creep model", Advances in Materials Science and Engineering, 2016, 2016, 10 pp.
606	79. Beushausen, H. and Bester, N. "The influence of curing on restrained shrinkage cracking of
607	bonded concrete overlays", Cement and Concrete Research, 87, 2016, pp. 87-96.
608	80. Altoubat, S., Talha Junaid, M., Leblouba, M. and Badran, D. "Effectiveness of fly ash on the
609	restrained shrinkage cracking resistance of self-compacting concrete", Cement and Concrete
610	Composites, 79, 2017, pp. 9-20.
611	81. Samouth, H., Roziere, E., Wisniewski, V. and Loukili, A. "Consequences of longer sealed
612	curing on drying shrinkage, cracking and carbonation of concrete", Cement and Concrete
613	<i>Research</i> , 95 , 2017, pp. 117-131.
614	82. Khan, I., Castel, A. and Gilbert, R.I. "Tensile creep and early-age concrete cracking due to
615	restrained shrinkage", Construction and Building Materials, 149, 2017, pp. 705-715.
616	83. Shen, D., Liu, K., Ji, Y., Shi, H. and Zhang J. "Early age residual stress and stress relaxation
617	of fly ash high-performance concrete", Magazine of Concrete Research, 2017 [Article in
618	press].
619	84. Yoo, DH., Banthia, N. and Yoon, YS. "Ultra-high performance fiber-reinforced concrete:
620	Shrinkage strain development at early ages and potential for cracking", Journal of ASTM
621	International, 45 (6), 2017, pp. 2061-2070.
622	85. Menu, B., Jolin, M., Bissonnette, B. and Ginouse, N. "Evaluation of early age shrinkage
623	cracking tendency of concrete", in: Proceedings of the CSCE annual conference on leadership
624	in sustainable infrastructure, Vancouver, Canada, June, 2017, pp. EMM649-1-EMM649-8.
625	86. Sadati, S. and Kayat, K.H. "Restrained shrinkage cracking of recycled aggregate concrete",
626	<i>Materials and Structures</i> , 50 , 2017, 206-221.

[52]

- 87. Hogancamp, J. and Grasley, Z. "The use of microfine cement to enhance the efficacy of carbon
 nanofibers with respect to drying shrinkage crack resistance of Portland cement mortars", *Cement and Concrete Composites*, 83, 2017, pp. 405-414.
- 88. Kanavaris, F., Soutsos, M. and Chen, J.-F. "Effect of temperature on the cracking risk of
 concretes containing GGBS", in: Proceedings of the 2nd RILEM/COST conference on early
 age cracking and serviceability in cement-based materials and structures EAC02, Staquet, S.
 and Aggelis, D. (eds), Brussels, Belgium, September, 2017, pp. 257-263.
- 634 89. Kanavaris, F. "Early age behaviour and cracking risk of concretes containing GGBS", PhD
 635 Thesis, Queen's University Belfast, UK, 2017.
- 636 90. Zhou, X., Dong, W. and Oladiran, O. "Experimental and numerical assessment of restrained
 637 shrinkage cracking of concrete using elliptical ring specimens", *Journal of Materials in Civil* 638 *Engineering*, 26(11), 2014.
- 639 91. Oladiran, O. "Assessment of restraint shrinkage cracking of concrete through elliptical rings",
 640 PhD Thesis, Brunel University London, 2014.
- 92. Dong, W., Yuan, W., Zhou, X. and Wang, F. "The fracture mechanism of circular/elliptical
 concrete rings under restrained shrinkage and drying from top and bottom surfaces", *Engineering Fracture Mechanics*, 189, 2017, pp. 148-163.
- 644 93. Dong, W., Zhou, X.M., Wu, Z.M., Luo, H. and Kastiukas, G. "Quantifying the influence of
 645 elliptical ring geometry on the degree of restraint in a ring test", *Computers and Structures*,
 646 207, 2018, pp. 111-120.
- 647 94. Dong, W., Zhou, X. and Wu, Z. "A fracture mechanics-based method for prediction of cracking
 648 of circular and elliptical concrete rings under restrained shrinkage", *Engineering Fracture*649 *Mechanics*, 131, 2014, pp. 687-701.

650	95. Dong, W., Zhou, X., Wu, Z. and Xu, B. "Investigating crack initiation and propagation of
651	concrete in restrained shrinkage circular/elliptical ring test", Materials and Structures, 50,
652	2017, pp. 1-13.

- 96. Dong, W., Zhou, X., Wu, Z. and Kastiukas, G. "Effects on specimen size on assessment of
 shrinkage cracking of concrete via elliptical rings: Thin vs. thick", *Computers and Structures*,
 174, 2016, pp. 66-78.
- 656 97. He, Z., Zhou, X. and Li, Z. "New experimental method for studying early-age cracking of
 657 cement-based materials", *ACI Materials Journal*, **101**(1), 2004, pp. 50-56.
- 658 98. Gao, Y., Zhang, H., Tang, S. and Liu, H. "Study on early age autogenous shrinkage and crack
 659 resistance of fly ash high-strength lightweight aggregate concrete", *Magazine of Concrete*660 *Research*, 65(15), 2013, 906-913.
- 99. Samouth, H., Roziere, E., Bendimerad, A.Z. and Loukili, A. "Viscoelastic properties of selfconsolidating concrete: Influence of the sustainable approach", *Cement and Concrete Composites*, 86, 2018, pp. 273-287.
- 100. Bamforth, P. "Early-age thermal crack control in concrete", CIRIA, C660, London, UK.
- 101. Micro-Measurements, "Strain gage selection: Criteria, procedures, recommendations", Strain
 gages and instruments, Tech Note TN-505-5, August, Wendell, USA, 2014.
- 667 102. Omega Engineering, "Practical strain gage measurements", Application note 290-1, USA,
 668 1999.
- 103. AASHTO, "AASHTO PP 34 Estimating the cracking tendency of concrete", Provisional
 Standard, *American Association of State Highway and Transportation Officials*, Washington
 DC, USA, 1998.

- 104. AASHTO, "AASHTO PP 34-99 Standard practice for estimating the cracking tendency of
 concrete", *American Association of State Highway and Transportation Officials*, Washington
 DC, USA, 1999.
- 675 105. AASHTO, "AASHTO PP 334-08 Standard method of test for estimating the cracking
 676 tendency of concrete", *American Association of State Highway and Transportation Officials*,
 677 Washington DC, USA, 2008.
- 678 106. ASTM, "ASTM C1581-04 Standard test method for determining age at cracking and induced
 679 tensile stress characteristics of mortar and concrete under restrained shrinkage", *ASTM* 680 *International*, West Conshohocken, PA, USA, 2016.
- 107. ASTM, "ASTM C1581/C1581M-09a Standard test method for determining age at cracking
 and induced tensile stress characteristics of mortar and concrete under restrained shrinkage",
 ASTM International, West Conshohocken, PA, USA, 2016.
- 108. ASTM, "ASTM C1581/C1581M-16 Standard test method for determining age at cracking
 and induced tensile stress characteristics of mortar and concrete under restrained shrinkage",
 ASTM International, West Conshohocken, PA, USA, 2016.
- 687 109. Timoshenko, S. and Goodier, J. "Theory of elasticity", *McGraw Hill International Editions*.
- Timoshenko, S. "Strength of materials, part II: Advanced theory and problems", 3rd Edition,
 D. Van Nostrand Co. Inc., New York, 1962.
- 690 111. Neville, A.M. "Properties of concrete", 5th Edition, *Pearson Education Limited*, Harlow,
 691 Essex, UK, 2011.
- Hansen, W. "Constitutive model for predicting ultimate drying shrinkage of concrete", *Journal of the American Concrete Society*, **70**(5), 1987, pp. 329-332.

694	113. Bissonnette, B., Pierre, P. and Pigeon, M. "Influence of key parameters on drying shrinkage
695	of cementitious materials", Cement and Concrete Research, 29(10), 1999, pp. 1655-1662.
696	114. Soutsos, M., Hatzitheodorou, A., Kanavaris, F. and Kwasny, J. "Effect of temperature on the
697	strength development of mortar mixes with GGBS and fly ash", Magazine of Concrete
698	Research, 69(15), 2017, pp. 787-801.
699	115. Grasley, Z.C., Lange, D.A., D'Ambrosia, M.D. and Villalobos-Chapa, S. "Relative humidity
700	in concrete", Concrete International, 28(10), 2006, pp. 51-57.
701	116. Granja, J., Azenha, M., Barros, J. and Faria, R. "Service life behaviour of concrete structures:
702	a multiphysics approach to self-induced stresses", internal report, Department of Civil
703	Engineering, University of Minho, Portugal [in Portuguese], 2011.
704	117. Azenha, M., Sousa, S., Faria, R. and Neves, A. "Thermo-hygro-mechanical modelling of self-
705	induced stresses during the service life of RC structures", Engineering Structures, 33(12),
706	2011, pp. 3442-3453.
707	118. Azenha, M., Leitao, L., Granja, J.L., de Sousa, C., Faria, R. and Barros, J.A.O. "Experimental
708	validation of a framework for hygro-mechanical simulation of self-induced stresses in
709	concrete", Cement and Concrete Composites, 80, 2017, pp. 41-54.
710	119. Sellevold, E., Bjontegaard, O., Justnes, H. and Dahl, P.A., "High performance concrete: early
711	volume change and cracking tendency", in: Proceedings of the international RILEM
712	conference on thermal cracking in concrete at early ages, Springenschmid, R. (ed), E & FN
713	SPON, 1994, pp. 229-236.
714	120. Esping, O. and Löfgren, I. "Investigation of early age deformation in self-compacting

715 concrete", in: Proceedings of the 2nd international symposium on advances in concrete through

- science and engineering, Marchand, J., Bissonnette, B., Gagné, R., Jolin, M. and Paradis, F.
 (eds), Quebec, Canada, September, 2006, pp. 207-224.
- 121. Löfgren, I. and Esping, O. "Early age cracking of self-compacting concrete", in: Proceedings
 of the international RILEM conference on volume changes of hardening concrete: testing and
 mitigation, Jensen, O.M., Lura, P. and Kovler, K. (eds), Lyngby, Denmark, August, 2006, pp.
 251-260.
- 122. Esping, O. "Early age properties of self-compacting concrete Effects of fine aggregate and
 limestone filler", PhD Thesis, Chalmers University of Technology, Sweden, 2007.
- Toledo Filho, R.D., Ghavami, K., Sanjuan, M.A. and England, G.L. "Free, restrained and
 drying shrinkage of cement mortar composites reinforced with vegetable fibres", *Cement and Concrete Composites*, 27(5), 2005, pp. 537-546.
- 124. Zhu, H., Li, H.R. and Zhu, X.C. "On concrete restrained eccentric ring and square eccentric
 ring shrinkage test methods", *Construction and Building Materials*, 84, 2015, pp. 239-244.
- 125. Weiss, J., Lura, P., Rajabipour, F. and Sant, G. "Performance of shrinkage-reducing admixtures
 at different humidities at and early ages", *ACI Materials Journal*, **105**(5), 2008, pp. 478-486.
- 126. Wei, Z., Falzone, G., Das, S., Saklani, N., Le Pape, Y., Pilon, L., Neithalath, N. and Sant, G.
 "Restrained shrinkage cracking of cementitious composites containing soft PCM inclusions: A
 paste (matrix) controlled response", *Materials and Design*, **132**(5), 2017, pp. 367-374.
- 127. Xia, Q., Li, H., Yao, T., Lu, A., Tian, Q. and Liu, J. "Cracking behaviour of restrained
 cementitious materials with expansive agent by comprehensive analysis of residual stress and
 acoustic emission signals", *Advances in Cement Research*, 29(2), 2017, pp. 81-90.
- 128. Choi, H., Lim, M., Kitagaki, R., Noguchi, T. and Kim, G. "Restrained shrinkage behaviour of
 expansive mortar at early ages", *Construction and Building Materials*, 84, 2015, pp. 468-476.

- 129. Sant, G. "The influence of temperature on autogenous volume changes in cementitious
 materials containing shrinkage reducing admixtures", *Cement and Concrete Composites*,
 35(7), 2012, pp. 855-865.
- 130. Radlinska, A., Moon, J. H., Rajabipour, F. and Weiss, W. J. "The ring test A review of recent
 developments", in: Proceedings of the RILEM international conference volume changes of
 hardening concrete, Lyngby, Denmark, August, 2006, pp. 205-214.
- 131. Schlitter, J.L., Senter, A.H., Bentz, D.P., Nantung, T. and Weiss, W.J. "A dual concentric ring
 test for evaluating residual stress development due to restrained volume change", *Journal of ASTM International*, 7(9), 2010, pp. 1-13.
- 132. Schlitter, J.L., Barrett, T. and Weiss, W.J. "Restrained shrinkage behaviour due to combined
 autogenous and thermal effects in mortars containing super absorbent polymer (SAP)", in:
 RILEM Proc. PRO 74 "Use of Superabsorbent Polymers and Other New Additives in
- *Concrete*", Proc. Int. RILEM Conf., 15-18 August, 2010, Lyngby, Denmark, Eds. O.M. Jensen,
 M.T. Hasholt and S. Laustsen, RILEM Publications S.A.R.L., Bagneux, France, 2010, pp. 233242.
- 133. Schlitter, J.L., Bentz, D.P. and Weiss, W.J. "Quantifying stress development and remaining
 stress capacity in restrained, internally cured mortars", *ACI Materials Journal*, **110**(1), 2013,
 pp. 3-11.
- 134. Raoufi, K., Schlitter, J.L., Bentz, D.P. and Weiss, W.J. "Parametric assessment of stress
 development and cracking in internally cured restrained mortars experiencing autogenous
 deformations and thermal loading", *Advances in Civil Engineering*, 2011, 2011, 16 p.
- 135. Briffaut, M., Bendoudjema, F., Torrenti, J.M. and Nahas, G. "A thermal active restrained
 shrinkage ring test to study the early age concrete behaviour of massive concrete structures",
 Cement and Concrete Research, 41(1), 2011, pp. 56-63.

- 136. Briffaut, M., Bendoudjema, F., Torrenti, J.M. and Nahas, G. "Numerical analysis of the thermal
 active restrained shrinkage ring test to study the early age behaviour of massive concrete
 structures", *Engineering Structures*, **33**(4), 2011, pp. 1390-1401.
- 137. Briffaut, M., Bendoudjema, F. and D'Aloia, L. "Effect of fibres on early age cracking of
 concrete tunnel lining. Part II: Numerical simulations", *Tunnelling and Underground Space Technology*, **59**, 2016, pp. 221-229.
- 138. Bazant, Z. and Xi, Y. "Drying creep of concrete: constitutive model and new experiments
 separating its mechanisms", *Materials and Structures*, 27(1), 1994, pp. 3-14.
- 139. Lamour, V., Haouas, A., Moranville, M. and Schell, R. "A new technique for characterisation
 of early-age cracking of mortars", in: Proceedings of the international symposium on concrete
 science and engineering: A tribute to Arnon Bentur, Kovler, K., Marchand, J., Mindness, S.
 and Weiss, J. (eds), *RILEM Publications SARL*, Evanston, IL, USA, March, 2004.
- 140. Monge, J., Lamour, V., Moranville, M. and Grilliot, G. "Early age cracking of a thin mortar
 layer: Experimental study and macroscopic modelling", in: Proceedings of the 2nd national
 congress of building mortars, November, Lisbon, Portugal, 2007.
- 141. Ismail, M., Gange, R., Francois, R. and Toumi, A. "Measurement and modelling of gas transfer
 in cracked mortars", *Materials and Structures*, **39**(1), 2006, pp. 43-52.
- 142. Gagne, R., Francois, R. and Masse, P. "Chloride penetration testing of cracked mortar
 samples", in: Proceedings of the international conference on concrete concrete under severe
 conditions, environment and loading, Banthia, N., Sakai, K. and Gjorv, O.E. (eds), Vancouver,
 Canada, June, 2001, pp. 198-205.

784	143. Messan, A., Ienny, P. and Nectoux, D. "Free and restrained early-age shrinkage of mortar:
785	Influence of glass fiber, cellulose ether and EVA (ethylene-vinyl acetate)", Cement and
786	Concrete Composites, 33(3), 2011, pp. 402-410.
787	144. Messan, A. "Contribution à l'étude du comportement au très jeune âge des structures minces
788	en mortier", PhD Thesis, Université de Montpellier, France, 2006.
789	145. Kovler, K. "Do supplementary cementitious materials and blended cements indeed increase
790	cracking potential of concrete?" RILEM Proc. PRO 113 "Concrete with supplementary
791	cementitious materials", Proceedings of the International RILEM conference on materials,
792	systems and structures in civil engineering, Jensen, O.M., Kovler, K. and De Belie, N. (eds),
793	22-24 August, 2016, Technical University of Denmark, Lyngby, Denmark, RILEM
794	Publications S.A.R.L., Paris, 2016, pp. 371-382.

795