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Impact of drying on concrete and concrete structures

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Abstract

This study reviews research showing changes in the performance of reinforced concrete structures and members caused by drying conditions and aims to contribute to evaluating the structural safety in the long-term use of concrete. Additionally, to build a consensus on the changes in the physical properties of concrete materials after drying, the review focused on experiments intended to produce a uniform distribution of moisture-induced material property changes in the interior of the cross-section.

There is generally no effect on the change in the maximum loading capacity of a structure when the design is based on the flexural performance of the components. However, in the case of structures dominated by members determined by the shear capacity of the components, the reduction of the maximum loading capacity can be a problem. The decrease in stiffness is mainly due to the opening of shrinkage cracks and the decrease of Young's modulus of concrete after drying. The change in the compressive strength of concrete due to drying is governed by the specific strength change of hardened cement paste caused by the colloidal nature. Still, it is also affected by the aggregate shrinkage, which changes the damage in concrete under drying.

Keywords: Drying, Shrinkage; Stiffness change; Cracking; Member ultimate strength

1 Introduction

In the report by Roper [1], there was "an unusual series of failures in reinforced concrete structures in the Cape Province, Union of South Africa." This was a sizeable unexpected shrinkage of aggregate and resultant excessive drying shrinkage of concrete. Because aggregates that show excessive drying shrinkage can be available worldwide, Roper investigated many rock types of concrete aggregate. Later, Tarui Bridge in Wakayama, Japan, also experienced fatal damage due to the considerable drying shrinkage of concrete originating from used aggregate produced in the particular region [2], which has been reinforced. Since then, shrinking aggregate has also been a concern in Japan [3–5]. A prestressed box girder, which showed excessive long-time deflection, collapsed in 1996 [6,7], discussed in the technical committee TC-MDC led by Bažant in RILEM [8]. Long-term creep and shrinkage [8] and uneven deformation of members [9,10] were discussed. Structural health monitoring sensors, such as accelerators and velocimeters, which were installed in concrete buildings, have reported that almost all the concrete structures showed a decrease in the first-mode natural frequency and suggested a reduction in the stiffness of the structures [11]. A detailed analysis determined that this reduction in stiffness occurred between earthquakes and not during them [12], indicating that drying influences the reduction of structural stiffness. This structural stiffness reduction may cause unexpected responses during earthquakes and also cause resonance of equipment in the building and resultant unforeseen problems. All these issues were related to drying.

Drying is the most common environmental condition for concrete structures. In general, the life of concrete begins in a wet state. This is because the water required for cement hydration should be sufficiently provided in the concrete mixture to achieve the required design strength. In addition, it is necessary to provide the necessary workability of concrete that requires an appropriate amount of water in the mixture. In the case of ultra-high-strength and high-performance concrete, self-desiccation occurs due to the hydration reaction of the cement. However, the internal equilibrium relative humidity (RH) is still higher than the RH of most commonly exposed environments. For normal-strength concrete, the equilibrium humidity inside the concrete after 28 days of casting is more than 96% RH at 20°C [13]. In the case of the ultra-high-strength/performance concrete with an extremely low water–cement ratio, it is possible to be less than 80% RH [13]. Nevertheless, this is higher than the average annual RH of ~60% in Japan [14]. There are few regions where concrete does not dry out in an exposed environment.

Considering concrete and its exposed environments, understanding the impact of drying on concrete and concrete structures is necessary for the long-term use of concrete structures, which contributes to the sustainability of society. In this study, the changes in the performance of concrete and concrete structures caused by the volume change of its

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components due to drying (including the effects of internal desiccation of high-strength concrete in some cases, because the fundamental impact is similar), especially regarding strength and stiffness rather than the deformation problems, are presented, and future issues are discussed.

2 Structural response

2.1 Frames and structures

A fundamental study of frame structures suffered from self-balancing forces due to thermal deformation and/or drying shrinkage of members was conducted in the 1950s. Umemura considered the theoretical impact of deformation of the member on the frame structures and concluded that a perfectly plastic structure does not need to consider the effect of self-balancing forces due to shrinkage on the ultimate loading capacity, but it might not be realistic because the real structure does not satisfy the condition of the perfect plastic [15]. Aoyama and Kato investigated a miniature reinforced concrete (RC) frame structure with one layer and one span, considering the auto-strain (shrinkage) of the member, and found that it is possible that the yielding capacity is reduced by approximately 7% and the stiffness of the structure is reduced to 1/3 of the original stiffness, while the ultimate loading capacity of the frame was not changed by the shrinkage of the member [16]. Okada et al. investigated a wall-type miniature RC structure, imitating a part of a nuclear reactor building, and experimentally confirmed that the drying shrinkage has an impact on the stiffness, while there is no impact on the ultimate loading capacity [17]. Similarly, Yoshida et al. investigated the impact of drying-induced cracking on the stiffness change of an RC pier numerically by using the finite element method, and found that shrinkage-induced cracking only affected the stiffness and not the ultimate loading capacity [18].

Teshigawara et al. investigated the recorded data of responses of 11 accelerometers installed in an 8-story steel-RC building of the Building Research Institute of Japan, and found that sudden drops in the predominant frequency (the natural frequency of the predominant response of the building) occurred between earthquakes but not during each earthquake, except for the case of the Great East Japan earthquake 2011 [12], as shown in Fig. 1. This is the first data interpretation for long-term recorded building responses, which suggests that reduction in the predominant frequency occurs gradually in general environments. Following this analysis, Maruyama collected recorded data of building responses, including nuclear reactor buildings in Japan, as shown in Fig. 2 and proposed that this reduction in stiffness is caused mainly by the drying environment [11] because stiffness decrease occurs in situations other than during an earthquake and was universally confirmed. It could be possible that some other deterioration, such as alkali-silica reaction or corrosion-induced cracking of cover concrete may contribute to this phenomenon, but the concrete buildings listed in Fig. 2 have thinner member size rather than civil infrastructures and they have a surface coating, therefore they easily get dried. In addition, the materials were carefully selected because they are relatively important structures so as that such structural health monitoring system was installed, considering these conditions, the risk of rebar corrosion and alkali-silica reaction, or other deterioration was small. Maekawa et al. investigated the impact of shrinkage-induced cracking in the RC structure on the structural performance of RC buildings by using multi-scale thermo-hygral analysis, and found that “the shrinkage effect may chiefly come to the junction planes between members of different dimensions, especially for the case of normal RC buildings” [19]. Jaafari et al. investigated two types of RC portal frames: one was sealed and the other was exposed to drying conditions such as construction sites, and dynamic loading tests were conducted. They monitored the shrinking and cracking behavior of the frames and obtained pseudo-dynamic loading experimental results [20]. The stiffness change due to drying was confirmed, and the ultimate capacity of the frames was obtained in their experiments.

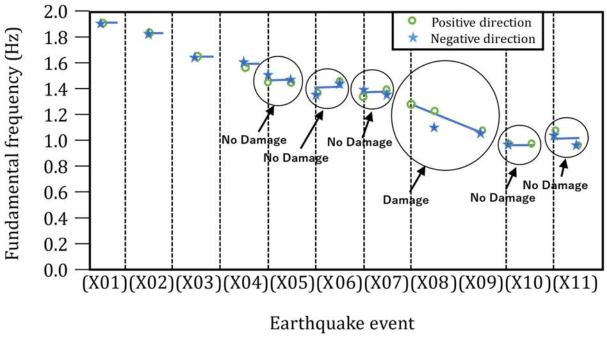


Figure 1. Change in the fundamental frequency of the structure of each earthquake event from 1998 (left) to 2012 (right) [12].

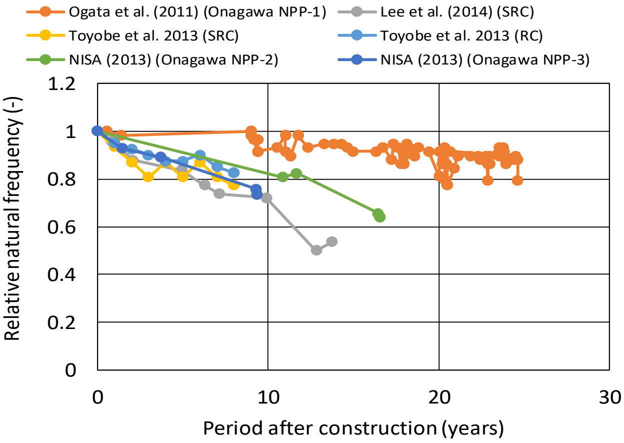


Figure 2. Change in the relative natural frequencies of concrete buildings (after [11]).

2.2 RC Members

2.2.1 Beam member

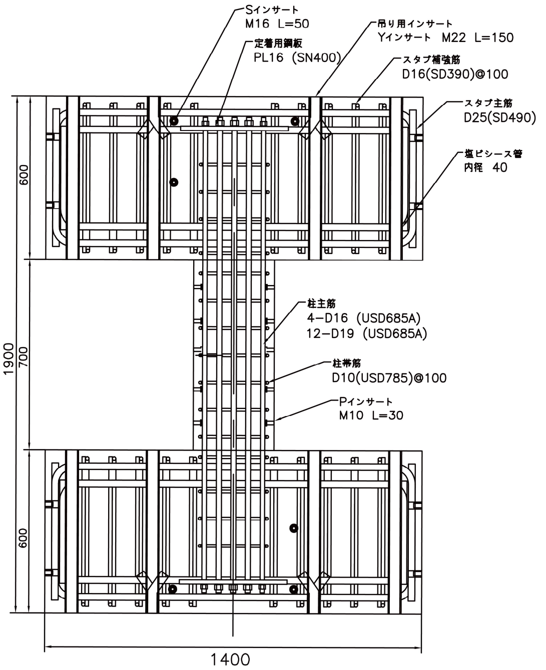
Regarding the effect of the volume change of concrete in simple beams, it has been clarified that, for flexural behavior, the crack initiation load decreases, the flexural crack width increases due to the release of compressive strain of reinforcing steel caused by shrinkage of concrete, and the incremental curvature before and after loading increases.

Simple formulas to evaluate those phenomena have been proposed [21–23]. To the extent that the maximum bearing capacity was determined by the yielding of the reinforcement, the maximum bearing bending capacity was not affected by shrinkage. In terms of shear behavior, a reduction in diagonal crack initiation capacity has been noted for specimens without shear reinforcement [24,25], and it has been pointed out that this effect is due to the restraining influence of the main reinforcement. Thus, if the shear capacity of beams can be explained by truss theory and concrete contribution to diagonal crack initiation capacity, shrinkage reduce the shear capacity through the reduction of diagonal crack initiation capacity. Experimental results [25] and numerical results [26,27] support this. However, because the neutral axis, location, and angle of shear crack initiation and crack propagation may be changed by applying shear reinforcements, the applicability of this concept should be clarified. Since a detailed study of the shear loading mechanism of beams has been carried out numerically [28], a proper understanding of the shrinkage effect should be further developed in the future.

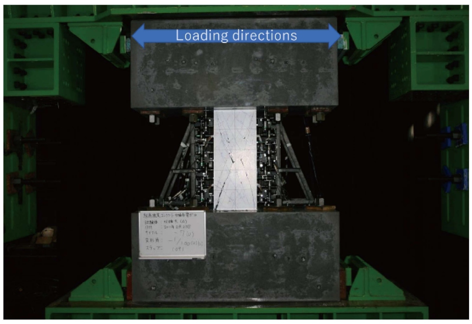
2.2.2 Column

Collins et al. pointed out that the cover of high-strength RC columns tends to peel off before the maximum bearing capacity, which reduces the bending capacity [29]. The mechanism of earlier peeling off can be explained by the autogenous and drying shrinkage of the cover concrete. Lampropoulos and Dritsos evaluated the flexural capacity of RC columns by considering the strength increase due to the restraining effect of concrete using numerical analysis, and pointed out that the reduction in the restraining effect due to shrinkage causes a decrease in flexural capacity under high axial forces [30]. According to the results of the flexural shear tests on ultra-high strength RC columns at the same age with and without long-term loading of 1/3 axial force ratios for approximately one year, there was no significant difference in the flexural shear tests between the two specimens when high-strength deformed bars were used for the axial reinforcement [31]. To evaluate the effects of shrinkage and creep deformation on the performance of RC column members, RC columns were constructed using 90 N/mm^2 and 150 N/mm^2 classes of high-strength concrete, and flexural shear load tests were conducted after approximately 1400 days of axial loading. The results of the flexural shear loading test showed that: 1) shrinkage, loading, creep (axial force ratio of 0.3), and temperature change caused the strain of the main reinforcements by 1500 µm/m in the case of 90 N/mm^2 class concrete and 2500 µm/m in the case of 150 N/mm^2 class concrete; 2) the compressive strength of the concrete after spalling of the concrete cover decreased due to the effects of long-term compressive loading; 3) the specimens that experienced long-term compressive loading developed horizontal cracks (eight cracks of less than 0.04 mm) during axial force unloading due to the strain difference between the concrete and the reinforcement; and 4) in the shear loading tests, it was observed that larger shrinkage caused the main reinforcement compressive yielding capacity to decrease, the axial compression to increase at the same drift angle, and the load-bearing capacity to decrease rapidly under cyclic loading [32]. Based on the fact that there are two peaks in the bending moment – drift angle relationship of a typical ultra-high strength RC column, Muramatsu et al. proposed a method for calculating the flexural capacity [33]. The first peak is caused by the spalling of the cover concrete, and the second peak is caused by the yielding of the tensile or compressive main reinforcements or damage to the core concrete. The magnitudes of the first and the second peaks depend on the various conditions of the member. Their proposal is that the stress-strain relationship of unrestrained concrete is used to evaluate the primary peak, while the stress-strain relationship of restrained concrete inside the transverse reinforcements is used to evaluate the secondary peak. The flexural capacity is evaluated using the stress-strain relationship of the restraining concrete inside the transverse reinforcements, without evaluating the concrete cover.

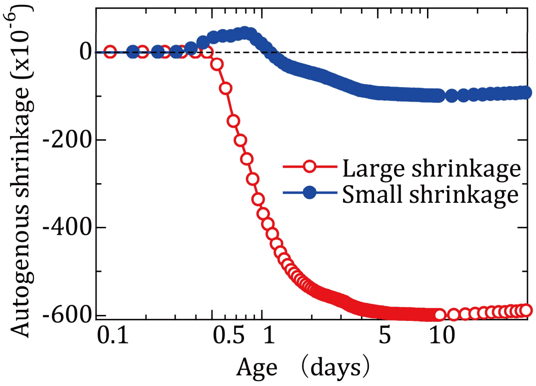
Maruyama et al. studied the effect of autogenous shrinkage on the shear behavior of RC short columns in ultra-high strength concrete by preparing normal high strength concrete and ultra-high strength concrete with an expansive additive and shrinkage reducing agent (Fig. 3). Through experimental investigations, the following points have been clarified: 1) the shear capacity of RC columns does not change significantly by autogenous shrinkage; 2) the yielding of shear reinforcement is increased due to the initial compression of the reinforcement by the self-shrinkage of the concrete; 3) the effect of shrinkage is mainly on the maximum bearing capacity on the negative loading cycle, which is presumably due to the increase in the number and width of cracks caused by shrinkage; and 4) the stiffness of the column before shear cracking, evaluated by the load-deformation relationship, decreased by 5% due to shrinkage, and the shear stiffness decreased by 25% for the initial stiffness [34].



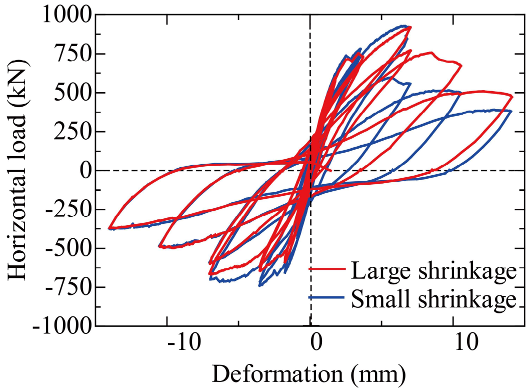
(a) specimen



(b) Loading condition



(c) shrinkage before loading experiment



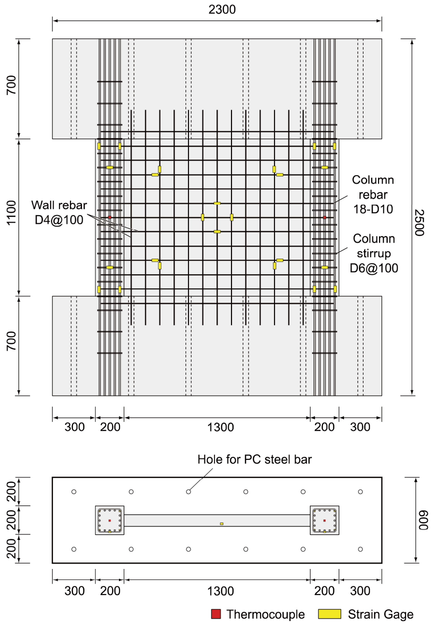
(d) Load-deformation relationships

Figure 3. Experimental results of short RC column using ultra-high strength concretes: a) specimen, b) loading condition, c) shrinkage of the specimen, d) load-deformation relationships. After [34]. Note: (a) DXX means the deformed bar with the nominal diameter of XX mm. The high strength steel with the nominal strength of 685 MPa (USD685A) was used for main reinforcing bars and steel with the nominal strength of 785 MPa (USD785) was used for stirrups. (b) The setup and loading condition is similar to that of Fig.4 (b). (c) the column was separately placed to simulate the temperature history of the real size column by using heat insulator, and shrinkage of the specimen at the central part was measured by embedded strain gauge. Thermal expansion coefficient was assumed to be 10 μ/°C. (d) Horizontal load is the load to push/pull the stab at the top of the column, and the bottom stab was fixed by prestressed steel rods. The deformation was the horizontal deformation at the top of column, as the measurment setup was shown in (b).

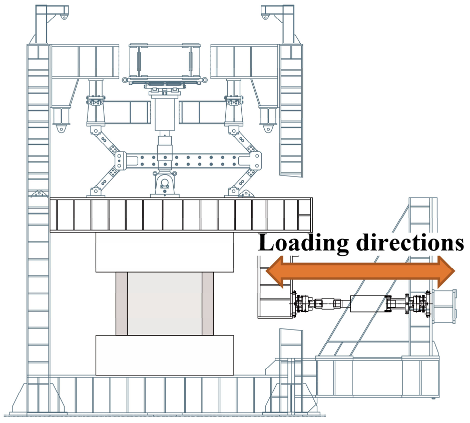
2.2.3 Shear wall and slab

Walls and slabs are relatively thin members whose shrinkage can be restrained by jointed members, such as beams and columns. Therefore, these members can be significantly affected by the shrinkage.

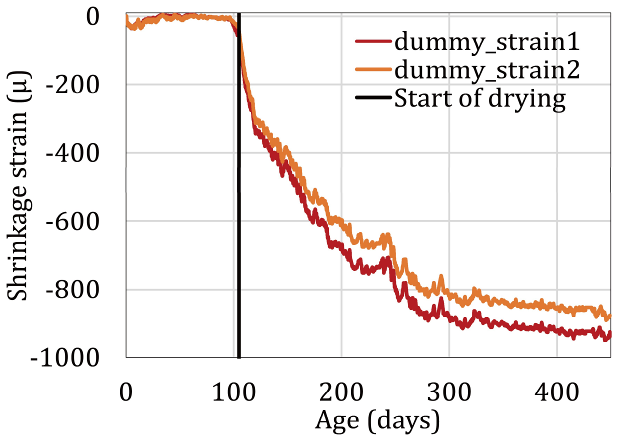
Sasano et al. prepared two fully cured shear RC walls to avoid additional hydration during drying, and one was subjected to cyclic incremental loading after curing, and the other was loaded after approximately one year of drying in the experimental room [35]. The concrete properties were evaluated by using the specimens before and after drying, and the Young's modulus of concrete ($\varnothing$100×200 mm^3) decreased by 14%, the compressive strength of concrete increased by 10%, and the fracture energy of concrete (100×100×400mm^3) increased by 46%. From the results of the loading tests, it was confirmed that the maximum bearing capacity was not affected by drying, and the initial stiffness, which is determined by the load-deformation relationship, decreased to 50% after drying (Fig. 4). In addition, the deformation at the maximum load capacity increased by approximately 8%. This result may influence the design of high-rise buildings using core walls. As for the maximum bearing capacity, a detailed study using a rigid-body spring network model showed that the increase in crack width caused by the drying shrinkage strain of concrete caused a reduction in the macroscopic concrete strength in the strut [36], which should have caused a reduction in the shear capacity of the wall. However, it was found that the strength-increasing effect of drying offset the reduction and resulted in the same shear capacity. Considering the fact that the strength of concrete after drying is affected by aggregate types, as will be discussed later, further study is needed to determine whether this effect should be considered in the design state. Regarding the stiffness of the structure, the calculation showed that the crack opening due to drying shrinkage of concrete is a dominant factor rather than the stiffness reduction of concrete material due to drying.



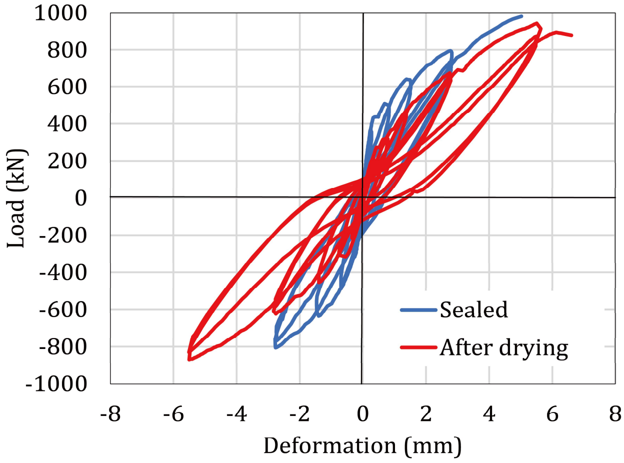
(a) specimen



(b) Loading setup



(c) shrinkage before loading experiment

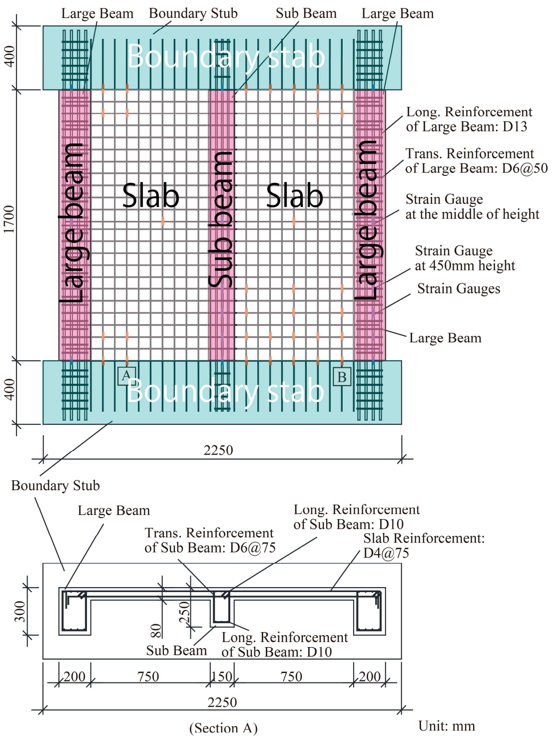


(d) Load-deformation relationships

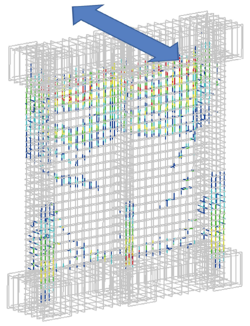
Figure 4. Experimental results of RC shear walls with/without drying shrinkage: a) specimen, b) loading setup, c) shrinkage of dummy specimen, d) load-deformation relationships. After [35].

Note: (a) DXX means the deformed bar with the nominal diameter of XX mm. (c) Shrinkage of the wall was measured in the dummy specimen whose size was the same as that of wall without reinforcements. The shrinkage was measured by embedded strain gauge and thermal deformation was collected with the temperature history and measured coefficient of thermal expansion. The data is corresponding to the "After drying" in (d). (d) Load represents the horizontal load to push/pull the top stab.

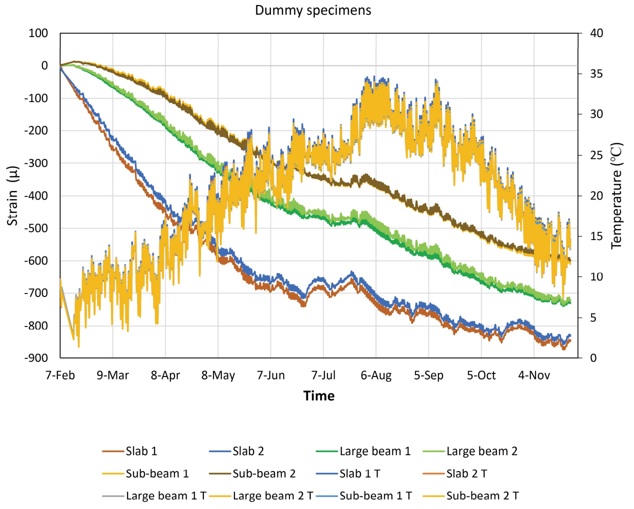
Satya et al. prepared two fully cured slabs with beams to avoid hydration during drying, and one was loaded immediately after curing in water for approximately 100 days, and the other was loaded after drying for approximately 300 days. The concrete properties were evaluated by using the specimens before and after drying, and after drying, the Young's modulus of the concrete specimens decreased by 8%, compressive strength increased by 7%, and fracture energy increased by 26%. From the results of the loading tests (Fig. 5), it was confirmed that the maximum bearing capacity was almost the same without any effect of drying, and the initial stiffness, which is determined by load-deformation relationship, decreased to 76% in the dry state. The deformation at the time of maximum bearing capacity was almost the same, and only the concrete contribution at a smaller displacement was found. This result indicates the possibility that the design based on the rigid floor assumption does not satisfy increases with drying.



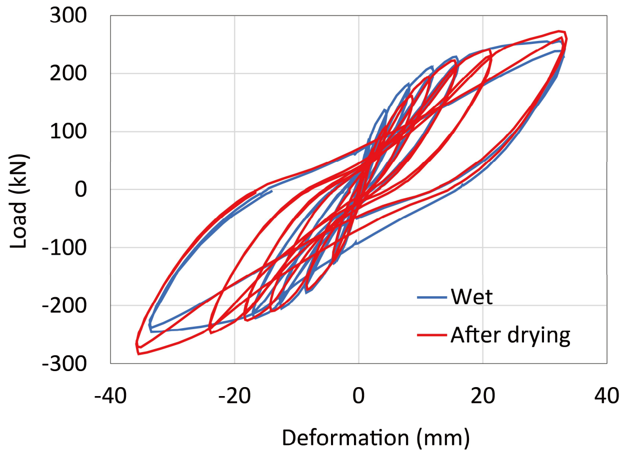
(a) specimen



(b) Loading direction



(c) shrinkage before loading experiment



(d) Load-deformation relationships

Figure 5. Experimental results of RC slabs with/without drying shrinkage: a) specimen, b) loading condition, c) shrinkage and temperature histories of dummy specimens, d) load-deformation relationship. After [37].

Note: (a) DXX means the deformed bar with the nominal diameter of XX mm. (c) the legends whose final character is "T" represents the temperature (right axis). Shrinkage of the specimen at the central region was measured by the embedded strain gauge. All the data were obtained by the dummy specimens whose sectional size was the same as that of corresponding member shown in (a) and the length was 300 mm. (d) Load represents the horizontal load to push/pull the top stab to bend the slab with beams. The same setup shown in Fig. 4(b) was used.

2.2.4 Concrete-filled steel tube

Concrete in concrete-filled steel tubes (CFTs) generally does not dry out. However, the use of high-strength concrete has increased in recent years, but the effect of autogenous shrinkage seems to be neglected, so it will be described here.

Nishizawa et al. reported on the behavior of various types of strain and displacement meters buried in a real building from the construction process, with the aim of evaluating the structural performance of high-rise buildings from health monitoring [38]. In this study, the strains of steel and concrete in a CFT structure during crane dismantling deviated from each other, and only the strain of the steel pipes recovered after crane dismantling. It was confirmed that the integrity between the steel and concrete was broken. However, it was also clarified that even if the strains deviated, it did not mean that the concrete did not bear the axial force at all. Matsumoto et al. conducted an experimental study on the structural performance of CFT columns made of ultra-high-strength steel [39]. In this study, the stubs were connected by through columns, and the axial force was transmitted from the steel tubes. In this experiment, it was pointed out that the initial stiffness (the secant stiffness at 1/400 deformation) was approximately 10% smaller than the calculated value, indicating that the Bernoulli-Navier assumption or the integrity between the concrete and steel pipe was not maintained in the initial behavior. On the other hand, from the viewpoint of ultimate bearing capacity, there is no effect of autogenous shrinkage because the bearing capacity calculated based on the Bernoulli-Navier assumption and the experimental data are in good agreement. As for the CFT, the load-bearing mechanism of long-term loading in actual structures is not clear at present; therefore, monitoring of actual structures and long-term behavior experiments are necessary.

3 Concrete

The effects of the mixing proportion and curing environment on concrete properties, including compressive strength, are manifold (e.g., [40]). In this study, the changes in the physical properties of concrete, especially during the first drying, are presented. In some previous studies, the moisture content was varied once subjected to intense drying (e.g., oven drying at 105°C) in order to eliminate the colloidal effect of the main hydrate, calcium silicate hydrate (C-S-H) (e.g., [41–43]); however, this is not our objective; therefore, such research is not discussed here. Studies that discuss the development of physical properties by considering the moisture content as a condition in which the hydration of cement does not continue sufficiently are also not covered [40,44,45]. In addition, studies that are considered to have a large variation in moisture content inside the specimens are also omitted from the discussion because such experimental data do not show the material properties [46–49]. In this section, the author will focus on the experiments in which changes in physical properties due to drying of relatively well-cured specimens, especially those in which the moisture content inside the specimen is uniform. Real size reinforced concrete members need several decades to reach the thermodynamic equilibrium, and most of the concrete inside the real size reinforced concrete member experiences its property change under the gradual drying. Such concrete property change at the given position in the real size concrete member should be evaluated by the data of the specially designed experiments.

In the paper by Pihlajavaara [50], the specimens were sealed and cured for 2 years and then conditioned with saturated salt solution at different humidity for 3 years. The specimen size was 40×40×160 mm^3. The specimens were subjected to a bending test followed by a compression test using a 4×4 cm loading plate. The effect of the additional hydration was considered negligible in this experiment. In this experiment, the compressive strength showed that there was a local maximum at 80-90% RH, followed by a decrease in strength to approximately 50% RH, followed by an increase in strength below 50% RH. The percentage increase in strength after drying (105°C, oven-drying) relative to the strength at the time of sealing was 30% (W/C=0.50) and 60% (W/C=0.70), indicating that the larger the water–cement ratio, the greater the percentage increase in strength. Pihlajavaara attributed this local maximum value to the "binding forces of the condensed water surfaces in capillaries". The flexural strength tended to increase with drying, and there was no decrease in strength due to drying, as observed in other experiments.

Glucklich and Korin prepared specimens of 140 × 12.5 × 11.5 mm^3 with mortar of W/C=0.346, which were subjected to accelerated hydration at 70°C for 3 hours followed by 30 days of water curing [51]. The specimens were dried using a saturated salt of $Mg(ClO_4)_2$ to prepare specimens with different moisture contents and then sealed at different moisture contents to equalize the moisture distribution inside the specimen. A uniform increase in compressive strength with decreasing moisture saturation degree, an increase in fracture energy from below 50% of moisture saturation degree were observed. Young's modulus showed a maximum value at 80% moisture saturation degree and a local maximum value at 20% moisture saturation degree. In this experiment, the effect of rapid drying on micro-crack initiation [52] could not be ignored; hence, there was a large variation in the data.

Yurtdas et al. showed a trend of increasing strength and decreasing Young's modulus and Poisson's ratio with drying (21°C, 45% RH, and 60°C oven drying) for mortar specimens [53]. In the experiment by Burlion et al., the drying shrinkage strain, mass change, strength, and Young's modulus of mortar specimens with a size of 40 × 40 × 160 mm^3 and ∅110 × 220 mm^3 were measured during the drying process at 60% RH after curing in water for 28 days [54]. The compressive strength increased by approximately 28%, and the Young's modulus decreased by approximately 25%. From the difference in the strength changes of the different specimens, it was concluded that the capillary suction increased the mechanical strength of the material and degraded the elastic properties by induced microcracks. Although the effect of additional hydration cannot be excluded, the general behavior of the strength increase is considered to be covered in this research. Yurtdas et al. [55] conducted a similar study to Burlion et al. [54] for mortar specimens with different W/C and, like Pihlajavaara, found that the larger the water–cement ratio, the greater the strength gain after drying. In addition, Yurtdas concluded the same results for self-compacting concrete [56].

Maruyama et al. prepared specimens of ∅5 × 10 cm^3 for concrete and mortar with W/C=0.55 [57]. In the mixture proportions of concrete, the volume proportions of coarse aggregate, fine aggregate, and paste were identified, and the type and size of coarse aggregate were varied as parameters. After 180 days of sealed curing, the materials were dried at different humidity and temperature conditions for approximately 150 days to obtain the data of mass and shrinkage changes with time, as well as strength and Young's modulus after drying. Simultaneously, a detailed analysis of the post-drying alteration of the hardened cement paste (HCP) with a specimen thickness of 3 mm was conducted [58].

From these experiments, the tensile strength (bending strength) of the HCP specimens and the compressive strength of the mortar increased from the sealed condition to approximately 80% RH; after reaching the local maximum value, the strength decreased to 40% RH, and then increased again from below 40% RH, reaching a maximum value below 11% RH. These trends are summarized in Fig. 6. The results are consistent to the data of Pihlajavaara [50]. This trend occurs when the concrete is made, especially when the maximum aggregate size is small, and when the aggregate shrinkage is large (e.g., sandstone with a large amount of clay minerals). In the case of aggregates with small shrinkage, such as pure limestone or thermally modified chert, the effect of micro-cracking is particularly prevalent, and the minimum value of strength observed at approximately 40% RH is low. The concrete strength change due to drying from 80%RH to 40%RH was greatly affected by a micro-crack formation determined by the volume change mismatch between aggregates and HCP. In this regard, there is a consistency with the findings of Yurtdas et al. [53, 55] and Burlion et al. [54].

The increase in strength caused by severe drying below 40%RH was identical among all the concrete, but if the strength decrease at approximately 40%RH is large, the strength recovery will not attain the original strength under sealed conditions. In the past, a consensus on the compressive strength of concrete after drying could not be achieved because of the lack of consideration for the internal equilibrium state, strength increase due to additional hydration during drying, and the different shrinkage properties of aggregates. The schematic mechanisms of concrete strength change due to drying are summarized in Fig. 7.

Based on a detailed investigation of the compressive strength of cylindrical concrete specimens by using the rigid-body spring network model (RBSM) [59], the compressive strength is determined by the following steps; 1) vertical cracks at the sides of coarse aggregates, 2) vertical crack connect each other, and the concrete cylinder is divided into several pillars like the columnar joint of rock, 3) mid-span of the outside pillars is detached from internal pillars and bending of pillars occur (like buckling of the pillar). At this moment, the total beard load by pillars is reduced, and the maximum loading capacity is determined. The compressive shear strength of HCP determines the vertical crack propagation.

Consequently, the bending strength HCP shows the similar trend of compressive strength of concrete as a function of equilibrium RH. Shrinkage-induced micro-cracks around the aggregates also contribute to the crack propagations and connections, divide the specimen into several pillars, and reduce the compressive strength by facilitating detaching and bending of pillars at the periphery of the specimen.

There is some debate as to why paste and mortar show this trend. Burlion and Yurtdas pointed out that the increase in strength due to drying is explained by capillary suction, but this may be the dominant effect up to 80% RH, as pointed out by Pihlajavaara. In fact, the calcium silicate hydrate (C-S-H) in the cement paste has a colloidal nature [60] and changes the structure of the agglomeration by surface energy change and capillary effect [58,61–73]. Considering that the irreversible shrinkage strain of drying shrinkage of HCP occurs especially in the vicinity of 80% RH to 40% RH [74,75], most of the change in the agglomeration structure of C-S-H is considered to occur in this relative humidity range. It should be noted that gel pore water drying occurs below 80% RH, which is confirmed by ^{1}H-NMR relaxometry, and this supports the idea that the C-S-H structure change occurs at less than 80% RH. In this humidity range, the strength of the paste shows a decreasing trend, and it is hypothesized that agglomeration of C-S-H caused by the capillary pressure within C-S-H sheets, resultant creation of the large pores, and coarsening of cement paste reduces the strength is more dominant than the apparent strength-increasing effect of the capillary pressure on the solid of HCP. The intense increase in strength below 40%RH is attributed to the surface energy change [76], or to an increase in strength due to the reduction of the C-S-H interlayer space and production of bonds between C-S-H sheets by intercalated cations [77]. The microstructural change of C-S-H under drying is discussed elsewhere [78].

With regard to Young's modulus of concrete, in general, Young's modulus after drying decreased to 50-80% of the original Young's modulus. This behavior is explained by the creation of microcracks around the aggregate and crack opening due to inhomogeneous shrinkage strain between the coarse aggregate and mortar/HCP [59], as pointed out by [53,57,79]. The tensile strength of concrete after drying showed similar trends as the compressive strength of concrete [80].

These mechanisms for alteration of concrete properties are considered to be identical for Portland cement-based concrete with high water–cement ratios, but there are not enough studies on the behaviors at low water–cement ratios or concrete containing supplementary cementitious materials.

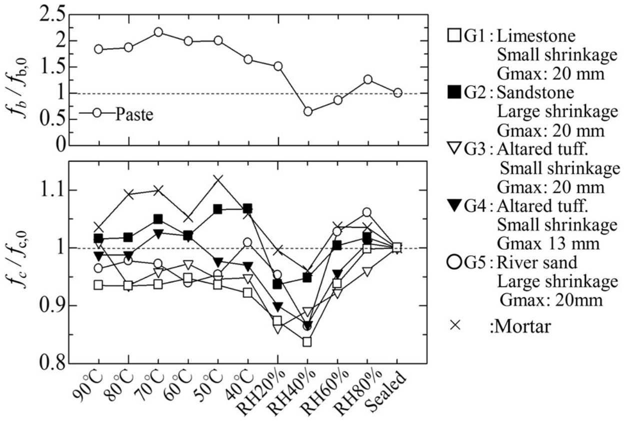


Figure 6. Change in bending strength of hardened cement paste (top) and compressive strength of mortar and concretes (bottom) after drying.

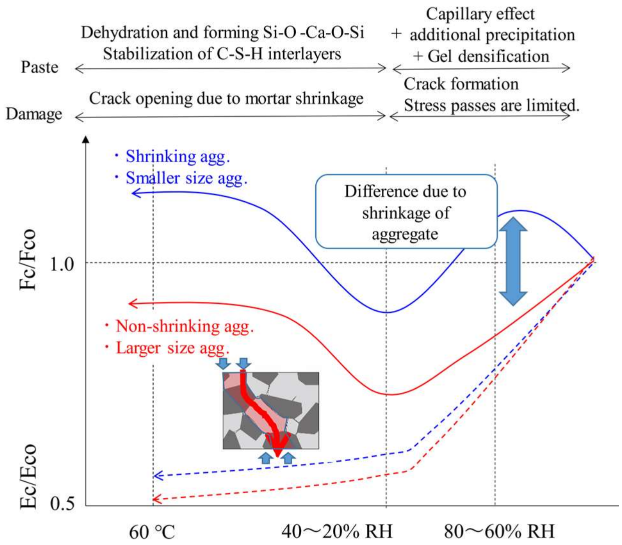


Figure 7. Schematic illustration of compressive strength change of concrete due to drying

4 Summary

This study aims to contribute to the long-term use of RC structures by summarizing previous studies on the changes in the physical properties of concrete after drying, and showing examples of experimental and numerical evaluations of performance changes in RC structures and members after drying. From a structural point of view, the stiffness reduction due to drying can not be ignored. The stiffness of reinforced concrete members can be reduced to 50% of the original undried member. The maximum loading capacity is still an unsolved problem, but the reinforced concrete members whose failure mode is not affected by drying and the final capacity is controlled by the yielding of reinforcing bars will not be the problem. In the case of reinforced concrete shear walls, there is a possibility that the maximum loading capacity is decreased by the reduction of compressive strength of concrete affected by drying. The deformation at the loading capacity is also an important issue for the structural performance, but this is also not clarified yet. Further study is needed.

Properties of concrete can be varied by drying. There are two major factors that determine the physical properties of concrete. One is the colloidal nature of calcium silicate hydrates which is very sensitive under the first drying process and changes the stiffness, strength, and volume of hardened cement paste. This change in the strength of the hardened cement paste directly affects the strength of concrete after drying. The second one is the volume change mismatch between aggregate and hardened cement paste. The shrinkage property of aggregate shows a significant role in the alteration of concrete strength and Young's modulus under drying. Low shrinkage aggregates used in concrete reduce the compressive strength and Young's modulus of concrete after drying rather than the large shrinkage aggregates.

To systematize the knowledge for long-term use, it is necessary to accumulate health monitoring data of actual structures, crack investigations, and detailed analysis of physical properties. For example, it has been reported that an additional reaction between hydrates and rock-forming minerals in thick concrete members contributed to a significant increase in strength [81,82]. This phenomenon cannot be observed in laboratory experiments. Therefore, a detailed analysis of field concrete is a necessary step to find knowledge gaps between laboratory experiments and real structures. In addition, it has been pointed out that there are some anomalies in the water transport in concrete [83–87], which are different from those of other rigid porous materials, and it is necessary to study the influence of these anomalies on the behavior of concrete under drying environments at the actual member sizes.

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CReDiT Authorship Statement

Ippei Maruyama: Conceptualization, Formal analysis, Funding acquisition, Project administration, Visualization, Writing-original draft

References

[1] H. Roper, Volume Changes of Concrete Affected by Aggregate Type, J. PCA Res. Dev. Lab. 2 (1960) 13-19.

[2] Japan Society of Civile Engineers, Special committee for fatal damage of Tarui bridge, Interim report by special committee for fatal damage of Tarui bridge, 2005.

[3] T. Fujiwara, Effect of Aggregate on Drying Shrinkage of Concrete, J. Adv. Concr. Technol. 6 (2008) 31-44. https://doi.org/10.3151/jact.6.31

[4] K.I. Imamoto, M. Arai, Simplified evaluation of shrinking aggregate based on BET surface area using water vapor, J. Adv. Concr. Technol. 6 (2008) 69-75. https://doi.org/10.3151/jact.6.69

[5] G. Igarashi, I. Maruyama, Y. Nishioka, H. Yoshida, Influence of mineral composition of siliceous rock on its volume change, Constr. Build. Mater. 94 (2015) 701-709. https://doi.org/10.1016/j.conbuildmat.2015.07.071

[6] Z.P. Bažant, Q. Yu, G.-H. Li, Excessive Long-Time Deflections of Prestressed Box Girders. II: Numerical Analysis and Lessons Learned, J. Struct. Eng. 138 (2012) 687-696. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000375

[7] Z.P. Bažant, Q. Yu, G.-H. Li, Excessive Long-Time Deflections of Prestressed Box Girders. I: Record-Span Bridge in Palau and Other Paradigms, J. Struct. Eng. 138 (2012) 676-686. https://doi.org/10.1061/(ASCE)ST.1943-541X.0000487

[8] Z.P. Bažant, Mi. Jirásek, M.H. Hubler, I. Carol, RILEM draft recommendation: TC-242-MDC multi-decade creep and shrinkage of concrete: material model and structural analysis*: Model B4 for creep, drying shrinkage and autogenous shrinkage of normal and high-strength concretes with multi-decade applicabili, Mater. Struct. 48 (2015) 753-770. https://doi.org/10.1617/s11527-014-0485-2

[9] M. Ohno, N. Chijiwa, B. Suryanto, K. Maekawa, An investigation into the long-term excessive deflection of PC viaducts by using 3D multi-scale integrated analysis, J. Adv. Concr. Technol. 10 (2012) 47-58. https://doi.org/10.3151/jact.10.47

[10] K. Nakarai, R. Sato, Y. Ogawa, K. Kawai, Evaluation of long-term deflection of a PC box girder bridge using effective bending stiffness formula, Proceeding Japan Concr. Inst. 35 (2013) 469-474.

[11] I. Maruyama, Multi-scale review for possible mechanisms of natural frequency change of reinforced concrete structures under an ordinary drying condition, J. Adv. Concr. Technol. 14 (2016) 691-705. https://doi.org/10.3151/jact.14.691

[12] L. Li, A. Nakamura, T. Kashima, M. Teshigawara, Earthquake damage evaluation of an 8-story steel-reinforced concrete building using Sa-Sd Curves, J. Struct. Constr. Eng. 79 (2014) 1107-1115. https://doi.org/10.3130/aijs.79.1107

[13] B. Persson, Self-desiccation and its importance in concrete technology, Mater. Struct. Constr. 30 (1997) 293-305. https://doi.org/10.1007/BF02486354

[14] Japan Meteorological Agency, Tokyo, monthly mean relative humidity, (2021). https://www.data.jma.go.jp/obd/stats/etrn/view/monthly_s3.php?prec_no=44&block_no=47662&year=&month=&day=&view=a7 (accessed September 19, 2021).

[15] H. Umemura, Self-balancing forces and ultimate strength of plastic frame structure, Proc. Annu. Res. Meet. Kanto Chapter. 31 (1955) 165-166.

[16] H. Aoyama, M. Kato, Loading experiment study on reinfoced concrete frame structure with auto-strain (part1) "jikohizumi wo motsu tekkinkonnkuri-tora-men no hakaijikken dai 1 hou," Proc. Annu. Res. Meet. Kanto Chapter, Archit. Inst. Japan. 43 (1958) 34-40.

[17] T. Okada, K. Akino, S. Yoshizaki, Y. Inada, S. Sugano, Hysteresis restoring force characteristics experiment for nuclear power plant building : part 6 scale effect, "genshiryoku tateya no fukugenryokutokusei shiken sono 6: suke-ru efect shiken," Summ. Tech. Pap. Annu. Meet. Archit. Inst. Japan. B, Structu (1967) 1089-1090.

[18] I. Yoshida, H. Kanemitsu, M. Yamashita, K. Higuchi, Seismic analysis of RC pier with earthquake resistant wall, Doboku Gakkai Ronbunshu. 1987 (1987) 349-358. https://doi.org/10.2208/jscej.1987.386_349

[19] R. Kurihara, N. Chijiwa, K. Maekawa, Thermo-hygral analysis on long-Term natural frequency of RC buildings with different dimensions, J. Adv. Concr. Technol. 15 (2017) 381-396. https://doi.org/10.3151/jact.15.381

[20] C. Jaafari, D. Bertrand, T. Guillot, E. Prudhomme, N. Tardif, J.F. Georgin, F. Delhomme, R. Trunfio, N. Chateur, E. Bruyere, E. Augeard, L. Baillet, P. Guéguen, S. Grange, Effect of early age drying shrinkage on the seismic response of RC structures, Mater. Struct. Constr. 53 (2020) 1-19. https://doi.org/10.1617/s11527-020-01552-2

[21] M. Tanimura, R. Sato, Y. Hiramatsu, Serviceability performance evaluation of RC flexural members improved by using low-shrinkage high-strength concrete, J. Adv. Concr. Technol. 5 (2007) 149-160. https://doi.org/10.3151/jact.5.149

[22] V. Gribniak, G. Kaklauskas, D. Bacinskas, Shrinkage in reinforced concrete structures: A computational aspect, J. Civ. Eng. Manag. 14 (2008) 49-60. https://doi.org/10.3846/1392-3730.2008.14.49-60

[23] V. Gribniak, G. Kaklauskas, R. Kliukas, R. Jakubovskis, Shrinkage effect on short-term deformation behavior of reinforced concrete - When it should not be neglected, Mater. Des. 51 (2013) 1060-1070. https://doi.org/10.1016/j.matdes.2013.05.028

[24] R. Sato, H. Kawakane, A new concept for the early age shrinkage effect on diagonal cracking strength of reinforced HSC beams, J. Adv. Concr. Technol. 6 (2008) 45-67. https://doi.org/10.3151/jact.6.45

[25] K. Nakarai, S. Morito, M. Ehara, S. Matsushita, Shear strength of reinforced concrete beams: Concrete volumetric change effects, J. Adv. Concr. Technol. 14 (2016) 229-244. https://doi.org/10.3151/jact.14.229

[26] E. Gebreyouhannes, K. Maekawa, Numerical simulation on shear capacity and post-peak ductility of reinforced high-strength concrete coupled with autogenous shrinkage, J. Adv. Concr. Technol. 9 (2011) 73-88. https://doi.org/10.3151/jact.9.73

[27] E. Gebreyouhannes, T. Yoneda, T. Ishida, K. Maekawa, Multi-scale based simulation of shear critical reinforced concrete beams subjected to drying, J. Adv. Concr. Technol. 12 (2014) 363-377. https://doi.org/10.3151/jact.12.363

[28] H. Nakamura, T. Iwamoto, L. Fu, Y. Yamamoto, T. Miura, Y.H. Gedik, K. Nakarai, S. Morito, M. Ehara, S. Matsushita, C.-K. Chiu, K.-N. Chi, F.-C. Lin, N. Ueda, Shear Resistance Mechanism Evaluation of RC Beams Based on Arch and Beam Actions, J. Adv. Concr. Technol. 16 (2018) 563-576. https://doi.org/10.3151/jact.16.563

[29] M.P. Collins, D. Mitchell, J.G. Macgregor, Structural Design Considerations for High-Strength Concrete, Concr. Int. (1993) 27-34. https://www.concrete.org/publications/internationalconcreteabstractsportal/m/details/id/4217.

[30] A.P. Lampropoulos, S.E. Dritsos, Concrete shrinkage effect on the behavior of RC columns under monotonic and cyclic loading, Constr. Build. Mater. 25 (2011) 1596-1602. https://doi.org/10.1016/j.conbuildmat.2010.10.001

[31] T. Komuro, K. Imai, T. Korenaga, F. Watanabe, A Study on Long-Term Compressive Properties of Ultra-High Strength Reinforced Concrete Columns, "Tyoukoukyoudo tekkinn konkuri-tohashira no tyoukiassyuku tokusei ni kansuru kousatsu," Proc. Japan Concr. Instituite. 30 (2008) 223-228.

[32] N. Takamori, Y. Sato, M. Matsudo, J. Sasaki, Effect of Long-Term Properties on Seismic Performance of Reinforced Concrete Short Columns Made of Ultra-High Strength Materials "tyoukoukyoudozairyou wo motiita tekkin konkuri-tozou tantyuu no taishinseinou ni oyobosu tyoukiseijyou no eikyou," Fujita Tech. Res. Rep. 45 (2009).

[33] A. Muramatsu, T. Komuro, K. Imai, T. Korenaga, M. Nishiyama, An evaluation method of flexial strength of high strength concrete columns using stress block, J. Struct. Constr. Eng. (Transactions AIJ). 71 (2006) 127-134. https://doi.org/10.3130/aijs.71.127_2

[34] I. Maruyama, H. Suwada, M. Teshigawara, M. Tanimura, Y. Mitani, Effect of autogenous shrinkage of short RC column perfrmance with ultra-high strength concrete "tyoukoukyoudo konkuri-tono jikohizumi ga RChashira no kouzoukyodou ni oyobosu eikyou ni tuiteno kisokento," Proc. Work. Res. Comm. Perform. Eval. Crack Control Syst. High Perform. Expand. Concr. Japan Concr. Inst. 1 (2011) 385-392.

[35] H. Sasano, I. Maruyama, A. Nakamura, Y. Yamamoto, M. Teshigawara, Impact of drying on structural performance of reinforced concrete shear walls, J. Adv. Concr. Technol. 16 (2018) 210-232. https://doi.org/10.3151/jact.16.210

[36] F.J. Vecchio, M.P. Collins, The Modified Compression-Field Theory for Reinforced Concrete Elements Subjected to Shear, ACI J. Proc. 83 (1986) 219-231. https://doi.org/10.14359/10416

[37] P. Satya, T. Asai, M. Teshigawara, Y. Hibino, I. Maruyama, Impact of Drying on Structural Performance of Reinforced Concrete Beam with Slab, Materials (Basel). 14 (2021) 1887. https://doi.org/10.3390/ma14081887

[38] T. Nishizawa, T. Ohno, J. Tobita, N. Fukuwa, Optical fiber monitoring of the column axial force of high-rize buildings during construction, AIJ J. Technol. Des. 15 (2009) 751-756. https://doi.org/10.3130/aijt.15.751

[39] S. Matsumoto, H. Narihara, T. Komuro, S. Yasuda, H. Nakao, E. Sato, Experimental study on structural performance of CFT column using super high strength steel, part 6 Beam-clumn test of build box column filled with Fc150 concrete, Summ. Tech. Pap. Annu. Meet. Archit. Inst. Japan. C-1 (2008) 113-114.

[40] W.H. Price, Factors Influencing Concrete Strength, ACI J. Proc. 47 (1951) 417-432. https://doi.org/10.14359/12003

[41] P.J. Sereda, R.F. Feldman, E.G. Swenson, Effect of sorbed water on some mechanical properties of hydrated Portland cement paste and compacts, Highw. Res. Board Spec. Rep. (1966) 58-73.

[42] T. Okajima, T. Ishikawa, K. Ichise, Moisture effect on the mechanical properties of cement mortar, Trans. Japan Concr. Inst. 2 (1980) 125-132.

[43] H. Hotta, K. Takiguchi, Influence of drying and water supplying after drying on tensile strength of cement mortar, Nucl. Eng. Des. 156 (1995) 219-228. https://doi.org/10.1016/0029-5493(94)00948-X

[44] S.L. Wood, Evaluation of the Long-Term Properties of Concrete, ACI Mater. J. 88 (1992) 630-643. https://doi.org/10.14359/1201

[45] S. Popovics, Effect of Curing Method and Final Moisture Condition on Compressive Strength of Concrete, J. Am. Concr. Inst. 83 (1986) 650-657. https://doi.org/10.14359/10658

[46] F.M. Bartlett, J.G. Macgregor, Effect of Moisture Condition on Concrete Core Strengths, ACI Mater. J. 91 (1994). https://doi.org/10.14359/4160

[47] S. Wu, X. Chen, J. Zhou, Influence of strain rate and water content on mechanical behavior of dam concrete, Constr. Build. Mater. 36 (2012) 448-457. https://doi.org/10.1016/j.conbuildmat.2012.06.046

[48] F. Soleilhet, F. Benboudjema, X. Jourdain, F. Gatuingt, Role of pore pressure on cracking and mechanical performance of concrete subjected to drying, Cem. Concr. Compos. 114 (2020) 103727. https://doi.org/10.1016/j.cemconcomp.2020.103727

[49] F. Soleilhet, F. Benboudjema, X. Jourdain, F. Gatuingt, Effect of transient drying on mechanical properties of concrete specimens, Eur. J. Environ. Civ. Eng. (2021) 1-20. https://doi.org/10.1080/19648189.2021.1952488

[50] S.E. Pihlajavaara, A review of some of the main results of a research on the ageing phenomena of concrete: Effect of moisture conditions on strength, shrinkage and creep of mature concrete, Cem. Concr. Res. 4 (1974) 761-771. https://doi.org/10.1016/0008-8846(74)90048-9

[51] J. Glucklich, U. Korin, Effect of moisture content on strength and strain energy release rate of cement mortar, J. Am. Ceram. Soc. 58 (1975) 517-521. https://doi.org/10.1111/j.1151-2916.1975.tb18772.x

[52] Z.P. Bazant, J. Raftshol, Effect of cracking in drying and shrinkage specimens, Cem. Concr. Res. 12 (1982) 209-226. https://doi.org/10.1016/0008-8846(82)90008-4
[53] I. Yurtdas, N. Burlion, F. Skoczylas, Experimental characterisation of the drying effect on uniaxial mechanical behaviour of mortar, Mater. Struct. 37 (2004) 170-176. https://doi.org/10.1007/BF02481616
[54] N. Burlion, F. Bourgeois, J.F. Shao, Effects of desiccation on mechanical behaviour of concrete, Cem. Concr. Compos. 27 (2005) 367-379. https://doi.org/10.1016/j.cemconcomp.2004.05.004
[55] I. Yurtdas, H. Peng, N. Burlion, F. Skoczylas, Influences of water by cement ratio on mechanical properties of mortars submitted to drying, Cem. Concr. Res. 36 (2006) 1286-1293. https://doi.org/10.1016/j.cemconres.2005.12.015
[56] I. Yurtdas, N. Burlion, J.F. Shao, A. Li, Evolution of the mechanical behaviour of a high performance self-compacting concrete under drying, Cem. Concr. Compos. 33 (2011) 380-388. https://doi.org/10.1016/j.cemconcomp.2010.12.002
[57] I. Maruyama, H. Sasano, Y. Nishioka, G. Igarashi, Strength and Young's modulus change in concrete due to long-term drying and heating up to 90°C, Cem. Concr. Res. 66 (2014) 48-63. https://doi.org/10.1016/j.cemconres.2014.07.016
[58] I. Maruyama, Y. Nishioka, G. Igarashi, K. Matsui, Microstructural and bulk property changes in hardened cement paste during the first drying process, Cem. Concr. Res. 58 (2014) 20-34. https://doi.org/10.1016/j.cemconres.2014.01.007
[59] H. Sasano, I. Maruyama, Mechanism of drying-induced change in the physical properties of concrete: A mesoscale simulation study, Cem. Concr. Res. 143 (2021) 106401. https://doi.org/10.1016/j.cemconres.2021.106401
[60] L. Jesser, Kolloide chemische reaktionen des tonerdezementmörtels, Zement. 16 (1927) 741.
[61] L.A. Tomes, C.M. Hunt, R.L. Blaine, Some factors affecting the surface area of hydrated portland cement as determined by water-vapor and nitrogen adsorption, J. Res. Natl. Bur. Stand. (1934). 59 (1957) 357. https://doi.org/10.6028/jres.059.039
[62] J.J. Völkl, R.E. Beddoe, M.J. Setzer, The specific surface of hardened cement paste by small-angle X-ray scattering effect of moisture content and chlorides, Cem. Concr. Res. 17 (1987) 81-88. https://doi.org/10.1016/0008-8846(87)90062-7
[63] J.J. Thomas, A.J. Allen, H.M. Jennings, Structural changes to the calcium-silicate-hydrate gel phase of hydrated cement with age, drying, and resaturation, J. Am. Ceram. Soc. 91 (2008) 3362-3369. https://doi.org/10.1111/j.1551-2916.2008.02636.x
[64] P.C. Fonseca, H.M. Jennings, The effect of drying on early-age morphology of C-S-H as observed in environmental SEM, Cem. Concr. Res. 40 (2010) 1673-1680. https://doi.org/10.1016/j.cemconres.2010.08.007
[65] I. Maruyama, N. Sakamoto, K. Matsui, G. Igarashi, Microstructural changes in white Portland cement paste under the first drying process evaluated by WAXS, SAXS, and USAXS, Cem. Concr. Res. 91 (2016) 24-32. https://doi.org/10.1016/j.cemconres.2016.10.002
[66] C.M. Hunt, L.A. Tomes, R.L. Blaine, Some effects of aging on the surface area of Portland cement paste, J. Res. Natl. Bur. Stand. Sect. A Phys. Chem. 64A (1960) 163. https://doi.org/10.6028/jres.064A.016
[67] W.A. Gutteridge, L.J. Parrott, A study of the changes in weight, length and interplanar spacing induced by drying and rewetting synthetic CSH (I), Cem. Concr. Res. 6 (1976) 357-366. https://doi.org/10.1016/0008-8846(76)90098-3
[68] A. Bentur, R.L. Berger, F. V. Lawrence, N.B. Milestone, S. Mindess, J.F. Young, Creep and drying shrinkage of calcium silicate pastes III. A hypothesis of irreversible strains, Cem. Concr. Res. 9 (1979) 83-95. https://doi.org/10.1016/0008-8846(79)90098-X
[69] L.J. Parrott, W. Hansen, R.L. Berger, Effect of first drying upon the pore structure of hydrated alite paste, Cem. Concr. Res. 10 (1980) 647-655. https://doi.org/10.1016/0008-8846(80)90028-9
[70] L.J. Parrott, W. Hansen, R.L. Berger, Effect of first drying upon the pore structure of hydrated alite paste. Cem. Concr. Res. 10 (1980) 647-655. https://doi.org/10.1016/0008-8846(80)90028-9
[71] L.J. Parrott, J.F. Young, Effect of prolonged drying upon the silicate structure of hydrated alite pastes, Cem. Concr. Res. 11 (1981) 11-17. https://doi.org/10.1016/0008-8846(81)90004-1
[72] G.G. Litvan, R.E. Myers, Surface area of cement paste conditioned at various relative humidities, Cem. Concr. Res. 13 (1983) 49-60. https://doi.org/10.1016/0008-8846(83)90127-8
[73] D.H. Bager, E.J. Sellevold, Ice formation in hardened cement paste, Part II - drying and resaturation on room temperature cured pastes, Cem. Concr. Res. 16 (1986) 835-844. https://doi.org/10.1016/0008-8846(86)90006-2
[74] R.A. Helmuth, The reversible and irreversible drying shrinkage of hardened portland cement and tricalcium silicate pastes, Portland Cement Association. Research and Development Laboratories, Skokie, Ill., 1967.
[75] I. Maruyama, N. Kishi, A. Aili, The Relative Humidity Range for the Development of Irreversible Shrinkage in Hardened Cement Paste, J. Adv. Concr. Technol. 19 (2021) 585-592. https://doi.org/10.3151/jact.19.585
[76] F.H. Wittmann, Surface tension skrinkage and strength of hardened cement paste, Matériaux Constr. 1 (1968) 547-552. https://doi.org/10.1007/BF02473643
[77] E. Gartner, I. Maruyama, J. Chen, A new model for the C-S-H phase formed during the hydration of Portland cements, Cem. Concr. Res. 97 (2017) 95-106. https://doi.org/10.1016/j.cemconres.2017.03.001
[78] M.J.A. Qomi, L. Brochard, T. Honorio, I. Maruyama, M. Vandamme, Advances in atomistic modeling and understanding of drying shrinkage in cementitious materials, Cem. Concr. Res. 148 (2021) 106536. https://doi.org/10.1016/j.cemconres.2021.106536
[79] N. Burlion, F. Bourgeois, J.-F. Shao, Effects of desiccation on mechanical behaviour of concrete, Cem. Concr. Compos. 27 (2005) 367-379. https://doi.org/10.1016/j.cemconcomp.2004.05.004
[80] M. Lin, M. Itoh, I. Maruyama, L. Mao, I. Mitsuki, M. Ippei, Mechanism of Change in Splitting Tensile Strength of Concrete during Heating or Drying up to 90°C, J. Adv. Concr. Technol. 13 (2015) 94-102. https://doi.org/10.3151/jact.13.94
[81] J. Rymeš, I. Maruyama, R. Shimamoto, A. Tachibana, Y. Tanaka, S. Sawada, Y. Ichikawa, O. Kontani, Long-term material properties of a thick concrete wall exposed to ordinary environmental conditions in a nuclear reactor building: The contribution of cement hydrates and feldspar interaction, J. Adv. Concr. Technol. 17 (2019) 195-215. https://doi.org/10.3151/jact.17.195
[82] I. Maruyama, J. Rymeš, A. Aili, S. Sawada, O. Kontani, S. Ueda, R. Shimamoto, Long-term use of modern Portland cement concrete: The impact of Al-tobermorite formation, Mater. Des. 198 (2021) 109297. https://doi.org/10.1016/j.matdes.2020.109297
[83] C. Hall, W.D. Hoff, S.C. Taylor, M.A. Wilson, B.G. Yoon, H.W. Reinhardt, M. Sosoro, P. Meredith, A.M. Donald, Water anomaly in capillary liquid absorption by cement-based materials, J. Mater. Sci. Lett. 14 (1995) 1178-1181. https://doi.org/10.1007/BF00291799
[84] M. Saeidpour, L. Wadsö, Evidence for anomalous water vapor sorption kinetics in cement based materials, Cem. Concr. Res. 70 (2015) 60-66. https://doi.org/10.1016/j.cemconres.2014.10.014
[85] C. Zhou, F. Ren, Z. Wang, W. Chen, W. Wang, Why permeability to water is anomalously lower than that to many other fluids for cement-based material?, Cem. Concr. Res. 100 (2017) 373-384. https://doi.org/10.1016/j.cemconres.2017.08.002
[86] P.J. McDonald, O. Istok, M. Janota, A.M. Gajewicz-Jaromin, D.A. Faux, Sorption, anomalous water transport and dynamic porosity in cement paste: A spatially localised 1H NMR relaxation study and a proposed mechanism, Cem. Concr. Res. 133 (2020) 106045. https://doi.org/10.1016/j.cemconres.2020.106045
[87] R. Kiran, H. Samouh, A. Matsuda, G. Igarashi, S. Tomita, K. Yamada, I. Maruyama, Water Uptake in OPC and FAC Mortars under Different Temperature Conditions, J. Adv. Concr. Technol. 19 (2021) 168-180. https://doi.org/10.3151/jact.19.168