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COMPARACION ENTRE LOS MODELOS DE CÁLCULO Y ENTRE LOS ENSAYOS PARA EVALUAR LA RETRACCIÓN DEL HORMIGÓN

Trabajo Fin de Máster

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The Acknowledgment

To my family, for supporting me during all this time, especially my mother who instilled in me the interest to learn and improve myself day by day and

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CHAPTER 1: INTRODUCTION

Cement is a binder material whose main physical characteristics are adhesion and cohesion, which allow the fragments to join together to form a compact whole.

The etymology of the word comes from the Latin caementum , which means "mortar" and also comes from the verb caedere (to precipitate) and today cement is the most widely used binder in the world.

According to its origin, cement can be classified into two large groups: clay cements that come from the manufacture of clay, and limestone and pozzolanic cements that come from alumino-siliceous materials, this comes from pyroclastic materials emanated by volcanoes or of organic origin.

Cement is the principal material used in the concrete which is the most used materials in the world , like every material the concrete suffer from several disadvantages one of them is the shrinkage .

The phenomenon of concrete shrinkage has been won by far, the position of the most frequent cause, of most of the cracks that afflict our structures.

The truth is that if shrinkage is responsible for half of the cracks attributed to it, still continues to occupy a place of privileged interest for scholars and users of the material.

Despite this, the lack of knowledge that exists about the phenomenon itself and its causes is paradoxical.

Great efforts and technological advances (Altoubat S. y., 2001)<1>, (Kovler K. I., 1999)<2>, (Kovler K. , 1999)<3>, (F, 1999)<4>, have been carried out in recent years, both to understand these dimensional changes and to prevent their development.

The advent of high-performance concrete with high amounts of cement and low (water /cement) , the emergence of self-compacting agents that increase the volume of paste , the use of low-exudation concrete (with silica fume or other similar material) or the diffusion of ever thinner elements (bridge plates, Outinord, covers),the use of recycled concrete aggregate And more environmentally friendly materials, has caused shrinkage to demand more attention than ever and its importance is repeated ad nauseam by hundreds of elements whose monolithism has been interrupted by a crack.

Objectif of the work

The main objective of this work is to make a comparison between shrinkage estimation methods, both in or related to its experimental determination and in the theoretical models for its evaluation.

To compare the applicability of tests to characterize shrinkage in various types of concrete.

Analyze various estimation models from the international literature: ACI 209-92, MC2010, Eurocode EC-2, B3, SAKATA, CEB-FIP1990 and GL2000.

These models vary in complexity, computational accuracy, and in the number of parameters needed in the computation.

This analysis will be done with special emphasis on the necessary parameters in the calculation.

Check the sensitivity of the parameters and factors used in the short-term and long-term shrinkage prediction models.

Document structure

In the chapter2 , a general explanation of cement and concrete as a construction material is made, in addition to the microstructure of hydrated cement and the distribution of water in the cement paste.

In chapter 3 , an explanation of the phenomenon of concrete shrinkage is made, showing the different types of shrinkage, as well as the elements that affect this phenomenon and various methods to limit concrete shrinkage.

Chapter 4 discusses the tests to measure and evaluate various types of shrinkage according to international standards.

Chapter 5 discusses concrete shrinkage prediction models where the sensitivity of each model factor over time is verified.

In chapter 6, a comparison is made between factors of the models, in addition to the limitations and requirements of each concrete shrinkage model.

in chapter 7 it would be a conclusion of the work where the results of the interior chapters are briefly presented in addition to future research and lines .

CHAPTER2 : Structure of the concrete and Cement pastes

2.1 Structure of Dehydrated cement.

To understand the hydration process of cement paste, a few notions of the main components of dehydrated cement must be had.

(González.Gm, 1974) [5], synthetically describes this point.

The author explains that cement has limestone and clay as raw materials, being substitutable in some cases by other raw materials that contain the same oxides.

These two materials can be , dry, or wet, before their manufacture, from the processing of these materials, the crude is obtained, which, after being calcined in the furnace at temperatures between 1350 and 1450ºC, becomes the material that we know as clinker. After obtaining it, this clinker is ground and undergoes a small addition of gypsum, of between 2 to 4% in weight, which provides volumetric stability to the material, according to (Verbeck & Helmuth, 1969)[6].

After this operation, the final product is obtained, cement.

2.1.1Clinker

Clinker is made up of silicates and aluminates with complicated formulas.

When studying the chemistry of Portland cement, it is assumed that these silicates and aluminates are made up of combinations of the simplest oxides and anhydrides, of which the most important are the following :

- Cal, CaO, in abbreviated notation. Approximately 70% of the total material.
- Silica, SiO_2, S in abbreviated notation. Approximately 25% of the total material.
- Alumina, Al_2O_3, A in abbreviated notation. In small quantities.
- Ferrite, Fe_2O_3, F in shorthand notation. In small quantities.

By combining these compounds, the main mineralogical constituents that make up clinker can be more comfortably defined, which are:

- Tricálcic silicate, SC3
- Dicalcium Silicate, SC2.
- Aluminum-ferrito-tetracalcico, AFC4.
- Tricalcium aluminate, AC3.

The above components determine the properties of the cement.

Thus, mechanical resistances are due to the sum of SC3 and SC2, the first being the one that gives the short-term resistances and the second the one that grants them in the long term.

Likewise, since the modulus of elasticity is directly related to mechanical resistance, it also depends on these two components.

On the other , AC3 accelerates the hardening process during the first hours.

In addition, AC3 and AFC4, especially the latter, act as fluxes, lowering the necessary temperature inside the oven for firing. Likewise, resistance to sulfates and the freeze-thaw process depends on AC3, the resistance to attack by both being less as the AC3 content increases.

The sum of SC3 and SC2 ranges between 60% and 80% by weight, without one of the two components having an ostensibly greater presence in the mixture.

Meanwhile, AC3 can vary from 2 to 14% of the total content by weight, helping to generate a cement resistant to sulfates as long as its content is less than 5%.

In turn, AFC4 usually presents percentages of around 10% of the total weight.

In addition to these major components, there are other elements in a lower percentage in cement, although not for that reason they are less important, (Neville A. , Properties of Concrete, Fourth Edition, 1995),[7].

Some examples of these compounds are MgO, TiO2, Mn2O3, K2O and Na2O. the sum of which is usually equivalent to a small percentage of the total mass of the cement.

2.1.2 Portland Cement:

The most commonly used hydraulic cement to make concrete is Portland cement, which is primarily made up of hydraulic calcium silicates.

The calcium silicate hydrates that are formed with the hydration of Portland cement are mainly responsible for its adhesive characteristics and are stable in an aqueous medium. Portland cement is basically the result of grinding clinker and gypsum together.

Clinker is mainly composed of calcareous materials, such as limestone, alumina, and silica, found as clay or shale.

In the manufacturing process, the raw material is finely ground and thoroughly mixed in a certain proportion, then it is calcined at high temperatures where the material is synthesized and partially melts, forming balls known as clinker.

The clinker, in turn, is cooled and ground in combination with a little plaster to obtain a fine powder, and finally the resulting product is Portland cement.

2.2 The hydrated cement paste:

2.2.1 Microstructure

(Mehta, 2006) [8], describes the hydrated cement paste as the result of the mixture of Portland cement and water.

The product of this reaction is a colloidal type material, that means, it has a specific area of the material very high.

The hydration of the cement mainly generates a porous gel, composed of hydrated calcium silicate, S-C-H, which houses part of the uncombined water between its layers, its loss under certain circumstances being responsible for the drying shrinkage.

This phase is very heterogeneous, being able to present solid areas, without defects, next to other eminently porous ones.

The former are those in which there has been an optimal water-cement ratio, with a correct development of the hydration process, that is, the acquisition of resistance by the material.

The weakest porous areas are those in which this process has been less efficient.

It is important, therefore, to carry out a good curing of the material, since its resistance does not depend on the general behavior of the microstructure, but on its defective areas, which represent planes of easy breakage.

In concretes with normal strengths, these points of greatest weakness usually coincide with the third phase present in a concrete, the interface between aggregate and cement paste.

Thus, when a direct or indirect compression failure test of one of these concretes occurs, the aggregates are not part of the failure, but remain whole and it is the paste that is detached from them.

However, when the concrete is of high resistance, a factor mainly linked to the greater resistance of the cement, it is common for the break to go through the aggregate, which has less resistance than the hydrated cement paste.

(Verbeck & Helmuth, 1969), [6], define the state of knowledge about the structure of the cement paste already hardened.

These concepts are explained from studies carried out with an optical microscope and, for a greater level of detail, with an electronic microscope.

The use of an electron microscope makes it possible to correctly distinguish the different parts of the cement hydration products.

From its use it is known that the hydration process begins suddenly after contact between water and cement grains.

Different phases are distinguished, namely that of hydrated calcium silicates, S-C-H, that of calcium hydroxide, that of hydrated calcium sulfoaluminates, and finally, that of clinker grains that have not been hydrated.

Although (Verbeck & Helmuth, 1969)[6], already define the components of the hydrated cement paste correctly, the phases in this material are described below from what has been published by (Mehta, 2006), [8], as it is a more complete model due to its lower age.

Thus, the different phases present in the hydrated cement paste are defined below :

- **Hydrated calcium silicates: S-C-H:** occupy between 50 and 60% of the total volume of the solid compounds in a fully hydrated Portland cement paste.
  It is, therefore, the most important phase with respect to the physical and mechanical properties of the material.
  After two hours from the mixing of the cement with the water, the formation of this phase begins to be observed.
  Morphologically, it begins by being made up of fluted needles that, as the hydration process progresses, become so long and numerous that they form a single laminar interface throughout the entire pasta.
  Thus, it is a slightly crystalline structure in which networks of a massive structure with an apparently regular organization are frequently observed.

- **Calcium hydroxide**: crystalline structure also known as portlandite that constitutes between 20 and 25% of the solid phase of the material.
  This compound has a defined stoichiometry, that is, $Ca(OH)_2$.
  This material tends to form large hexagonal prismatic structures,However, the morphology is affected by the available space, by the hydration temperature and by the impurities present in the mixture, in some cases structures without a clear morphology are generated.
  Because it has a much smaller specific surface than the S-C-H phase, its contribution to the development of cement strength is much less.

- **Hydrated calcium sulfoaluminates:** structure that occupies between 15 and 20% of the solid phase of the cement paste, playing a minor role on the properties of the material as a whole.
  During early stages of hydration, particles of hydrated trisulfate, $C_6AS_3H_{32}$, better known as ettringite, emerge from this phase, which accumulate as prismatic

crystals in the shape of a striated needle.

In ordinary Portland cement pastes, ettringite is commonly transformed into hydrated monosulfate, C_4ASH_{18}, The presence of this substance makes concrete vulnerable to sulfate attack.

- **Unhydrated clinker:** they can be more or less frequent depending on the size and distribution of the cement particles and the degree of hydration of the cement, although they can be found at very advanced ages of the material.

  Thus, the smaller particles dissolve earlier and disappear from the system, but the larger particles remain, reducing their size.

  Due to the little space available around it, the hydration products tend to accumulate around the cement particles, generating a solid layer around them. At older ages, due to the smaller amount of space available, the hydration of the clinker generates an increasingly dense material, very similar to the original clinker particle

  Verbeck and Helmuth, [6], mention the fact that when the hydration temperature of the cement is very high, the rapid development of the reaction means that a high percentage of the volume of the cement grains does not react, so that the products of hydration are concentrated in the areas that surround the non-hydrated particles.

2.2.2 Water distribution in the hydrated cement paste

Hydrated cement, after combining with water, occupies twice the volume that it covered in its anhydrous phase.

Thus, the space previously occupied by cement and water separately, after hydration occurs, will become occupied by a solid phase which, as it does not occupy 100% of the available volume, is flanked by free spaces of various sizes.

This space not occupied by the cement paste is made up of what are known as capillary pores.

In a well-hydrated cement, these pores, of irregular volume, must be in a size range between 10 and 50 nm, although in pastes with a high water-cement ratio, at early ages these cavities can measure between 3 and 50 μm.

These spaces, according to modern literature, are divided into two types according to their size, namely, macropores and micropores.

Macropores are known as those with a size greater than 50 μm, being related to the resistance and impermeability of the concrete.

The Micropores are those smaller than 50 µm, being responsible for drying shrinkage, a phenomenon explained later, and for creep.

It is interesting to mention the fact that for water-cement ratios greater than 0.38, the volume of the gel, product of the hydration reaction, is not enough to fill all the space available in the mix, which is why they will form these capillary pores.

-These pores are connected, forming a network of cavities that facilitates the exchange of water with the outside.

-This can be filled through a correct process of hydration of the cement, a measure that will cause this interconnection between the pores to occur between the sheets of the gel structure of the S-C-H phase.

In the very phase structure of hydrated calcium silicates, S-C-H, there is also some space for the deposition of water atoms, as explained above according to the (Feldman, 1970) , [9], models.

This space, being so small, 0.5 to 2.5 µm~~nm~~, does not contribute negatively to the porosity or the strength of the cement.

From the foregoing it follows that the water storage capacity in the hydrated cement paste is high due to its high porosity.

Apart from the existing water vapor in some empty pores or partially filled with liquid, this stored water can be classified, according to its ease of being removed from the cement paste, as follows:

- **Capillary water:** which is divided into two types, that present in pores greater than 50 µm~~nm~~, called free water because its elimination does not induce efforts in the system, and that present in pores between 5 and 50 µm~~nm~~.

  The latter exerts a certain hydrostatic tension, so that when this water disappears, a compressive stress is induced in the walls of the capillary pores that causes the system to contract, that is, retraction.

  This water disappears below 45% relative humidity.

- **Adsorbed water:** which is strongly linked to the solid surface, so that it can be considered to be part of the structure of the material as a whole due to the influence of the attractive forces of the cement paste, van der Waals forces of physical attraction.

  Most of this physically adsorbed water can be lost if the material is exposed to a relative humidity of 30% or less.

  This water is the main responsible for the drying shrinkage that affects the cement paste under normal environmental conditions.

- **Water between layers of the SCH phase or interstitial water:** which in these layers is strongly physically bound to the material through hydrogen bonding, being only below relative humidity of 11% when its total elimination of the microstructure is possible.

  When this happens, the shrinkage of the porous structure of the gel undergoes a significant shrinkage.

- **Chemically combined water :** which is an integral part of the microstructure of cement and which cannot be eliminated by drying the material, its state can only be modified by breaking down the state of the hydrates after a heating process.

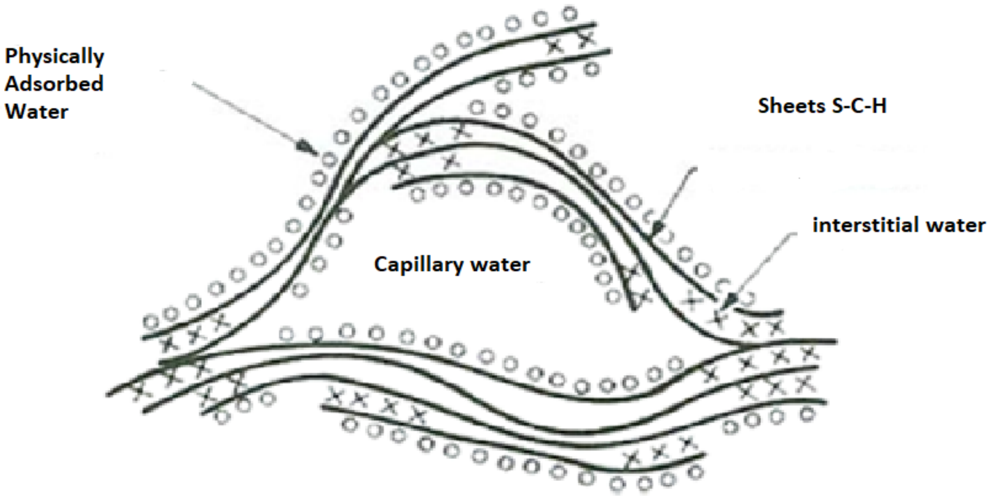


Figure1 Scheme of the types of water associated with the porous calcium silicate hydrated gel, derived from the hypotheses of (Feldman, 1970), [9].

2.3Self-compacting concrete (SCC)

Self-compacting concrete is a very fluid concrete that is poured without the need to vibrate, and that in its hardened state meets all the requirements of conventional concrete , (Okamura, 2000)[10].

Self- compacting concrete (SCC) is a new and emerging technology in the concrete industry.

This concrete is characterized by its high degree of workability and its ability to flow through congested structural elements with reinforcement simply by the action of its own weight, filling all the spaces adequately without segregating and without the need for external compaction.

In rheological terms, SCC differs from conventional vibrated concrete, due to its low elastic limit and moderate viscosity, which allows it to achieve high fluidity and maintain its homogeneity.

SCC contains basically the same components as conventional concrete (cement, aggregates, sand, additions, water, and additives), but there is a clear difference in the final composition of the mix.

Compared to conventional concrete, the SCC mix has a high volume of additions, such as limestone or fly ash, higher content of superplasticizers, and the maximum size of the coarse aggregate is smaller.

In general, the final composition of the SCC implies higher content of paste and lower content of gravel.

These modifications in the composition of the mixture influence the behavior of the concrete in its hardened state, and specifically, on the shrinkage and creep.

It is commonly accepted that shrinkage depends primarily on the characteristics of the paste and the aggregate content.

It is generally considered that a concrete with a higher paste content and a lower aggregate content shows greater deformation due to shrinkage and creep.

2.3.1 compressive strength

Self-consolidating concrete with a similar ratio of water to cement or cement binder will generally have a slight higher resistance compared to traditional vibrated concrete, due to the lack of vibration which provides an improvement interface between the aggregate and the hardened paste.

-The compressive strength development will be very similar so the maturity test will be an effective way to control the development of strength .

Various properties of concrete can be related to the compressive strength of concrete, the only concrete engineering property that is specified and routinely tested.

2.3.2 Tensile strength

Self-compacting concrete can be supplied in any specified compressive strength class. for a given strength and maturity class of concrete, it can be safely assumed that the tensile strength is the same as the one for normal concrete since the volume of paste (cement + fines + water) does not have a significant effect on tensile strength.

In the design of reinforced concrete sections, the flexural tensile strength of the concrete is used for the evaluation of the cracking moment in prestressed elements, for the design of control reinforcement width and spacing of cracks resulting from restrained early thermal shrinkage, for drawing moment curvature diagrams, for the design of unreinforced concrete pavements and for fiber-reinforced concrete.

2.3.3 Modulus of elasticity

The modulus of elasticity (E value, the relationship between stress and strain), is used in the elastic calculation of deflection, often the controlling parameter in the design of slabs, and of pre- or post-tensioned elements.

Since most of the volume of concrete is aggregate, the type and amount of aggregate and E-value, have the most influence.

Selecting an aggregate with a high E-value will increase the modulus of concrete elasticity.

However, increasing the volume of the paste could decrease the E value, Because SCC most of the time has a higher paste content than ordinary vibrated concrete, there are some differences can be expected and the E-value may can be lower, but this should be adequately covered by the safe assumptions about which are based on the formulas given in EN1992-1-1.

If SCC has a slightly lower E modulus than traditional vibrated concrete, this will affect the relationship between compressive strength and warping due to pre- or post-tensioning.

For this reason, careful control must be exercised over the strength at the time prestressing is performed and strands or post-tensioning wires come loose.

2.3.4Durability

The durability of a concrete structure is closely related to the permeability of the surface layer, which must limit the entry of substances that can initiate or spread possible harmful actions (CO2, chloride, sulfate, water, oxygen, alkalis, acids, etc.).

In practice, durability depends on the material selection, composition of the concrete, as well as on the degree of supervision during placement, compaction, finished and cured.

In case of no having a good compaction of the surface layer, due to hard vibration difficulties in small spaces between the formwork and reinforcing bars or other inserts has been a principal factor of the poor durability performance of reinforced concrete structures exposed to aggressive environments .

This is one of the priority reasons for the original development of SCC in Japan.

Traditional vibrated concrete is subjected to compaction by vibration, which is a discontinuous process.

In the case of internal vibration, even when executed correctly, the volume of the concrete within the area of influence of the vibrator does not receive the same compaction energy.

Same as the case of external vibration, the compacting result is essentially heterogeneous, depending on the distance to the vibration sources.

The result of the vibration is, therefore, a concrete in the structure with an uneven compaction and, therefore, with different permeabilities, which favors the selective entry of aggressive substances.

Naturally, the consequences of incorrect vibration have stronger negative effect on permeability and thus on durability.

Self-compacting concrete with the proper properties will be free from these deficiencies and will result in a Consistently low and uniform permeability material, offering fewer weak points for damaging actions of the environment and therefore better durability. The comparison of permeability between SCC and normal Vibrated concrete will depend on (water/cement) , (water/binder) or materials selection.

2.3.5 cement

Every cements conform to the European standards can be used for production of the self-compacting concrete, to get a better choice of cement type is the one dictated by the specific requirements of each application .

2.3.6 Mineral fillers

The particle size distribution, shape, and water absorption of mineral fillers can affect water demand./sensitivity , Consequently the suitability for use in the manufacture of the self-compacting concrete.

Calcium carbonate based mineral Fillers most of the time are used to can give excellent rheological properties.

the most advantageous fraction is less than 0.125 mm and in general it is desirable that >70% pass a 0.063mm sieve.

Fillers specifically ground for this application offer the advantage of an improved batch for particle size distribution batch consistency, giving better control over water demand and making they are particularly suitable for SCC compared to other available materials.

Chapitre 3 Concrete Shrinkage phenomenon

3.Shrinkage

Shrinkage is the deformation of concrete in a fresh or hardened state caused by the loss of moisture, and that does not depend on the external load applied.

(Wittmann, 1982),[11] defines three types of shrinkage: capillary shrinkage, chemical shrinkage, and drying shrinkage.

Capillary retraction, also called plastic shrinkage , is related to the shrinkage of concrete in its fresh state and acts during the first hours after pouring the concrete.

“Chemical shrinkage is a term used for various types of shrinkage that are caused by chemical reactions in concrete” .

Whittman defines six different types of chemical shrinkage, moreover in this work only the autogenous retraction will be commented, as well drying shrinkage and carbonation shrinkage.

Losing water and losing volume produces internal tensile stresses that give rise to the famous shrinkage cracks, although depending on the amount of fines, the amount of cement, the type of cement, the water-cement ratio, and the thickness of the structural element.

whether it is reinforced concrete or not and the ambient temperature, the shrinkage can be small or large.

Although the phenomenon of shrinkage does not cause big structural damage to concrete elements in the conventional concrete, the control is important from the point of view of durability since the cracks caused facilitate the penetration of aggressive agents that can damage the reinforcement.

To control these cracks, there are different methods on the market, such as the use of chemical additives to reduce shrinkage or fibers to control shrinkage.

The diagram in Figure 2 shows the different types of shrinkage throughout the different phases of concrete, from its hydration of the concrete to its hardening.

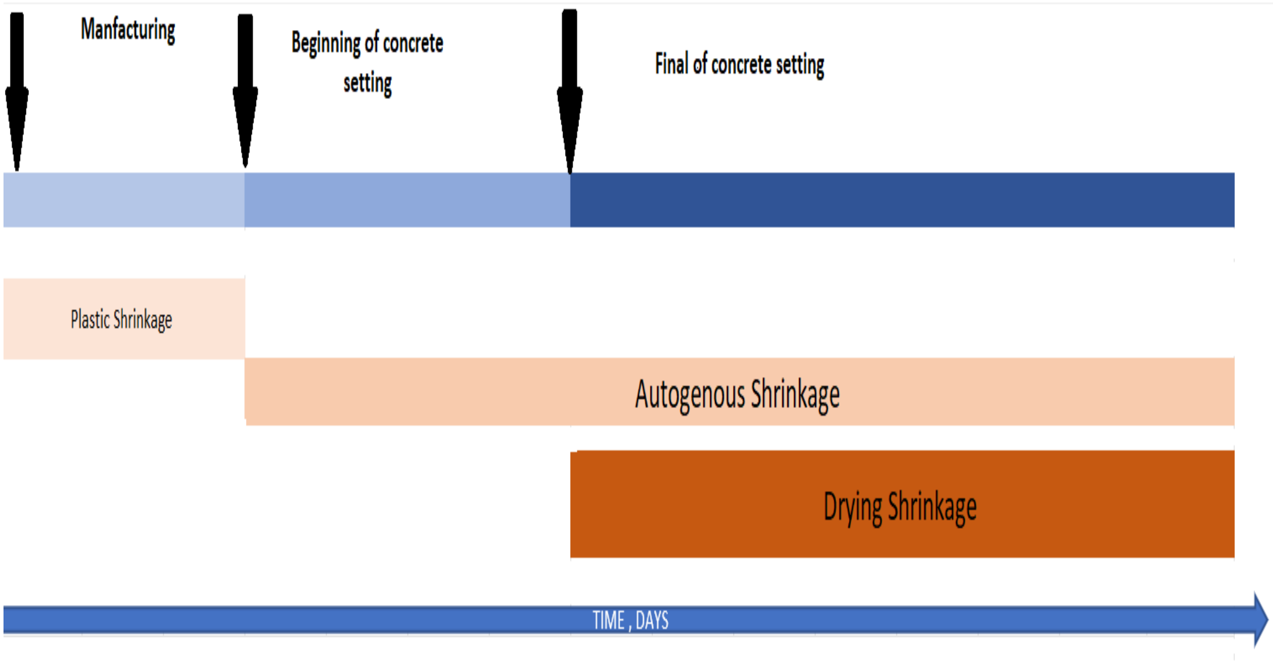


Figure2 Types of shrinkage during the different phases of concrete.

3.1Plastic Shrinkage

Plastic shrinkage is that which occurs on the fresh surface of the concrete during the first hours after it has been concreted, that is, while the concrete is still in at plastic state and before they ~~have ~~develop~~d~~ significant strengths.

This type of shrinkage is not unacceptable as long as it is properly controlled, but on some occasions it can be accompanied by the development of deeply unsightly fissures. Plastic shrinkage and related cracks most often occur on horizontal surfaces.

In this stage, the volume of the paste undergoes a contraction of the order of 1% with respect to the absolute volume of dry cement.

This retraction occurs within the first eight hours , (Fernández Cánovas, 2007)[12].

When concrete begins to set and is exposed to the dry atmosphere, the surface in contact with it begins to lose water immediately.

This water is eliminated in a capillary process, gradually losing that of the largest pores by evaporation.

Capillary stresses develop at the points where the water remains, which induces compressive stresses in the concrete.

This shrinkage acts on the exposed surface of the newly placed concrete causing rapid drying before the material can reach strength values that can absorb the internal stresses that are generated, creating cracks due to plastic shrinkage.

This cracking is usually associated, on the one hand, with extreme environmental conditions (high temperatures, low humidity and high wind speed).

On the other hand, it can be associated with specific characteristics, both in the composition of the concrete and in the arrangement of the reinforcement , (Mora J. &., 2003)[13]

In the event that the loss of water during the plastic phase of the concrete is high, cracks can be generated on the face of the material exposed to the environment.

If, in addition, the retraction movement due to this phenomenon is restricted, for example in massive structures, deep cracks of irregular shape can occur, (Lerch, 1956), [14] comments.

(Lerch, 1956) [14] explains that the main cause of plastic shrinkage and the cracking derived from it is an excessive loss of water by evaporation from the concrete surface. Although the same materials, proportions, handling, finishing and curing are used, these cracks can develop simply due to the presence of environmental conditions that sufficiently favor the loss of water by evaporation.

If, while aggregates and cement settle, the evaporation rate exceeds the amount of water that rises to the surface of the material, cracking due to plastic shrinkage will most likely develop.

This circumstance can be appreciated the moment the concrete loses its surface shine, At that moment the concrete surface has reached some rigidity, so it can no longer adjust to the volumetric changes produced by plastic shrinkage and cracking occurs because the tensile strength of the material has not been sufficiently developed.

Some projects have tried to avoid this phenomenon by increasing the exudation capacity of the concrete by increasing the water-cement ratio or by varying the type of cement or aggregate.

However, it has been appreciated that the variation of these parameters does not have any kind of influence on the plastic shrinkage and the cracking associated with it.

It has been shown that environmental factors directly affect the development of this phenomenon.

Specifically, the factors that have the greatest influence are the increase in wind speed, the decrease in relative humidity, the increase in the air temperature and that of the setting of the concrete, the decrease in the air temperature at the same temperature.

of the concrete and the increase in the temperature of the concrete at the same humidity and air temperature.

To avoid the development of cracks related to plastic shrinkage, different measures can be taken on site, such as moistening the aggregates, the formwork or the substrate, avoiding high temperatures of the concrete, starting the curing of the concrete as soon as possible after concreting, temporarily cover the concrete to prevent evaporation or erect barriers for the wind and solar radiation incident on concrete.

It should be noted that this phenomenon increases as the amount of cement increases in the concrete as a whole and when the water-cement ratio decreases.

3.2Autogenous shrinkage

In a concrete with a low water / cement ratio, it may happen that there is not enough water to complete the hydration process. Under these conditions, the free water found in the capillary pores will be consumed to continue the hydration process.

This phenomenon of internal water consumption, also called auto-drying, it is the cause of the autogenous shrinkage of concrete.

In vibrated concretes with normal strengths, autogenous shrinkage is small, with values lower than 100×10^{-6}, and they are normally included in drying, (Newman, 2003).[15]

In the case of high-strength concretes, autogenous shrinkage can be significant, with values up to 700 × 10 -6 (Neville A. , Properties of Concrete, Fourth Edition, 1995),[7].

Autogenous shrinkage tends to increase with elevated temperatures, high cement content, finer cements, and with cements that are high in C3A and C4AF.

All of these factors also accelerate the hydration process, The use of additives, such as fly ash, tends to decrease autogenous shrinkage.

In contrast to normal concrete, UHPFRC is susceptible to a very high ultimate autogenous shrinkage of about 800 με because of its low water-to-binder ratio (W/B), (Koh, Ryu, Kang, & Ryu, Gumsung;, 2011).[16].

In self-consolidating concrete SCC the (water / cement) ratio is not higher than in conventional concrete, so there is no reason why autogenous shrinkage is different in this type of concrete.

Some research does indicate higher autogenous shrinkage values, (Song & Byun, K.J., Kim, S.H., Choi, D.H, 2001), [17], showed that in SCC mixtures the autogenous shrinkage is greater for mixtures with finer additions.

(Khayat & Richard Moring, ,, 2003) , [18], have reported values of the order of 50 to 100 $\times 10^{-6}$ for SCC mixtures with a water / cement ratio of 0.38.

This shrinkage occurs mainly in low-porous elements.

Therefore, the shrinkage is relatively small and in practice (except in large solid concrete structures) it is not necessary to take it into account as a separate factor from drying shrinkage, which typically includes shrinkage caused by autogenous changes.

It is more important when the water-cement ratio is low (less than 0.40). (Neville A. , 1977),[19].

3.3 Drying Shrinkage

The drying shrinkage occurs, according to (Mehta, 2006)[8], due to a hygrometric gradient with the surrounding air.

If the environment has a relative humidity lower than that present inside the concrete, this material tends to contract, producing the phenomenon of shrinkage.

As the characteristics of the medium change and it becomes more humid, the humidity gradient changes sign and the specimen increases its volume.

This phenomenon is called swelling.

This phenomenon depends on how the water behaves inside the cement paste.

Thus, in a study on the drying shrinkage of cement, (Hobbs, 1971),[20], defines three different periods of weight loss or gain, which has a direct relationship with the shrinkage behavior during the drying process:

i. Predominant uncombined capillary water loss. The cement does not retract too much since it has enough water for the hydration reactions, although weight is lost rapidly.
As the thickness of the specimen increases, this period takes longer to finish because the water dissipates more slowly.

ii. Loss of water by capillarity and by the moisture diffusion mechanism, consisting of an internal moisture gradient of the concrete due to the influence of the environment.

iii. Loss of moisture by dominant diffusion. When this phenomenon plays a role, shrinkage and water loss have a linear relationship.

Drying shrinkage is a deformation related to loss of moisture from hardened concrete. In figure 3 you can see how the contraction develops as a function of relative humidity.

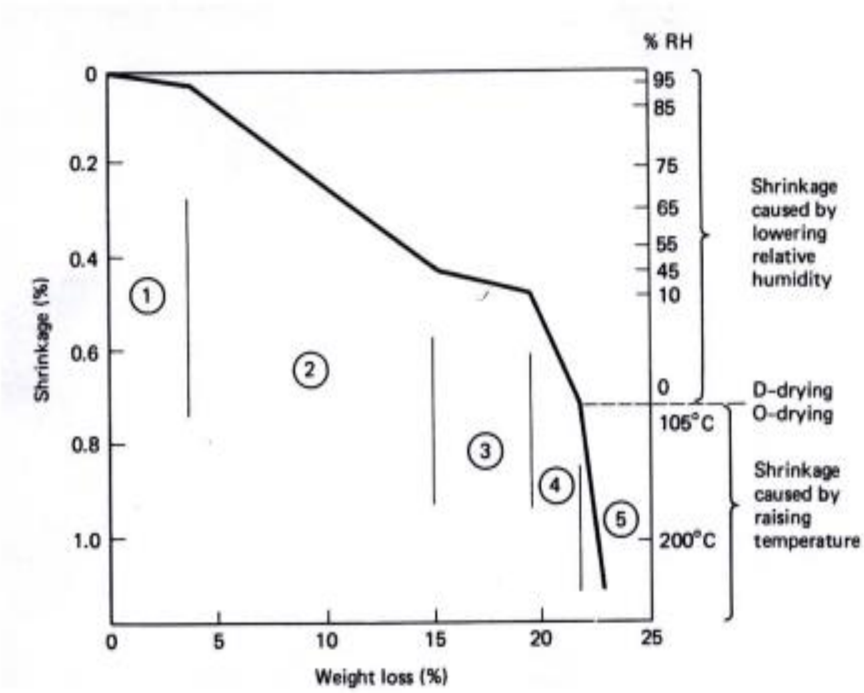


Figure3 Relationship between shrinkage and moisture loss in pastes cement., (Mindess & Young, F.J., 1981),[21]

According to figure 3, shrinkage increases with decreasing relative humidity.

The decrease in relative humidity increases the humidity gradient between the paste and the environment, accelerating the loss of water to the outside.

The drying process begins with the loss of free water found in the capillary pores (phase 1 and 2 in figure 3).

In these first phases, the shrinkage of the paste is not yet visible, but an internal gradient of moisture by which the water adsorbed to the silica gel moves into the pores.

In the event that the relative humidity drops below 45%, the loss of water continues and begins to affect the water absorbed at the surface of the C-S-H silica gel (phase 3). The internal water of the C-S-H gel (phase 4) is then lost, and finally the decomposition of the gel takes place (phase 5).

3.4 Carbonation Shrinkage.

In hardened concrete, the phenomenon of carbonation occurs, due to the action of CO_2 from the environment.

This reacts in the presence of humidity with Ca $(OH)_2$ forming calcium carbonate.

This process causes a carbonation shrinkage that, although not as important or deep as that of drying, is superimposed on it, increasing it.

Carbonation contraction is due to the dissolution of calcium hydroxide or portlandite crystals in the compressed areas as a consequence of drying contraction and the precipitation of carbonate crystals in the stress-free areas (Fernández Cánovas, 2007).[12]

This reaction is presented below:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

$$C\text{-}S\text{-}H + CO_2 \rightarrow CaCO_3 + SiO_2 + H_2O$$

The reactions described above take place only in solution, so the reagents must be dissolved before reacting, that is, there must be water for this phenomenon to occur.

At that time, there is a reduction in the pH of the solution that forms the porous gel of the cement paste to a value whereby the steel lodged within the concrete no longer has sufficient protection against the phenomenon of corrosion.

As can be seen in the previous equations, the original components of the hydrated cement paste generate calcium carbonate, $CaCO_3$, Carbonation of calcium hydroxide.

$Ca(OH)_2$, in calcium carbonate, causes an increase in volume.

The chemical reactions that take place lead to a reorganization of the microstructure of the cement paste, generating a decrease in porosity and, paradoxically, a total decrease in the volume of material.

This effect produces a differential shrinkage between the surface and the internal zone of the affected concrete, which can cause surface cracking.

Carbonation and therefore the shrinkage due to it reaches its maximum value for a relative humidity of 50 to 60%, its value being negligible for a humidity close to 10%, with a humidity of 50% a long-lasting mortar can Retract 50 % more than if carbonation had not occurred.

4. Factors influencing the Shrinkage

The factors that affect the development of Shrinkage are numerous. The factors that affect shrinkage can be classified into three groups:

- factors related to the dosage of the mixture.
- factors related to the environment

- factors related to the method of execution.

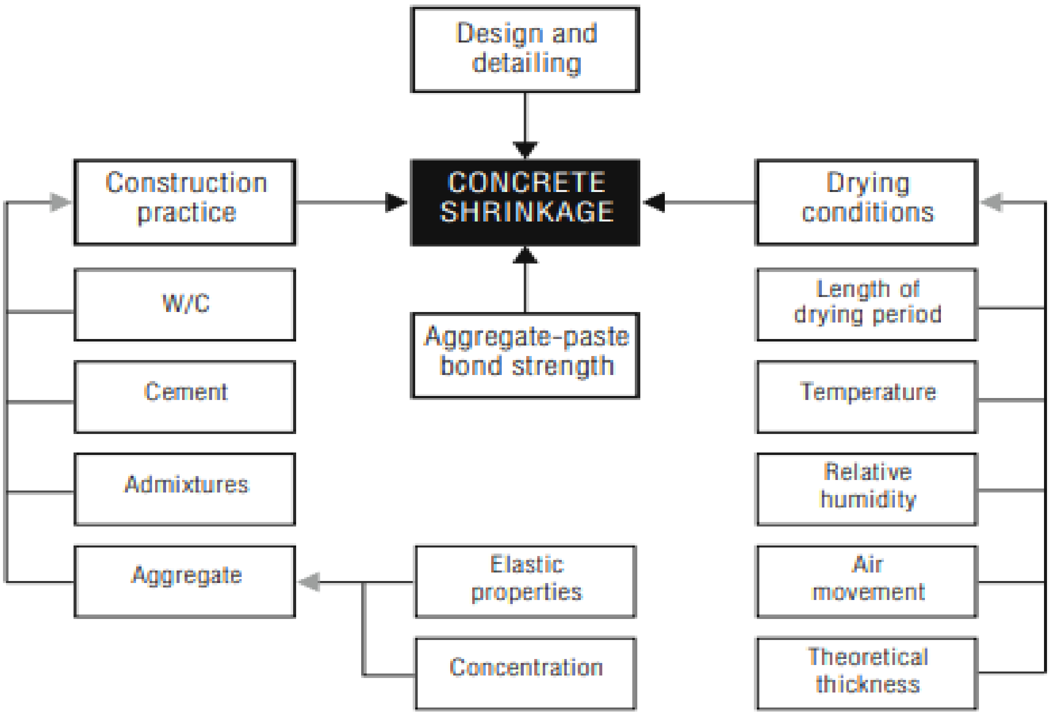


Figure4 Factors Affecting Concrete Shrinkage

4.1 Factors related to the dosage of the mixture

The factors related to the dosage of the mixtures, the content of aggregates, size and distribution of aggregates, the water-cement ratio, type of cement, additives and additions can be mentioned.

- Water / cement ratio

At the same dose of cement per m^3, the shrinkage will increase with the (w / c) ratio; In other words, there will be a greater quantity of mixing water, which does not intervene in the hydration of the cement, which must be eliminated, producing greater shrinkage. The amount of water has a great influence on the shrinkage, since it reduces the volume of aggregates introduced into the concrete, which are what really slow down the shrinkage.

In figure 4 , (Fernández Cánovas, 2007),[12] it is presented from the amount of water in a mixture, you can get an idea of the order of magnitude of the shrinkage.

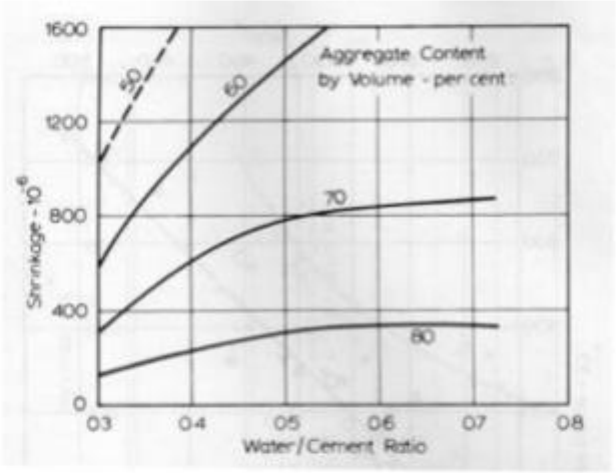


Figure5 Concrete shrinkage as a function of mixing water , (Fernández Cánovas, 2007),[12].

- Volume and size of aggregate.

The most important factor affecting the amount of shrinkage is the aggregate content. Although this phenomenon occurs in the paste, the aggregate has the function of limiting these deformations.

It must be remembered that the volume of concrete is made up of the volume of paste plus the volume of aggregate, which means that greater volume of paste implies less volume of aggregate.

The influence of aggregate on shrinkage can be quantified using the following expression , (Newman, 2003), 15]

$$S_c = S_p (1\text{-}a)^n$$

Where:

S_c: is the shrinkage of the concrete.

S_p: is the shrinkage of the paste.

a: is the aggregate content in the concrete mix.

n: is an experimental value. The values of n vary between 1.2 and 1.7.

According to this expression, the increase in aggregate content contributes to reducing shrinkage.

For example, increasing the aggregate volume from 71% to 74% reduces shrinkage by approximately 20%.

Figure 5 shows the direct relationship between aggregate content and concrete shrinkage.

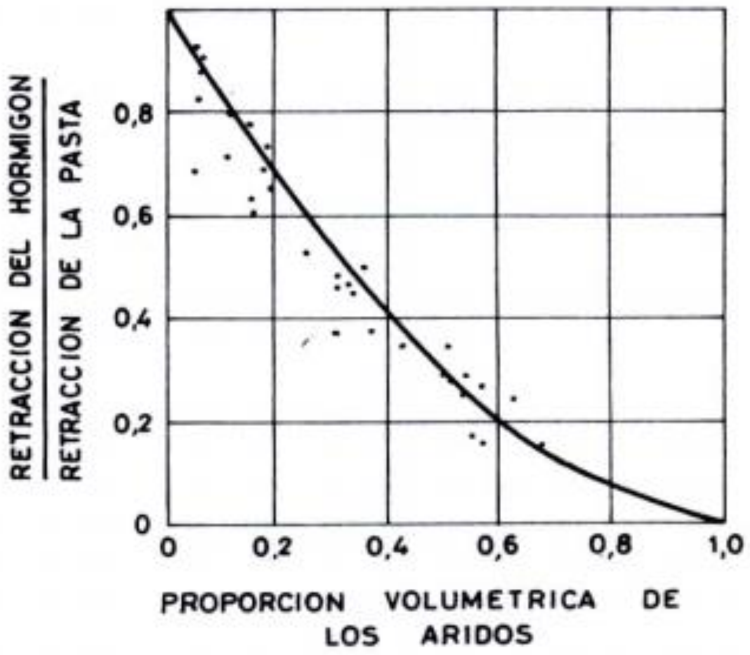


Figure6 Influence of the amount of aggregates of different natures on shrinkage , (Liniers, 2003),.[22]

In relation to the size and distribution of the aggregate according to (Neville A. , 1995)[7], the larger the maximum size, the greater the aggregate content due to its distribution. This decreases the volume of paste, which in turn reduces shrinkage.

However, the presence of fines in concrete significantly increases its shrinkage.

Under normal conditions, concrete contains between 50 and 80% by volume of aggregates.

The maximum size of the aggregate influences the shrinkage, since the greater the volume of aggregate, the less volume of paste, which translates into less shrinkage.

(Garcia Madrid & Horstman , 1985), [23], The nature of the aggregates is also an influencing factor, for example, concretes with light aggregates present greater shrinkage, since the aggregate has a lower modulus of elasticity so it is more deformable and will offer less resistance to shrinkage of the paste (Neville A. M., 2011),[24].

- Cement.

Generally concluded that the composition of the cement can affect the drying shrinkage, however the effect has not been fully determined.

The content of C3A and alkali has been found to have a dominant effect according to (Roper, 1974),[25].

the effect of C3A and alkali content on shrinkage is influenced by the gypsum content of the cement, that is, shrinkage of cements with the same C3A content differs for different gypsum contents. (Pickett, 1974) [26].

- Aggregates.

Aggregates have a limiting effect on shrinkage.

This effect is illustrated in figure 5 and shows that some types of aggregates, if they contract more than paste, significantly increase the contraction of concrete according to, (Welch, 2002),[27]

There is a direct relationship between the shrinkage of an aggregate and its absorption capacity.

That is, aggregates of good quality and low shrinkage are generally characterized by low absorption.

If the aggregate shrinks less than the paste, then the aggregate restricts the shrinkage in fact the shrinkage will decrease as the volume fraction of the aggregate increases.

The effect of the added volume fraction on drying shrinkage is shown in Figure 6.

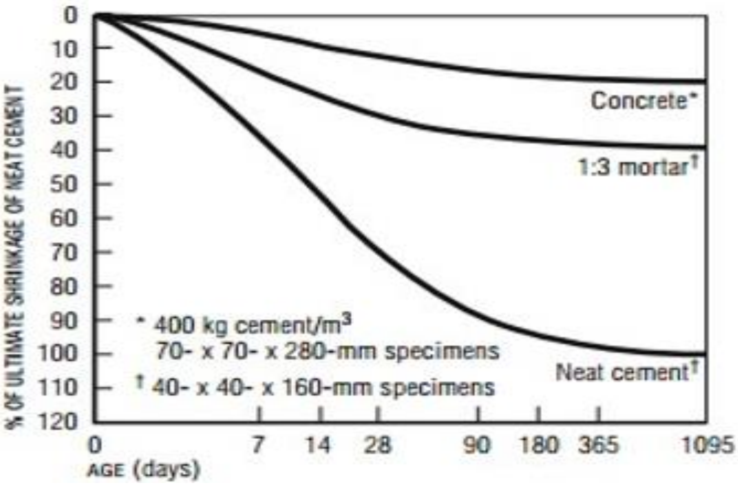


Figure7 Comparative drying shrinkage of concrete, mortar and pure cement paste, with a relative humidity of 50%, (Roper, 1974),[25].

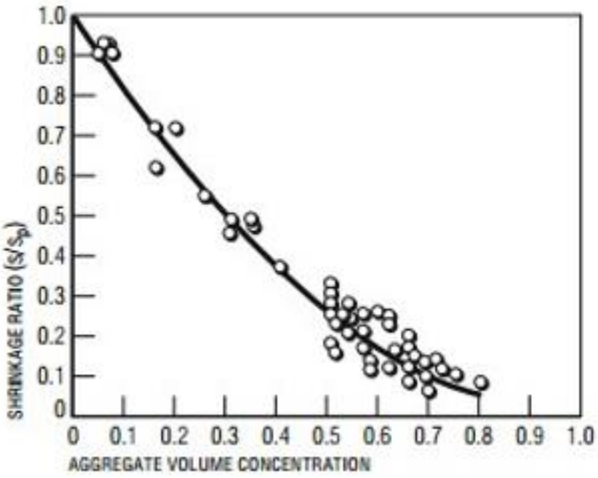


Figure8 Effect of aggregate volume concentration on shrinkage., (Roper, 1974),[25].

* s = shrinkage of concrete

* S_P = shrinkage of the paste.

Figure 5 and Figure 6 illustrate the substantial effect of added restriction on shrinkage. As can be seen, the shrinkage of concrete can be only 20% that of cement paste.

Aggregates of quartz, granite, feldspar, limestone, and dolomite generally produce concretes with low shrinkage, according to , ACI Committee 224R-01 ,[28].

- Additives

Concrete admixtures such as calcium chloride and mixtures such as granulated slag and pozzolans tend to increase the volume of fine pores in the concrete product and hydration of the cement, as well as water-reducing and setting retardant admixtures capable of affecting a better dispersion of anhydrous cement particles in water, Since the shrinkage in concrete is directly associated with the water retained by the small pores in the range of 3 to 20 nm, the concretes contain additives capable of refining the pores.

4.2 factors related to the environment

The external factors that affect the loss of moisture from the concrete are the environmental conditions, the size and the shape of the concrete piece.

They depend on the place where the structure is built, location, function and protection of the concrete elements that compose it, (Cement and Concrete Association of Australia., 2002),.[29]

- Environmental conditions

Relative humidity, wind speed and air temperature will affect the loss of moisture from the concrete surface.

The (NTC3938)[30] explains how any combination of these factors affects the evaporation rate.

Different environmental conditions on opposite sides of a member cause differential drying, hence differences in shrinkage with the possible consequence of deformation. When all other factors are equal, the typical effect of relative humidity variation on concrete drying shrinkage is shown in Figure 7

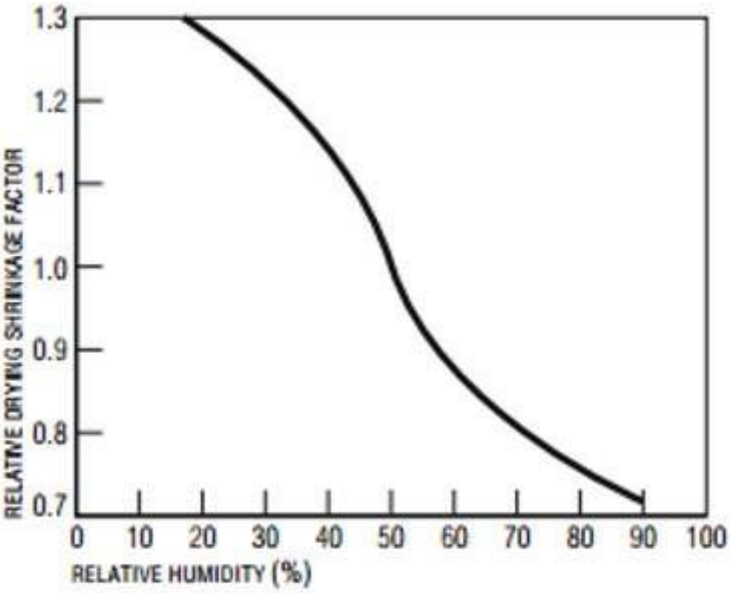


Figure9 Effect of relative humidity on drying shrinkage., (Blakey, 1963)[31].

- Temperature

(Ivan E. Houk & Borge, houghton, 1969),[32] They also carry out a study on the evolution of autogenous shrinkage in specimens with the same characteristics, but stored at different temperatures.

they were subjected to temperatures of 10, 21 and 38ºC.

The results show that autogenous shrinkage increases as the temperature to which the concrete is exposed increases throughout the process.

In addition, despite having spent 3 years of measurement, the deformations do not seem to have stabilized, especially for the samples exposed to higher temperature, which means that increased heat increases the level and duration of the hydration reaction.

4.3Factors related to the method of execution

Among the factors related to the execution method we have the curing period, type of curing, size and shape of the specimen, the age of application of the load, and the magnitude of the load**.**

The thickness of the element significantly affects the shrinkage of the concrete, the thinner elements present a greater shrinkage, when the thickness of the element is very small compared to its other two dimensions, we have higher shrinkage values, which makes the control of the same is of vital importance in surface elements such as slabs or pavements.

In Figure 10 we can see a graph based on the data collected in table 39.7 c of the (EHE-08)[33] where the influence of thickness on the shrinkage values can be seen.

The thinner concretes present a higher shrinkage value than the thicker ones. On the other hand, concretes with higher humidity have lower shrinkage values.

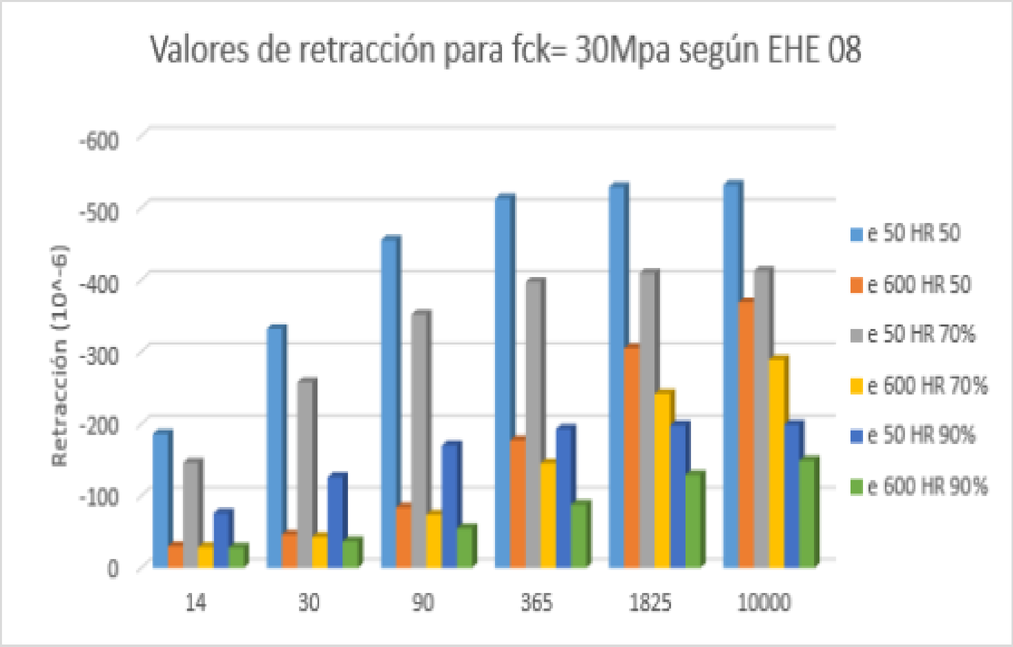


Figure10 Influence of the thickness of the pieces and the relative humidity in the shrinkage of the concrete.[33].

However, in small pieces the speed of development of the shrinkage is higher than in large pieces, and in general it is assumed that the shrinkage is proportional to the inverse of the volume / surface ratio.

According to (Mindess & Young, F.J., 1981)[21], in large pieces, the retraction speed is lower, but the ultimate value is higher than in small pieces.

This inverse relationship between development speed and ultimate shrinkage is related to differential shrinkage within the part.

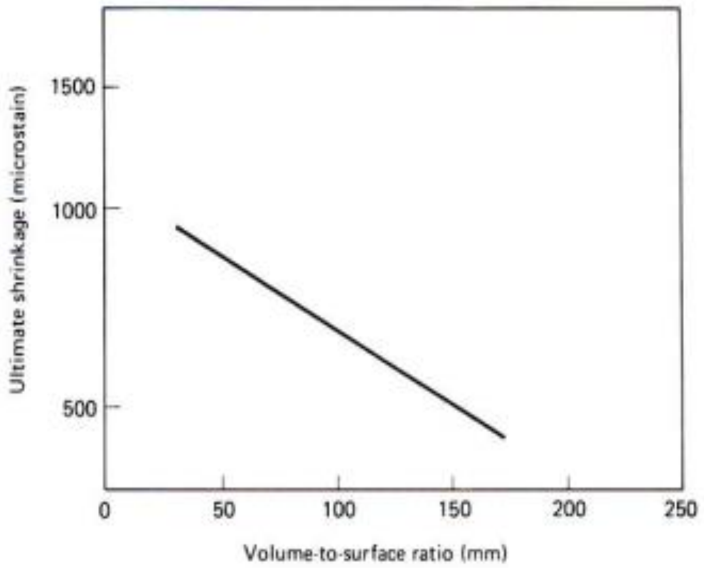


Figure11 Effect of the volume / surface relationship on the ultimate shrinkage of concrete [21].

According to (Neville A. , 1995),[7] the results of various investigations on this aspect are contradictory, but in general, the curing period is not an important factor in shrinkage.

Using steam curing can reduce concrete shrinkage by up to 30% , (Attiogbe & See, Daczko, 2002),[34].

4.4 Methods to control Shrinkage.

4.4.1 Shrinkage compensating concrete

according to (ACI224R-01, 2001) [35],In shrinkage compensating concrete, the expansion of the cementitious paste during the first days of hydration will develop a low level of prestress, inducing tensile stresses in the steel and compressive stresses in the concrete.

The level of compressive stresses developed in the shrinkage compensating concrete varies between 0.2 and 0.7 MPa.

Normally when the water begins to evaporate from the concrete shrinkage occurs. The shrinkage of the concrete will reduce or eliminate its precompression.

The initial expansion of the concrete reduces the magnitude of any tensile stress that develops due to unrestrained shrinkage.

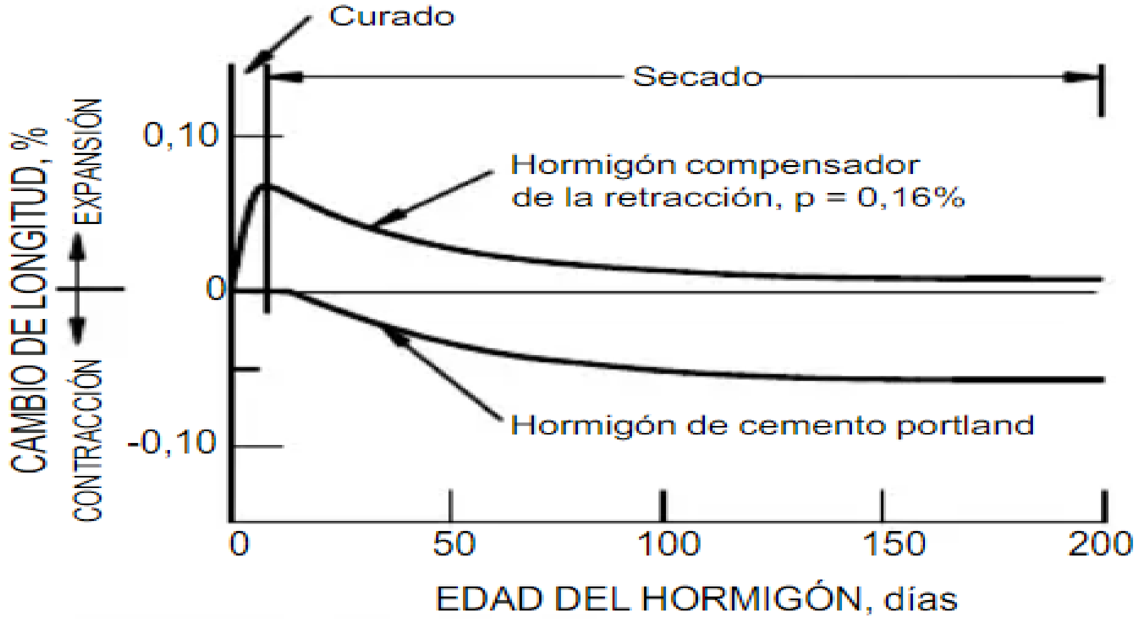


Figure12 Length Change Characteristics for Shrinkage Compensating Concrete and Portland Cement Concrete (Relative Humidity = 50%) (ACI224R-01, 2001)[35].

Figure 12 compares a typical length change history of a shrinkage compensating concrete with that of a Portland cement concrete.

The amount of reinforcement normally used in reinforced concrete made with Portland cements is generally more than adequate to provide the necessary elastic restraint for shrinkage-compensating concrete.

To fully exploit the expansive potential of shrinkage compensating concrete, to minimize or prevent shrinkage cracking of concrete surfaces, it is important to initiate effective and interrupted water curing (wet cover or flooding) immediately after final finishing.

Both spray-wet cured membranes and impermeable covers have been used successfully on slabs over well-saturated subgrades.

4.4.2 Shrinkage reducing additives

Shrinkage Reducing Additives (SRA) have proven to be an effective method of reducing shrinkage cracking in concrete.

They can be based on glycol or on waxes such as paraffin and, generally, they are presented in a liquid state to be added in the last phase of mixing.

This type of additives reduce the evaporation rate in the first hours (Zhanga, Huaxia, & Shuai, 2022) [36], which indicates a lower movement of water from the interior of the mass to the exterior, an increase in capillary pressure, (A.B.Eberhardt & R.J.Flatt, 2019), [37].

According to , (Zhan & Zhi-hai He, 2019),[38] The (SRA) is one of the most readily used admixtures in cementitious material to reduce the shrinkage in early age, and has been adopted in the repairing overlay to enhance its compatibility with concrete , (Liua & Fanga, 2022), [39].

As well , some studies made by (Debondt, Tengfei Fu , & Jason , 2021) [40], (Seng & Shima, , 2005),[41].reported that SRA can reduce the wetting and sorptivity moisture diffusivity of some materials, which improve the durability of concrete under humid conditions

According to (Chan & Chern,, 2005)[42] SRA is a chemical admixture based on neopentyl glycol, or other similar products which reduce the autogenous and drying and shrinkage the SRA should be (1–2% by mass of cement) .

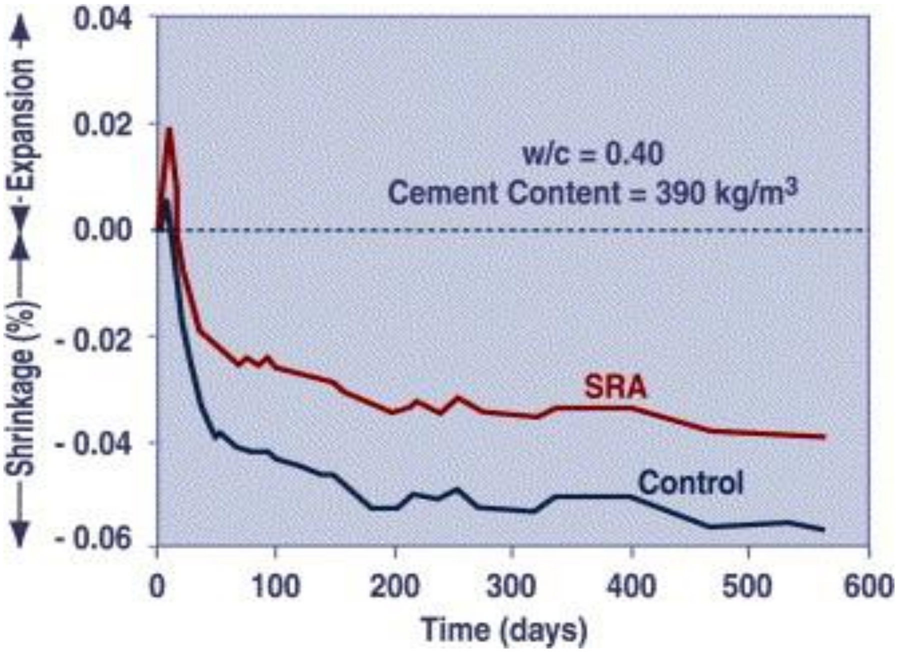


Figure13 Length change as a function of time for concretes with and without SRA, wet cured during the first week [42].

Figure 13 shows a typical shrinkage after 1 week of wet curing in concretes with w/c of 0.40 and content cement of 390 kg/m3 , the red line present the concrete with SRA and the blue ligne without SRA. the presence of SRA reduce the drying shrinkage at the first months by 0.02 to 0.04 % compare to the control concrete .

4.4.3 Fibers

Fibers can control the plastic shrinkage as by stopping and hinder the movement of water through the concrete mass.

however, (Aghaee & H.Khayat, 2021)[43], affirmed that this effect has less impact when the Concrete begins the hardening phase.

The fibers most used to control shrinkage are polypropylene monofilament fibers, which are distributed homogeneously throughout the concrete mass.

These fibers lack structural character but effectively reduce the shrinkage of the concrete. They are generally small in size, with lengths around 12 mm and diameters of 30 µm. This allows a large number of fibers to be dispersed throughout the concrete mass at the same dosage with respect to larger fibers, making it more efficient for solids and liquids to move.

Figure14 Commercial fibers for shrinkage control.

CHAPITER 4 : Tests for the evaluation of shrinkage

- Shrinkage evaluation

The phenomenon of shrinkage can be evaluated in different ways, such as determining the changes in length or the cracks it causes.

Although the standard method ASTM C 157 exists, however this method only evaluates changes in length.

In fact, (Chopin, Lebourgeois, & Francy, 2003) [44] talks about the need to create new test methods.

In 1989 Paillere made use of a type of specimen whose flared ends were clamped to restrict movement , (Persson, 2005),[45] so that the piece cracked in the center.

In 1990, still without a standard method to evaluate restrained shrinkage, resumed the use of an annular steel mold that causes a uniaxial stress distribution.

Later, this method, although modified, became part of the regulations, becoming a standard test model (Bouzoubaa & Lachemi , 2001)[46].

5.Tests for the evaluation of shrinkage

There are several types and methods to evaluate concrete shrinkage, they are mainly based on the measurement of changes in length, crack opening or its quantity.

These tests are usually accompanied by other complementary measurements, such as the measurement of the plastic seat, capillary pressure, temperature and humidity.

The evaluation of the shrinkage is carried out by comparison with different types of concrete, always starting from a control concrete.

In this way, the effects caused by the different agents added to the concrete can be evaluated.

Retraction tests can be performed by allowing or restricting movement. Shrinkage cracking occurs when the movement of the concrete mass is impeded in any of the directions, this causes traction in the concrete that has not yet acquired sufficient strength to support them.

Since cracking occurs when movement is restricted, restricted shrinkage tests are particularly important, where the size and number of cracks are evaluated.

5.1 Free shrinkage test

The test consists of evaluating the changes in length experienced by a concrete sample without limiting its movement.

For this, prismatic samples are manufactured on non-slip molds in such a way that movement in all directions is allowed.

The measurement of the deformation can be taken in different ways.

Figure 15 shows a type of mold in which stops are embedded in the mass on which displacement sensors are placed, placed horizontally on a sliding surface.

In this type of tests, specimens are manufactured that have two dimensions much smaller than the other two, so that the shrinkage in these two dimensions is negligible. Another method of measurement is to place the specimen vertically with a dial gauge on top so that the shortening of the specimen is measured.

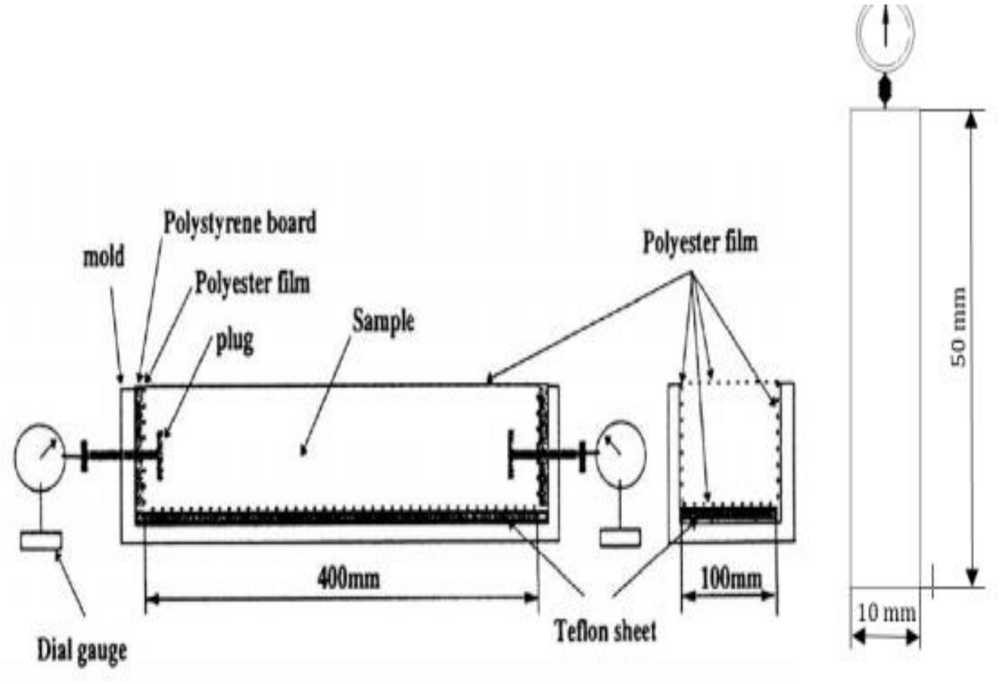


Figure15 (Right) Mold for free shrinkage placed horizontally. - (Turcry, Loukili, , & Haider, 2002)[47]. (Left) Vertical specimen with comparator.

As well the American Society for Testing and Materials have similar test who is high recommended by the Kansas Department of Transportation , the test called (ASTMC157-75, 2017) [48],where 3 concrete three prisms with size of 7.62 cm* 7.62cm * 30.48cm fixed to a dial gauge indicator which is used to measure variation in length to evaluate the shrinkage for both the 7- and 14-day, or other factor effect .

As well other so similar test was made by the European standard (BS EN 12390-16, 2019)[49],

5.2 Restricted shrinkage test

As for tests with constraint of movement, one of the methods that appears most in the literature since the 1980s , (Hammer, Johansen, & Bjontegaard , 2001),[50] is the restricted ring test.

This test is included in the (ASTMC 1581) standard [51] and consists of the manufacture of a concrete ring that will exert a force on a metal ring during its hardening.

This test gives us information on the pressure exerted by the concrete on the metal ring, during its hardening, this pressure is measured by strain gauges placed inside the inner metal ring. Once the crack is created, this pressure ceases, which is reflected in the strain-time graph.

The fissures that appear can be counted as well as their opening.

In Figure 16 shoes the configuration of the ring according to the ASTM 1581 standard.

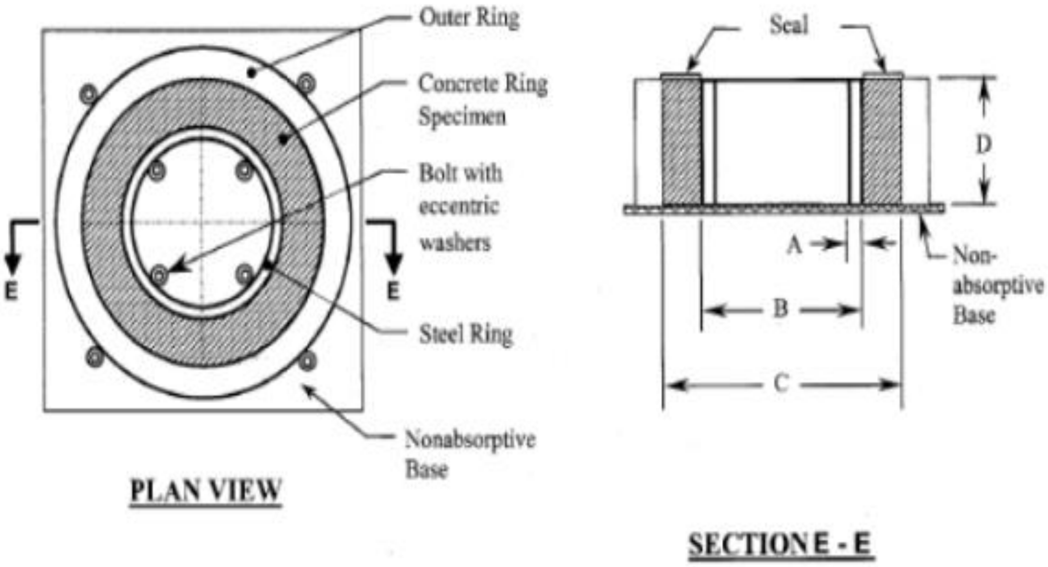


Figure16 Ring according to standard ASTM 1581 [51].

5.3 Plastic shrinkage test

This test is carried out in different ways, the ASTM (C1579) standard, [52] proposes a plastic shrinkage test model, which consists of pouring concrete on a mold with three elevations, two of which are smaller, causing a restriction of movement, while a central one of greater height causes a weaker section that forces the crack to appear in a controlled manner.

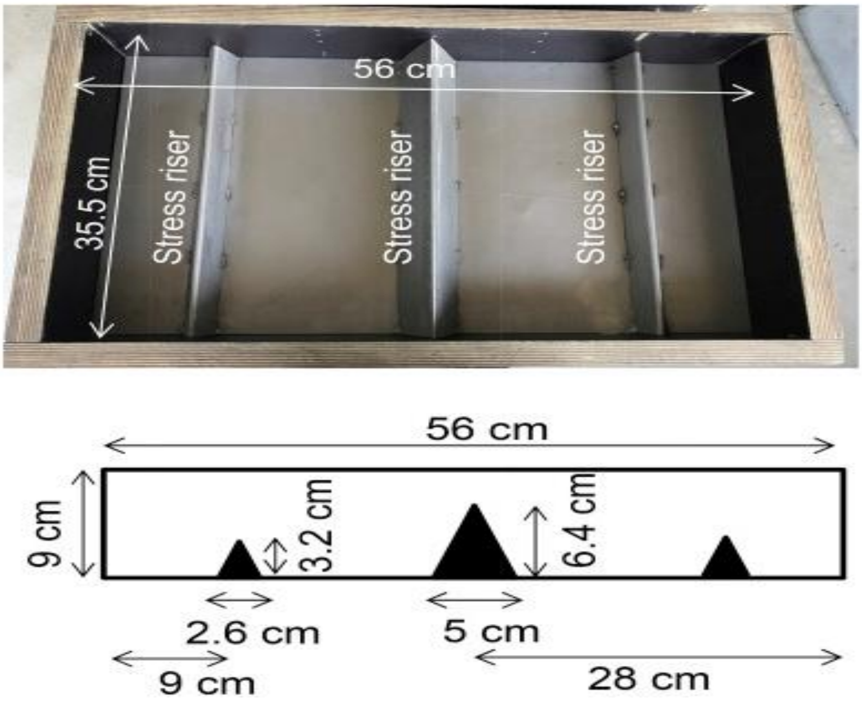


Figure17 Mold proposed in the standard ASTM C 1579 [52].

Other models have a central notch and cause the restriction on the sides of the prism by means of anchors embedded in the concrete mass.

The crack opening can be measured by different methods, which can be the use of Figure 17 gauges, manual measurements, or photographic techniques.

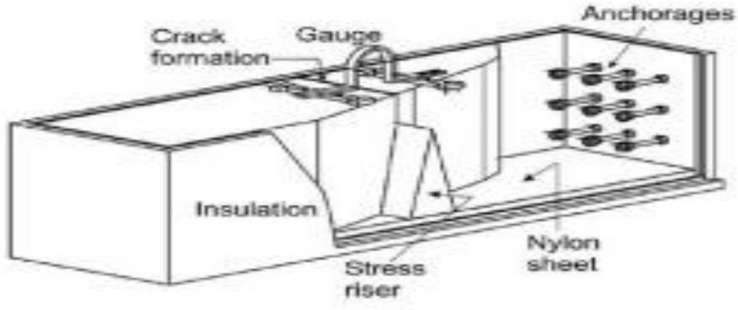


Figure18 Mold proposed in the ASTM C 1579 standard mold with notch and anchors [52]

These tests are carried out in chambers with controlled environmental conditions and a scale is placed under the test tube, which will indicate the rate of loss of mass due to evaporation of water from the sample.

Some authors take measurements of capillary and surface pressure [52].

5.4 Drying shrinkage test

Drying shrinkage is usually evaluated using thin plates. In some cases, a wind flow is generated that affects the concrete specimens and favors drying, keeping the environmental conditions under control at all times.

At the end of the test, measurements of the location and opening of the cracks are taken.

- **Plastic shrinkage test ASTM C 1579 – 06**

This test basically consists of comparing two concrete samples: one made with a control concrete and the other with the mixture to be studied. The molds have measures of 355x560x100mm.

A sheet of metal is placed at the base of the mould, whose plan dimensions coincide with those of the base of the mould, so that it fits perfectly.

The sheet has three elevations: two of them are responsible for restricting the movement of the concrete, caused by shrinkage, and a third, larger, located in the center, forces the appearance of the crack in that place,

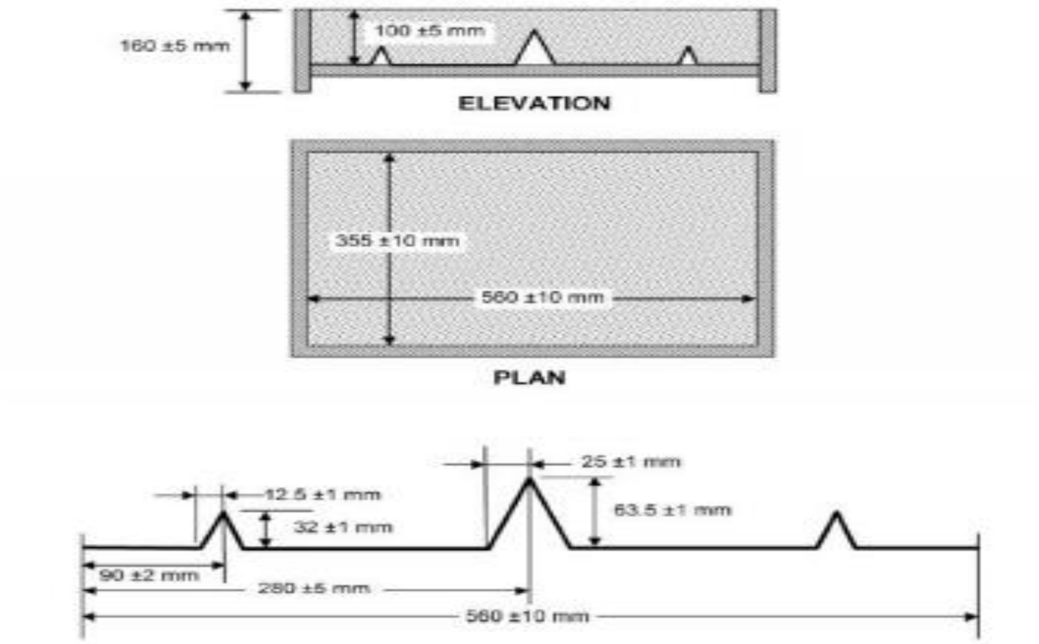


Figure19 Sketch of the mold and the metal base according to the ASTM (C1579) standard,[53].

The entire test is carried out in a drying chamber that provides uniform environmental conditions. The chamber contains inside some fans, a heater, a dehumidifier and a humidifier.

These devices maintain constant environmental conditions, which according to the specification of the standard must be 36±3ºC of temperature and 30±10% humidity.

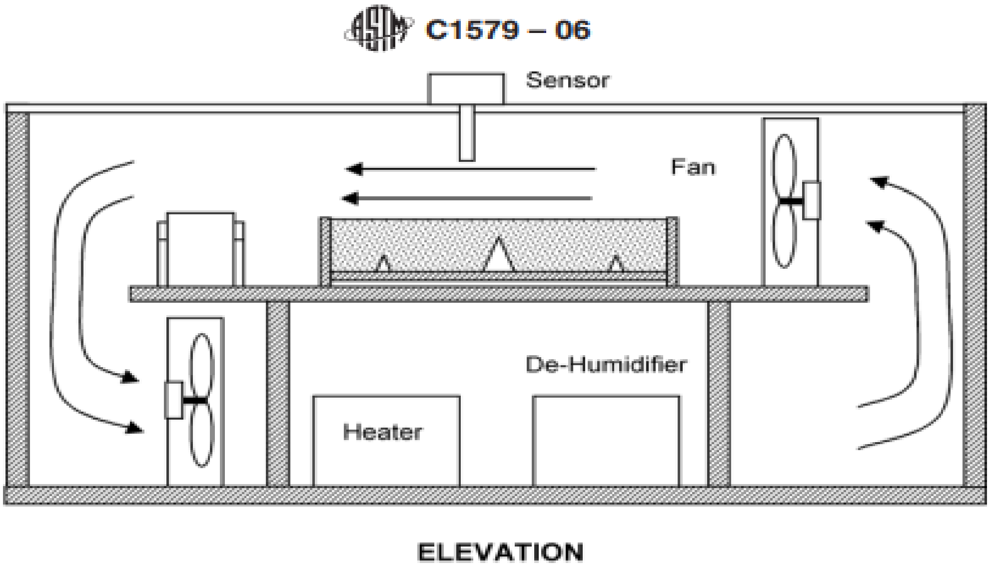


Figure20 Sketch of the chamber proposed by the ASTM C 1579-06 standard,[53].

5.5 Autogenous shrinkage test

The autogenous shrinkage of the concrete is generated by the internal reactions of the concrete, this type of shrinkage occurs during various states of the concrete.

The ASTM (C1698-09)[54] standard proposes a test model for this type of shrinkage, in which corrugated polypropylene molds with low density and little resistance to longitudinal displacement are used.

These elements are filled with the concrete paste to be studied, displacement sensors are placed at the ends and sealed.

To correctly assess autogenous shrinkage, continuous measurements of these displacements are taken.

Figure21 Instruments used for autogenous shrinkage measurement [54].

The unrestricted linear shrinkage of the mortars was measured using corrugated plastic molds with a diameter of 29 mm. and length of 420 mm.

Three identical specimens were prepared for each mortar.

The samples were stored in a climatic chamber with a temperature of 22 ± 1 °C and a relative humidity of 45 ± 5%.

The length of the specimens was recorded every half hour for the first 12 hours after the time setting and then once a day for 28 days.

Reference The length of the samples was measured immediately after the setting time. Consecutive length measurements were used to calculate autogenous strain.

5.6 Summary Shrinkage test

There are several techniques to study shrinkage in concrete, among which we can mention linear specimens with restriction at the ends or with one end fixed and the other mobile; the slab-type specimen where the restraints are perpendicular, and the ring type .

techniques to study shrinkage in concrete, change depending on several factors like unit of countries , type of concrete (mortar, normal concrete , fiber concrete ,percentage of fines in the concrete, the type of shrinkage to measure) but in this work the objective is Divide those techniques to measure concrete shrinkage into classes according to the type of shrinkage and List the advantages , the inconvenient of every technology

- ASTM C 1581

This test method is applicable to mixtures with aggregates 0.5 in. [13 mm] maximum nominal size or less.

This test method is useful in determining the relative probability of early cracking of different cementitious mixtures and to aid in the selection of cement-based materials that are less likely to crack under shrinkage.

The actual tendency to crack in service depends on many variables, including the type of structure, degree of restraint, rate of property development, construction and curing methods, and environmental conditions.

This test method can be used to determine the relative effects of material variations on induced tensile stresses and cracking potential.

These variations may include, but are not limited to, aggregate source, aggregate gradation, cement type, cement content, water content, supplemental cementitious materials, or chemical mixtures.

This test method is not designed for expansive materials.

This method can be used for mortar and concrete.

This method is used for Restrained Shrinkage.

- ASTM C157

This test method covers the determination of changes in length due to causes other than externally applied forces and temperature changes in laboratory-made hardened hydraulic-cement concrete and mortar specimens exposed to controlled conditions of temperature and humidity.

This standard is not intended to address all safety issues, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety, health, and environmental practices and determine the applicability of regulatory limitations prior to use.

This method can be used for mortar and concrete.

This method is used to measure Drying shrinkage principally.

ASTM C157 is used to measures free shrinkage of concrete.

ASTM C157 is easy to operate , economic and allow for continuous measurements, that why this method is one of the most used in the world.

- ASTM C1579

This test method can be used to compare the plastic shrinkage cracking behavior of different concrete mixes containing fiber reinforcement.

This test method compares the surface cracking of fiber-reinforced concrete panels with the surface cracking of control concrete panels subjected to prescribed conditions of restraint and moisture loss that are severe enough to produce the cracking before the final setting of the concrete.

The airflow across the ASTM mould is heterogeneous. In this case, using a wind tunnel is recommended.

The crack reduction ratio defined in the ASTM C 1579 standard is based only on the crack width. Since in some cases it is possible to have shorter cracks, it is better to calculate this ratio based on the crack area instead.

- With use of heater and fan this method can measure drying shrinkage.
- This method can be used for mortar and concrete.

- ASTM C1698

This test method measures the apparent deformation of a sample of sealed cement mortar , including those containing admixtures, various supplemental cementitious materials, and other fine materials, at constant temperature and not subjected to external forces, from the time of testing final fit up to a certain age. This strain is known as autogenous strain.

- This method can not measure drying shrinkage.

- This method can be used just for mortar or cement paste.

- This method can measure early age deformation.

- This method can be expensive.

- This method is so useful for ultra-high performance concrete (UHPC).

5.7 creep

According to (Kumar & Shanagam, 2014)[55], Creep is a time-dependent deformation of concrete under load over a specified period of time, Basically as long term pressure or stress on.

Normally The deformation occurs in the same direction of the force is being applied on the concrete Element .

In general, the Creep doesn’t cause fail in concrete but can produce serious cracks.

The essential influence values are similar to those for shrinkage, with the well-known creep-producing stress having considerable effects on the creep strain.

Special attention must be paid to the duration of the load, the moment of application of the load and the scope of the actions.

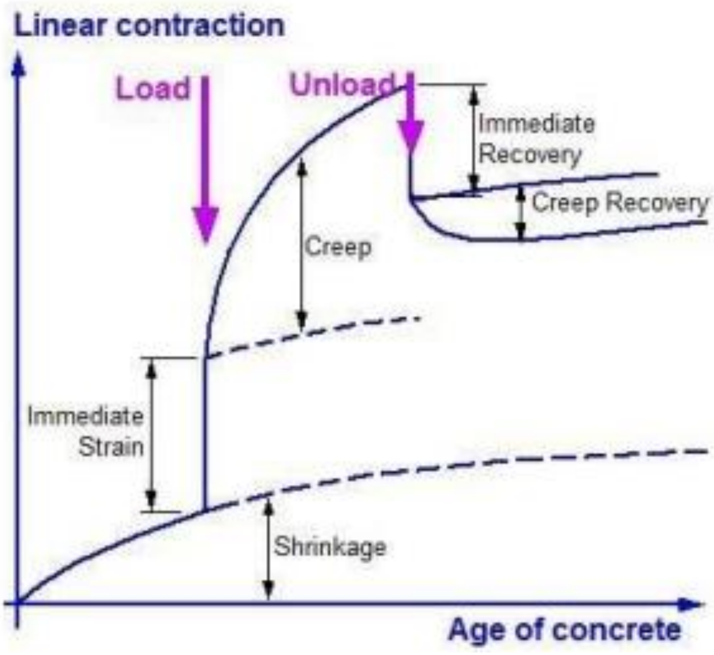


Figure22 Elastic and creep deformation of mass concrete under constant load followed by load removal[55].

Chapter 5 Concrete Shrinkage Estimation Models

6. Shrinkage estimation models

Estimating shrinkage realistically is an important aspect in the evaluation of concrete structures, to guarantee their durability and behavior in service.

An erroneous prediction of this phenomenon can produce excessive deformations and cracking.

These pathologies are perhaps the most frequent problems of structures.

Although it is difficult to estimate concrete deformations precisely, since this phenomenon is the result of various physical processes, which in turn are affected by numerous variables, over the years several models have been developed to calculate concrete shrinkage.

All these models are empirical, they reflect some of the physical mechanisms of these phenomena and have been calibrated with laboratory tests or on real models.

The most common models are those included in the different codes and regulations, but there are also other models developed for calculating shrinkage and creep.

They all vary in complexity and calculation accuracy, The models used in this work that come from regulations are ACI 209-92, CEB-FIP 90 and Eurocode EC-2, The Bazant B3 models , the Lockman and Gardner GL2000 , Sakata model and MC2010.

6.1 Introduction

Shrinkage has complex mechanisms involving many interrelated factors, and there is no single theory which can fully explain these mechanisms.

This studies is essential as a basis for shrinkage models.

The ACI 209-82 is the current standard code model recommended by the American Concrete Institute, and is accepted by building codes in the United States.

The CEB-FIP 90 model is recommended by the CEB-FIP model code 1990 (Euro-International Committee for Concrete and the International Federation for Prestressing).

The B3 model is based on consolidation, has a clear physical background, and considers most of the internal and external factors that affect shrinkage .

The GL 2000 model is a modified Atlanta 97 model, influenced by the CEB-FIP 90 model, and was developed to correct the negative relaxation at early loading ages

The European standard EN 1992-1-1:2004, Eurocode 2, has been prepared by the committee CEN/TC 250 technician, This regulation is used I all European countries to predict the concrete shrinkage .

The Sakata shrinkage model was developed by Sakata and it is dedicate for the drying shrinkage strain. The presented model was based on several parameters such as member geometry confirmed by Japan Society of Civil Engineers JSCE and represent the east-Asiatic model for concrete shrinkage.

the MC-2010 IS new model of the Euro-International Committee, a pre-normative code of reference in Europe, apart from having substantially changed its formulation with respect to its predecessor the CEB-FIP1990, has a specific section for lightweight concrete as well as a new function for calculation of autogenic shrinkage.

These seven models are the most commonly used shrinkage and creep models for normal strength concrete.

Every mode have several parameters and factors some of them are commune and some others are unique and belong just for that model as well some of the parameters and factors have remarkable effect other not .

To verify the effect of each factor in the shrinkage model this work will study each factor or parameter separately using different value and conserving the other factors to verificate the efficacity of it in the shrinkage prediction model.

6.2 GL2000 Model

The GL2000 model developed by (Gardner & Lockman, 2001)[56],is a modified version of the GZ model proposed by (Gardner & Zhao, 1993)[57].

This model was developed as a practical "office" method for calculating shrinkage and yielding of structures in the design phase.

One of the characteristics of this model is that it requires few variables for its calculation, and that it is relatively easy to use.

This model is applicable to conventional concrete with an average strength of less than 82 MPa and a water/cement ratio between 0.4 and 0.6.

The curing period must be at least one day and the age of the concrete at the loading age must be equal to or greater than the curing period.

The parameters necessary for the calculation are the following:

- concrete age at start of shrinkage, days.
- age of the concrete at the moment of loading, days.
- Relative humidity, in %.
- Average compressive strength of concrete at the age of 28 days, MPa.
- Type of cement.
- Volume/surface ratio of the section

6.2.1 Shrinkage calculation model

The GL2000 model uses the following expression to calculate shrinkage, εsh .

$$\varepsilon_{sh} = \varepsilon_{shu}\beta(h)\beta(t)$$

Where :

εshu : is the ultimate retraction. This parameter depends on the characteristics of the concrete, specifically the compressive strength and the type of cement.

$$\varepsilon_{shu} = 1000K\left(\frac{30}{f_{cm28}}\right)^{1/2} \cdot 10^{-6}$$

Where:

fcm28 : is the average compressive strength of concrete at 28 days, MPa.

K :is a coefficient that depends on the type of cement.

K

K =0.1 for cement type|

K=0.7   for cement type‖

K=1.15 for cement type‖|

β(h) :is the coefficient that takes into account the relative humidity.

$$\beta(h) = 1 - 1{,}18h^4$$

h : is the relative humidity, in decimals.

β(t) : is the coefficient that describes the development of shrinkage as a function of the

time and depending on the geometric characteristics of the piece.

$$\beta(t) = \left(\frac{t - t_c}{t - t_c + 0{,}15 \cdot \left(V / S\right)^2}\right)^{0,5}$$

Where:

tc :is the age of the concrete at the start of shrinkage, in days.

t :is the age of the concrete, in days.

V/S :is the volume/surface ratio, in mm.

6.2.2 Typical shrinkage curves

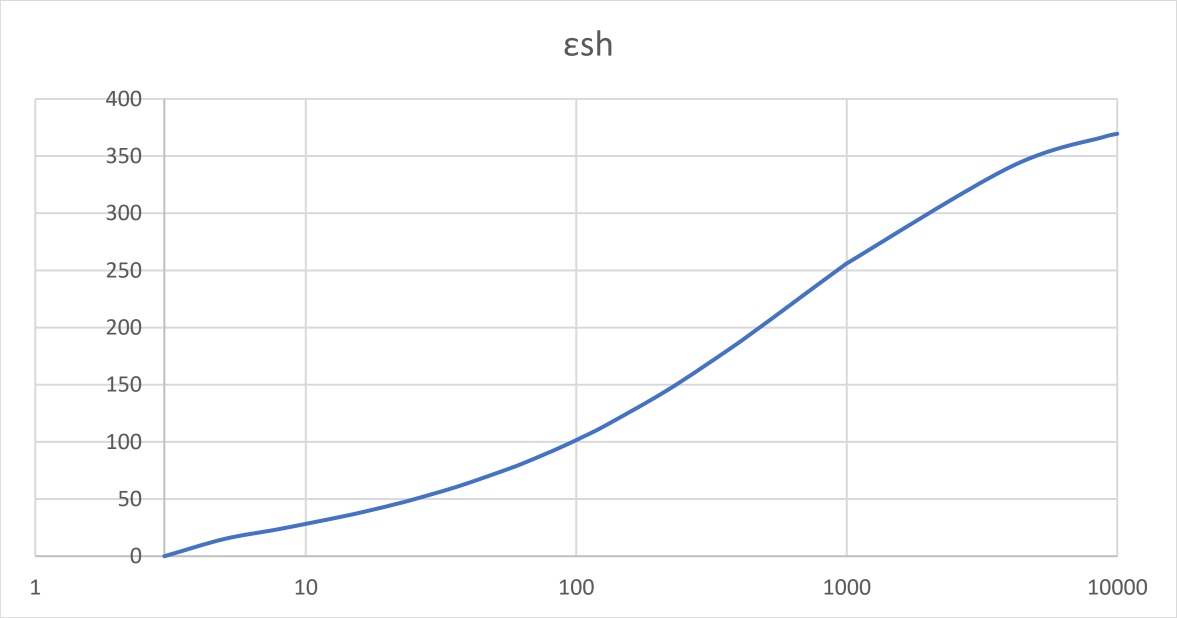


Figure23 Development of shrinkage according to GL2000 model.

En the following work , a comparison is made between the parameters of the GL2000 shrinkage prediction model to see wish factor and parameter have more influence.

6.2.3 Relative Humidity effect

To see the variation of the shrinkage-time curve due to the effect of humidity, every time the percentage of humidity value will be changing , keeping the other parameters constant.

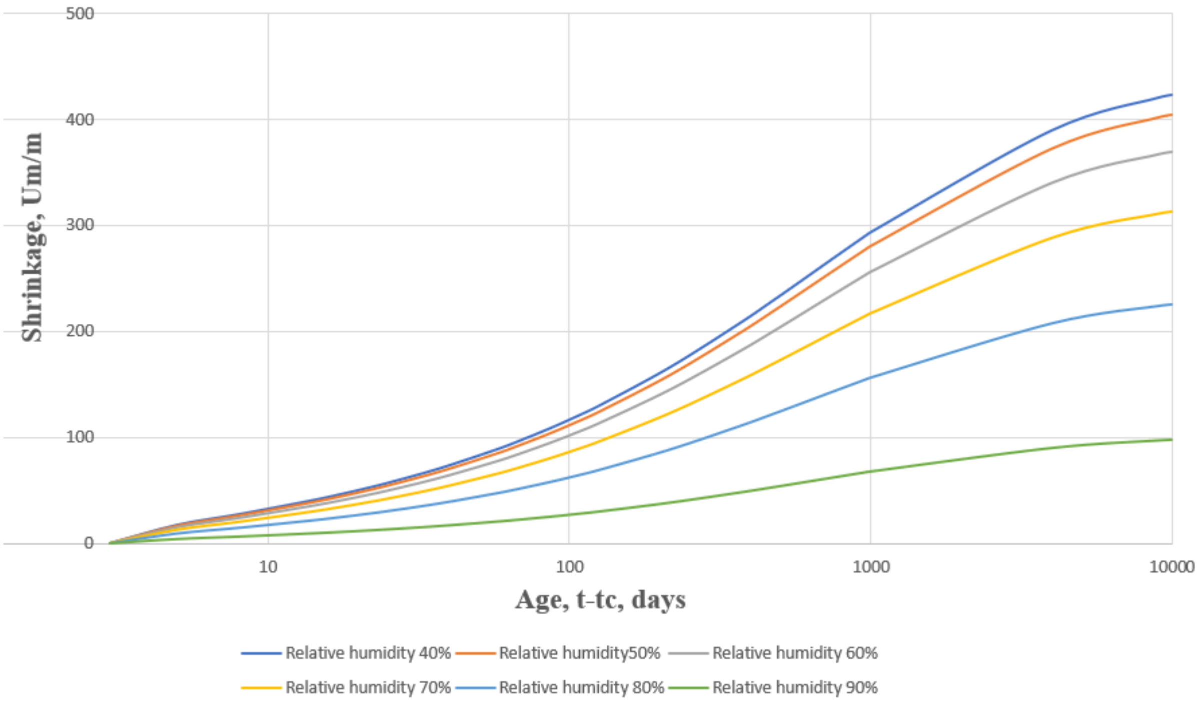


Figure24 Shrinkage development, εsh, with different relative humidity RH40%, 50%, 60% 70% 80% and 90 % (60 MPA, tc =3 days, v/s =95.23 mm).

Due to the figure 2 It is so clear the humidity effect on the shrinkage every time the there is less humidity the shrinkage risk is bigger .

6.2.4 Cement type effect

the Gl 2000 model admits a K value for each type of cement.

The following table will represent K value for every type of cement

K value	0.7	for cement type 1
	1	for cement type 2
	1.15	For cement type 3

Table 1. Factor K value .

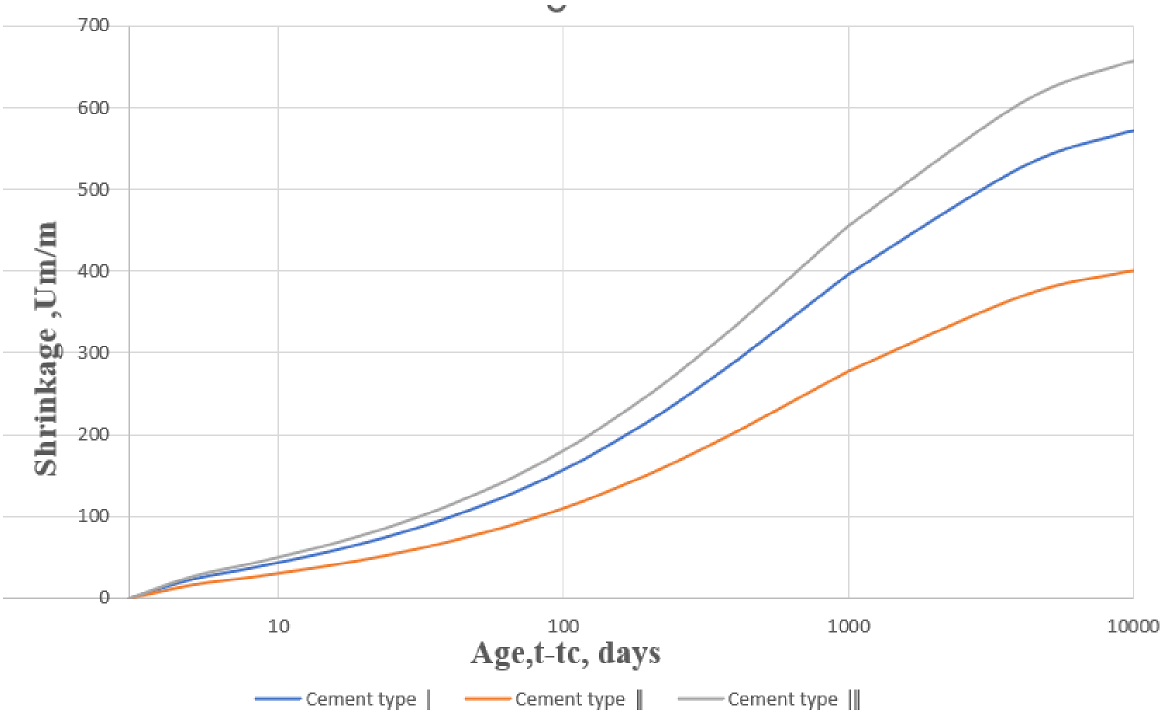


Figure25 Shrinkage development, εsh, with different cement type (60 MPA, tc =3 days, v/s =95.23 mm , RH= 60%).

According to figure 3 Concrete type III cement with value of (K=1.15) shows greater shrinkage, followed by cement type I (K=1.0) and type II (K=0.75).

The shrinkage development start to differentiate between cement type in medium term , but in long term the difference is very remarkable .

6.2.5 Average compressive strength effect

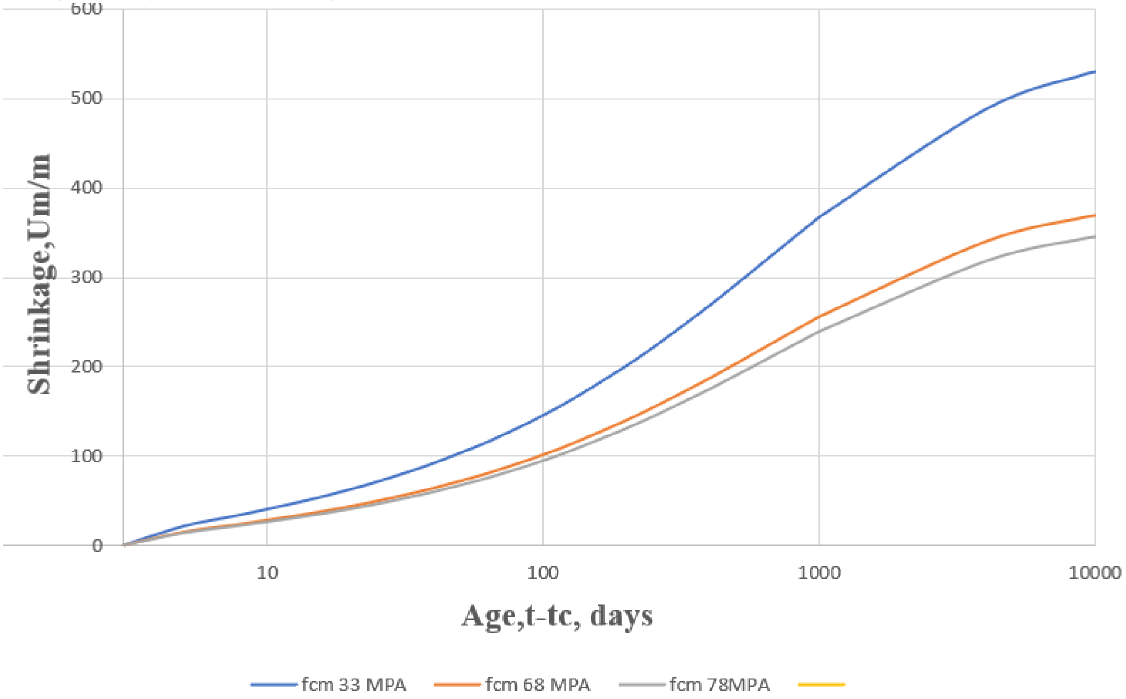


Figure26 Shrinkage development, εsh, with different average compressive Strength (tc =3 days, v/s =95.23 mm , RH= 60%).

*fcm = fck+8 .

According to figure 4 the shrinkage have a remarkable impact in long term but in the short term the shrinkage value is almost same whatever is the average compressive strength moreover the difference between impact of concrete with fcm =58 MPa,fcm =68MPa and fcm=78 MPa is so small .

the shrinkage risk decreases with increase in resistance

6.2.6 Volume/surface ratio effect

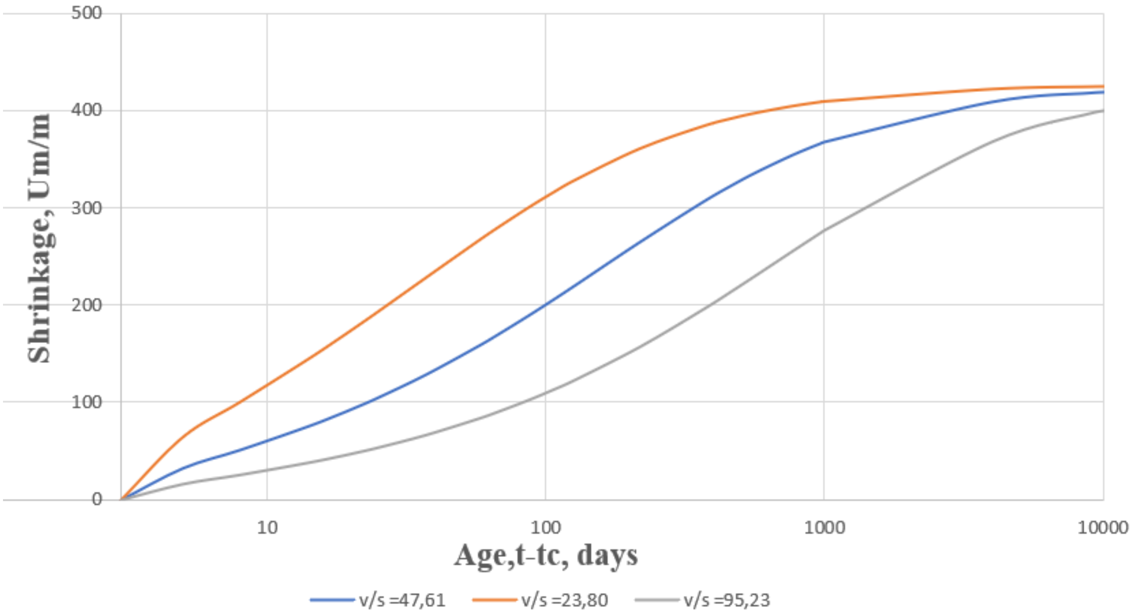


Figure27 Shrinkage development, εsh, with different average volume/surface ratio .
(fcm= 60MPa tc =3 days, , RH= 60%).

β(t) is the coefficient who represent the development of shrinkage as a function of time and depending on the geometric characteristics of the piece.

In fact, the value of β(t) is directly related to the value of the volume/surface ratio.

Unlike the other parameters the volume/ surface ratio have impact in short term from the first days and it is quite remarkable in medium term but in the end what ever is the (V/S) the shrinkage stabilize in almost same value .

6.3 ACI 209R-92

The current model of (ACI209R-92, 1992) [58],is based on the work of Branson and Christianson (1971), with some modifications introduced in ACI 209R-82.

Initially this model was developed for the precast industry, but over the years it has become the reference model for concrete in the US.

This model is also used in Canada, Australia and part of Latin America.

It is a purely empirical model, based on experimental results prior to the year 1968 (Al-Manaseer, 2005)[59]

The model is applicable to normal weight concrete and to lightweight concrete with type I and III cements, and cured under moist or steam conditions.

At its most basic level, the necessary parameters are:

- Age when shrinkage begins.
- Curing method.
- Relative humidity, expressed in decimals, γ
- Volume/surface ratio, or average thickness, mm.
- Air content

This model allows the use of corrective factors that consider the content of fine aggregate, the content of air, the consistency of the mixture, and the content of cement.

This model have been Reapproved 2008.

6.3.1 Shrinkage calculation model

For the calculation of the shrinkage, εsh,t, after 7 days of humied curing, it is used the following equation:

$$(\varepsilon_{sh})_t = \frac{t}{35+t}(\varepsilon_{sh})_u$$

The shrinkage, εsh,t, after 1 to 3 days of steam (vapor)curing is:

$$(\varepsilon_{sh})_t = \frac{t}{55+t}(\varepsilon_{sh})_u$$

Where:

t is the age of the concrete after the initial curing of the concrete.

$$(\varepsilon_{sh})_u = 780\gamma_{sh} \times 10^{-6}\, m/m$$

The coefficient γsh represents the product of all the correction factors

applicable, defined in the following equation.

$$\gamma_{sh} = \gamma_{cp} \cdot \gamma_{\lambda} \cdot \gamma_{vs} \cdot \gamma_{s} \cdot \gamma_{\psi} \cdot \gamma_{c} \cdot \gamma_{\alpha}$$

Where:

ɣcp is a correction factor for moist curing periods other than 7 days.

ɣλ is a correction factor for relative humidity.

ɣvs is a correction factor for the size of the part.

γs is a correcting factor for the consistency of the concrete.

γψ is a correction factor for the fine aggregate content.

γc is a correction factor for the cement content.

γα is a correction factor for air content.

To determine the value of the correction factor for initial curing, γcp, the values in the following table are used

Period of cured, days	correction factor, γcp γcp
1	1,2
3	1,1
7	1
14	0,93
28	0,86
90	0,75

Table 2. Shrinkage correction factor for initial curing .

To determine the value of the correction factor for relative humidity, ɣλ, are used

the following expressions:

$$\gamma_{\text{ʎ}} = 1.40 - 0.010\gamma \qquad for\ 40 < \gamma < 80$$

$$\gamma_{\text{ʎ}} = 3 - 0.030\gamma \qquad for\ 80 < \gamma < 100$$

Where:

ʎ is the relative humidity in percent.

la relación volumen/ superficie para estimar el coeficiente ɣvs.

Where :

$$\gamma_{vs} = 1{,}2\exp(-0{,}00472v/s)$$

v is the volume of the piece in mm^3

s is the section of the part in mm^2

The ACI 209-92 model includes corrective factors for the composition of the mixture.

These factors consider the effect of consistency, percentage of aggregate fine, cement and air content.

In case of not having these data, the ACI 209 indicates that can preside over these factors.

The correcting factor for concrete consistency, γs, is:

$$\lambda_s = 0{,}89 + 0{,}00161s$$

Where

s is the seat of the concrete, in mm.

In the case of SCC, the settlement can not be measured, and it is decided to put the 1 as value.

The correction factor for the percentage of fine aggregate, $\gamma\Psi$, is:

$$\text{Para } \Psi \leq 50\% \qquad \gamma_\Psi = 0{,}30+0{,}014\ \Psi$$

$$\text{Para } \Psi > 50\% \qquad \gamma_\Psi = 0{,}90+0{,}002\ \Psi$$

Where Ψ is the ratio between the fine aggregate and the total aggregate by weight, expressed

in percentage.

The correction factor for the cement content, γc, is:

$$\gamma_c = 0{,}75+0{,}00061c$$

Where

c is the cement content in kg/m3.

The correction factor for air content, γα, is:

$$\gamma_\alpha=0{,}95+0{,}008\alpha$$

Where α is the air content, in %.

6.3.2 Typical shrinkage curves

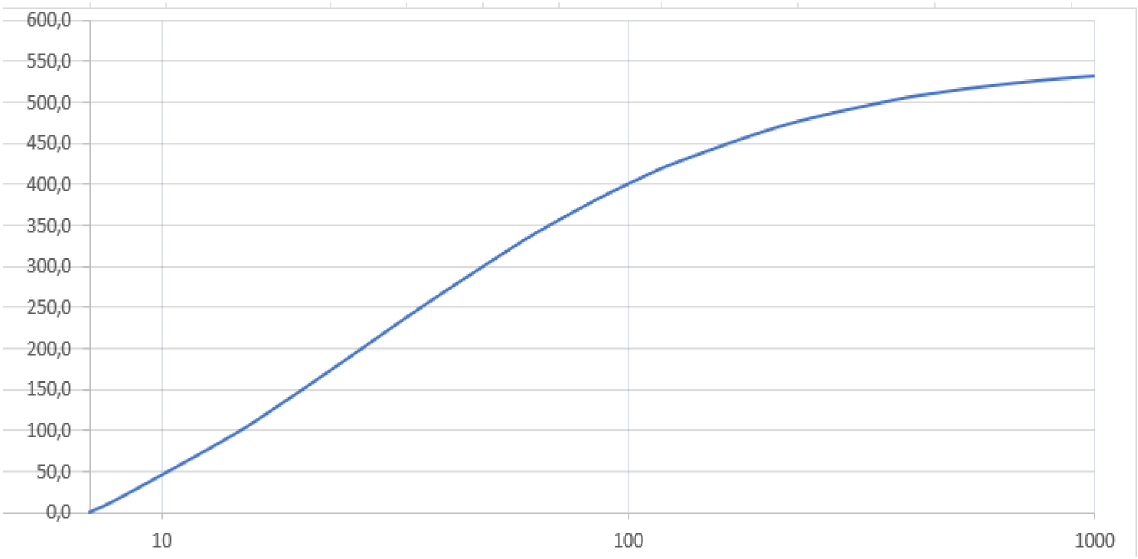


Figure28 Development of shrinkage according to ACI 209R-92 model.

6.3.3 Relative Humidity effect

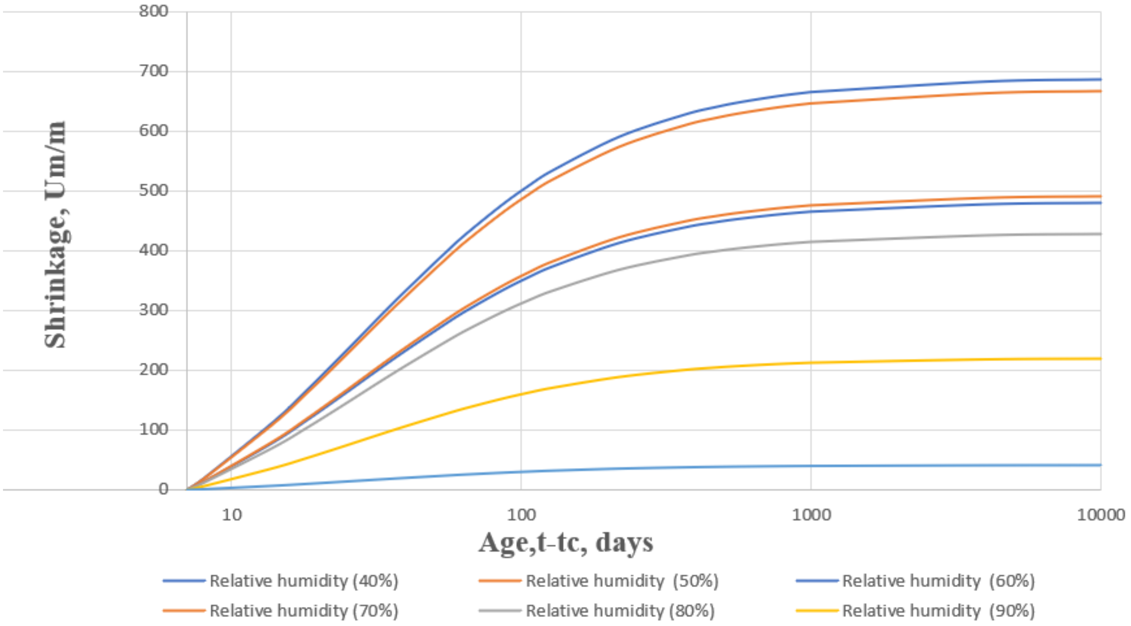


Figure29 Shrinkage development with different relative humidity RH = 40%, 50%, 60% 70% 80% , 90 % and 98% (60 MPA, curing days 7 days, v/s =95.23 mm) according to ACI 209-92.

According to figure shrinkage have remarkable effect special in medium and long term , for relative humidity of 98% the shrinkage risk is so low in the opposite side 40% of relative humidity represent a very high shrinkage risk .

6.3.4 Cement quantity

The ACI209R-92 does not have a constant for cement type or strength value but this model use the cement quantity in kg/m^3 in function instead.

In the next figure represent the effect of different quantity of cement on the concrete shrinkage, keeping other factor with same value except the ones relationated with the cement quantity factor .

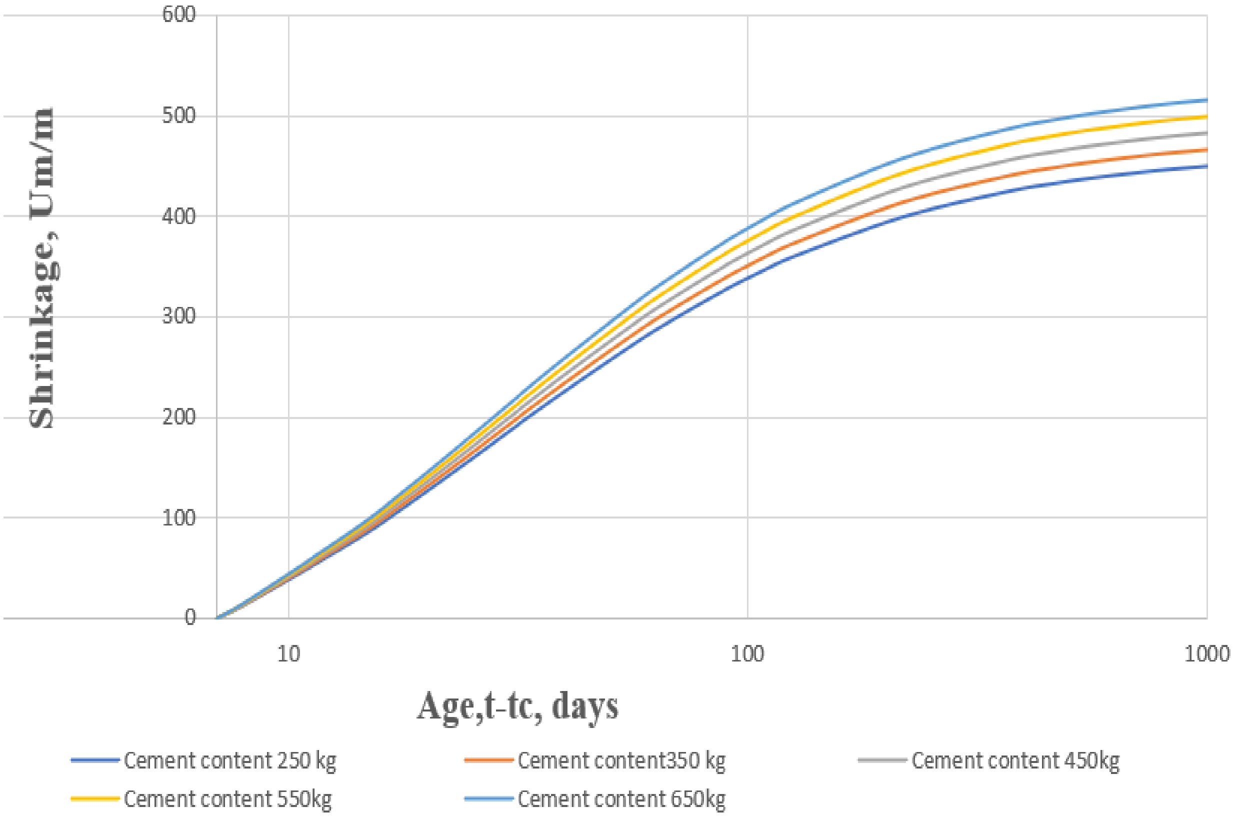


Figure30 Shrinkage development with different cement content according to ACI209-92.

Due to the figure 30 there is not almost any remarkable difference between the shrinkage value which reflect the no importance of this factor in the shrinkage prediction model .

According to the same figure the concrete with low cement content have less risk of shrinkage,what it mean as more the hight cement content in the concrete as more the shrinkage risk .

6.3.5 Effect of Volume/surface ratio of the section.

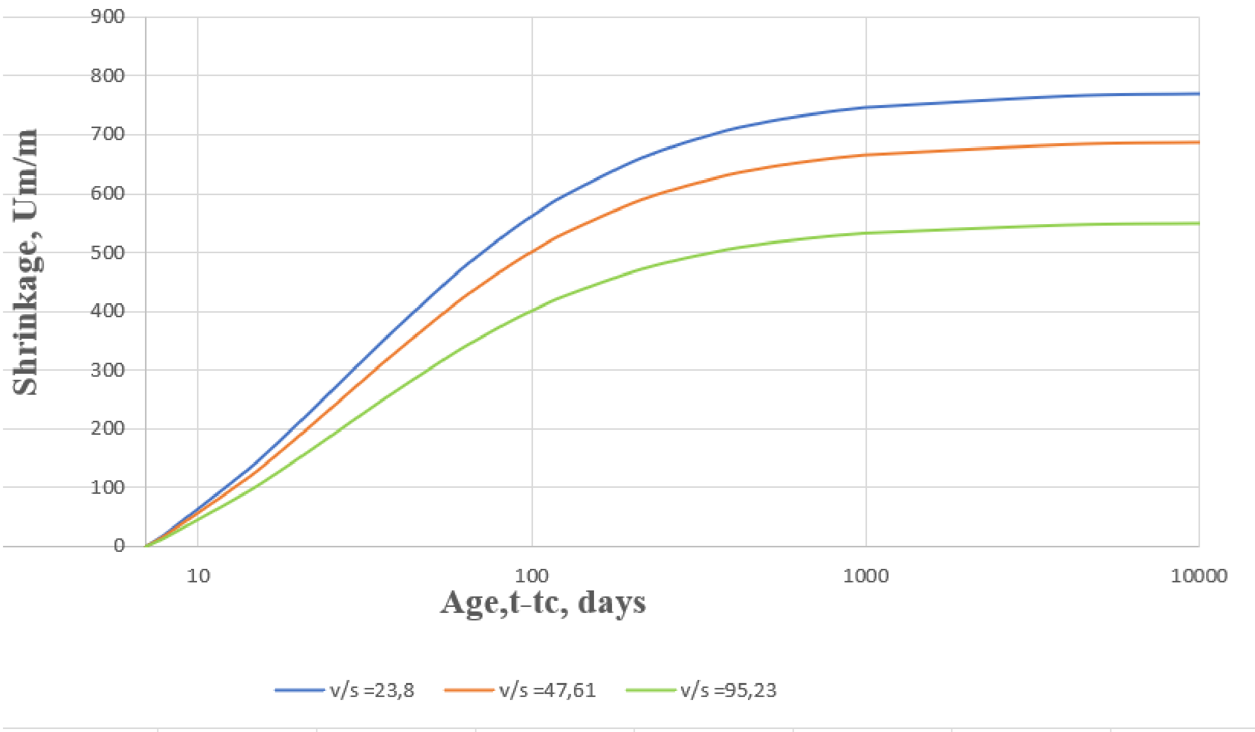


Figure31 Shrinkage development with different average volume/surface ratio .

Figure 31 shows that the volume/surface ratio(V/S) have impact in long term moreover as smaller (V/S)ratio is the shrinkage risk is bigger.

6.3.6 Effect of Fine aggregate content on shrinkage development

The ACI209-92 is the only concrete shrinkage prediction model which use the fine aggregate content as a factor in the shrinkage.

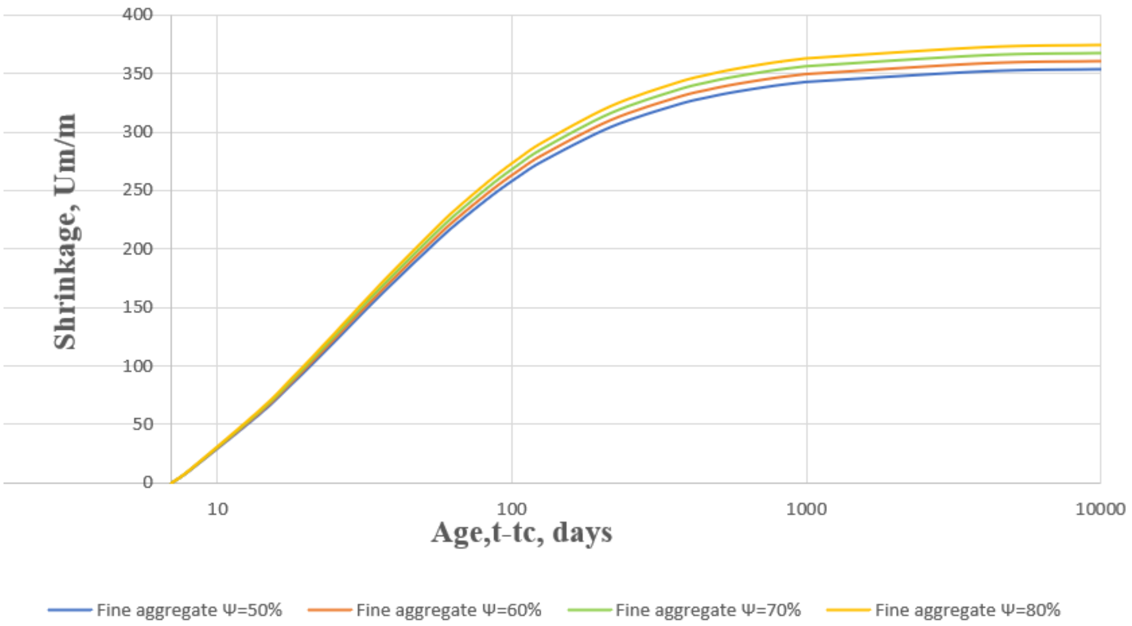


Figure32 Shrinkage development with different fine aggregate according to ACI209-92.

According to figure 10 the fine aggregate have small impact of the shrinkage and there is no difference on the value of shrinkage what ever is the percentage of the fine aggregate what mean that this factor doesn’t have big importance in the shrinkage prediction.

6.3.7 Effect of curing on Shrinkage development

ACI 209-92 includes two expressions that describe the concrete curing type .

The first is for concrete cured seven days in wet conditions which called moist cured concrete and the second is for concrete cured three days with vapor which called steam cured concrete.

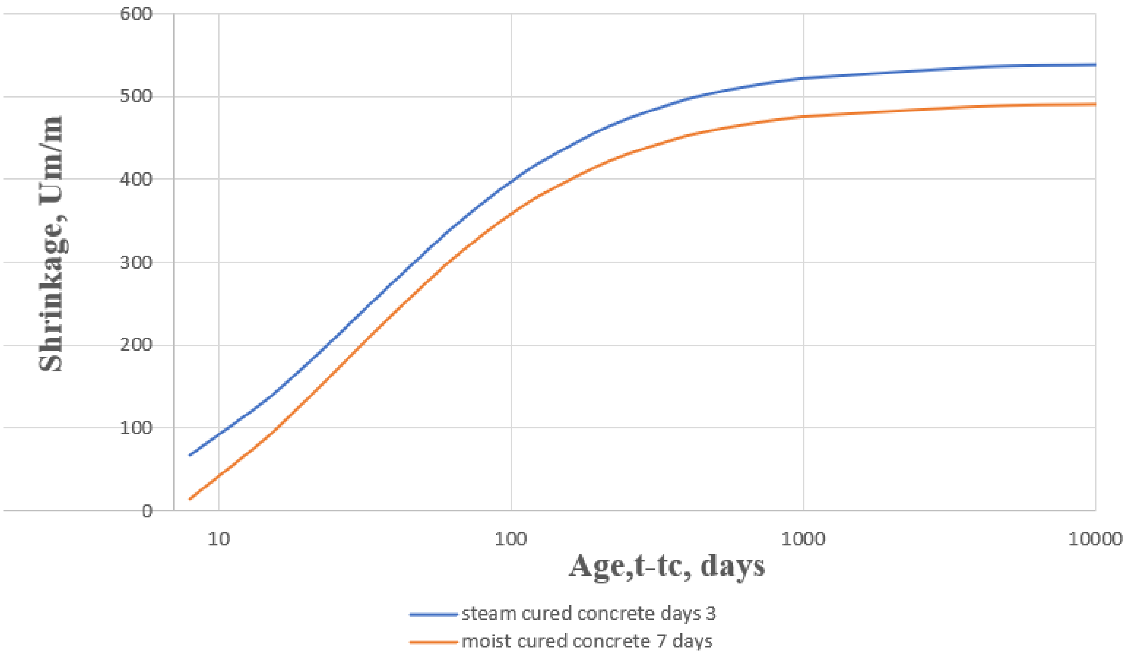


Figure33 Shrinkage development with moist and steam concrete curing according to ACI209-92.

Due to figure 33 the curing factor have impact in long term where moist cured concrete which was cured for 7 days have less value shrinkage then the concrete with steam cured which was cured for 3 days but the difference is so small .

6.4 CEB-FIP 1990

(CEB-FIP1990, 1991),[60],is one of the most widely used international codes, and is considered a reference for many national codes, including the EHE and the Eurocode.

In 1990, the European Committee for Béton (CEB) adopted a new guide to estimate creep and shrinkage.

This guide replaces the previous guide, CEB-FIP 1978.

The CEB-FIP 90 calculation models are valid for ordinary structural concrete, 12 MPa < fck ≤ 80 MPa, and exposed to relative humidity of the environment in the range of 40% to 100% and temperatures from 5ºC to 30ºC.

The effect of temperature in the range 0 < t < 80ºC.

The parameters required in the calculation are:

- Concrete age at start of shrinkage, ts, days.
- Age of the concrete at the moment of loading, t0, days.
- Relative humidity, RH, in %.
- average compressive strength of concrete at the age of 28 days, fcm, MPa.

- Type of cement.
- Average thickness, h, mm.

6.4.1 Shrinkage calculation model

The shrinkage stresses can be calculated using the following expressions:

$$\varepsilon_{cs}(t,t_s) = \varepsilon_{cso} \cdot \beta_s(t-t_s)$$

Where:

εcso is the basic shrinkage coefficient.

βs(t-ts) is the coefficient that describes the development of shrinkage over time.

t is the age of the concrete, in days.

ts is the age of the concrete at the beginning of shrinkage .

The basic shrinkage coefficient, εcso, is calculated using the following expression:

$$\varepsilon_{cs0} = \varepsilon_s(f_{cm}) \cdot \beta_{RH}$$

$$\varepsilon_s(f_{cm}) = \left[160 + 10\beta_{sc}(9 - \frac{f_{cm}}{f_{cmo}})\right] \cdot 10^{-6}$$

Where:

fcm is the average compressive strength of the concrete at the age of 28 days,

MPa.

Fcmo adopts the value of 10 MPa.

βsc is the coefficient that depends on the type of cement:

4	SL slow-setting cements.
5	for normal or fast hardening cements N and R.
8	for RS fast-setting cements.

Table 3. Value of coefficient depending on the type of cement βsc .

The coefficient that depends on the relative humidity, βRH, can be obtained by:

$$\beta_{RH} = -1.55 * \beta_{sRH} \qquad for\ 40\% < RH < 99$$

Where

$$\beta_{sRH} = 1 - \left(\frac{RH}{RH_0} \right)^3$$

RH	es the relative Humidity
RHo	takes the value of 100%.

The development of shrinkage over time is given by:

$$\beta_s(t - t_s) = \sqrt{\frac{(t - t_s)/t_1}{350(h/h_o)^2 + (t - t_s)/t_1}}$$

Where :

h	is the basic dimension of the element, mm. h=2Ac/u
Ac	is the cross section.
u	is the perimeter of the element in contact with the atmosphere.
t_1	takes the value of 1 day.
h_0	takes the value of 100 mm.

6.4.2 Typical curves for shrinkage

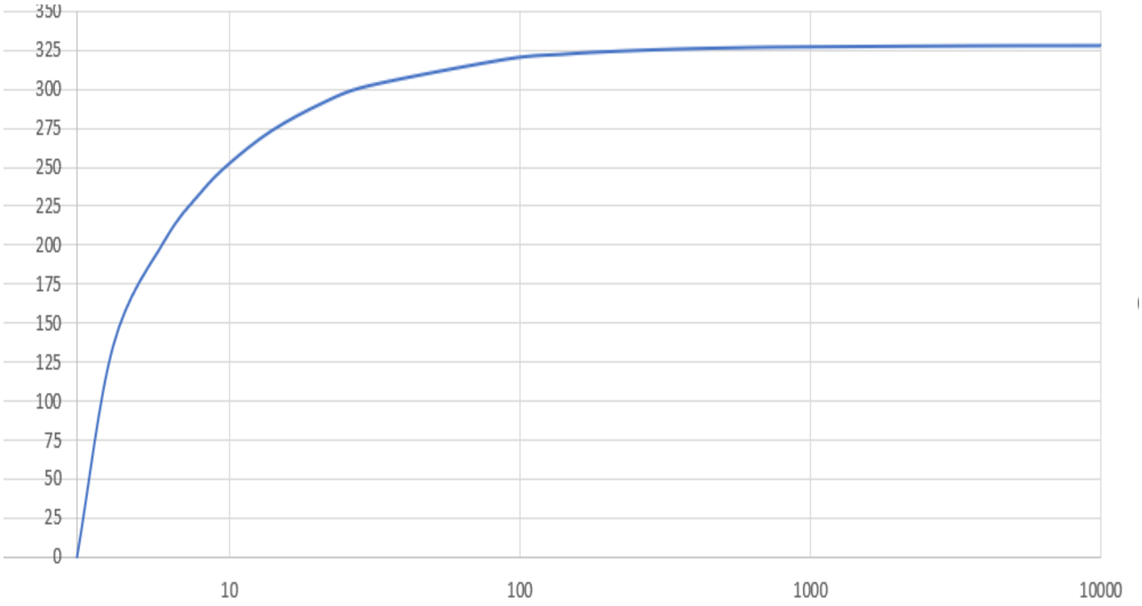


Figure34 Development of shrinkage according to CEB-FIP 1990 model.

6.4.3 Relative Humidity effect

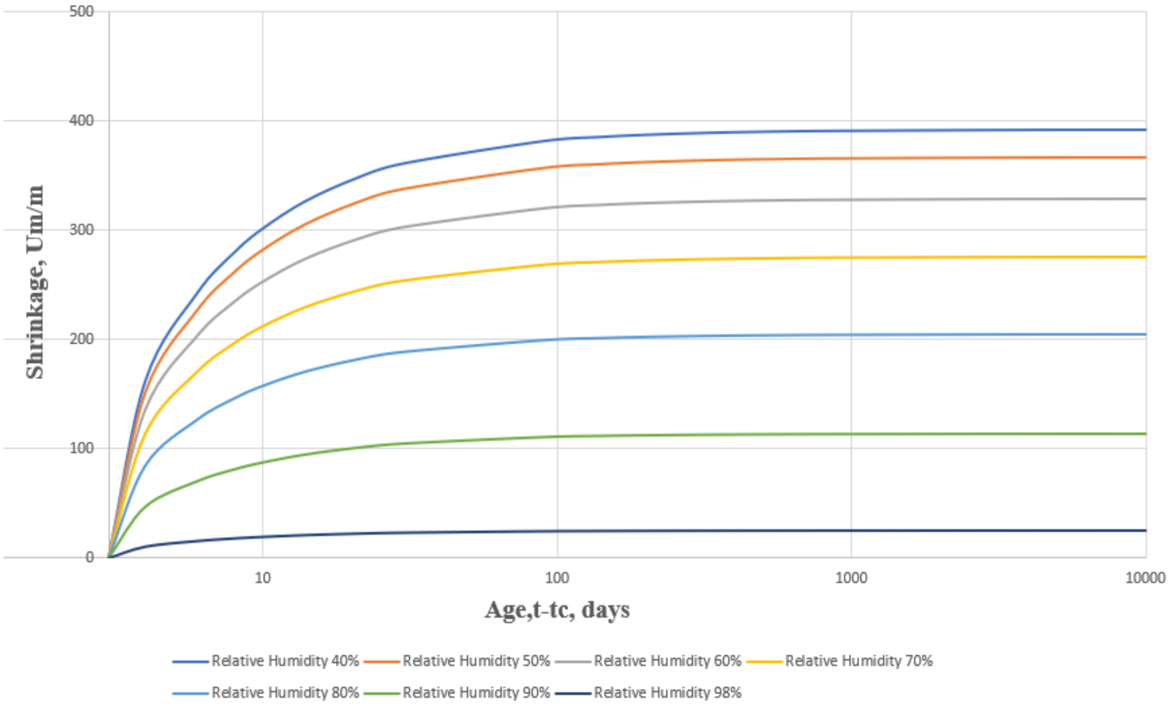


Figure35 Relative humidity effect according to CEB-FIP 1990 model.

Due to figure 35 we can see that the shrinkage is so small at 90% and 98 % of relative humidity unlike at 40% relative humidity where shrinkage risk is high.

The evolution of shrinkage start in short term and continue in medium and long term and the difference in the shrinkage influence is remarkable between the variety of the relative humidity percentage .

6.4.4 Development of shrinkage for concrete with different types of cement

The model CEB-FIP, 1991 corrector factor called β_{sc} for different type of cement depending on the rate of hardening In the following table there is type value of β_{sc}.

type of cement	βsc value
Slow hardening cement (SL) . EC 32.5.	4
Normal hardening cement (N) EC 32.5R; EC 42.5.	5
Rapid hardening cements (R) EC 42.5R.	5
Fast-setting, high-strength cements. (RS) EC 52.5.	8

Table 4. βsc value

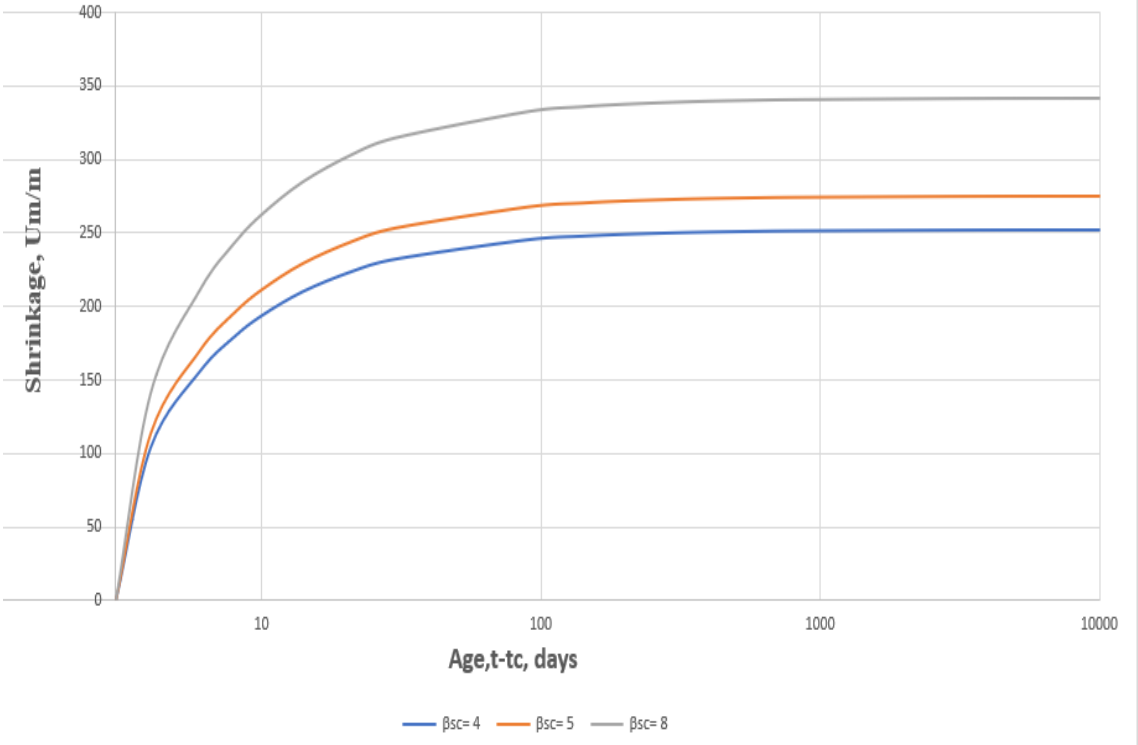


Figure36 Cement type effect on shrinkage according to The CEB-FIP 1990 model .

The shrinkage evolution start in short term and continue in medium term but in large term the evolution stabilize , the difference of shrinkage impact between Slow hardening cement and Normal hardening cement is so small unlike the shrinkage for Fast-setting, high-strength cements which have higher impact and more expose to the shrinkage risk .

6.4.5 Average compressive strength effect

As GL2000 concrete shrinkage prediction model the CEB-FIP 1990 use the Average compressive strength as a factor in the next figure will present the effect of this factor changing with different value keeping the other factors constant .

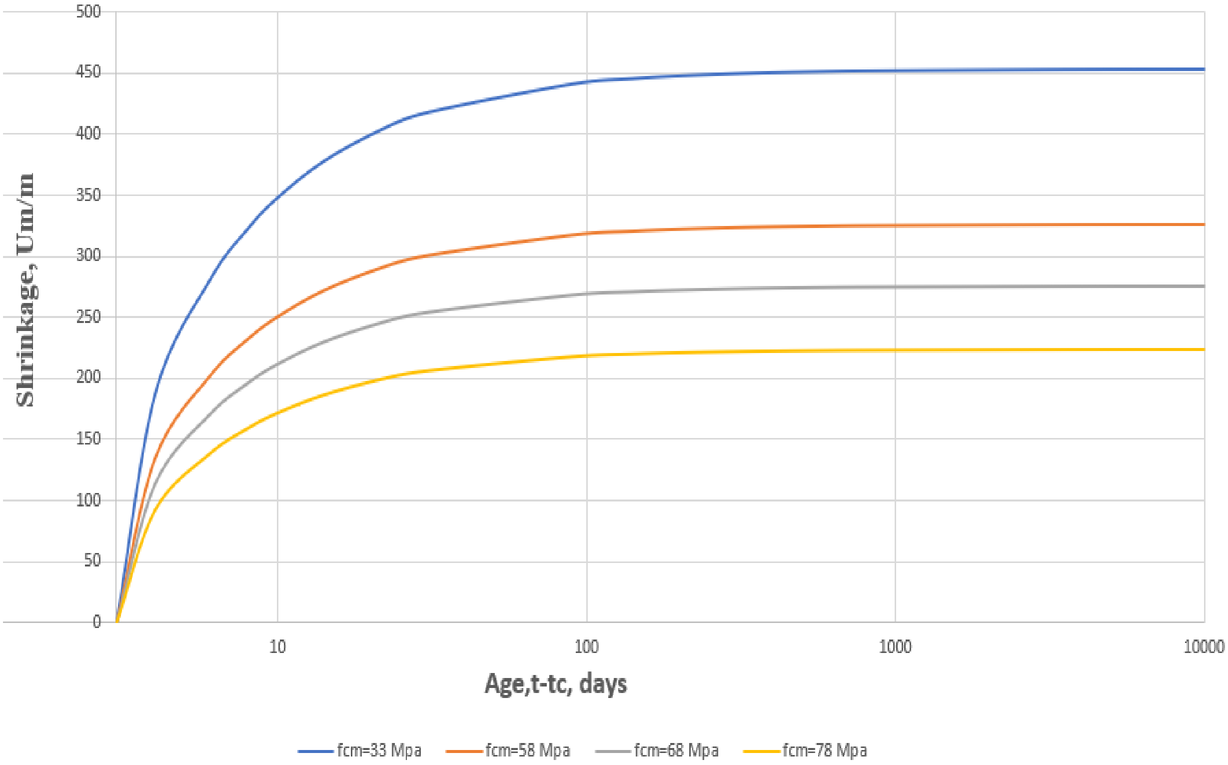


Figure37 Different average compressive Strength effect on shrinkage according to The CEB-FIP 1990 model .

Due to figure 15 the average compressive Strength fcm have remarkable effect on the concrete shrinkage and it start in short term but in large term the shrinkage stabilize as less the fcm value the shrinkage risk is higher .

6.4.6 Effect of Volume/surface ratio of the section

The CEB-FIP 1990 is different of the other models and doesn't admit the regular forma of volume / area but it have another way to measure element size including the time started by calculating the constant "**h "** who represent the the basic dimension of the element then the constant βs(t-ts) who represent The development of shrinkage as a function of time and basic dimension of the element.

To see the effect of the dimension of the element with the shrinkage of the concrete, a comparison is made with different dimensions using the same type of concrete, relative humidity.

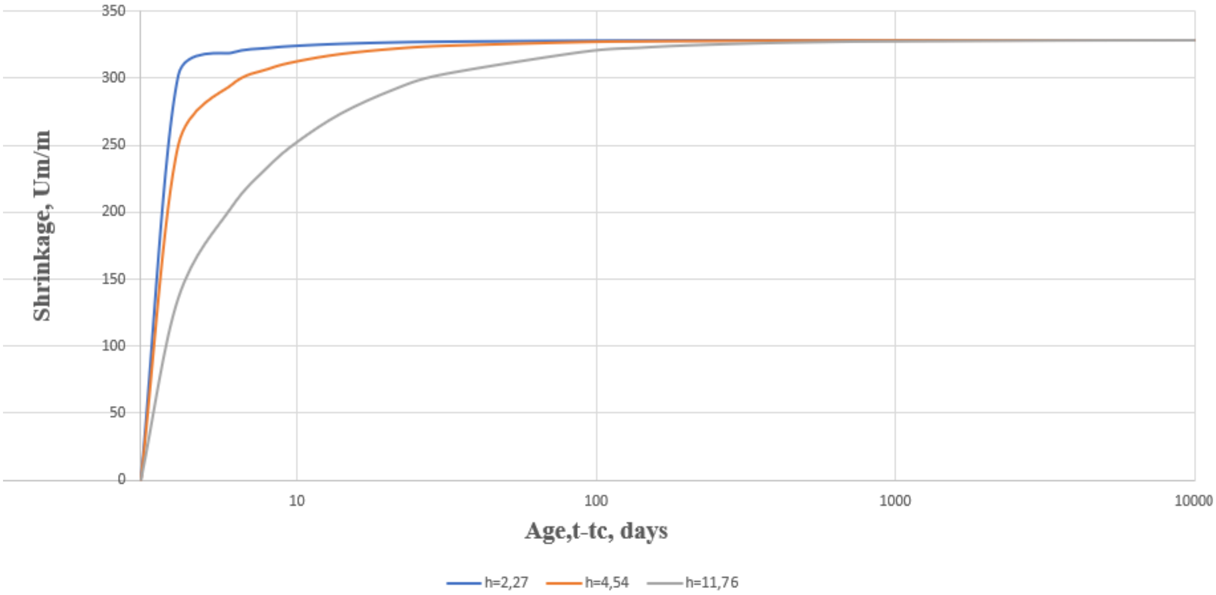


Figure38 Effect of element size (h) mm on shrinkage according to CEB-FIP 1990 model

Due to figure 15 the variation in the shrinkage is not big also whatever is the size of the element the shrinkage get the same value after 100 days .

Unlike the others shrinkage prediction model , The CEB-FIP 1990 model doesn't give big importance for the element size and show that size impact starts at short term more over the as bigger is the element the shrinkage risk is less .

This model is not applicable to concrete subjected to extreme high temperatures or low, very dry climatic conditions or structural concrete of light aggregates.

6.5 Eurocode 2 (EC-2)

The European standard EN 1992-1-1, (Eurocode2),[61], has been prepared by the committee technical CEN/TC 250.

This standard should give rise to national standards and all contradictory national regulations must used .

Spain is one of the countries that is obliged to implement this regulation.

This model have been Reapproved 2004.

The following sections detail the shrinkage estimation models of EN 1992-1-1.

- Concrete age at start of shrinkage, ts, days.
- Age of the concrete at the moment of loading, t, days.
- Relative humidity, RH, in %.
- average compressive strength of concrete at the age of 28 days, fcm, MPa.
- Type of cement.
- Average thickness, h_0, mm.

6.5.1 Shrinkage calculation model

The Eurocode is the first model that separates shrinkage into its two components:

drying shrinkage and autogenous shrinkage.

The total shrinkage, εcs, is the sum of drying shrinkage and autogenous shrinkage.

The total shrinkage is represented with the following function :

$$\varepsilon_{cs} = \varepsilon_{cd} + \varepsilon_{ca}$$

Where :

εcs is the total shrinkage.

εcd is the drying shrinkage.

εca is the autogenous shrinkage.

The development of drying shrinkage with time, εcd(t),

$$\varepsilon_{cd}(t) = \beta_{ds}(t,t_s)\, k_h\, \varepsilon_{cd,0}$$

Where :

εcd,0 is the basic drying shrinkage. It is calculated using the following expression:

$$\varepsilon_{cd,0} = 0,85\left[\left(220 + 110\cdot\alpha_{ds1}\right)\cdot\exp\left(-\alpha_{ds2}\cdot\frac{f_{cm}}{f_{cmo}}\right)\right]\cdot 10^{-6}\cdot\beta_{RH}$$

βRH is factor of relative humidity :

$$\beta_{RH} = 1,55\left[1-\left(\frac{RH}{RH_0}\right)^3\right]$$

RH is the relative humidity of the environment, in %.

RH0 is constant and admit the value of 100%.

αds1 and αds2 are coefficients that depend on the type of cement.

In the following present the value of αds1 and αds2 for every cement type according to the Eurocode 2 (EC-2) .

type of cement	coefficient **αds1**	coefficient **αds2**
for the cement class S	3	0,13
for the cement class N	4	0,12
for the cement class R	6	0,11

Table 5. Value of α_{ds1} and α_{ds2} according to Eurocode 2.

t is the age of the concrete at the moment considered, t.

ts is the age of the concrete, in days, when drying shrinkage begins

(or swelling). This is normally when the period of cured.

h_0 is the effective size, mm, of the section.

=2Ac/u.

Ac is the area of the section.

u Is the perimeter of the part of the section exposed to drying.

The ultimate drying shrinkage, εcd,∞

$$\varepsilon_{cd,\infty} = k_h\cdot\varepsilon_{cd0}$$

The autogenous shrinkage, εca(t), is a linear function of the compressive strength of the concrete.

$$\varepsilon_{ca}(t) = \beta_{as}(t) \cdot \varepsilon_{ca}(\infty)$$

Where :

$$\varepsilon_{ca}(\infty) = 2{,}5 \cdot (f_{ck} - 10)10^{-6}$$

$$\beta_{as}(t) = 1 - \exp(-0{,}2 \cdot t^{0{,}5})$$

6.5.2 Typical curves for shrinkage

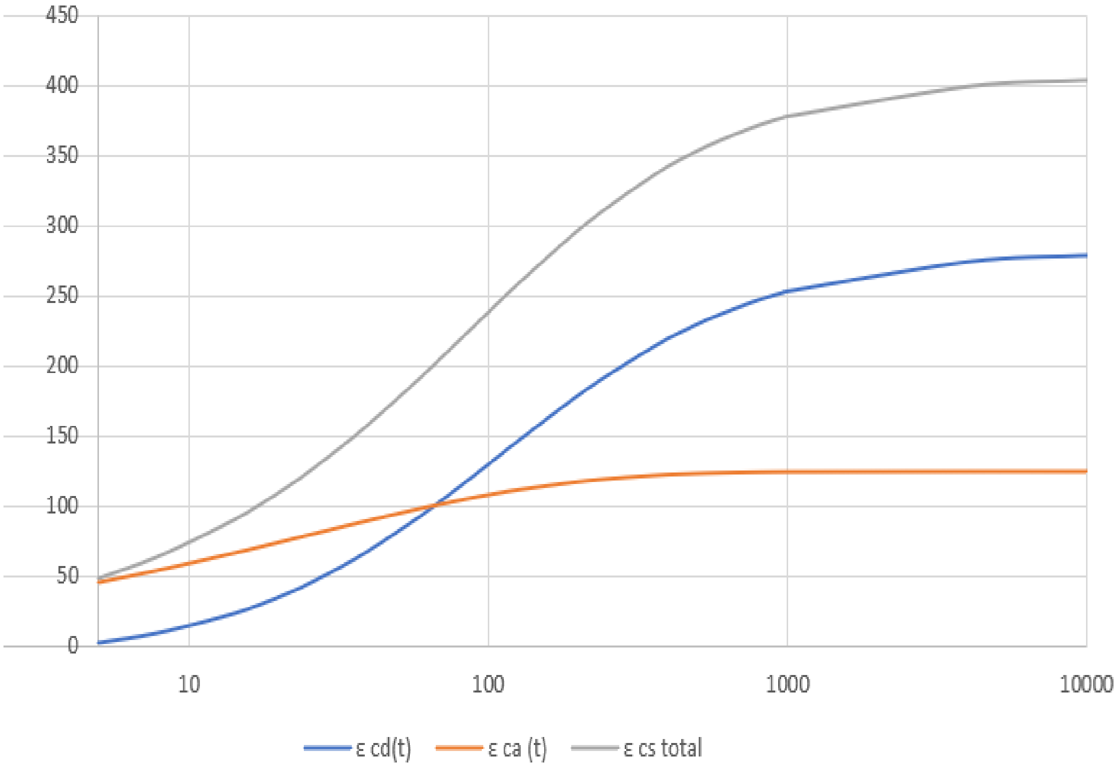


Figure39 Development of shrinkage according to Eurocode 2 model .

En the figure 39 we can see tree curves who represent the autogenous shrinkage, the drying shrinkage and the total .

The total shrinkage is the summatory drying shrinkage and autogenous shrinkage

The autogenous shrinkage is relatively small, because it is related to the concrete strength, 60 MPa in this case .

The Eurocode 2 is the only concrete shrinkage prediction model who measure the autogenous shrinkage

6.5.3 Relative Humidity effect

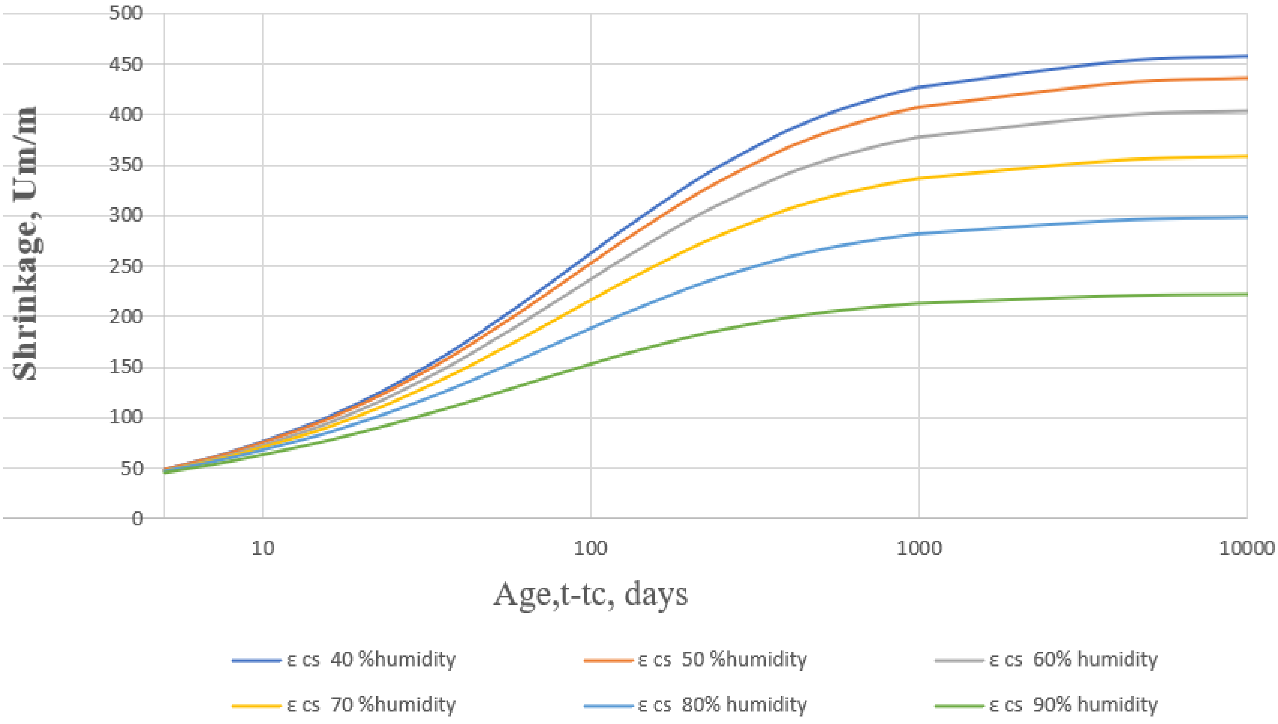


Figure40 relative humidity effect on concrete shrinkage according to Eurocode 2 model.

Due to figure 40 the shrinkage development start from first days but the difference between relative humidity have influence just long term .

6.5.4 Cement type effect

The Eurocode 2 have two coefficient αds1 and αds2 in the shrinkage function to calculate the effect of the cement type .

To see the effect of cement type the value of αds1 and αds2 will be changed keeping the other factors constant.

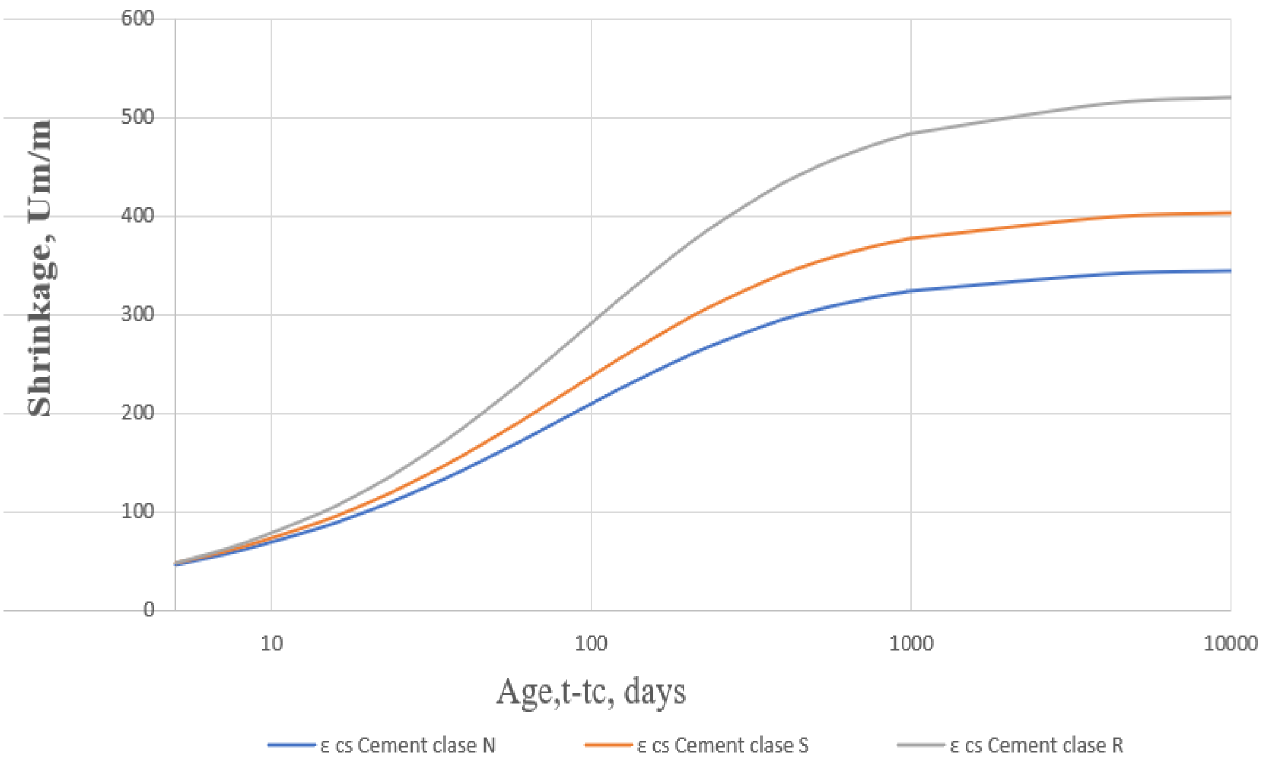


Figure41 Cement type effect on shrinkage according to Eurocode 2 model .

According to figure 41 the cement type factor have influence on concrete shrinkage in long term and the cement clase S is the most Exhibition to the shrinkage risk .

6.5.5 Effect of the effective size

Eurocode 2 model doesn't use the volume /surface as a factor in shrinkage prediction but use the effective size of the section (h_0)instead which used to get the value of the kh the coefficient that depends on the geometry witch used to calculate the drying shrinkage .

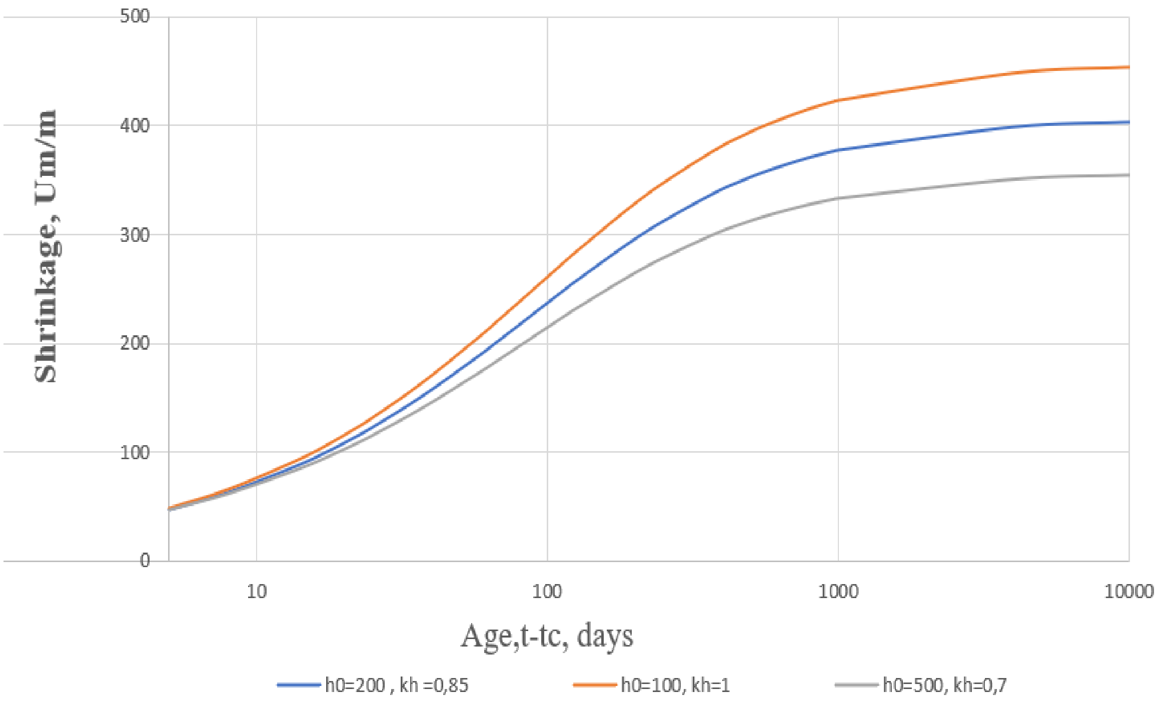


Figure42 Effect of coefficients h_0 and kh on the total shrinkage according to Eurocode 2.

The effective size have remarkable effect on long term as well doesn't have effect on the autogenous shrinkage

The effective size have impact but what ever is the value of coefficients h_0 and kh the shrinkage doesn't change much.

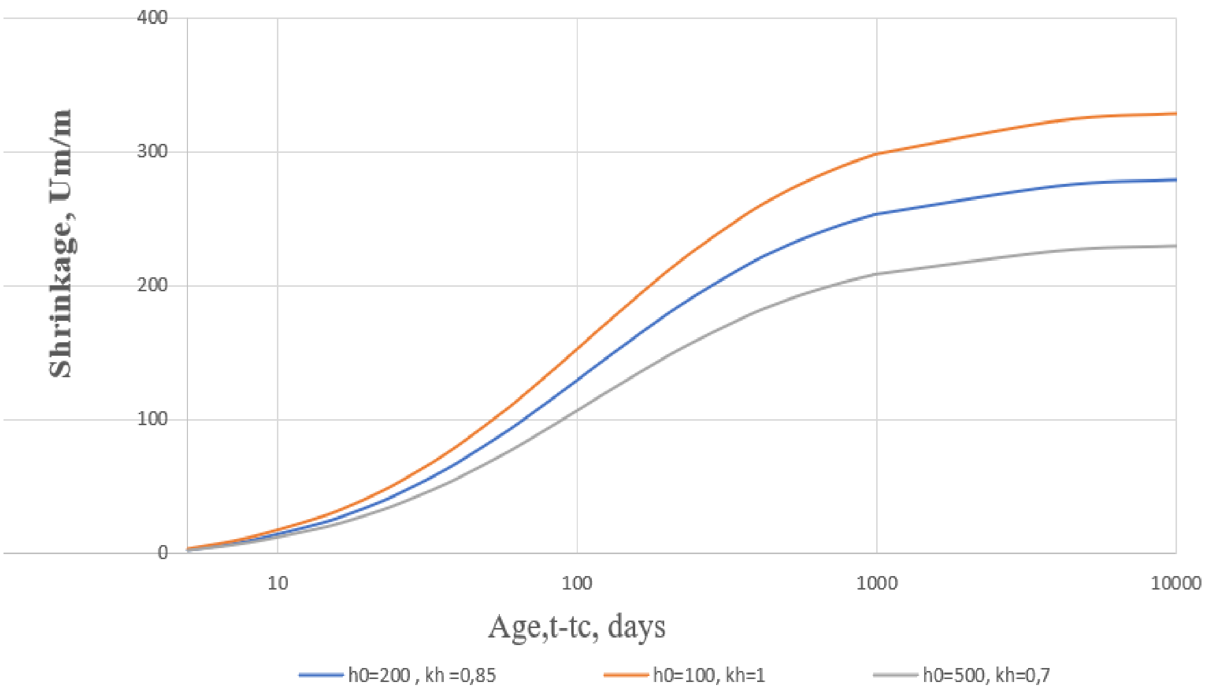


Figure43 Effect of coefficients h_0 and kh on the drying shrinkage according to Eurocode 2.

6.5.6 Average compressive strength effect

In this model the Average compressive strength fcm have been calculated in the draying and the compressive strength in 28 days fck have been used in the autogenous shrinkage

The next figures will present the development of the total shrinkage and autogenous shrinkage change the value of fck , and fcm .

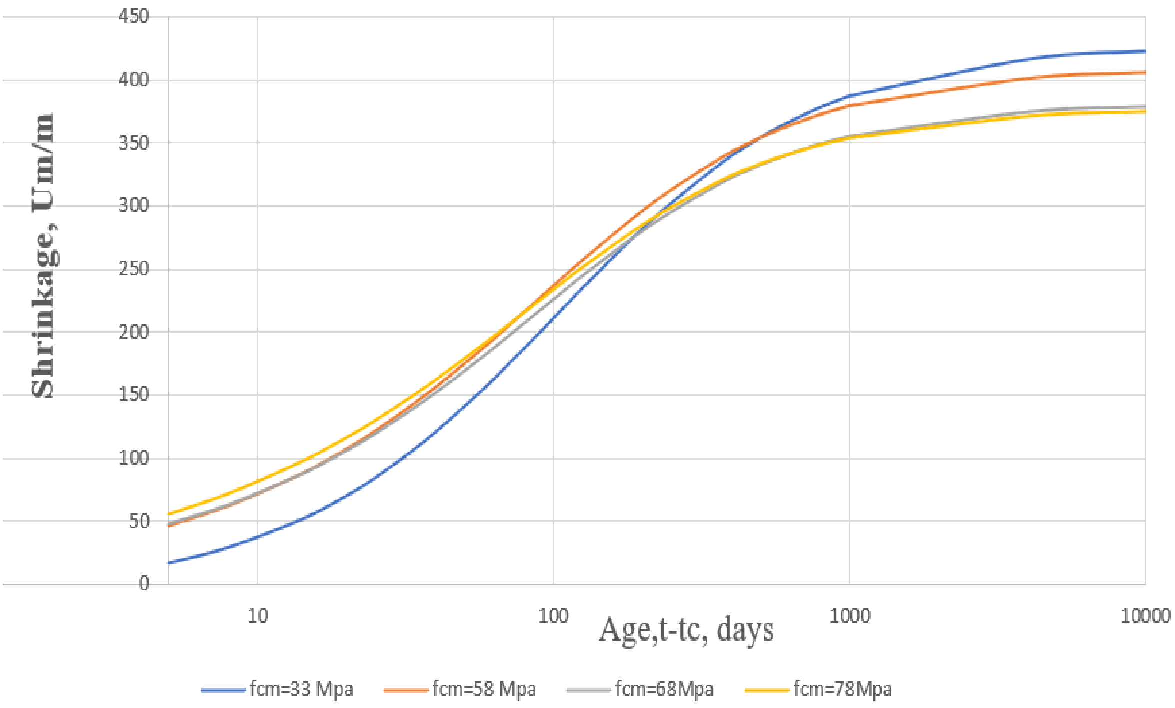
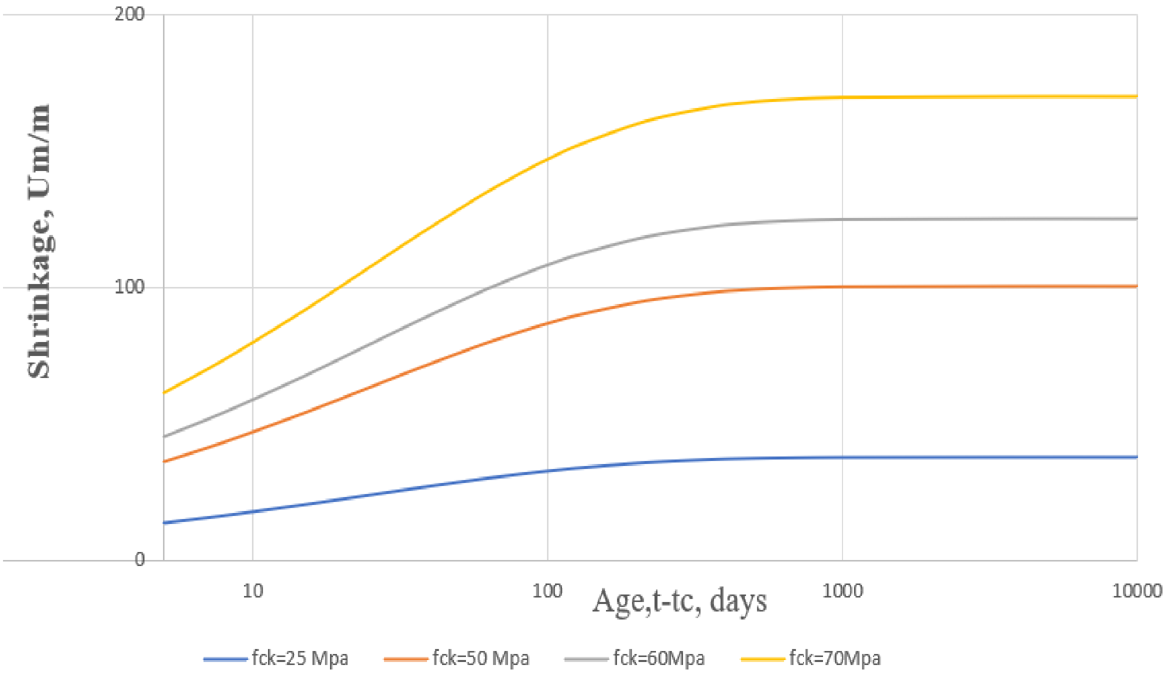


Figure44 Average compressive strength effect on total shrinkage according to Eurocode 2 model.

Due to figure 20 the average compressive strength doesn't have influence as well there are no big difference in the impact of fcm value.



Compressive strength (fck) effect on autogenous shrinkage according to Eurocode 2 model.

Due to figure 21 the compressive strength have effect on short and medium term and unlike the total shrinkage .

the higher value of fck represent more risk , but in all cases the shrinkage value is relatively small.

6.6 Model B3 of Bažant

The B3 model was developed by (Bažant, 1995),[62]at Northwestern University, United States, and is the third revision of the previous models, BP and BP-KX

This model is based on the theory of solidification, according to which aging of concrete is due to the increase in volume of the resistant portion of the material.

According to (Bazant, 2000),[63] The aging of concrete is related to the continuous progress of the hydration reactions in paste.

This model is relatively complex and requires numerous parameters related to the dosage of the mixture.

According to (Bažant, 1995),[62], its application is necessary only in cases of special structures where it is important to estimate the shrinkage and creep more precisely.

This model is applicable to Portland cement concrete cured for at least

least one day with the following characteristics:

− 0.35 ≤ water/cement ≤ 0.85.

− 2.5 ≤ aggregates/cement ≤13.5.

− 17 MPa ≤ fc28 ≤ 70 MPa.

− 160 kg/m3 ≤ cement ≤ 720 kg/m^3.

The parameters necessary for the calculation are the following:

- Concrete age at start of shrinkage, days.
- Age of the concrete at the moment of loading, days.
- Relative humidity, in %.
- Average thickness, mm.
- Shape of the section.
- Curing conditions.
- Average compressive strength of concrete at the age of 28 days, MPa.
- Type of cement.
- Water content.

6.6.1 Shrinkage calculation model

The average shrinkage, εsh(t,t0), of a section is calculated by the following expression:

$$\varepsilon_{sh}(t,t_0) = -\varepsilon_{sh\infty} k_h S(t)$$

Where:

S(t) is the function of time.

$$S(t) = \tanh\sqrt{\frac{t-t_0}{\tau_{sh}}}$$

kh is the coefficient 0f the relative humidity,

$$\text{kh} = \left\{ \begin{array}{l} \text{1-h3 for h <0.98} \\ \text{-2.2 for h=1} \end{array} \right\}$$

τsh represents the age necessary for the shrinkage to reach half of the final retraction.

$$\tau_{sh} = k_t (k_s D)^2$$

D is the effective thickness

$$\mathrm{D = 2v / s}$$

ks is the shape factor of the section.

Ks = 1.25 for a rectangular prism which is the case of this study.

$$\mathbf{k_t = 8,5 t_0{}^{-0,08} \bar{f}_c{}^{-1/4}}$$

kt is the parameter used in the calculation of τsh in days/cm^2.

εsh∞(t,t0) defines the ultimate retraction as a function of time

$$\varepsilon_{sh\infty} = \varepsilon_{s\infty} \frac{E(607)}{E(t_0 + \tau_{sh})}$$

Where

$$E(t) = E(28)\left(\frac{t}{4 + 0{,}85t}\right)^{1/2}$$

For the calculation of $\varepsilon s\infty$ the following expression used:

$$\varepsilon_{s\infty} = -\alpha_1\alpha_2\left[1{,}9 \times 10^{-2}\,\omega^{2.1}\,\bar{f}_c^{\,-0{,}28} + 270\right]10^{-6}$$

Where :

ω is the water content, in kg/m3.

α1 is a factor that depends on the type of cement.

α2 is a factor that depends on the type of curing.

the values of the parameters α_1 and α_2

	value of the factor α1 according to the type of cement
α1	= 1 for cement type I
	=0,85 for cement type Ⅱ
	=1,1 for cement type Ⅲ

Table 6. value of the factor α_1 according to the type of cement

	value of the factor α2 value of the factor according to the type of curing
α2	= 0,75 for steam-cured concrete (vapor)
	=1,2 for normal cured concrete
	=1,1 for concrete in conditions of 100% relative humidity

Table 7. value of the factor α_2 according to the type of cement

6.6.2 Typical curves for shrinkage calculated with the B3 model

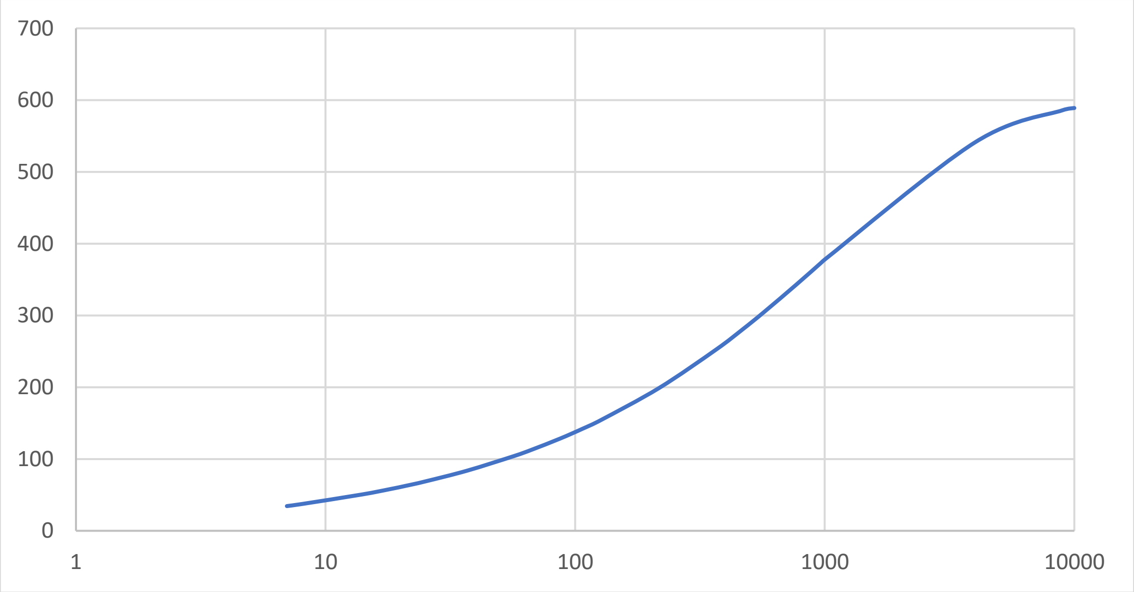


Figure45 Development of shrinkage according to B3 model.

6.6.3 Relative Humidity effect

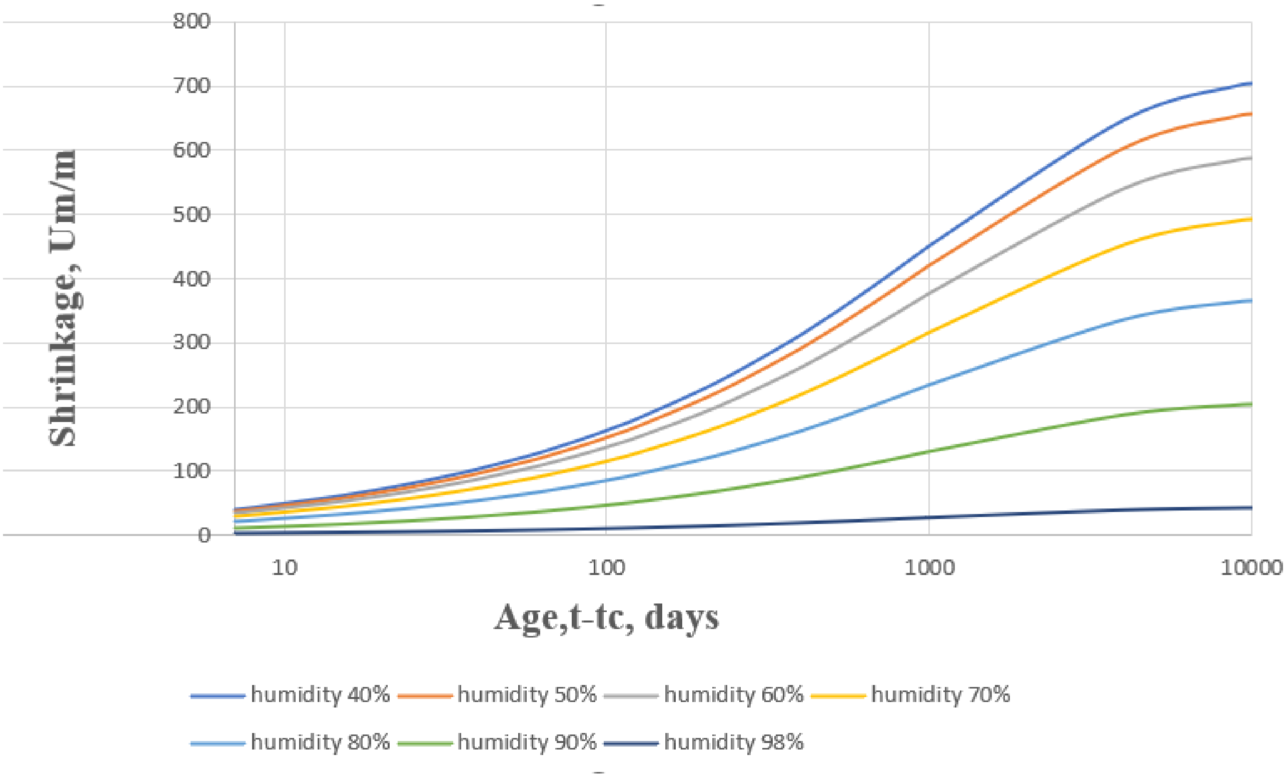


Figure46 humidity effect according to B3 model.

According to figure 46 the humidity have strong effect on concrete shrinkage , same as other models the low humidity increases the shrinkage while the Hight humidity percentage as 98 % make shrinkage almost zero .

6.6.4 Effect of curing type

The B3 model is one of the few models that offer a factor for the type of curing of the concrete, The factor name is α2.

The next figure will show the effect of α2 using the different value of the factor but conserving

The same value for other parameters and factors.

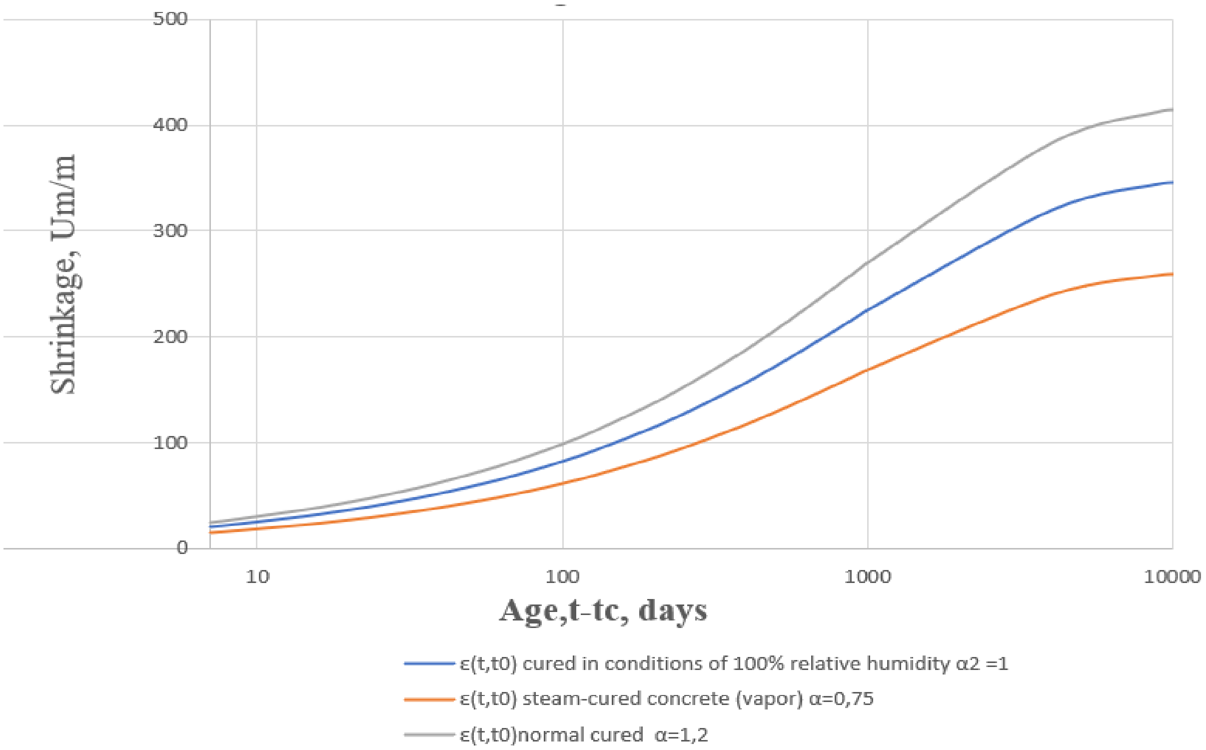


Figure47 Cure factor effect α_2 according to B3 model.

According to the to figure 25 the cure factor does have effect on the concrete shrinkage bur the effect isn’t present on the short term.

6.6.5 Development of shrinkage for concrete with different types of cement

Same as other prediction models , the B3 model offer a factor α_1 who represent different type of cement .

To see the effect of α1 on concrete shrinkage α_1 will be changed with value that model B3 offer keeping the same value of other parameters and factors except the ones who are related to type of cements.

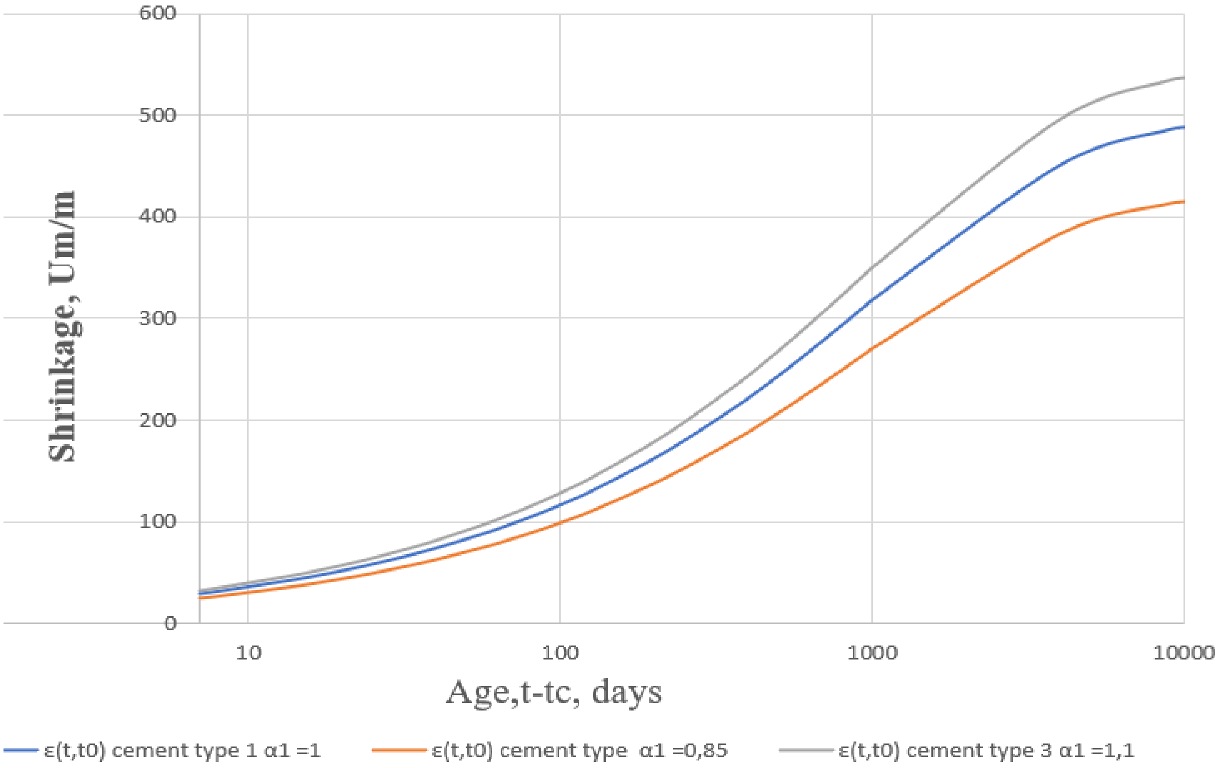


Figure48 Effect of cement type on concrete shrinkage according to model B3.

Figure 48 shows that the factor α_1 who represent the cement type does not have any effect expect small variation after 1000 days .

This explain that in model B3 the cement effect is not that important and his effect doesn't action until long period.

6.6.6 the water content effect on concrete shrinkage

The B3 model is the one of few model who consider the water content on concrete as a factor.

All the other model they used the concrete strength f_{ck} or Average compressive strength f_{cm} as a factor

The next figure represent the shrinkage evaluation with different value of water /cement ratio conserving other factor .

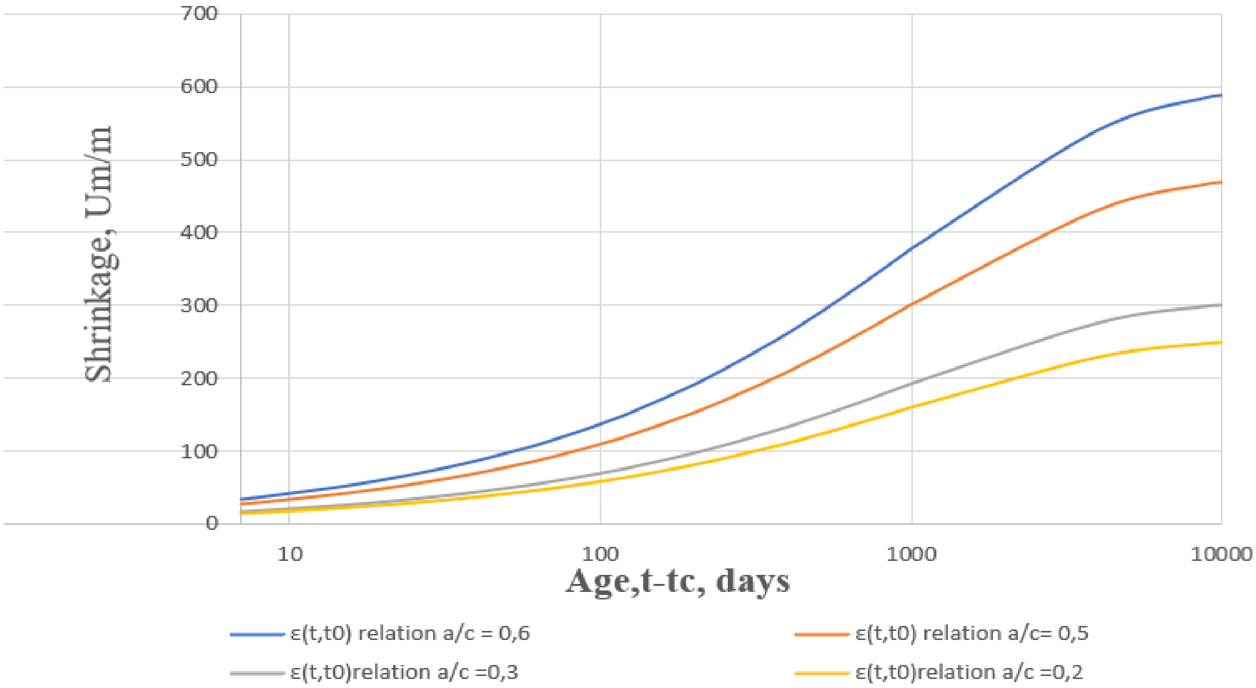


Figure49 Effect of water content in concrete shrinkage according to model B3.

Water content represent indirectly the concrete strength but according to B3 model the effect is not remarkable in short term nither on medium term but on long term the water content have a big effect on shrinkage .

6.6.7 Effect of Volume/surface ratio of the section

The B3 model have consider the volume / surface ratio as a effective thickness factor called D who will be used to determinate the parameter τ_{sh} .

The next figure represent the effect of the thickness on the concrete shrinkage .

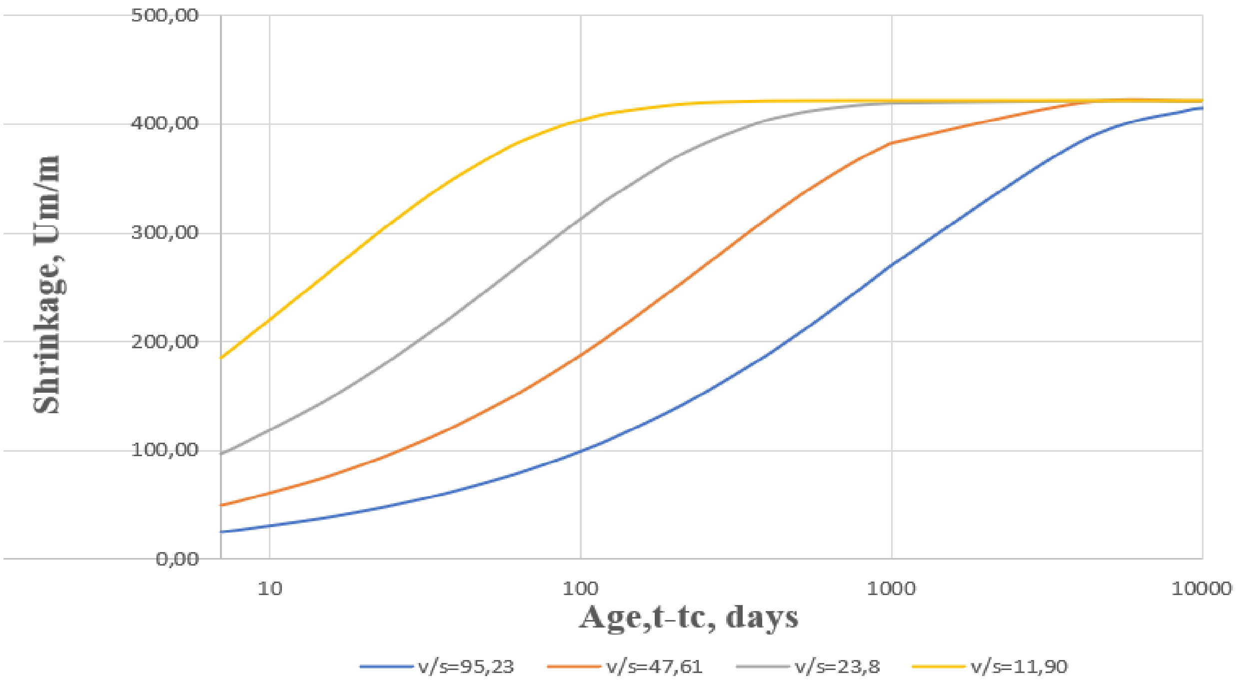


Figure50 Figure Effect of volume/surface in concrete shrinkage according to model B3.

According to figure 28 if the volume /surface ratio is bigger then the shrinkage is less that means every time the size of concrete element is bigger the shrinkage danger is less.

Unlike the other factors the volume/surface ratio “D” of the B3 models start the impact from the first days of shrinkage prosses but it stabilize in very long term .

6.6.8 Compressive strength effect

Although the model b3 uses the water content as factor In the shrinkage prediction function but this model use the compressive strength to calculate other parameter .

The next figure represent several value of fck keeping the other factors constant except the the ones related with the compressive strength.

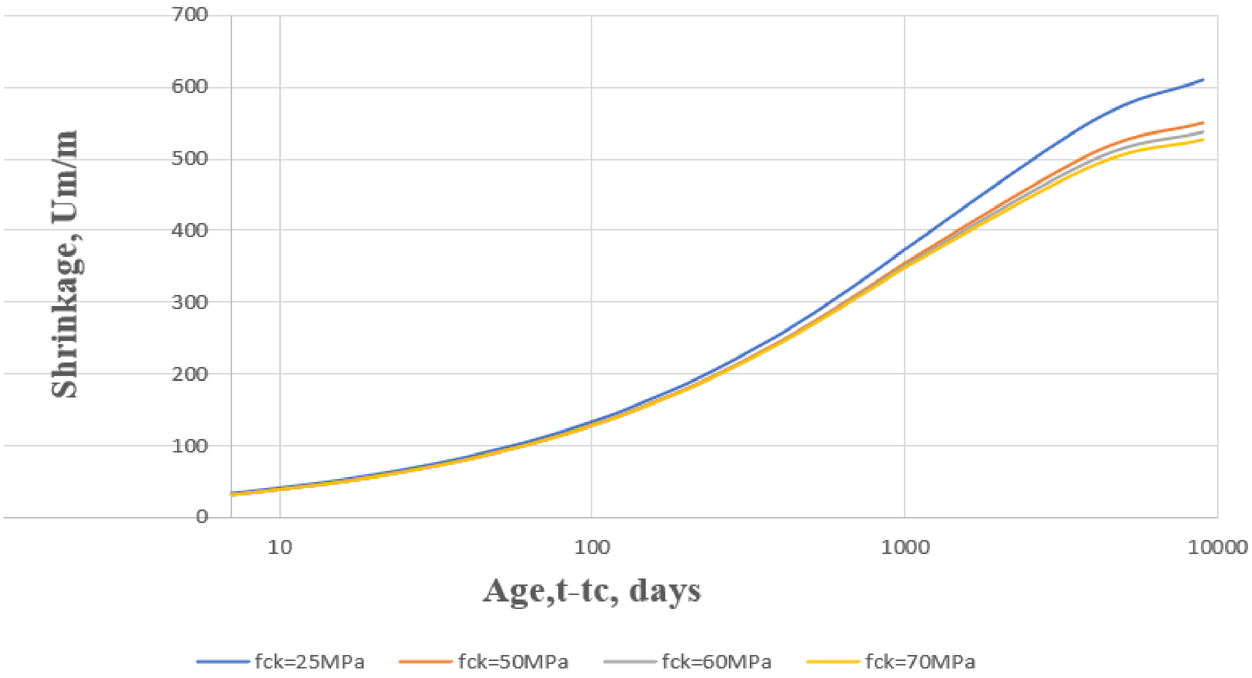


Figure51 Effect of compressive strength in concrete shrinkage according to model B3.

Due figure 29 The compressive strength have impact in long term but the several value of fck doesn't show deference in the in the impact .

6.7 Sakata (SAK) shrinkage prediction model

Since the early 1980s Sakata has been working on a research project to develop a prediction model based on statistical method from many experimental data.

He proposed new prediction equations of creep and shrinkage of concrete which was published in 1996 by Japan society of civil engineers in the standard specification for design and construction of concrete structure.

(sakata, 2001)[64],developed an exponential model (SAK) for the drying shrinkage strain. The presented model was based on several parameters such as member geometry, relative humidity, cement, and water contents.

The prediction model works for a wide range of compressive strengths.

The main source of the date used in establishing the new prediction equations was the shrinkage data collected by The International Union of Laboratories and Experts in Construction Materials (RILEM) and Japan Society of Civil Engineers JSCE.

The RILEM database consists mainly of data from the western countries, whereas the JSCE has collected data from papers.

The necessary parameters in the calculation of the current model are:

- The age of the concrete at the beginning of shrinkage
- Relative Humidity
- Compressive strength of concrete at the age of 28 days, MPa
- Volume-surface ratio
- Medium thickness
- Cement type
- Water content

6.7.1 Shrinkage calculation model

$$\varepsilon'_{ds}(t,t_0) = \frac{\varepsilon'_{ds\infty}\cdot(t-t_o)}{\beta+(t-t_o)}$$

Where

$$\beta = \frac{4W\sqrt{V/S}}{100+0.7t_o}$$

β	is term representing the time dependency of drying shrinkage.
W	is water content (kg/m^3).
V	is factor representing the volume.
S	is factor representing the surface .
V/S	reprsente volume-surface ratio.
t0	is the age of concrete at the beginning of drying (days)
t	is age of concrete

.

$$\varepsilon_{ds\infty} = \frac{\varepsilon_{ds\rho}}{1+\eta\cdot t_o}$$

ε_{dsre} represent final value of drying shrinkage strain (x10-6).

Where

$$\eta = 10^{-4}\{15\exp(0.007f'_c(28))+0.25W\}$$

And

$$\varepsilon_{ds\rho} = \frac{\alpha(1 - RH/100)W}{1 + 150\exp\left\{-\frac{500}{f_c'(28)}\right\}}$$

Where

RH is the relative humidity

f'$_{c(28)}$ is compressive strength of concrete at age of 28 days(N/mm2).

α is the cement type factor .

the next table show value of α for every type of cement .

α	is 11 for ordinary or low-heat cement
	is 15 for high-early-strength cement

Table 8. Value of α cement factor according to SAKATA model.

6.7.2 Typical curves for shrinkage calculated with the Sakata model

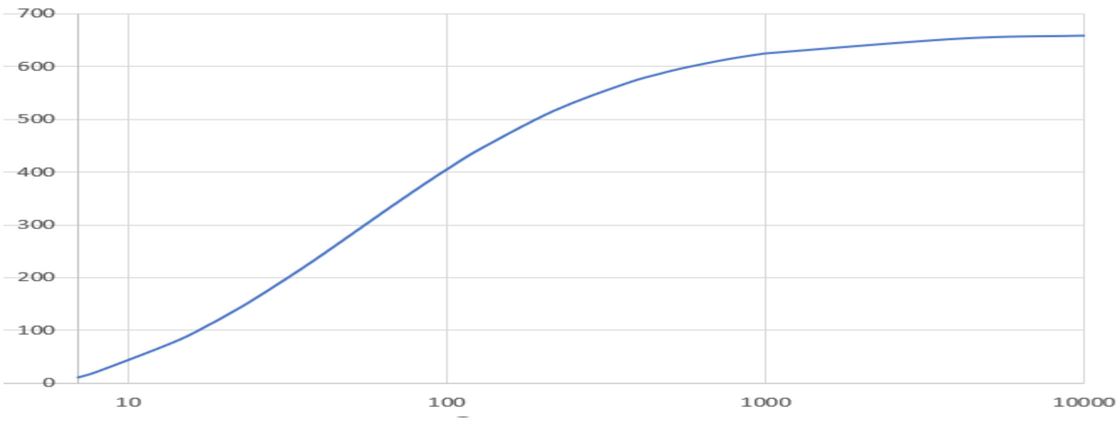


Figure52 Development of shrinkage according to Sakata model.

6.7.3 humidity effect

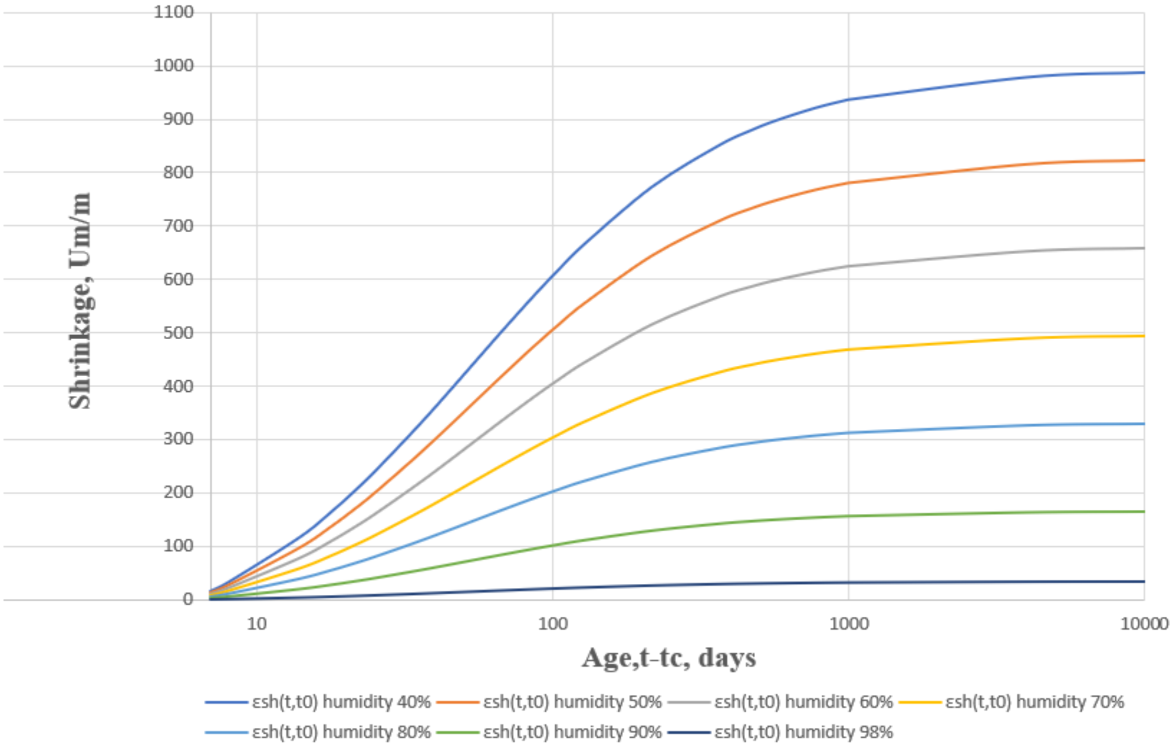


Figure53 Humidity effect according to Sakata model.

As it seems in the figure the humidity have remarkable effect on concrete shrinkage specialy in long term but with the time the shrinkage stabilize .

6.7.4 Development of shrinkage for concrete with different types of cement

the Sakata model offer the factor α who represent different type of cement however α can represent just 2 type of cement .

To see the effect of α on concrete shrinkage α will be changed with value that model Sakata offer , keeping the same value of other parameters and factors except the ones who are related to type of cements.

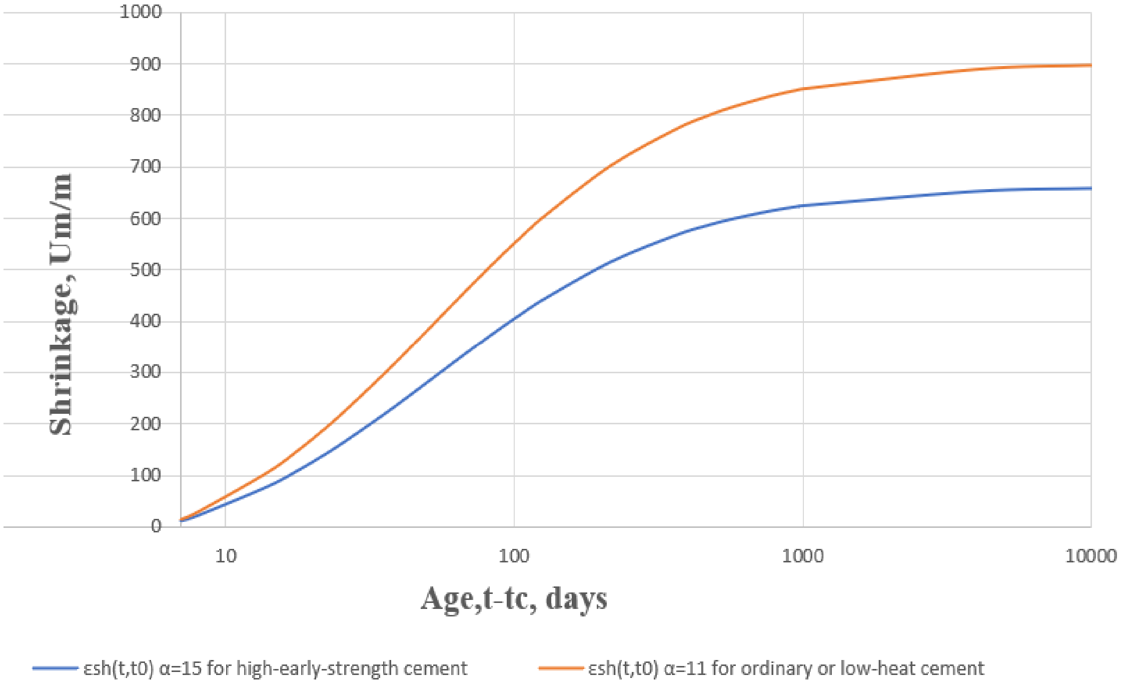


Figure54 Cement effect according to Sakata model .

According to the figure 31 the cement factor α have a striking effect on the concrete shrinkage since the first days and the shrinkage getting worse with time .

As well the value of shrinkage is relatively large comparing with others shrinkage prediction models .

6.7.5 effect of Volume/surface ratio of the section.

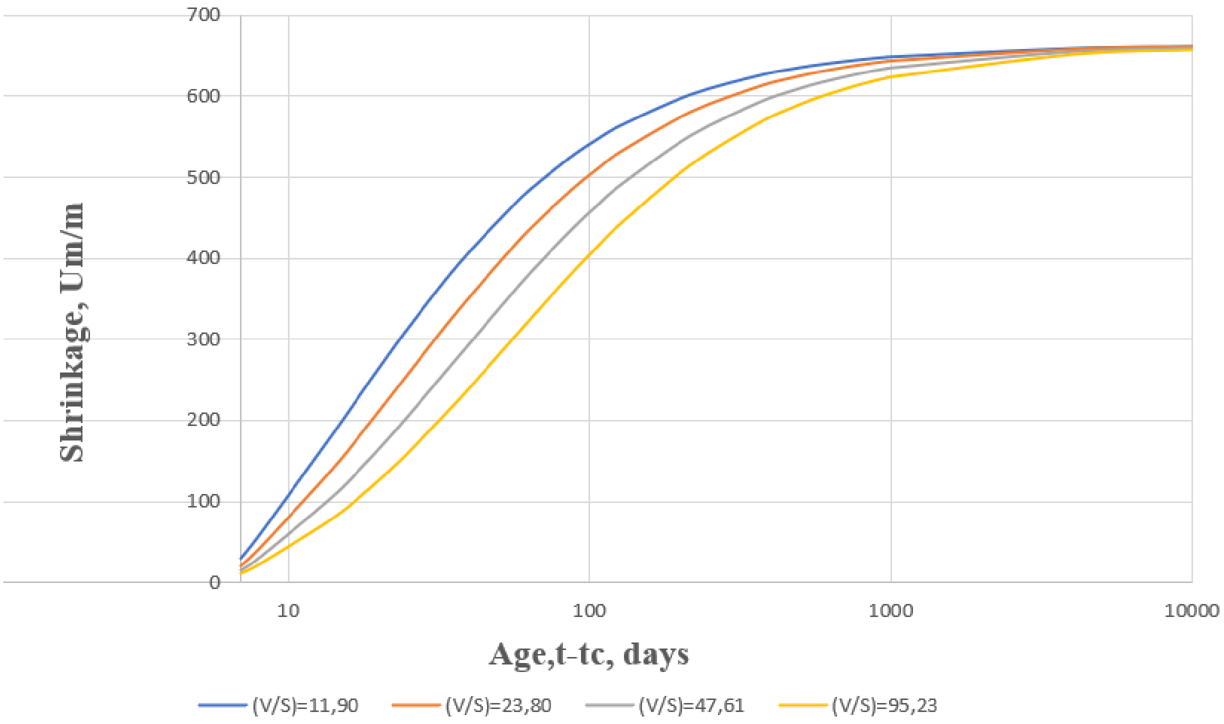


Figure55 Volume/surface ratio effect on shrinkage according to Sakata model.

Figure 55 shows different behavior of concrete shrinkage that to say whatever is the volume /surface ratio the shrinkage hardly change in short and medium term , but in large term the difference start to appear and in very long term the difference is so noticeable with big value .

According to Sakata concrete shrinkage prediction model everytime the volume/surface ratio is bigger the value of concrete shrinkage is bigger moreover the shrinkage value doesn't change id the volume/surface ratio smaller then 23.80mm^2 and stay stable with same value .

6.7.6 the water content effect on concrete shrinkage

Same as B3 concrete shrinkage prediction model the Sakata model use the water content as factor in the calculation of the shrinkage prediction .

The factor W represent the water content en (kg/m^3).

The water content relate to the factor water/cement ratio , The next figure represent the shrinkage evaluation with different value of water /cement ratio conserving other factor .

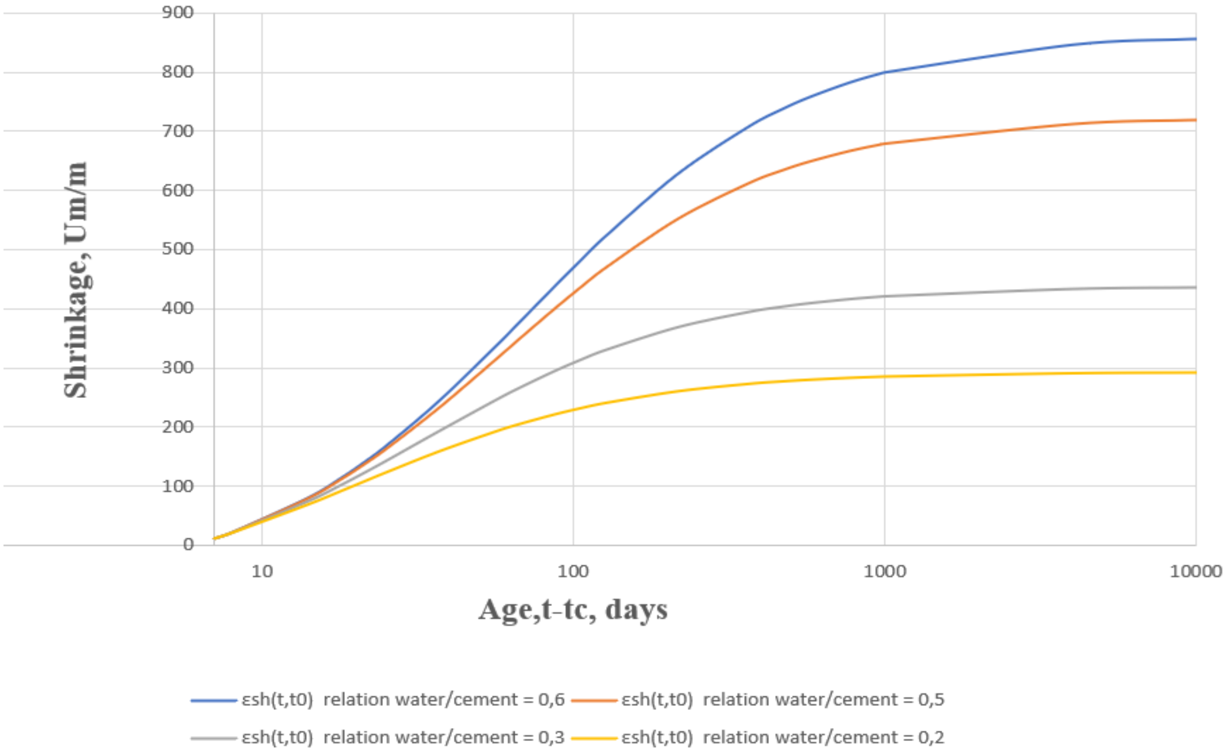


Figure56 Water content effect on concrete shrinkage according to Sakata model.

According to figure 33 water content doesn't represent any variation in short term whatever is the water content but in medium term the shrinkage start the variation and long term the shrinkage with high water content get the biggest shrinkage .

6.7.7 Compressive strength effect

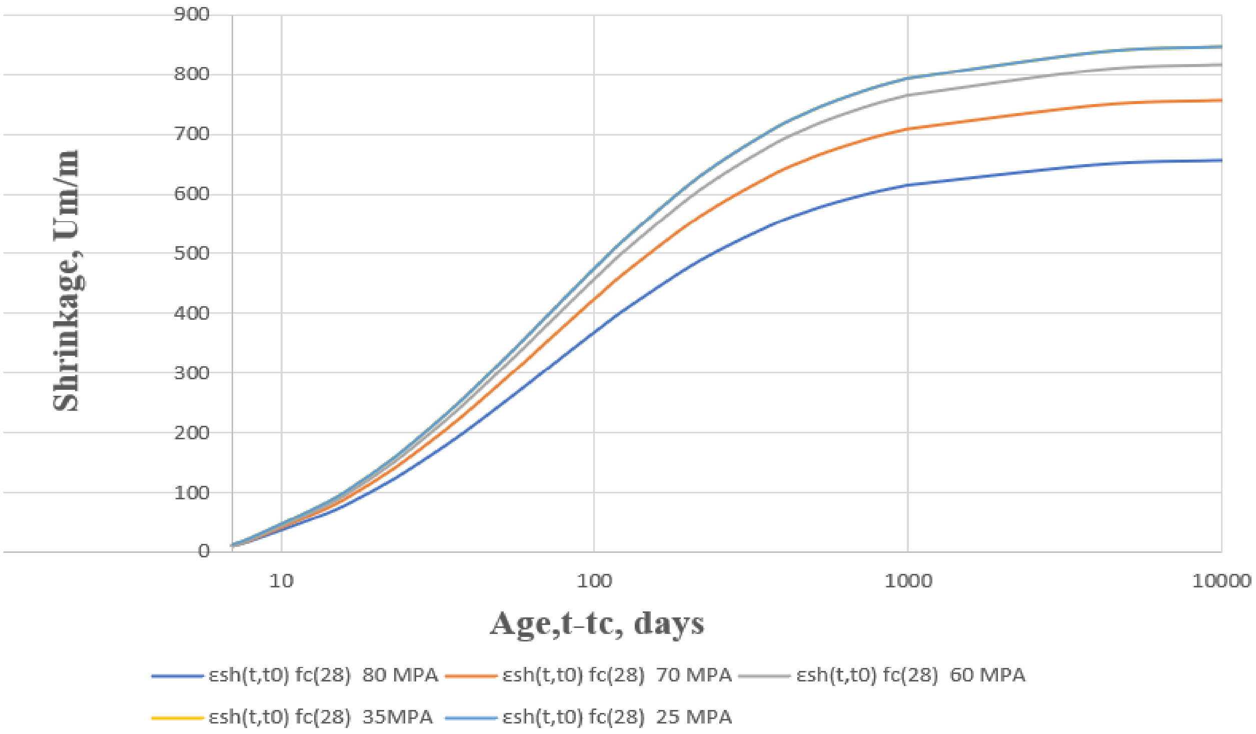


Figure57 Compressive strength effect according to Sakata model .

Due to figure 57 the compressive strength doesn't have remarkable effect on the concrete shrinkage as well for concrete less the 40 MPa the shrinkage have always same value .

6.8 FIB-MC2010

the (MC-2010, 2010)[65] ,is new model of the Euro-International Committee, a pre-normative code of reference in Europe, apart from having substantially changed its formulation with respect to its predecessor the CEB-FIP1990, has a specific section for lightweight concrete as well as a new function for calculation of autogenic shrinkage.

The necessary parameters in the calculation of the current model are:

- Concrete age at start of shrinkage, ts, days.
- Age of the concrete at the moment of loading, t0, days.
- Relative humidity, RH, in %.
- average compressive strength of concrete at the age of 28 days, fcm, MPa.
- Type of cement.
- Average thickness, h, mm.

6.8.1 Shrinkage calculation model

According to the concrete shrinkage prediction model MC-2010 , total shrinkage ε_{cs}(t,ts) is calculated as follows :

$$\varepsilon_{cs}(t,t_s)=\varepsilon_{cas}(t)+\varepsilon_{cds}(t,t_s)$$

Where

The total shrinkage is Total shrinkage is the sum of drying shrinkage ε_{cds}(t-t_s) and autogenous shrinkage ε_{cas}(t).

Autogenous shrinkage expressed with the following function :

$$\varepsilon_{cas}(t)=\varepsilon_{caso}(f_{cm})\cdot\beta_{as}(t)$$

Where

$$\varepsilon_{caso}(f_{cm})=-\alpha_{as}\left(\frac{f_{cm}/10}{6+f_{cm}/10}\right)^{2.5}\cdot10^{-6}$$

ε_{caso} (f_{cm}) is the estimation of the autogenous shrinkage as a function of f_{cm} at infinite time.

And

$$\beta_{as}(t)=1-\exp\left(-0,2\cdot\sqrt{t}\right)$$

Bas(t) is estimation of the autogenous shrinkage of a temporary function.

The drying ε_{cds}(t-t_s) is It is calculated by means of a value of the drying shrinkage at infinite time, a coefficient that accounts for the relative humidity and a function that describes the development of the phenomenon over time.

$$\varepsilon_{cds}(t,t_s) = \varepsilon_{cdso}(f_{cm}) \cdot \beta_{RH}(RH) \cdot \beta_{ds}(t - t_s)$$

Where

$$\varepsilon_{cdso}(f_{cm}) = \left[(220 + 110 \cdot \alpha_{ds1}) \cdot \exp(-\alpha_{ds2} \cdot f_{cm}) \right] \cdot 10^{-6}$$

ε_{cds0} (f_{cm}) is a value of the drying shrinkage at infinite time.

And

$$\beta_{RH} = 1.55(1 - (\frac{RH}{100})^3)$$

β_{RH} is coefficient that accounts for the relative humidity.

And

$$\beta_{ds}(t - t_s) = \left(\frac{(t - t_s)}{0{,}035 \cdot h^2 + (t - t_s)} \right)^{0.5}$$

B_{ds} (t-t_s) is function that describes the development of the phenomenon over time.

Where

A_{ds1} and α_{ds2} are coefficient dependent on the type of cement.

Cemente type	α_{as}	α_{ds1}	α_{ds2}
32,5N	800	3	0,013
42,5N	700	4	0,012
52,5N or 52,5R	600	6	0,012

Table

h is $2A_c/u$, (mm).

h is section thickness.

A_c is the cross section,(mm^2).

u is the perimeter of the section in contact with the medium ,(mm).

fcm is mean compressive strength of concrete at 28 days ,(MPa).

t = is age of the concrete, (Days).

ts is age of the concrete at the beginning of drying,(Days).

6.8.2 Typical curves for shrinkage calculated with the MC-2010 model

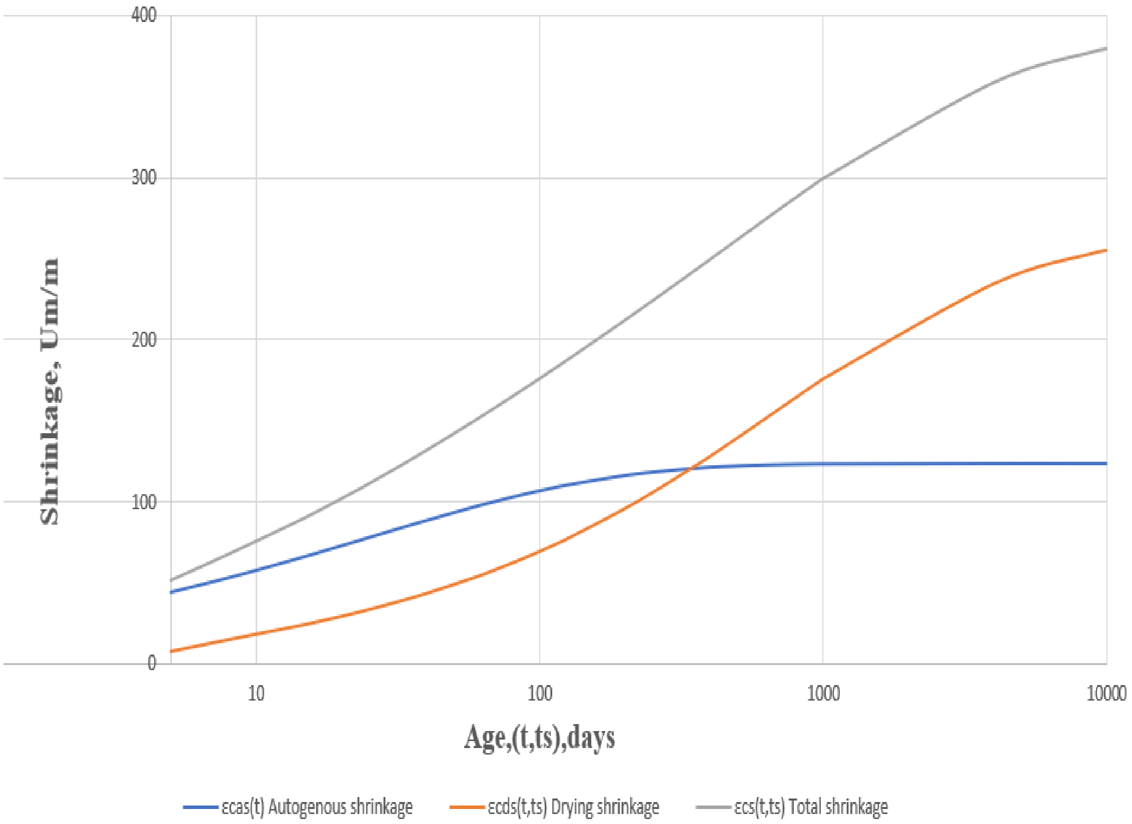


Figure58 Development of shrinkage according to MC-2010 model.

6.8.3 Humidity effect

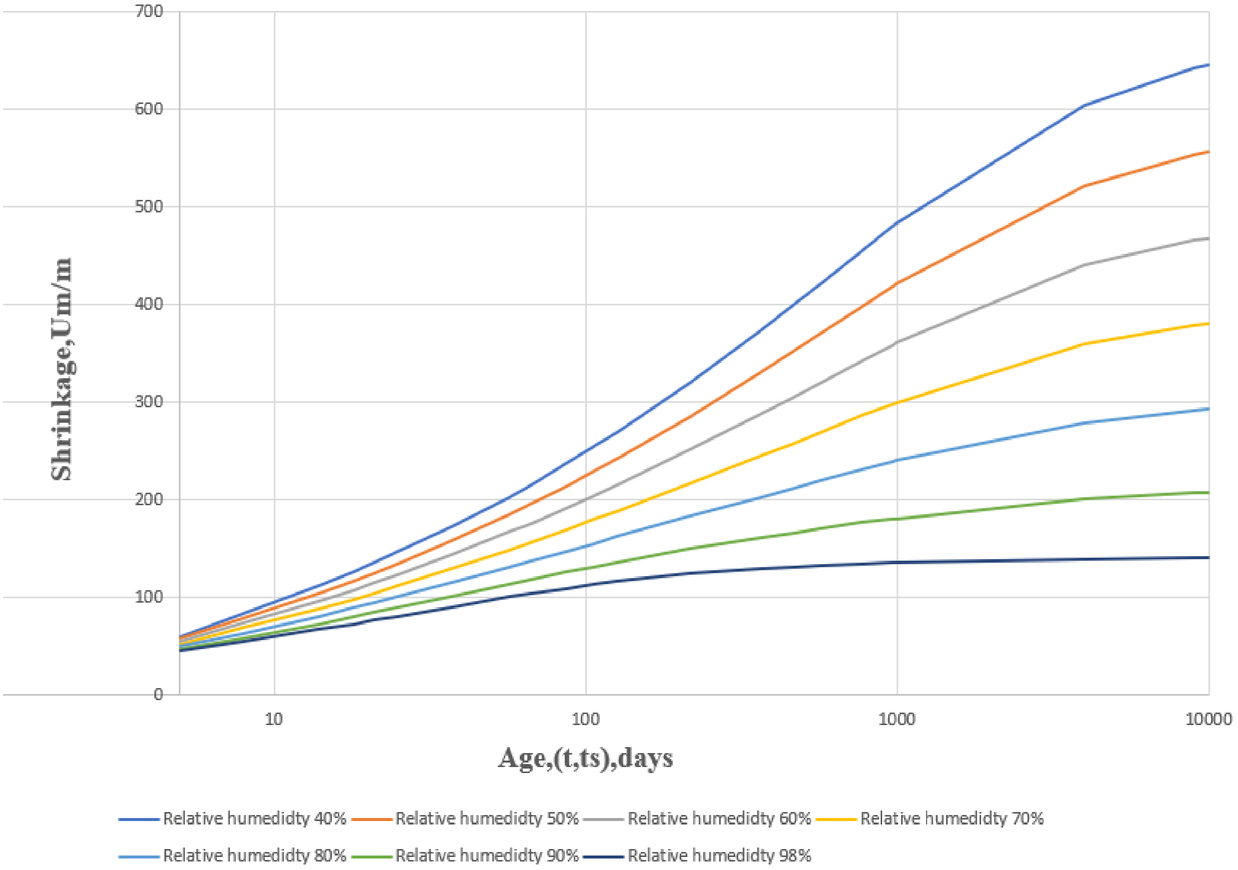


Figure59 Figure Relative humidity effect according to Mc-2010 model.

The relative humidity have important effect on concrete shrinkage in long term but in short term the humidity haven’t remarkable impact .

As less is the humidity percentage the shrinkage risk is higher .

6.8.4 Development of shrinkage for concrete with different types of cement

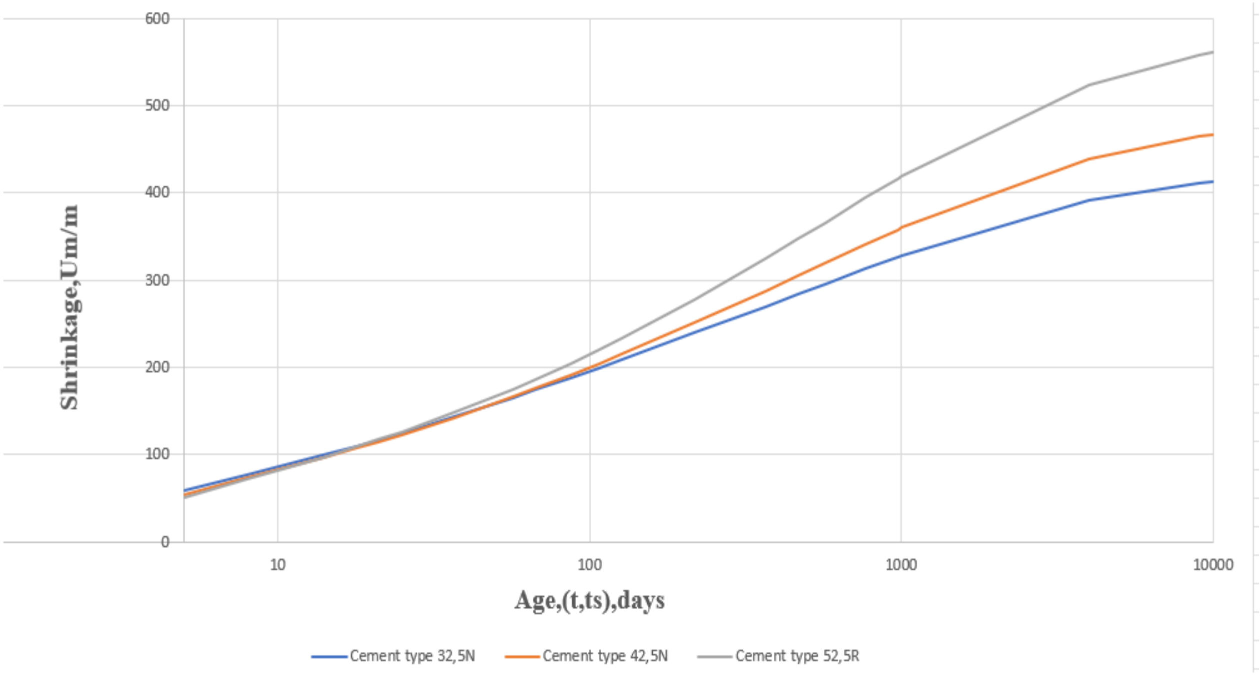


Figure60 Effect of cement type on concrete shrinkage according to model MC-2010.

The cement type doesn’t have any effect on short or medium term but in very long term there figure shows a small difference where the cement type 52.5R is the most exposed to the shrinkage risk .

6.8.5 Compressive strength effect

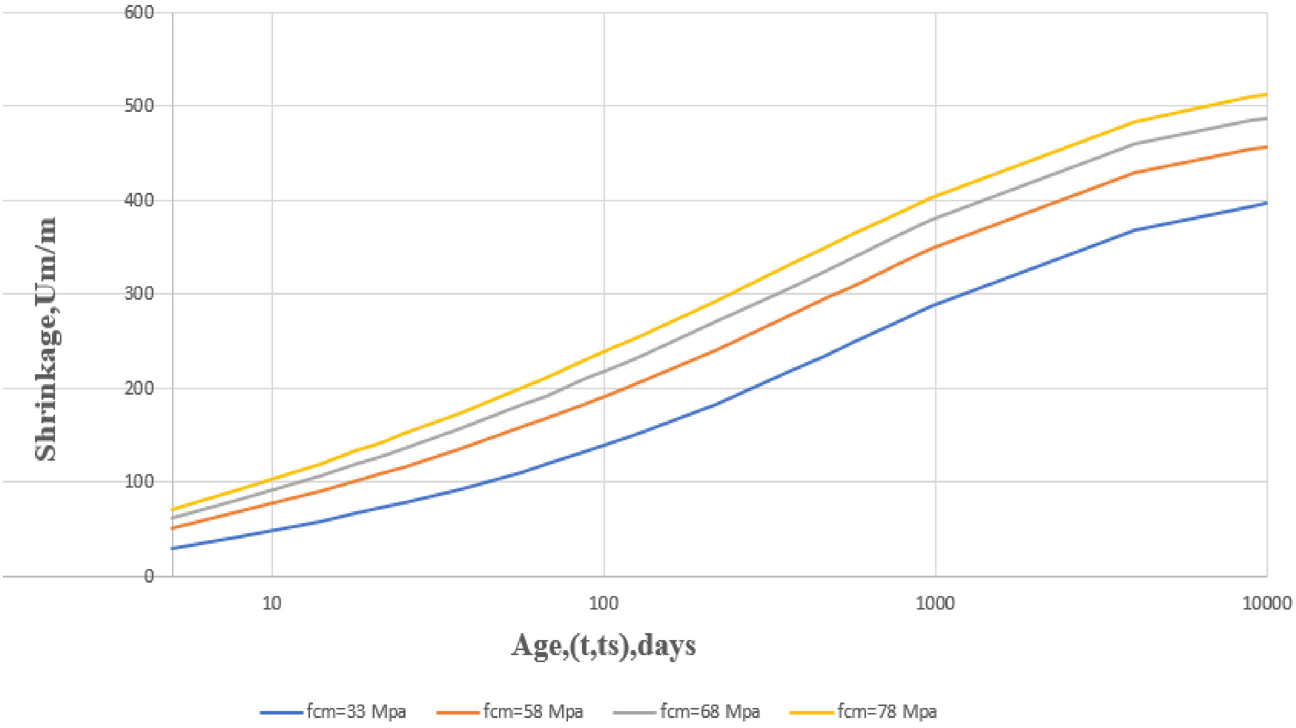


Figure Effect of compressive strength in total shrinkage according to model MC-2010.

The impact of compressive strength have small impact in short and long term in total shrinkage which reflect the small importance of this factor .

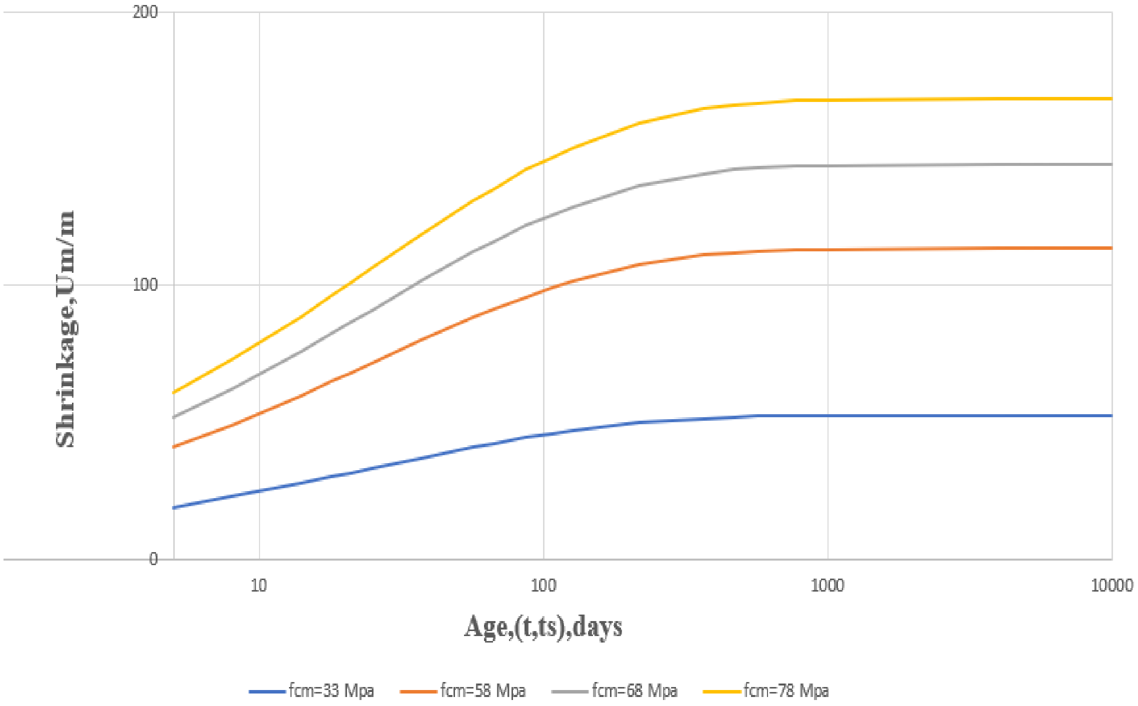


Figure61 Compressive strength (f_{cm}) effect on autogenous shrinkage according to Eurocode 2 model.

Unlike the total shrinkage the compressive strength have remarkable impact in autogenous shrinkage from the first days , where it shows that the lower value (f_{cm}) is more exposed to the shrinkage risk .

6.8.6 Effect of Volume/surface ratio of the section.

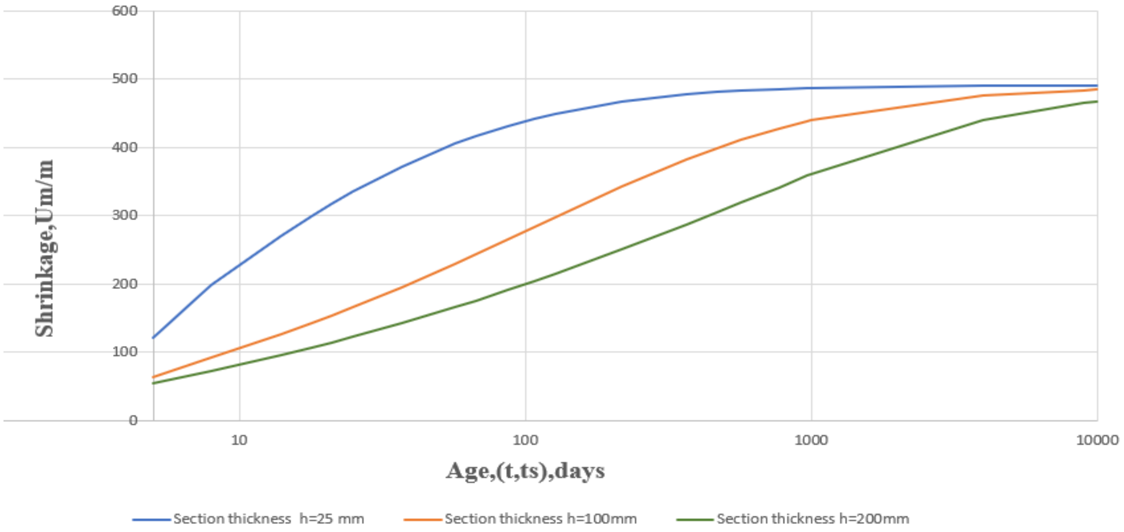


Figure62 Section thickness (h) effect on the concrete shrinkage according to MC-2010 model.

Due to figure the 42 the section thickness have big importance on short term but in very long term the shrinkage value will be stable and equal what ever is the value of (h).

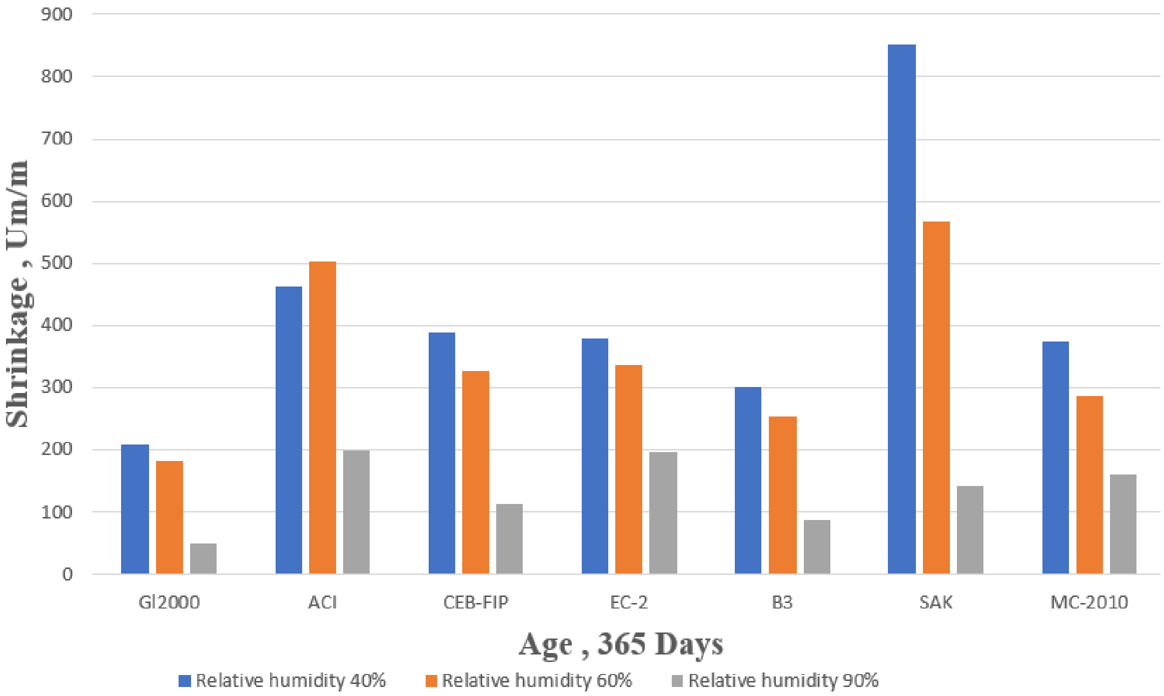
Chapiter 6 comparison between the different factors of concrete shrinkage prediction models

The shrinkage prediction models are vary, however they have similar factors and parameters .

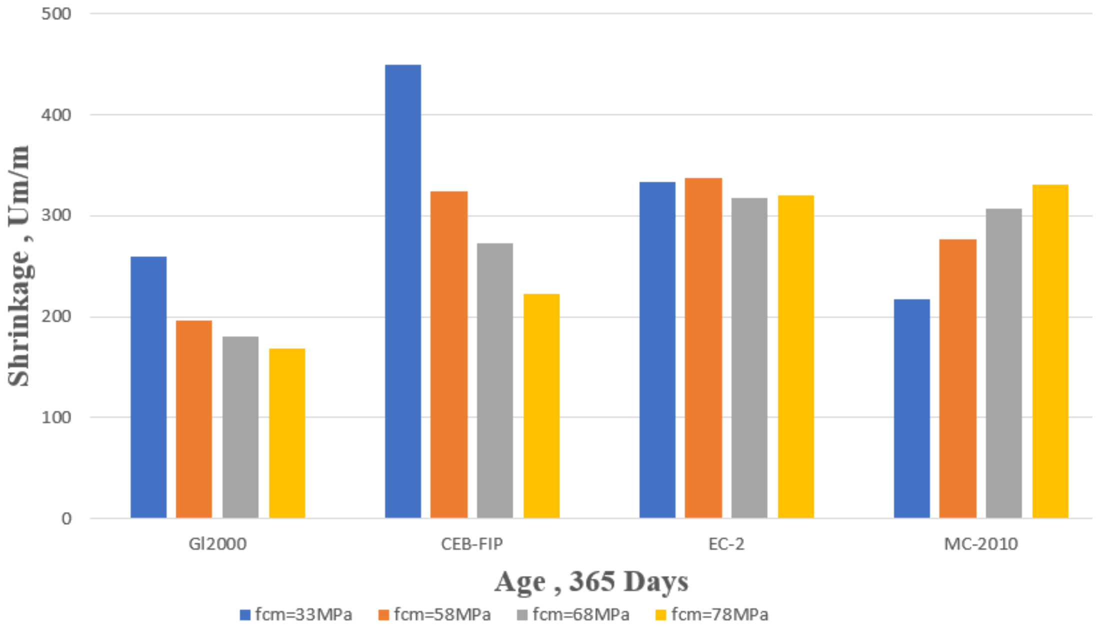
The next work will present difference of impact in the seven shrinkage model using the common factors with different value with object to show the sensitivity of each factor in the models .

All the value will be taken on the age of 365 days but the common factors will be different .

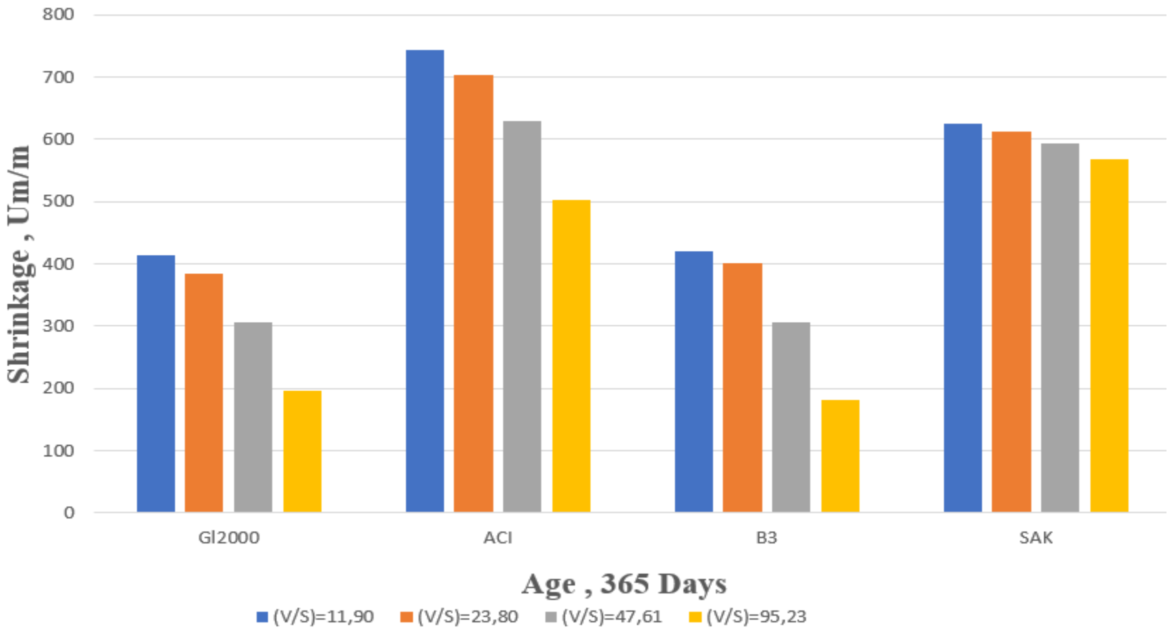
7.1 Difference in relative humidity



7.2 Difference in cement type



7.3 Volume/surface ratio of the section



Figure

7.4 Limitations and requirements of concrete shrinkage models

The shrinkage prediction models vary in there factors , parameter and complicity ,the next tables will be as a summary of the variables needed by each model to calculate shrinkage.

	GL2000	ACI209R-92	CEB-FIP1990	Eurocode 2 (EC-2)	B3	Sakata (SAK)	MC-2010
Shrinkage factors	6	5	6	5	10	5	5

Table 9. Number of factors for each shrinkage model.

The model B3 have the most number of factors but for the models ACI209R-92 , Eurocode 2and Sakata requires the least number of factors.

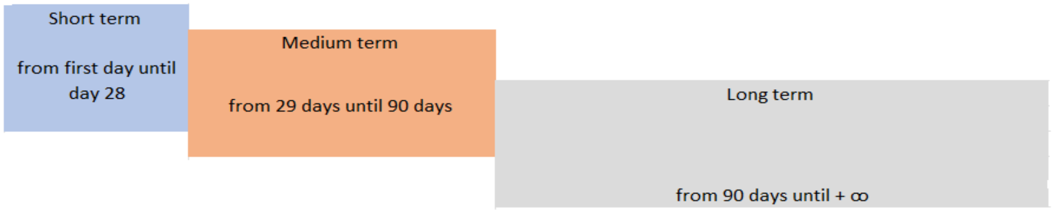
7.5 Factors of the shrinkage models and their behavior over time.

According to the previous work every factor of the six concrete shrinkage prediction models have impact but there impact have variable importance and act in deferent time term .

The next table show the number of days according to every time terms.

	Number of days
Short term	from 0 to 28
Medium term	from 29 to 90
Large term	from 90

Table 10. Terms of time en function of days .



4

The next table shows the impact of each factor over time in function of terms .

	Shrinkage prediction models						
Factors	GL2000	ACI209R-92	CEB-FIP1990	Eurocode 2 (EC-2)	B3	Sakata (SAK)	MC2010
Compressive strength	Long Term	-	Short Term	Medium Term	Long Term	Long Term	Medium Term
Relative humidity	Long Term	Medium Term	Short Term	Long Term	Long Term	Long Term	Long Term
Type of Cement	Long Term	-	Short Term	Long Term	Long Term	Medium Term	Long Term
Volume to surface area ratio (v/s)	Short Term	Long Term	Short Term	Long Term	Short Term	Short Term	Long Term
Water content	-	-	-	-	Long Term	Medium Term	-
Cement content en (kg/m3)	-	Long Term	-	-	-	-	-
Curing factor	-	Long Term	-	-	Long Term	-	-

Table 11. Impact of shrinkage models factors over the time .

7.6 Limitations of concrete shrinkage models.

	Shrinkage prediction models						
Factors	GL2000	ACI209R-92	CEB-FIP1990	Eurocode 2 (EC-2)	B3	Sakata (SAK)	MC2010
Compressive strength	x	x	x	x	x	x	x
Curing factor	x	x	-	-	x	-	-
Relative humidity	x	x	x	x	x	x	x
Volume to surface area ratio (v/s)	x	x	1,5*	2	x	x	3
Slump factor	-	x	-	-	-	-	-
Fine agg. to total aggregate (Af /A)	-	x	-	-	-	-	-
Cement type factor	x	4	x	x	x	x	x
Water content	-	-	-	-	x	x	-
Air content factor		x	-	-	-	-	-
Start day of shrinkage	x	-	x	x	x	x	x
Modulus of elasticity.	-	-	-	-	x	-	-

Table 12. Factors of concrete shrinkage models

1.2.3 The Eurocode 2 (EC-2) model has a different formula to measure the size of the part that consists of the area of the section and the perimeter.

4 The ACI209R-92 model use the cement content as factor and not the cement type.

5* The CEB-FIP1990 model doesn't use the volume/surface ratio but it uses Ac is the cross section and the perimeter of the element in contact with the atmosphere to to measure the size of the element.

- According to table 4 there are essential parameters which exist in all shrinkage prediction models like relative humidity and compressive strength.
- Even in the essential parameters every shrinkage prediction model has a different limits and tolerance.

The next table represent the limits of each parameters of every shrinkage prediction model .

	Shrinkage prediction models						
Factors	GL2000	ACI209R-92	CEB-FIP1990	Eurocode 2 (EC-2)	B3	Sakata (SAK)	MC2010
Compressive strength (N/mm2)	fcm<82	-	12<fcm<80	-	17<fc<70	20<fc<80	-
Relative humidity	-	40-99	40-99	40-99	-	40-90	40-99
Type of cemente	cement type I,II, III	-	SL-N-R-RS	S-N-R	cement type I,II, III	S-R	S-N-R
cement content (kg/m3)	-	-	-	-	160-720	-	-
water /cement ratio (w/c)	-	-	-	-	0,35<W/C<0,85	0,3<W/C<0,6	-

Table 13. Shrinkage prediction models limites .

- Not all models explain the limits of each Parameters but it is possible to know the limits testing variable value for every factors.
- Though almost of shrinkage prediction model have a type of cement as a essential parameter but the limits and the form to characterize cement are different.
- ACI209R-92 does not consider parameter for type cement but have factor γc who represent the cement content.

The next table will present the form how to characterize the cement for each shrinkage prediction model .

Shrinkage prediction model	Model Way of characterizing cement
GL2000	Cement is categorized according to the following criteria: – Type I – Type II – Type III
ACI209R-92	The type of cement is not considered. The cement content is considered
CEB-FIP1990	Cement is categorized according to the following criteria: – Slow hardening cement (SL) - CE 32.5 – Normal hardening cement (N) - CE 32.5 R; EC 42.5 – Rapid hardening cement (R) - CE 42.5R – Fast-setting, high-strength cement - (RS) CE 52.5
B3	Cement is categorized according to the following criteria: – Type I – Type II – Type III
Eurocode 2 (EC-2)	Cement is categorized according to the following criteria. – Class S for cement type CEM 32.5 N – Class N for cement type CEM 32.5R, CEM 42.5N – Class R for cement of the type CEM 42.5R, CEM 52.5 N, CEM 52.5R
MC2010	Cement is categorized according to the following criteria. – Class S for cement type CEM 32.5 N – Class N for cement type CEM 32.5R, CEM 42.5N – Class R for cement of the type CEM 42.5R, CEM 52.5 N, CEM 52.5R
Sakata (SAK)	Cement is categorized according to the following criteria: – Type I – Type II – Type III

Table 14. Cement type for each concrete shrinkage prediction model .

- The models GL200, B3 and Sakata are using the cement type according to the classification of American Society for Testing and Materials (ASTM).
- The models CEB-FIP1990 AND Eurocode 2 (EC-2) Are using the European classification for cement type .

Model Name	Detailed Fonction	Final Fonction
Gl2000	$\varepsilon_{sh=}1000K\left({}^{30}/_{f_{cm28}}\right)^{1/2} 10^{-6} * (1-1.18h^4) * \left(\frac{t-t_c}{t-t_c+0.15*({}^{V}/_{S})^2}\right)$	$\varepsilon_{sh} = \varepsilon_{shu}\beta(h)\beta(t)$
ACI209	$(\varepsilon_{sh})t = \frac{t}{35+t}\left(780\dot{\gamma_{cp}} * (1.4-0.010\gamma) * (1.2\exp\left(-0.00472*\frac{v}{s}\right)) * (0.89+0.00161s) * (0.3+0.014\Psi) * (0.75 + 0.00061c) * (0.95+0.008\alpha)\right) * 10^{-6}$	$(\varepsilon_{sh})_t = \frac{t}{35+t}(\varepsilon_{sh})_u$
CEB-FIP 1990	$\varepsilon_{cs}(t-t_{s)} = \left(160+10\beta_{sc}\left(9-\frac{f_{cm}}{f_{cmo}}\right)*10^{-6}\right)*(-1.55*(1-(\frac{RH}{RH_0})^3) * (\sqrt{\frac{{(t-t_s)}/{t_1}}{(350({}^{h}/_{h_0})^2)+{(t-t_s)}/{t_1}}}$	$\varepsilon_{cs}(t,t_s)=\varepsilon_{cso}\cdot\beta_s(t-t_s)$
Eurocódigo 2 (EC-2)	$\varepsilon_{cs} = (1-\exp(-0.2*t^{0.5})*(2.5*(f_{ck}-10)*10^{-6}) + \left[\frac{{}^{t}/_{t_s}}{(t-t_s)+0.04\sqrt{\frac{2A_c}{u}^3}}\right] * (0.85\left[(220+110*\alpha_{ds1})*\exp\left(-\alpha_{ds2}*\frac{f_{cm}}{10}\right)*(10^{-6}) * (1.55\left(1-(\frac{RH}{100})^3\right)\right]*K_h$	$\varepsilon_{cs} = \varepsilon_{cd}+\varepsilon_{ca}$
B3	$\varepsilon_{sh}(t,t_0) = \left(-\alpha_1\alpha_2(1.9*10^{-2}\omega^{2.1}f_c^{-0.28}+270)10^{-6}\frac{E(607)}{E(t_0+\tau_{sh})}\right)(1-h^3) * \tanh\sqrt{\frac{t-t_0}{8.5t_0^{-0.08}f_c^{-1/4}\left(k_s\frac{2v}{s}\right)^2}}$	$\varepsilon_{sh}(t,t_0) = -\varepsilon_{sh\infty}k_hS(t)$
Sakata (SAK)	$\frac{\left(\frac{{(\alpha*(1-h)*w)}/{(1+150\exp(-{}^{500}/_{f'_c}))}}{1+(10^{-4}*(15\exp(0.007*f'_c+0.25W))}\right)*(t-t_0)}{(\,{}^{4w*\left(\sqrt{\frac{V}{S}}\right)}/_{(100+0.7*T_0)}+(t-t_{0)}}$	$\varepsilon_{sh}(t,t_0) = \frac{\varepsilon_{sh\infty}*(t-t_0)}{\beta+(t-t_0)}$
MC-2010	$\varepsilon_{cs} = ((2220+110*\alpha_{ds1})\exp(-\alpha_{ds2}*fcm))10^{-6}(1-\exp(0.2\sqrt{t}) + \left(\frac{t-t_s}{0.035*2*({}^{A_c}/_{u})+(t-t_{s)}}\right)^{0.5} ** (-1.55*(1 - ({}^{RH}/_{100})^3)*$	$\varepsilon_{cs}(t,t_s)=\varepsilon_{cas}(t)+\varepsilon_{cds}(t,t_s)$

Table 15. Detailed Function according for each concrete shrinkage prediction model .

Table 4 shows the complicity of each function of the shrinkage prediction models , the B3 model is the most complicate one due to the high number of the factors and parameters however the Gl2000 is the simplest because few factor and direct function to calculate the parameters.

7.7 summary and remarks :

Every shrinkage prediction model have several parameters and factors moreover not all of them have the same impact and importance in the shrink age prediction function as well not all the factors and parameters act the same , some act in short term period others in long term period .

The objective of chapiter 6 was determination of effect , importance, sensitivity and the acting of each factors of the seven shrinkage prediction models In the next work will be small responding all the objective in the last titles .

7.7.1 GL2000

The relative humidity have direct effect on shrinkage and the variation of the percentage can make big difference in the impact of shrinkage every time the relative humidity get higher the danger of shrinkage decrease , but the it is not remarkable in short and medium term in the case of cement type the cement type 3 is the most cement exposed to the risk of shrinkage while the cement type 2 is the less .

The cement type factor and average compressive strength of concrete at the age of 28 days f_{cm28} have importante effect on shrinkage start from long term period .

As much the f_{cm28} is low the shrinkage get big value.

In obset side the volume/surface (V/S) ratio have clear remarkable acting in short term From the first day but whatever (V/S) ratio value is , in very long term all get same shrinkage value .

The GL2000 does not have function for type of curing .

7.7.2 ACI209R-92

The ACI209R-92 shrinkage prediction model have large interval for relative humidity (40%-98%) , the shrinkage value star start to differentiate from medium term and the deference become bigger with time , as les relative humidity is the shrinkage risk grow up .

the ACI209R-92 use the cement quantity as a parameter but there isn’t remarkable difference in shrinkage value while there the quantity measured in kg/m^3 is quite different , means that for ACI209R-92 the cement quantity factor is not so important factor , same as the curing parameter wish doesn’t represent big difference while the volume /surface ratio show remarkable shrinkage value from 100 days .

7.7.3 CEB-FIP1990

The parameter of relative humidity have large interval as well have remarkable impact from short term and continue intel long term same as others models as much the value of relative humidity is high the risk of shrinkage reduce .

For cement type impact is clearly for the Fast-setting, high-strength cements and it start from short term unlike the Normal hardening cement (N) and the Slow hardening cement (SL) wish have almost same shrinkage value .
In case of the volume /surface ratio (V/S) impact on shrinkage is only in short and in long term the shrinkage value stabilize no matter is the (V/S) value .

7.7.4 Eurocode

In the Eurocode 2 the development of shrinkage due to the Relative humidity start from the first days however there is not a remarkable difference in the short medium , term in long the difference start to appear and it became almost stable as much the humidity is high the risk of shrinkage became less.

Like others model the EC-2 show that the cement clase R is the most cement exhibited to the shrinkage risk nevertheless the shrinkage start to be remarkable from long term and it is almost same for the tree cement type in short and medium term

The size of the element have start from first days the autogenous shrinkage doesn't have strong effect on it because it is not a factor in the function of calculation moreover in total shrinkage the evaluation start as well from first days without a remarkable difference in long term the shrinkage start show difference and stabilize with time .

Average compressive strength (fcm) is factor in the function of the drying shrinkage but it doesn't have remarkable sensitivity where the shrinkage evaluation is almost same for all value of the (fcm) but in the case of autogenous shrinkage where the characteristic resistance o the mechanical compressive strength (fck) is used have remarkable intense on the shrinkage it start from short term and in long term become stable unlike other models as more the fck is less the risk autogenous shrinkage is less .

7.7.5 Model B3

The relative humidity according to B3 model is important and the impact start to appears from long term same as other models as less value of the relative humidity the shrinkage risk is higher.

The shrinkage model B3 offer 3 type of curing factor the normal cured is the most effected by shrinkage unlike the steam-cured concrete, the impact of the of curing factor start to appears in long term .

The cement type according to B3 model have factor α_1 but there are not a big difference between the three cement type , in some point of view the cement type have not a big impact for that it may not be important parameter.

The model B3 is one of few model who use the water content which is always related on direct form with cement quantity according to the previous work the water content is show the difference in long term as much the water content is higher the risk of shrinkage damage is higher

In most of parameters in B3 shrinkage prediction model start in long term but this is not case of the volume/ surface ratio (V/S) which start from fist day with important impact but in long term the shrinkage value stabilize not matter is the (V/S) value ,same as other model the smallest element which have the small (V/S) value is the most effected by the shrinkage.

7.7.6 Sakata (SAK)

The humidity is factor impact appear from medium term and in long term the shrinkage value become stable not matter number of days are .

The relative humidity of 98% have small shrinkage value which is almost 0 unlike the 40% of relative humidity which have very high shrinkage value more then all others shrinkage models.

Sakata model offer 2 factors for the cement type the shrinkage development start from short term and continue with remarkable effect in medium term and long term in unlike the other shrinkage model the ordinary cement get more risk of shrinkage .

the effect of volume/surface ratio in Sakata model is similar in short and medium terms what ever the value of (V/S) is from 100 days the deference start to appear unlike other models SAK model see that whenever the size of the element is bigger the shrinkage risk is bigger .

Water content has a impact on the shrinkage prediction and the difference between value start from medium term and continue in long term but in short term whatever is the value of water/cement ratio the shrinkage value is the same .

Similar to other concrete shrinkage module the high water/cement ratio represent a higher risk of concrete shrinkage .

The compressive strength is factor in Sakata concrete shrinkage prediction but the effect is not remarkable , although the shrinkage value is high , there is not remarkable difference in the value of shrinkage whatever is the value of concrete strength .

7.7.7 MC-2010

the relative humidity have remarkable impact on the concrete shrinkage in long term but in short term there is not big difference in the shrinkage value .

different to the EC-2 the shrinkage behavior doesn't stabilize 100% with time .

the cement effect according to MC-2010 have a minor sensitivity in short and medium term but it have remarkable effect the difference between cement types starts from long term the cement type 52.5R is the most cement exposed to the shrinkage risk.

The MC-2010 model use the Average compressive strength (fcm) in drying shrinkage and autogenous shrinkage .

in total shrinkage which is the summatory of drying and autogenous shrinkage the fcm have stable behavior since the first day the difference on the impact of different fcm value is small in short medium and long term , however in autogenous shrinkage the Average compressive strength have remarkable effect start in short term and medium term where the difference in the shrinkage become bigger and in long term the shrinkage value became stable .

The size of the element have different behavior of other factors according to MC-2010 model , it starts with remarkable impact in short and medium term as small is the element the shrinkage risk is bigger , nevertheless what ever is the size of element is the shrinkage value will stabilize and get the same value in long term .

8. Shrinkage behavior

8.1 Shrinkage behavior of ordinary concrete vibrated

The last title shows the impact ,influence and importance of each factor in every concrete shrinkage prediction model in individual form in function of shrinkage and time but the shrinkage models are set of factors that work together to get final shrinkage value .

To measure and see the behavior of the shrinkage estimate by the models an ordinary concrete vibrated have been to be compared by the seven shrinkage prediction model.

The next table shows the ordinary concrete vibrated components .

Concret Components	
Cements (kg ,m3)	350
Sand 0/0,315(kg,m3)	246,27
Sand 315/1 (kg,m3)	329,96
Sand1/4 (kg,m3)	350,17
Gravel4/8(kg,m3)	221
Gravel8/12(kg,m3)	636
Organic Additions	8,12
Total Water (l,m3)	189,3
Effective Water(l,m3)	175,8
Compressive strength 7 days (Mpa)	38,2
Compressive strength 28 days (Mpa)	45,2

Table 16. Ordinary concrete vibrated components .

The Next figure shows the behavior of the shrinkage in several shrinkage model under the same conditions wish are :

Relatie humidity en (%)	60
Cemente type	Cement type I
Volume/Surface ratio en (mm2)	95,23
Air content en %	3
(t) Age of concrete when en days	3
tc= ts Day when shrinkage start en days	1

Table 17. Condition of ordinary concrete vibrated

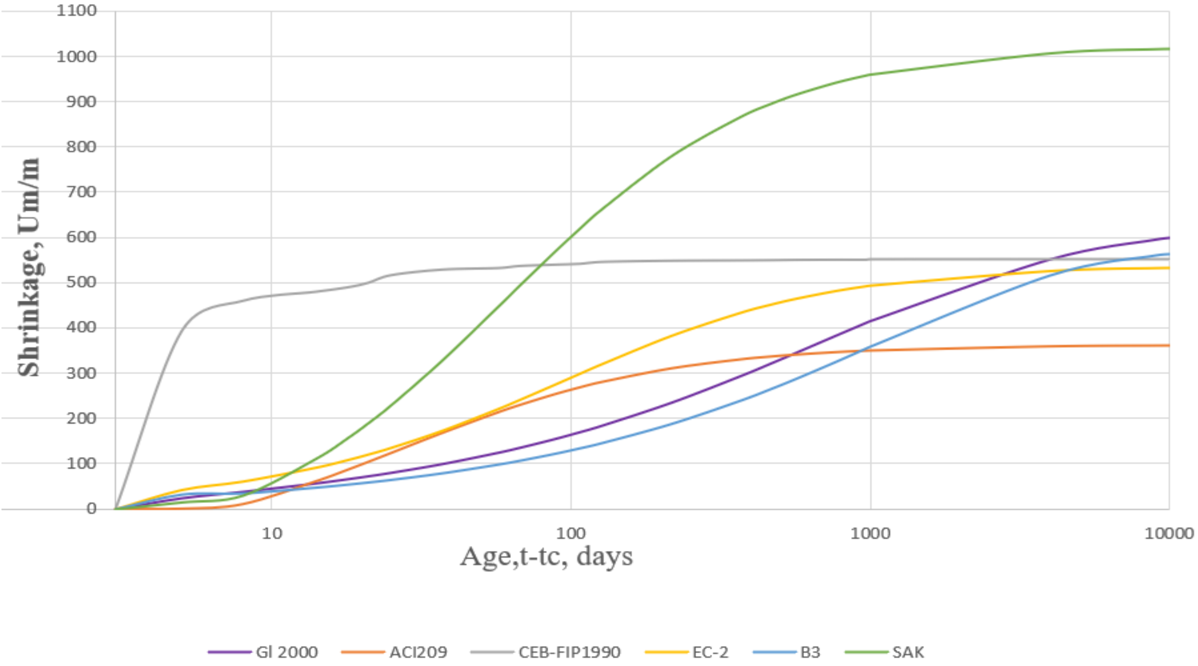


Figure 40 shrinkage behavior according to GL2000, ACI209R-92, CEB-FIP1990,EC-2,B3, SAK models .

Due to figure 40 the Sakata model is over estimated the shrinkage risk unlike the ACI209R-92 wish give the less value of the shrinkage .

The CEB-FIP1990 model is the only model whish can show the effect on shrinkage om short time but in medium term and long term the shrinkage value become stable .

The B3 ,GL2000 model have almost same behavior with small deference of shrinkage impact in time function , as well both of them have effect on large term .

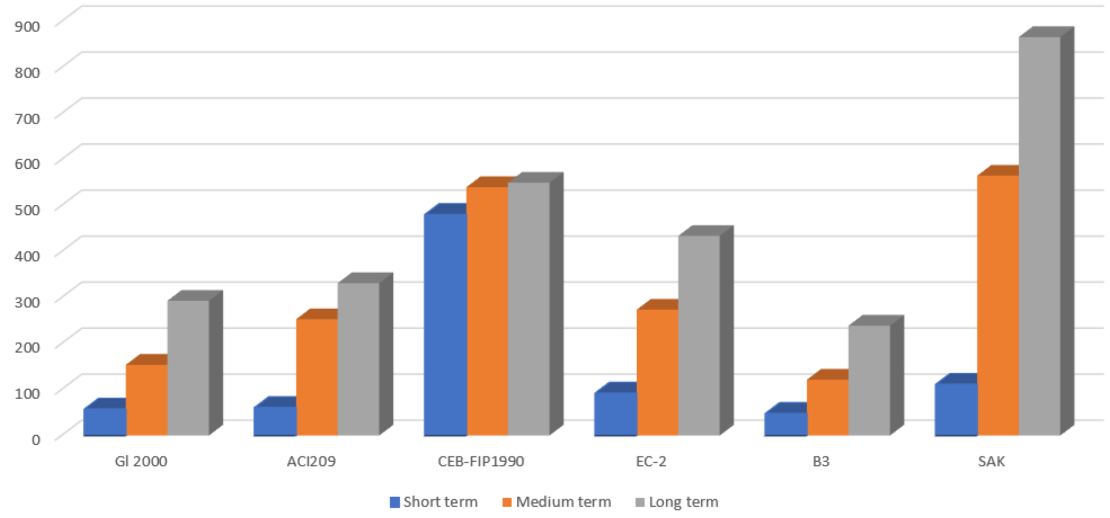
ACI and Eurocode 2 have same behavior in short and medium term , but in long term the EC-2 shows more effect on shrinkage then ACI209R-92.

The next table shows example of the value of shrinkage in short, medium and long term for each model in Um/m^{-1} .

	Short term	Medium term	Long term
DAYS	14	87	367
Gl 2000	57,073493	153,6799611	292,7902
ACI209R	60,543242	252,7022255	331,0719
CEB-FIP1990	480,08034	539,7590422	549,33287
EC-2	91,847861	273,3907334	433,74934
B3	47,787603	121,3321759	238,68556
SAK	110,90022	564,7170494	865,90372

Table 18. Value of shrinkage according to shrinkage prediction models in time terms function

Table example of shrinkage value in short, medium and long term according to all concrete shrinkage prediction models.



Graph 1 Shrinkage behavior of ordinary concrete vibrated in short , medium and long term .

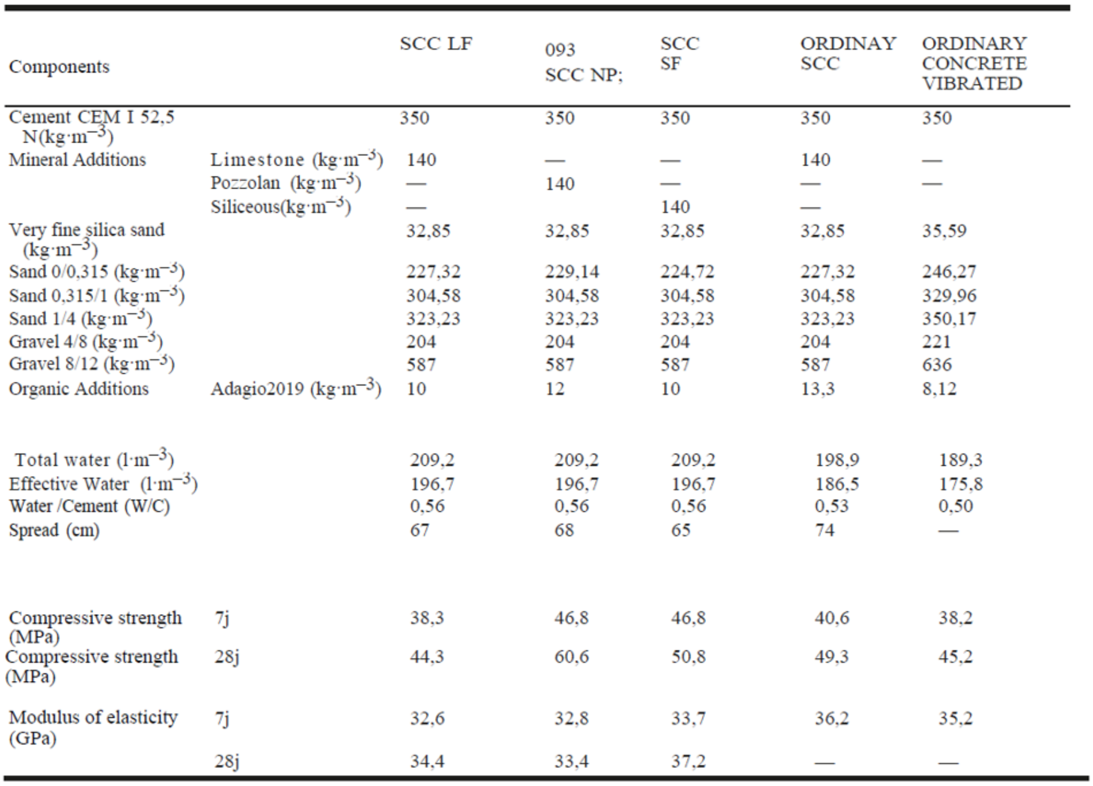
Graph 1 shows that CEB-FIP1990 have high shrinkage value at 14 days but after the value will be almost stable with small increase.

GL2000, ACI209, and B3 model have almost same shrinkage value at 14 days .

8.2 Behavior of shrinkage in self-compacting concrete with different mineral additions

Many factors effect on concrete shrinkage but not all of them are included in the concrete shrinkage prediction models one of the factors which not include in models is the mineral addition because most of the models are create to measure drying shrinkage, in fact the mineral addition have effect more in the autogenous shrinkage.

to study the fresh behavior in short and long-term , three self-compacting have been chosen with the same mix proportions, Only the nature of their mineral additions was different .



Components		SCC LF	093 SCC NP;	SCC SF	ORDINAY SCC	ORDINARY CONCRETE VIBRATED
Cement CEM I 52,5 N(kg·m^{-3})		350	350	350	350	350
Mineral Additions	Limestone (kg·m^{-3})	140	—	—	140	—
	Pozzolan (kg·m^{-3})	—	140	—	—	—
	Siliceous(kg·m^{-3})	—		140	—	
Very fine silica sand (kg·m^{-3})		32,85	32,85	32,85	32,85	35,59
Sand 0/0,315 (kg·m^{-3})		227,32	229,14	224,72	227,32	246,27
Sand 0,315/1 (kg·m^{-3})		304,58	304,58	304,58	304,58	329,96
Sand 1/4 (kg·m^{-3})		323,23	323,23	323,23	323,23	350,17
Gravel 4/8 (kg·m^{-3})		204	204	204	204	221
Gravel 8/12 (kg·m^{-3})		587	587	587	587	636
Organic Additions	Adagio2019 (kg·m^{-3})	10	12	10	13,3	8,12
Total water (l·m^{-3})		209,2	209,2	209,2	198,9	189,3
Effective Water (l·m^{-3})		196,7	196,7	196,7	186,5	175,8
Water /Cement (W/C)		0,56	0,56	0,56	0,53	0,50
Spread (cm)		67	68	65	74	—
Compressive strength (MPa)	7j	38,3	46,8	46,8	40,6	38,2
Compressive strength (MPa)	28j	44,3	60,6	50,8	49,3	45,2
Modulus of elasticity (GPa)	7j	32,6	32,8	33,7	36,2	35,2
	28j	34,4	33,4	37,2	—	—

Table 19. components of SCC concretes with mineral additions.

8.2.1 effect of mineral additions on total shrinkage according to concrete prediction model .

Shrinkage behavior on self-compacting concrete

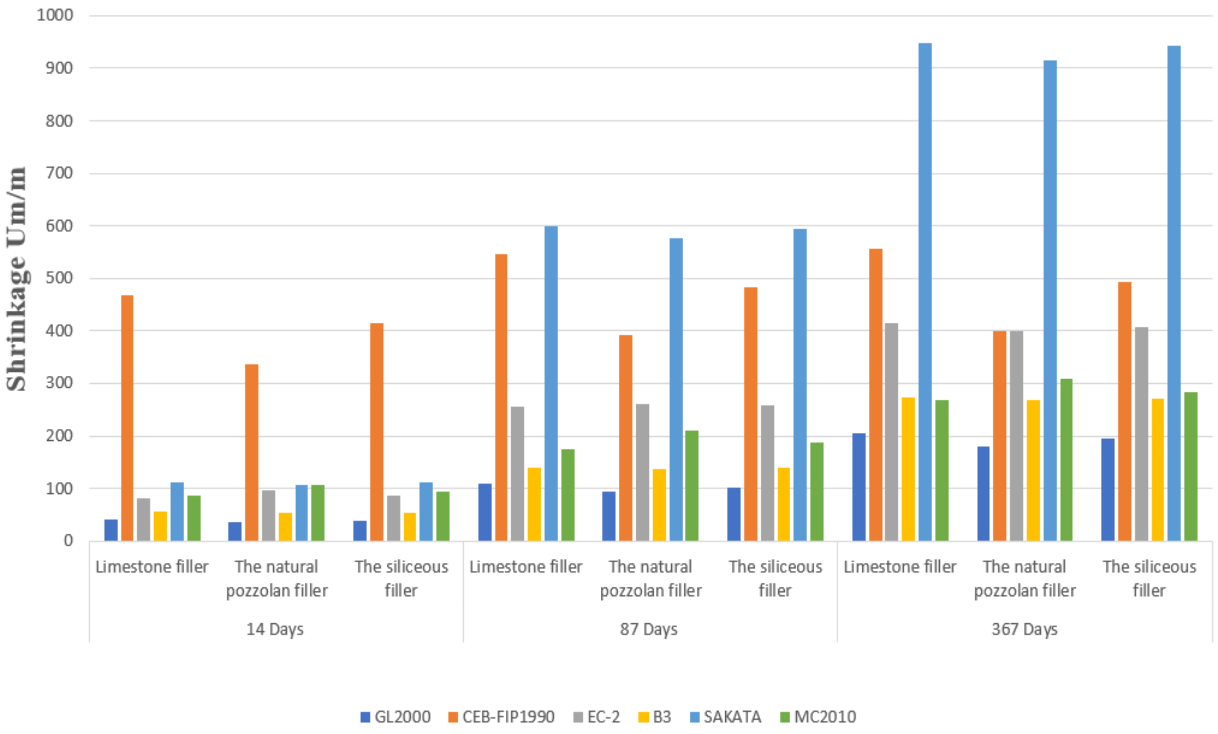


Figure effect of mineral addition on the shrinkage behavior .

According to figure the mineral doesn’t have big influence on the total shrinkage however in autogenous shrinkage it have small effect because the some mineral addition increases the compressive strength .

The concrete with natural pozzolan filler is the addition exposed to the shrinkage and the concrete silicious filler addition is the most exposed to the shrinkage risk.

8.3 Shrinkage in SCC concrete according to studies .

In recent years, numerous studies have been published on various aspects related to retraction in SCC, . Most research focuses on the influence of various aspects related to the dosage of mixtures.

This includes factors such as: the type and content of additions, cement, and aggregates and the relationships that characterize the mixture, such as the water / cement ratio, and the sand / total aggregate ratio.

There are also studies on the different types of shrinkage: autogenous, drying and plastic shrinkage, and some on the duration and type of concrete curing. The following is a brief summary of some studies of interest.

(skominas, 2013) [66],studied the shrinkage in mixtures of SCC with different limestone filler contents in prestressed pieces. The results showed that the limestone filler content does not influence the shrinkage of the concrete.

(hoseinian, 2003),[67] investigated the shrinkage of SCC exposed to different environmental conditions.

In this investigation, changes in temperature and humidity were considered. The results indicate that, in general, the shrinkage of SCC is bigger than the normal concrete exposed to similar environmental conditions.

(J.J, 2015) [68], studied the effect of several factors: paste volume, gravel / sand ratio, superplasticizer content, and compressive strength, on SCC shrinkage in steam-cured specimens. Chopin concluded that the compressive strength is the most determining factor in the shrinkage of the SCC, he also concluded that the volume of paste does not necessarily imply greater shrinkage, Moreover the type of additions can also influence the magnitude of autogenous shrinkage of the SCC.

(Alghazali & Myers, 2020)[69] ,concluded that the shrinkage in SCC is around 20% higher than in normal concret due to the lower content of aggregate in SCC.

(Leemann & Lura, 2014)[70] ,compared the shrinkage of scc and normal concerete with compressive strength, fc28, of 63 MPa.

The shrinkage, after 84 days, was similar for both concretes, with values of 700 and 660 µm / m for the normal concrete and SCC.

(Kumar, Palanisamy Murthi, & Sathis , 2020)[71] analyzed the behavior of SCC with a high content of fly ash.

Nine mixtures of SCC and one of normal concrete were used.

All mixtures contained 400kg /m^3 of powder (cement plus fly ash), and the water / powder ratio varied between 0.35 and 0.45. 40, 50, and 60% of the type F fly ash cement. According to the results, the compressive strength decreased with the increase in the fly ash content, with values between 26 and 48 MPa.

No notable differences were observed between the retraction of the SCC and the normal concret , with values between 504 and 851 µm/m, respectively, at 224 days. The HC shrinkage at this age was 541 µm/m.

(V.Prahatheswaram, 2022)[72] studied the mechanical properties and deformations of SCC, it was detected that the plastic shrinkage of SCC is up to four times greater than that of normal concrete .

(V.Prahatheswaram, 2022) [72] believes this is due to the low water / powder ratio and the delay in setting of SCC due to the high content of superplasticizers.

In relation to the total shrinkage (drying and autogenous), the shrinkage of SCC and normal concrete is similar, with values between 500 and 600 µm / m.

Regarding autogenous shrinkage, it was observed that it was higher in the SCC, with a value of 250µm/m, after 140 days, compared to 150 µm / m, of the normal concrete .

According to (Tu & Yan hua Zhang, 2012) [73] the aggregate size distribution significantly influences the shrinkage in SCC. Shrinkage was less in mixes with a dense distribution.

.According to this research, the evaporation of water decreased in this order: open distribution <straight <dense.

Mixes with les pasta volume show less shrinkage. Incorporation of silica fume increases shrinkage during the first two to three weeks.

chapter 7 conclusion and future lines

The phenomenon of shrinkage is so common and it starts to since the hydration of the concrete and can continue to many years .

The risk of concrete shrinkage can be different with concrete type , concrete with small water/cement ratio are more exposed to autogenous shrinkage however concrete with high water/cement ratio are more exposed to drying and plastic shrinkage .

The curing of the concrete is very important to limit the evaporation of water in concrete.

The temperature have important role in plastic ,drying and autogenous shrinkage while relative humidity have effect the plastic and drying shrinkage .

The phenomenon of shrinkage can be evaluated in different ways , there exist many stands to evaluate it but almost of them are similar .

techniques to study shrinkage in concrete, change depending on several factors like unit used in the countries and the type of concrete

the standard method ASTM C 157 can be effective only in drying shrinkage .

ASTM C 1579 – 06 can be used to evaluate plastic and drying shrinkage . This test method covers the determination of changes in length due to causes other than externally applied forces and temperature changes in laboratory-made hardened hydraulic-cement concrete and mortar specimens exposed to controlled conditions of temperature and humidity.

There are few test to evaluate the autogenous shrinkage the ASTM C1698-09 is the most common however this tast can be used just for mortar,This test method measures the apparent deformation of a sample of sealed cement mortar from early age deformation

ASTM C 1581 is useful in determining the relative probability of early cracking of different cementitious mixtures

Shrinkage has complex mechanisms involving many interrelated factors, and there is no single theory which can fully explain these mechanisms.

The average compressive strength have small sensibility as factor in the shrinkage prediction model GL2000.

ACI209R-92 is not adopted to evaluate the SCC concrete and does not use the average compressive strength as factor .

ACI209R-92 is the only model which use the air content and cement quantity as factors however this factor have small sensitivity .

Most of the factors in CEB-FIP1990 shows important impact of the shrinkage in short time .

The Eurocode 2 and MC-2010 are the only models which include the autogenous shrinkage in the function to predict the shrinkage.

The Eurocode 2 and MC-2010 have similar function to calculate the drying shrinkage and similar factors

The EC-2 is the only model which use the average compressive strength (fcm) and the mechanical compressive strength (fck) at the same time in the shrinkage perdition function .

The model B3 of Bazant have the highest number of factors while MC-2010 have the lowest number of factors

All the factors of the B3 model have shrinkage impact in long term except of the factor of volume/surface ratio.

The mechanical compressive strength have small intensity as factor in the B3 model

The B3 and Sakata shrinkage prediction model are the only models which use the water /cement ratio as factor.

Sakata model shows the highest value of shrinkage comparing to other models

Most of the shrinkage model are created to predict the drying shrinkage moreover the relative humidity is the principal factor with important impact in all the models.

Not all the shrinkage prediction use the same classification of the concrete ,where GL2000 and B3 used the American classification according to ASTM standers while MC-2010, CEB-FIP 1990, EC-2 and SAK models used the European classification.

The B3 and GL2000 have similar estimation for the ordinary concrete while the SAK have the highest estimation of shrinkage how ever ACI209 have the lowest estimation .

The mineral addition have so small impact on the concrete shrinkage, however it have small effect on the autogenous shrinkage some mineral addition increases the compressive strength.

All models are dedicated to ordinary concrete but MC-2010 have modificative function for lightweight aggregate concrete

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