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# Properties of fresh and hardened concrete

Priji.e.Moses[1], Prof. Dr. T.e. Kanchanabhan[2]
[1]*Research Scholar, Bharath University, Chennai*
[2]*Bharath University, Chennai*

***Abstract:*** *The present paper reviews the literature related to the properties of fresh and hardened concrete. Workability and fundamental rheological properties, reversible and non-reversible evolution, thixotropy, slump loss, setting time, bleeding, segregation and practical issues related to formwork filling and pressure, are addressed among the properties of fresh concrete.*
*Among hardened concrete properties compressive strength and other mechanical and physical properties of hardened concrete, such as tensile strength, elastic properties, shrinkage, creep, cracking resistance, electrical, thermal, transport and other properties are covered. Testing, interpretation, modeling and prediction of properties are addressed, as well as correlation with properties of fresh concrete and durability, effects of special binders, recycled and natural aggregates, fiber reinforcement, mineral and chemical admixtures. Special attention is given to the properties of hardened lightweight and self-compacting concrete.*

***Keywords :***
- *Fresh concrete (A);*
- *Hardened concrete;*
- *Portland cement (D);*
- *Properties (C)*

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## I. Introduction

The paper has been prepared jointly by Konstantin Kovler and Nicolas Roussel, while the second author was in charge of the properties of fresh concrete, and the first author dealt with those of hardened concrete.

Workability and fundamental rheological properties, reversible and non-reversible evolution, thixotropy, slump loss, setting time, bleeding, segregation and practical issues related to formwork filling and pressure are addressed among the properties of fresh concrete.

Properties of hardened concrete cover compressive strength, tensile strength, elastic properties, shrinkage, creep, cracking resistance, electrical, thermal, transport and other properties.

Special attention is given to the aspects of testing concrete properties, interpretation of test results, modeling and prediction of properties, as well as to correlation with properties of fresh concrete and durability, effects of special binders, recycled and natural aggregates, fiber reinforcement, mineral and chemical admixtures, and properties of special concretes.

## II. Properties of fresh concrete

### 2.1. Workability and fundamental rheological properties

Fresh concretes, as many materials in industry or nature, behave as yield stress fluids. There exists therefore a minimum value of the stress applied to the material for irreversible deformation and flow to occur. The behavior of fresh concrete in steady state is thus often approximated by a yield stress model of the following general form [1], [2], [3] and [4]:

Equation(1a)

$\dot{\gamma}=0 \rightarrow \tau<\tau 00$

Equation(1b)

$\dot{\gamma}\neq 0 \rightarrow \tau=\tau 00+f(\dot{\gamma})$

where$\tau 00$ (Pa) is the yield stress, $\dot{\gamma}$ (s− 1) the shear rate and $f$ is a positive continuously increasing function of the shear rate with $f(0) = 0$. Concretes are often described as Bingham fluid with a plastic viscosity $\mu p$ (Pa s), $f(\dot{\gamma}) = \mu p \dot{\gamma}$ [1].

This behavior results from a complex interplay between numerous physical phenomena, the understanding of which is still ongoing [3] and [4]. It can be kept in mind at this stage that the broad poly-dispersity of concrete components implies at least four main types of interactions (surface forces (or colloidal interactions), Brownian forces, hydrodynamic forces and various contact forces between particles). Depending on the size of the particles, on their volume fraction in the mixture and on external forces (e.g. the magnitude of either the applied stress or strain rate), one or several of these interactions dominate [5] and [6].

From both a workability and practical point of view, yield stress may be associated to filling capacity and more generally to whether or not concrete will flow or stop flowing under an applied stress whereas plastic viscosity may be associated to the velocity at which a given concrete will flow once flow is initiated. It can be noted that, in the field of concrete casting unlike polymer or metal casting, the applied stress is mainly due to gravity.

Although measurements of plastic viscosity have several practical applications (pumping, casting rates…), yield stress is the most important parameter for formwork filling in practice [1] and [7]. During an industrial casting process, a purely viscous fluid (i.e. no yield stress) would self level under the effect of gravity and the viscosity of the material will dictate the time needed to obtain a horizontal surface. In the case of a yield stress fluid such as concrete, if the shear stress generated by gravity during casting, which is a complex function of formwork shape and local density of steel reinforcements, becomes lower than the yield stress of the concrete, flow may stop before the concrete self levels or before the formwork is entirely filled.

### 2.2. Measurement of rheological properties

Yield stress is a unique material property and may, in the case of cement pastes (i.e. fine particles), be measured using conventional rheological tools such as Couette Viscometer [8] or parallel plates rheometer [9]. In the case of fresh concrete because of the coarse aggregates, large scales rheometers had to be developed [10], [11] and [12]. Even if, in situ, simpler and cheaper tests such as the slump test [13] are still often preferred, these apparatus represent a big step forward in the field of concrete science. However, there still exists a discrepancy between the various concrete rheometers [14] and [15]. Although they reach the same rheological classification of materials, they do not measure the same absolute values of the rheological parameters (i.e. $\tau 00$ and $\mu p$).

Concerning the measurement of yield stress, it has been demonstrated over the years that the result of the slump test, the most common industrial test for fresh concrete, can be correlated in specific conditions to the yield stress of a given concrete.

It is generally admitted that, similar to casting, during a slump test, flow stops when shear stress in the tested sample becomes equal to or smaller than yield stress [2]. Consequently the shape at stoppage is directly linked to the material yield stress. From a practical point of view, in civil engineering, two geometrical quantities may be measured, the ―slump‖ or the ―spread‖. The slump is the difference between the height of the mold at the beginning of the test and after flow stoppage. The spread is the final diameter of the collapsed sample. In most of the applications of the ASTM Abrams cone, the initial height of which is 30 cm, the slump is measured if it is smaller than 25 cm, otherwise the spread is measured (slump flow test for SCC).

Following the pioneering work of Murata [2], subsequent works established analogous relationships either for conical or cylindrical molds [16], [17], [18], [19], [20] and [21]. However, in the case of some conical molds or in the case of high yield stress values (i.e. low slumps) with cylindrical molds, a systematic discrepancy between predicted and measured slumps was obtained. Two different regimes, one regime of low slumps and one regime of large spreads, were recently identified [22]. Two analytical solutions describing these asymptotic regimes, namely large height to diameter ratio or large diameter to height ratio, are available in literature [23] and [24]. Numerical simulations of the slump test were also carried out for the ASTM Abrams cone [23]. An excellent agreement between predicted and measured slumps over a wide range of yield stress was obtained. It may be useful to remind here this correlation for slumps between 5 and 25 cm.

Equation(2)

$S=25.5-17.6\tau 00\rho$

with$S$ the measured slump and $\rho$ the density of the tested concrete.

### 2.3. Effect of time on fresh properties

#### 2.3.1. Reversible evolution and thixotropy

In the case of many modern cementitious materials, the knowledge of the yield stress at the end of the mixing phase is not sufficient to describe the observed behavior from the concrete mixing plant to the casting phase. An evolution of the material rheological behavior is often noted during this time period. This evolution is mainly due to the thixotropic behavior of cementitious materials.

Several authors [25], [26], [27], [28], [29], [30], [31], [32], [33] and [34] have demonstrated that, when left at rest, concrete builds up an internal structure. Its apparent (or static) yield stress increases whereas, when flowing, the material fluidity increases at a rate which increases with the applied shear rate.

It has been shown recently in [29], [30] and [34] that this evolution in the case of cement pastes can be correlated to the applied shear rate and to the recent flow history of the material. From a practical point of view, concrete often reaches its most destructured state during the mixing phase. According to its flow history between the mixing plant and the formwork (mixing truck, rest period, casting phase…), its apparent yield stress (or static yield stress) continuously evolves whereas its intrinsic yield stress (or dynamic yield stress), which is only linked to the mix design of the material, does not change.

From all of the above, it can be concluded that, in practice, a concrete is called thixotropic if it seems to build up a structure rather quickly at rest and becomes reversibly apparently more and more fluid while flowing. It has to be noted that, to be rigorously correct, all concretes, as a majority of mineral suspensions, are thixotropic. However, in the opinion of the present authors, it can be admitted that, in practice, a ―thixotropic concrete‖ is a concrete displaying a rather short structuration characteristic time (typically several minutes) and a de-structuration characteristic time of several tens of seconds in the 1 to 10 $s^{-1}$ shear rate range of industrial interest [34].

It has to be noted that, between the two aspects of thixotropy described here (structuration at rest and de-structuration under flow), the understanding and measuring of the first one is far more important from a practical point of view. In the potential points of practical interest such as formwork pressure, concrete is indeed not flowing. It is at rest and what really matters is the increase of its apparent yield stress. That is why recent approaches to quantify thixotropic behavior of fresh concrete have focused on the structuration phenomenon.

Billberg, in his recent work on thixotropy of SCC [31], has developed a very interesting method to measure the increase in apparent yield stress at rest. Measurements were performed using a concrete rheometer. Both static and dynamic yield stresses are measured in order to distinguish the reversible structuration due to thixotropy from the non-reversible evolution due to normal slump loss. Using this methodology, Billberg showed that apparent or static yield stress increases linearly with resting time. This was also reported in [34]. In both papers, the order of magnitude of the increase rate in yield stress was between 0.1 and 1.7 Pa/s. Finally, it can be noted that industrial methods allowing for simple, fast and cheap measurements of structuration rates have been recently developed [35].

### 2.3.2. Non-reversible evolution and slump loss

Unfortunately, in the case of concrete, things are more complex as hydration processes start as soon as cement and water are mixed together. The intrinsic or dynamic yield stress of the material is permanently and chemically evolving as described by Otsubo and co-workers [25] and Banfill [26]. Recently, Jarny and co-workers [32] have however shown using MRI velocimetry that, over short timescales, thixotropic (i.e. reversible) effects dominate while, over larger timescales, non-reversible processes dominate, which lead to irreversible evolutions of the behavior of the fluid. These two effects might in fact act at any time but, according to the above scheme, they appear to have very different characteristic times. As a consequence it is reasonable to consider that there exists an intermediate period, say around 30 min, for which irreversible effects have not yet become significant. This means that it seems possible to consider the effect of thixotropy and only thixotropy on short periods of time from the last strong remixing of the material (not more than 30 min as an order of magnitude) during which the irreversible evolutions of concrete can be neglected. When it is not the case, the material fluidity can strongly decrease and slump loss may be measured at an early stage of the casting process.
It can moreover be kept in mind that compatibility problems or delayed action of polymers may also be at the origin of slump loss or more generally dynamic yield stress evolution [36], [37], [38] and [39]. This complex topic at the boundary of physics and chemistry is however out of the scope of this paper.

### 2.3.3. Hydration and setting time

As discussed above, because of thixotropy and non-reversible effects, apparent yield stress is continuously increasing. It is now accepted that the flocculated structure of the cement grains is fixed just after mixing or remixing and that it does not change. Only the amplitude of the interaction force is changing with time. Moreover, no particular evolution occurs at the time of setting. Setting time of concrete is therefore only a technological parameter, defined according to standards [40].

Various empirical tests are used to study the hardening and setting of cementitious materials. These are sometimes alternatively described as consistency or setting time measurements. These tests include the Vicat needle, penetrometers of various shapes and the proctometer also known as the Proctor needle, as well as the Hilti nail gun [41]. Some of these techniques measure the penetration resistance (i.e. penetration force) under an imposed speed, while others measure the penetration depth for an imposed load.

The recent developments in ultrasound spectroscopy [42], [43], [44], [45], [46] and [47] and in oscillating rheometry [40] and [48] allows for the measurement of the evolutions of both shear and bulk elastic moduli during setting of cement paste. Based on these new techniques, recent papers showed the existence of a relation between shear yield stress and the empirical setting time measurements [40] and [49]. These correlations show that what is defined as initial setting time corresponds to a yield stress of the material of the order of a couple hundred kPa (to be compared to the few Pa or tens of Pa of a freshly mixed cement paste).

### 2.4. Stability of fresh concrete

Concrete is a multiphasic material. The densities of the numerous components entering traditional concrete mix fitting vary between 1000 kg/m3 (water) and 3200 kg/m3 (cement). Even lighter material may be used in the case of lightweight concrete. With such a mixture, gravity quickly becomes the enemy of homogeneity. In the field of cementitious materials, heterogeneities induced by gravity are divided in two categories depending on the phase that is migrating: bleeding and segregation. Both are induced by the density difference between the components but bleeding phenomenon is concerned with water migration whereas segregation is concerned with the movement of the coarsest particles.

#### 2.4.1. Cement paste and bleeding

Bleeding (i.e. the accumulation of water at the surface of the paste) of a potentially usable fluid cement paste shall be neglectable. It results from the difference in density between cement grains and water. Bleeding, in the range of interest of industrial cementitious materials, cannot be described as the settlement of individual cement grains in a dilute system but rather as a consolidation process (i.e. the upward displacement of water through a dense network of interacting cement grains) [50], [51] and [52]. The interactions between cement grains and permeability of freshly mixed cement pastes are therefore first order parameters of a cement paste resistance to bleeding. The bleeding phenomenon can be slowed down by the viscous nature of the interstitial fluid, which has to travel to the surface under the effect of gravity. Viscosity agents can therefore be used to reduce the amplitude of bleeding before setting [53]. They are able to thicken the interstitial water and slow down the bleeding phenomenon. This may reduce the practical consequences of bleeding and make them neglectable from an industrial point of view.

#### 2.4.2. Aggregates and segregation

Attempts to correlate rheology of fresh concrete to stability can be found in literature [54] and [55]. Figures linking either empirical test results or even quantitative measurement of segregation to slump or slump flow for a given concrete have often been plotted. Although a correlation may, in certain cases, be obtained, it has to be kept in mind that segregation is a multi-phasic separation phenomenon (the minimum number of phases is two: a suspending fluid and some solid inclusions). As such, the only relevant approach is a multi-phasic one. The rheological behavior of concrete has no role to play; only the rheological behavior of the suspending fluid(s) does matter. When correlations between concrete behavior and stability are measured, it is only because concrete behavior is strongly linked to the behavior of its suspending fluid(s).

Segregation (or stability) is often associated to static sedimentation. The particles settle in a given sample or in the formwork as their density is higher than the density of suspending fluid. However, it must not be forgotten that, if the inclusions density is lower than the suspending fluid density, the situation may be reversed. This is the case for instance for lightweight concretes. The physical phenomena are of course the same no matter the direction in which the particles are moving. Moreover, it must not be forgotten that some other reasons than gravity may induce segregation. Indeed, obstacles or confined flows may generate flow conditions in which the suspending fluid is not able to ―carry‖ its particles.

It was shown in [56], [57] and [58] that yield stress of the constitutive cement paste or mortar is the key parameter of concrete stability. Viscosity alone, although it plays a strong role in the dynamic segregation induced by flow [59], is not able to stabilize the coarsest particles at rest [57]. Thixotropy of the suspending phase (mortar or cement paste) can improve the ability of the material to stay homogenous during the ―dormant‖ period until setting by increasing the apparent yield stress of the suspending phase.

### 2.5. Fresh concrete properties and casting prediction tools

A lot of work has been carried out in order to understand the correlation between mechanical properties and mix design and many tests have been developed in order to measure these mechanical properties (mechanical strength and delayed deformations for instance) but, on the other hand, many developments were also carried out in the field of structural engineering in order to correlate the needed properties of the concrete to be cast with the structure to be built. This last step has been missing for years in the fresh concrete properties field. Only recently, researchers have started to work on casting prediction tools. It can be noted that this new research area has appeared at the same time as Self Compacting Concretes. This extremely fluid concrete was expected to be the answer to casting problems. However, it has to be kept in mind that, no matter how fluid a concrete is, there will always exist a formwork and steel bars configuration in which casting problems may occur.

#### 2.5.1. Formwork filling

As discussed above, the ideal mix design of a fluid concrete is located somewhere between two opposite objectives. On one hand, concrete has to be as fluid as possible to ensure that it would fill the formwork under its own weight. On the other hand, it has to be a stable mixture. Therefore, a compromise between stability and fluidity has to be reached. The most straightforward approach is to find the minimum fluidity (or workability) that will guarantee the adequate filling of the formwork and assume that this minimum fluidity will ensure an acceptable stability. The only available method in the traditional toolbox of the civil engineer is to try various mix design and, for each of them, cast the real size element and choose the most suitable mixture (if there is one). This is expensive, time consuming and does not guarantee that an answer will be obtained. However, in the case of stable fluid concretes, the numerical tools of non-Newtonian fluid mechanics become available. They allow the numerical simulation of the casting phase and, for a very low economical cost, the determination of the minimum needed fluidity.

Mori and Tanigawa [60] first demonstrated the applicability of Viscoplastic Divided Element Method (VDEM) to simulate the flow of concrete in a reinforced beam section and the filling of a reinforced wall. Kitaoji et al. [61] confirmed the applicability of 2D VDEM to simulate the flow of fresh concrete cast into an unreinforced wall. The results of a form filling experiment in a vertical wall have also been compared with the corresponding 3D simulation [62]. The results show good correlation with respect to detection of free surface location, dead zones and particle paths.

Numerical simulations were also applied to an industrial casting of a very high strength concrete pre-cambered composite beam in [63]. The results of the simulations carried out for various values of the rheological parameters (Bingham model) helped to choose the target value of the minimum fluidity needed to cast the element. The numerical predictions were validated by experimental observations of two trail castings. Although the assumptions needed to carry out the simulations were over-simplistic, a satisfactory agreement was found between predicted and measured concrete flow.

It is the opinion of the present authors that, in the future, computational modeling of flow could become a practical tool allowing for the simulation of either total form filling as described above or detailed flow behavior such as particle migration, orientation of fibers and formation of granular arches between reinforcement (―blocking‖) [64], [65], [66] and [67].

**2.5.2. Formwork pressure**

The consequences of thixotropy on casting processes are numerous but, in the last few years, for economic reasons, research has mostly focused on formwork pressure issues. In most of the current building codes or technical recommendations [68], [69], [70] and [71], the mainparameters affecting formwork pressure during casting are the density of concrete, the formwork dimensions, the pouring rate of concrete, the temperature, and the type of binder and admixture.

However, it was recently demonstrated that, in the case of modern fluid concretes such as SCC, the thixotropic behavior of the material plays a major role [72], [73], [74], [75] and [76]. It can be noted that this influence was in fact indirectly taken into account in the above semi-empirical technical recommendations via the effect of temperature and type of the binder, which are both strongly linked to the ability of the material to build up a structure at rest.

During placing, concrete behaves as a fluid but, as described above, if cast enough or if at rest, it builds up an internal structure and has the ability to withstand the load from concrete cast above it without increasing the lateral stress against the formwork. It was demonstrated in [74] and [75] that, for a SCC confined in a formwork and only submitted to gravity forces, the lateral stress (also called pressure) at the walls may be less than the hydrostatic pressure as some shear stress is supported by the walls. It was also demonstrated that this shear stress reached the value of the yield stress, which itself increased with time because of thixotropy. Finally, if there is no sliding at the interface between the material and the formwork, the yield stress (not less or not more) is fully mobilized at the wall and a fraction of the material weight is supported (vertically) by the formwork. The pressure exerted by the material on the walls is then lower than the value of the hydrostatic pressure.

As apparent yield stress is increasing with time because of thixotropy and hydration, formwork pressure decreases. During casting, the increase in apparent yield stress allows for a reduction in pressure. This is in competition with the casting process, which, by increasing the concrete height in the formwork, increases formwork pressure. If the concrete is thixotropic or if the casting rate is sufficiently low, the effect of structural build up will dominate and pressure will be far lower than hydrostatic pressure. Inversely, for non thixotropic concrete and high casting rates, pouring will dominate and pressure will be close to hydrostatic pressure. Khayat has shown in [77] that most models proposed in literature were based on these two aspects and that they were all able to predict accurately formwork pressure allowing for a reduction in the formwork cost during a casting process.

## III. Properties Of Hardened Concrete

The present chapter reviews the literature related to the properties of hardened concrete published after the previous congress (the 12th International Congress on the Chemistry of Cement (Montreal, 2007)). The focus is given on compressive strength, which is considered as the main engineering property of concrete. The rest of mechanical and physical properties of hardened concrete, such as tensile strength, elastic properties, shrinkage, creep, cracking resistance, electrical, thermal, transport and other properties, are addressed as well. A certain number of works addressing strength and other properties of hardened concrete have been published with the goal to develop new methods of testing, to interpret test results, to model and predict the development of properties in time or under specific mechanical or environmental loading. However, during preparation of the present state-of-the-art it was discovered that most of the papers on concrete properties address not the properties themselves, but rather their influence on numerous different factors (such as different type of loading, or introduction of chemical or mineral admixtures, recycled aggregates etc. into concrete mixes), or the properties of certain types of concrete, such as lightweight, self-compacting, fiber-reinforced, high-strength and other types of concrete. In view of this, the paper starts with the general review of hardened concrete properties and continues with reviewing of the properties of different types of concrete and of the effects caused by the replacement of conventional concrete constituents (Portland cement and aggregates) with new or special materials (including industrial by-products with cementitious or pozzolanic properties), or by their introduction to concrete mixes.

About 34,000 papers on properties of hardened concrete have been published in the years 2007–2010. This number exceeds by ~ 20% that in the 4 years preceded the previous (12th) International Congress on the Chemistry of Cement held in Montreal in 2007 (Fig. 1). As will be demonstrated in further sections, in some fields, such as in properties of hardened self-compacting concrete (SCC) and concrete made with recycled aggregates (RA), the real boom with publications has been observed in the last few years.

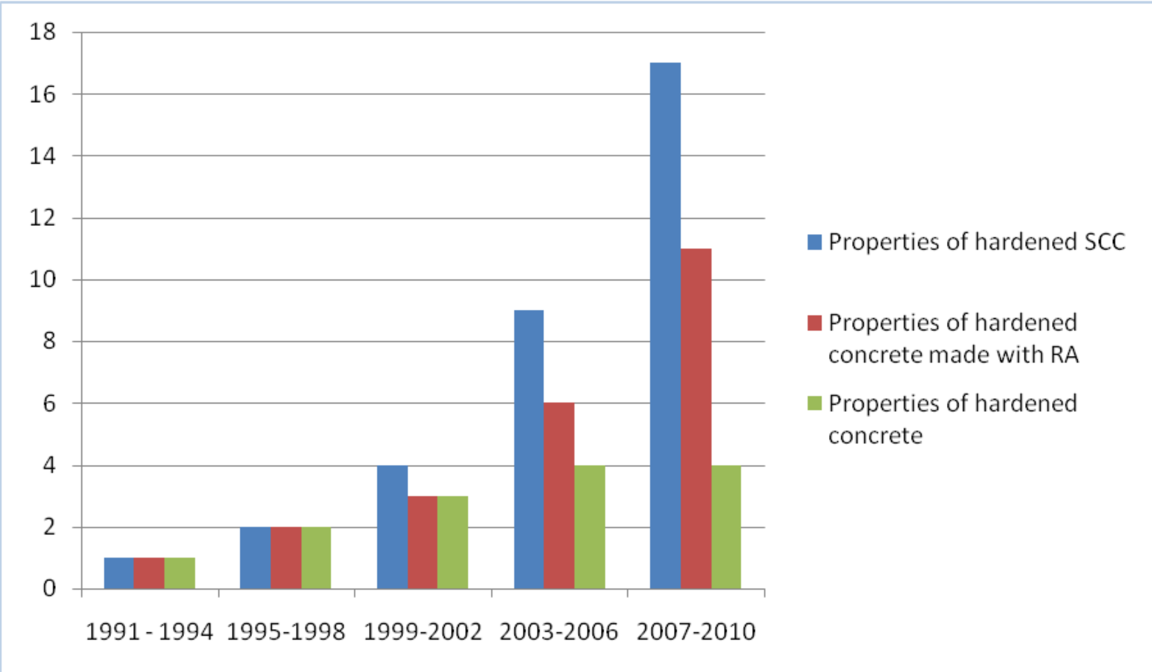


**Fig 1**

Growth in publications on properties of hardened self-compacting concrete (SCC), concrete made with recycled aggregates and concrete in general.

### 3.1. Testing and interpretation

Mechanical concrete properties at high temperatures depend on many parameters. The main parameters are the specimen type and the test conditions. The report [78] describes the test parameters and test procedures for relaxation tests in the range of 20 to 750 °C.

The paper [79] describes microwave reflection and transmission properties measured from various sides of hardened mortar and concrete specimens with different water-to-cement (w/c) ratios. These properties are important in predicting/measuring accurate electrical properties of cement-based materials which can eventually be utilized in structural health monitoring, public safety, and propagation-related research.

The paper [80] proposes a critical analysis of the studies since the 1950s attempted to quantify the influence of specimen shape on the determination of concrete compressive strength, with special regard to the problem of conversion from cylinder to cube strength and vice versa. To obtain quantitative predictions and to investigate on the influence of the friction between the platens of the testing machine and the concrete specimen, uniaxial compressive tests are numerically simulated by using a nonlinear finite element model.

Accurate determination of the compressive strength of very high strength concrete is difficult due to large testing machine capacity requirements and the need for cylinder end preparation. An experimental program was conducted to determine whether alternate specimen types can be reliably used to determine the compressive strength of an ultra-high-performance fiber-reinforced concrete (UHPFRC) in the strength range from 80 to 200 MPa [81]. The 76 mm cylinders as well as the 70.7 and 102 mm cubes are found to be acceptable alternatives to the standard 102 mm cylinders. The 70.7 mm cube specimen is recommended for situations where machine capacity and/or cylinder end preparation are of concern.

The compressive strength of normal strength concrete at elevated temperatures up to 700 °C and the effect of cooling regimes were investigated and compared [82]. Strength loss was more significant on the specimens rapidly cooled in water.

Most standardization agencies allow small-cylinder specimens (100 × 200 mm) to be used in compressive strength concrete testing. Some engineers are still skeptical about using small cylinders, however, as they believe that compressive strength testing results from small cylinders are too varied. Limited studies have been conducted regarding the precision of small cylinders compared to precision studies for conventional cylinders (150 × 300 mm). The paper [83] describes the results of a comparative concrete testing program conducted by 15 laboratories in Edmonton, Canada, over the past 10 years.

An integrated software package for performing simulations of a number of engineering test measurements, including isothermal calorimetry, adiabatic temperature change, chemical shrinkage, elastic moduli, and compressive strength, has been developed recently [84].

In the work [85] a program of systematic laboratory testing has been undertaken to determine the effect of displacement rates and moisture contents on concrete strength, axial strain, lateral strain and acoustic emission. Findings from those results were used to conduct a detailed analysis of the crack closure, crack initiation, secondary cracking, crack damage and peak failure of dry, partially wet and fully wet concrete specimens at displacement rates corresponding to loading rates (0.05–0.25 mm/min). The strength of wet concrete was significantly reduced in comparison with the strength of dry specimens at the same displacement rate (e.g. 25% reduction at the loading rate of 0.15 mm/min), and this reduction depended on displacement rate.

Many nondestructive methods for strength gain monitoring seem to have limited capabilities in monitoring of the strength gain in a continuous manner. Electro-mechanical impedance (EMI) sensing technique utilizing smart piezoelectric materials can serve as a tool for the implementation of an online strength gain monitoring of early-age concrete [86].

In the works [87] and [88] an effort to extend the applicability of the EMI sensing technique is made for in situ strength gain monitoring of early age concrete.

### 3.2. Modeling and prediction of properties

In the study [89] waste rubberized aggregates were used as sand in mortar production which had two different sizes, 0–1 and 1–4 mm. Flexural and compressive strengths were determined and modeled by artificial neural network and fuzzy logic methods. It is concluded that the strength decreases considerably with the content of waste rubber aggregates. The same type of modeling was used in another work of the authors dealing with properties of concrete made with waste autoclaved aerated concrete aggregate [90].

The article [91] introduces genetic programming (GP) as a new tool for the formulations of properties of self-compacting concretes (SCC). The GP based formulation is found to be reliable, especially for hardened concrete properties (compressive strength, ultrasonic pulse velocity and electrical resistivity).

A finite element-based cohesive zone model was developed using bilinear softening to predict the monotonic load versus crack mouth opening displacement curve of geometrically similar notched concrete specimens [92]. The softening parameters for concrete material are based on concrete fracture tests, total fracture energy (GF), initial fracture energy (Gf), and tensile strength (ft), which are obtained from a three-point bending configuration.

In the study [93] compression strength and physical properties of the forty concrete carrot specimens taken from some buildings which collapsed by 1999 earthquakes were investigated and the correlations between compressive strength and physical properties (ultrasound velocity and Schmidt rebound) determined. The models tried to maximize using Genetic Algorithm (GA) and Linear Programming (LP) depending on specimens' properties.

The main purpose of the paper [94] was to propose an incorporating improved grammatical evolution (GE) into the genetic algorithm (GA), called GEGA, to estimate the compressive strength of high-performance concrete (HPC).

Ultrasonic pulse velocity technique is one of the most popular non-destructive techniques used in the assessment of concrete compressive strength. However, ultrasonic pulse velocity is affected by a number of factors, which do not necessarily influence the concrete compressive strength in the same way or to the same extent. The paper [95] deals with the analysis of such factors on the velocity–strength relationship. The relationship between ultrasonic pulse velocity, static and dynamic Young's modulus and shear modulus was also analyzed. The influence of aggregate, initial concrete temperature, type of cement, environmental temperature, and w/c ratio was determined experimentally. The multi-layer feed-forward neural network was used for modeling the velocity–strength relationship.

Numerous empirical formulas have been developed for the relationship between concrete strength and w/c ratio. They are simple but have restricted limits of validity. A new type of strength formulas that have a second independent variable beside the w/c ratio, such as the cement content, or water content, or paste content, etc., is suggested in [96].

Various prediction models have been developed to predict the creep and shrinkage in concrete. RILEM has compiled the experimental studies which are stored in a computerized data bank [97]. Creep and shrinkage have been predicted up to 5000 days of observation by the ACI-209R-82 model, the B3 model, the CEB-FIP model code 1990, and the GL2000 model. Predicted values of creep and shrinkage were compared with the experimental results of Russell and Larson, in 1989, as well as the RILEM data bank. Prediction of creep and shrinkage by GL2000 model is found to be the closest to the experimental results.

Artificial neural networks (ANNs) were used to predict elastic modulus of both normal and high strength concrete [98]. The results predicted by ANN are also compared to those obtained using empirical results of the buildings codes and various models.

A micromechanics model for aging basic creep of early-age concrete is proposed in [99]. The viscoelastic boundary value problems on two representative volume elements, one related to cement paste (composed of cement, water, hydrates, and air), and one related to concrete (composed of cement paste and aggregates), have been formulated.

**3.3. Correlation with properties of fresh concrete and durability**

In several works an attempt to find a correlation between properties of hardened concrete, fresh concrete and durability, was undertaken. The following works can serve as an example.

The experimental study [100] examines the effects of mix design, formwork and consolidation on the quality of the surface of high w/c concrete. Pulse velocity, pull off strength and compressive strength were measured to evaluate the quality and mechanical properties of the hardened concrete. The results show that the rheological properties of fresh concrete can be correlated to the mechanical and permeation properties of the hardened concrete.

The experimental investigation on the frost-salt scaling resistance of air-entrained concrete containing CEM II/B-S 42.5N and CEM III/A 42.5N-HSR/NA slag-blended cements was performed in [101]. The mass of scaled material was increased for increased slag content, in spite of increased compressive and flexural strengths, decreased water absorption and water penetration depth. Increasing slag content resulted in a decrease of the total volume of air in hardened concrete and in a corruption of the air void system exhibited by a decrease of micropores content. The increase of mass of scaled material was proportional to the increase of the spacing factor of air voids, except for CEM III/A cement concrete exhibiting accelerated scaling.

The paper [102] provides an overview of the early-age properties of cement-based materials, from a materials science perspective. The major physical and chemical processes occurring at early ages are reviewed and strategies for mitigating early-age cracking are presented.

Concrete can crack during hardening, especially if shrinkage (including autogenous, thermal and drying components) is restrained. The concrete permeability due to this cracking may rise significantly and thus increase leakage and reduce durability. The restrained shrinkage ring test serves as an efficient tool to estimate cracking sensitivity. Different modifications have been suggested recently to improve the estimation, such as introducing an integrated cracking potential criterion, based on time-to-cracking and stress rate at cracking [103], and creating the thermal strain effects by increasing the temperature of the brass ring (by a fluid circulation) in order to expand it [104].

**3.4. Effect of special binders**

This study [105] investigated the use of two kinds of waste from landfills, calcium carbide residue and fly ash (FA), as a low CO2 emission concrete binder. Ground calcium carbide residue (CR) was mixed with original fly ash (OF) or ground fly ash (GF) at a ratio of 30:70 by weight and was used as a binder to cast concrete without Portland cement. The effects of FA finenesses and water to binder (W/B) ratios of CR–OF and CR–GF concretes on compressive strength, modulus of elasticity, and splitting tensile strength were investigated. The hardened concretes produced from CR–OF and CR–GF mixtures had mechanical properties similar to those of normal Portland cement concrete.

The paper [106] presents the engineering properties of inorganic polymer concretes (IPCs). The study includes a determination of the modulus of elasticity, Poisson's ratio, compressive strength, and the splitting tensile strength and flexural strength of IPCs, made with Class-F fly ash. IPC mix designs were adopted to evaluate the effects of the inclusion of coarse aggregates and granulated blast furnace slag into the mixes. The engineering properties of IPCs are close to those predicted by the relevant standards.

Hwangtoh-based alkali-activated concrete mixes were tested to explore the significance and limitations of the development of cementless concrete [107]. Hwangtoh, which is a kind of kaolin, was incorporated with inorganic materials, such as calcium hydroxide, to produce a cementless binder. The main variables investigated were the water–binder ratio and fine to total aggregate ratio. Compressive strength gain, splitting tensile strength, moduli of rupture and elasticity, stress–strain relationship, and bond resistance were measured. Test results show that the mechanical properties of hwangtoh-based concrete were significantly influenced by the water–binder ratio and to less extend by fine to total aggregate ratio.

**3.5. Effect of recycled aggregates**

The growth in publications on properties of hardened concrete made with recycled aggregates (RA), especially after the 11th International Congress on the Chemistry of Cement (Durban, 2003), is quite impressive. Fig. 1 shows that number of publications on this specific topic in the years since 2003 increased 3 times faster than in general. In most of these studies the new types of RA and their combinations were suggested and maximum replacement ratios of RA, which do not jeopardize mechanical properties of hardened concrete, were determined.

In the study [90], cylindrical compressive strength and ultrasound pulse velocity of hardened concrete were determined experimentally for concrete made with waste autoclaved aerated concrete aggregates. It is found that concrete lighter than crushed stone concrete can be produced by using this kind of RA.

Four different recycled aggregate concretes were produced in [108]; made with 0%, 25%, 50% and 100% of recycled coarse aggregates. The mix proportions were designed in order to achieve the same compressive strengths. Recycled aggregates were used in wet condition, but not saturated, to control their fresh concrete properties, effective w/c ratio and lower strength variability. The lower modulus of elasticity of recycled coarse aggregate concretes with respect to conventional concretes was found.

**3.6. Effect of natural aggregates**

The use of limestone in the construction industry has been increasing due to benefits as aggregate. Some of these benefits include good strength, low possibility of alkali–silica reaction and the decrease in drying shrinkage in concrete. The research [132] discusses the consumption and general characteristics of the limestone aggregate in USA and Japan. Then experiments were conducted on mixtures of different proportions of fine limestone and sand at different water/cement (w/c) ratios. The w/c ratios selected were 45%, 55% and 65% with fine limestone replacements of 0%, 30%, 50% and 100%. The water absorption and porosity of fine limestone and sand were measured to find a relation with the water entrapped in the pores of the surface of the rock and the drying shrinkage. The results show the increases in the compressive and flexural strengths and modulus of elasticity when the fine limestone proportion increases in the mixture. The most outstanding results are found on the drying shrinkage, which decreases considerably with the increase in fine limestone proportions.

**3.7. Effect of fiber reinforcement**

Effect of fiber reinforcement on the properties of hardened concrete continued to draw attention of the researchers, while many publications dealt with synthetic structural fibers, hybrid fibers and combination of fiber reinforcement and pozzolanic additions. The following studies illustrate these research activities.

The study [136] analyzes the impact of polypropylene fibers on mechanical properties of hardened lightweight self-compacting concrete (compressive strength with elapsed age, splitting tensile strength, elastic modulus and flexural strength). Polypropylene fibers did not influence the compressive strength and elastic modulus, however applying these fibers at their maximum percentage volume increased the tensile splitting and flexural strengths by 14.4% and 10.7%, respectively.

Concretes produced with three different replacement ratios of fly ash and three different types of steel and polypropylene fibers were compared to those without fibers in concrete with FA [137]. It is shown that fibers provide better concrete performance, while fly ash may adjust workability and strength losses caused by fibers, and improve strength gain.

### 3.8. Effect of slag and pozzolanic additions

The use of slag and pozzolanic additions in concrete is an important subject and is growing in importance day by day. Supplementary cementitious materials (SCM) have become an integral part of high strength and high performance concrete mix design. These may be naturally occurring materials, industrial wastes, or byproducts or the ones requiring less energy to manufacture. Some of the commonly used supplementary cementing materials are coal fly ash (FA), silica fume (SF), ground granulated blast furnace slag (GGBS), rice husk ash (RHA) and metakaolin (MK). SCM with cementitious or pozzolanic properties may both provide economical advantages and improve concrete quality and durability.

### 3.9. Effect of chemical admixtures

The influence of a new organic surface-applied corrosion inhibitor (SACI) on selected concrete properties is studied including compressive strength, tensile strength, steel–concrete bond strength, permeability, drying shrinkage, and freeze–thaw resistance [153]. The inhibitor is an aminoalcohol-based (AMA) corrosion inhibitor and it is applied on the hardened concrete surface. The results show that the inhibitor can be used safely and it does not have any significant harmful effect on the properties of hardened concrete and it improves some properties of concrete with its pore-blocking effect.

Lignosulfonate-based air-entraining (AE) water-reducing agents have been used in various concrete structures for over 50 years. Polycarboxylate-based superplasticizers, which are the main superplasticizers in use today, have been on the market for 20 years and have recently been applied to various kinds of concrete structures. Therefore, it is important to know the difference that these three dispersants (lignosulfonate-based (LG), B-naphthalenesulfonate-based (BNS), and polycarboxylate-based (PC)) have on concrete durability. The authors, using superplasticizers containing each dispersant, studied the properties of concrete at a w/c of 0.50 up to the age of 20 years [154]. This paper discusses the experimental results up to the age of 3 years following standard curing and artificial sea water curing, and under normal external exposure and exposure in a splash zone. As a result, no major difference has been observed in the effect on properties of the hardened concrete between PC and BNS, dispersants in superplasticizers. In addition, the authors consider that concrete incorporating PC-based superplasticizer or BNS-based superplasticizer has equal durability to that of concrete incorporating an AE water-reducing agent, most of which is in service over the long term.

An experimental investigation was conducted to evaluate the influence of elevated temperatures on the mechanical properties, phase composition and microstructure of SF concrete [155]. The blended cement used in this investigation consists of ordinary Portland cement (OPC) and SF. The OPC were partially replaced by 0, 5, 10, 15 and 20% of SF. The blended concrete paste was prepared using the water–binder ratio of 0.5 wt.% of blended cement. The fresh concrete pastes were first cured at 100% relative humidity for 24 h and then cured in water for 28 days. The hardened concrete was thermally treated at 100, 200, 400, 600 and 800 °C for 2 h. The compressive strength, indirect tensile strength, phase composition and microstructure of SF concrete were compared with those of the pure OPC. The results showed that the addition of SF to OPC improves the performance of the produced blended concrete when exposed to elevated temperatures up to 400 °C.

This state-of-the-art report [156] is focused on corrosion inhibitors used in concrete and is based on published studies in the last decade. Emphasis was given to the most commonly used inhibitors such as aminoalcohols (AMAs), calcium nitrites (CN) and sodium monofluorophosphates (MFPs). The report presents information related to (a) basic mechanism study, which gives information about the mechanism of protection provided by inhibitors, (b) effectiveness of inhibitors against corrosion in chloride contaminated and carbonated concrete, which deals with the preventive and curing effect of the inhibitors in different environments, (c) penetrability of the inhibitor, which underlines some difficulties of penetration into concrete for migrating corrosion inhibitors (MCIs), (d) influence on fresh and hardened concrete properties, which compares fresh concrete properties, mechanical performance and durability with and without inhibitor, and (e) field trials, which gives the limited data on the long-term performance of the inhibitors in real structures.

### 3.10. Properties of hardened light-weight concrete

The influence of surfactant concentration and pozzolanic amorphous nanodispersive SiO2 (ANS) additive on formation of autoclaved aerated concrete (AAC) structures and properties was investigated in [157]. It was established that in the AAC forming mixture the replacement of 1.0% milled sand by ANS accounts for considerably higher crystallinity of hardened binding material, and that the plate-like shape of crystals generated in this case is typical to hydrosilicates with lower ratio C/S. The formation of such AAC structure conditioned increase in compressive strength by 20.0%, bending strength by 31.0 and decrease in shrinkage at temperature of 700 °C by 0.1% versus AAC without surfactant and ANS. It is concluded that ANS added to AAC forming mass serve as nucleators during the hardening of concrete, stimulating higher crystallinity in the hardened structure than that without these additives and improving AAC mechanical properties. The ANS additive also helps to form the crystalline structure and to improve thermal resistance of concrete.

In the paper [158], cement paste characteristics and porous concrete properties are studied. The results indicate that cement paste characteristics are dependent on the w/c ratio, admixture and mixing time. Cement paste with high viscosity and high flow suitable for making porous concrete is obtained with the use of low w/c of 0.20–0.25, an incorporation of 1% superplasticizer, and sufficient mixing. Porous concretes having suitable void ratios are produced with appropriate paste content and flow, and sufficient compaction. Good porous concretes with void ratio of 15–25% and strength of 22–39 MPa are produced using paste with flow of 150–230 mm and top surface vibration of 10 s with vibrating energy of 90 kN m/m2. For low void ratio, high strength porous concrete of 39 MPa is obtained using paste with low flow. For high void ratio, porous concrete of 22 MPa is obtained using paste with high flow. Furthermore, the results indicate that the strength of porous concrete could be estimated from strength equation of porous brittle material.

Lightweight concretes can be produced by using processed natural material, processed by-product or unprocessed porous materials, depending upon the requirements of density and strength levels. The study [159] describes the use of pumice lightweight aggregate (PLA) to produce the lightweight concrete (LWC) for use in construction of load-bearing or non-load bearing elements. In this study, pumice aggregate lightweight concrete (PALWC) blocks were produced with different sizes of 8–16 mm as coarse pumice aggregate (CPA), of 4–8 mm as medium pumice aggregate (MPA) and 0–4 mm as fine pumice aggregate (FPA). According to the preliminary trial batch results, the optimum grade of aggregates was determined as 25% FPA, 25% MPA and 50% CPA by weight. To analyze the effects of CPA, MPA and FPA/cement ratios on the non-structural concrete engineering properties, the range of different pumice aggregate/cement (A/C) ratios from 6:1 to 30:1 by weight and cement contents from 32 to 180 kg/m3 were used to make PALWC mixture testing samples with a slump of 20 to 40 mm. The properties of PALWC with the range of different pumice aggregate/cement ratios were evaluated by conducting comprehensive series of tests on workability, compressive strength, elasticity modulus, bulk density, wetting expansion, drying shrinkage, water absorption and thermal conductivity. Experimental test results showed the PALWC of up to 25:1 A/C ratios has sufficient strength and adequate density to be accepted as load-bearing block applications. The PALWC of A/C ratio higher than 25:1 had sufficient strength, adequate density and the thermal conductivity to be accepted as for non-load bearing infill blocks for insulation purposes. The properties, which increase in value and indicate the increasing quality with lower A/C ratios (high cement contents), are compressive strength, modulus of elasticity and density. Properties, which decrease in value, with higher A/C ratios are water absorption, wetting expansion, drying shrinkage and thermal conductivity. It is shown that lowering the A/C ratios increases strength of PALWC, but increase of the A/C ratio increases the thermal insulation. The research shows that non-structural lightweight concrete can be produced by the use of fine, medium and coarse pumice aggregates mixes without using any additions or admixtures.

Polystyrene aggregate concrete (PAC) is a lightweight concrete with good deformation capacity, but its application is limited to non-structural use because of its apparent low strength properties. The study [160] was an effort to develop a class of structural grade PAC with a wide range of concrete densities between 1400 and 2100 kg/m3 through partial replacement of coarse aggregate with polystyrene aggregate (PA). The focus of this paper was to characterize the strength and long-term drying shrinkage properties of PAC. The parameters studied include PA content and curing conditions. The results show that the concrete density, concrete strength and elastic modulus of PAC decrease with increase of PA content in the mix. From the calorimetric test results, the increase in strength acceleration of PAC at early ages is due to the low specific thermal capacity of polystyrene aggregate. Besides, the long-term shrinkage and swelling of PAC are highly dependent on the PA content and the duration of water curing. Due to the non-absorbent property of polystyrene aggregate, the ratio of reversible to drying shrinkage observed for PAC was lower compared to that of the control mix.

The effect of different fibers on the workability, mechanical properties, drying shrinkage and water adsorption was investigated on expanded polystyrene (EPS) lightweight concrete of high strength and workability [161]. The results showed that the addition of fibers to the EPS lightweight concrete mixture during mixing substantially reduced the sedimentation of EPS beads and improved the uniformity of the mix as well. Compared with normal EPS concrete, fibers were demonstrated to have greatly increased strength, especially splitting tensile strength. It was also demonstrated that fibers restrained the long-term drying shrinkage. However, no significant effect was found of fibers on the water adsorption of EPS concrete.

Expanded perlite aggregate (EPA) is a heat and sound insulator, and lightweight material which ensures economical benefits in constructions. The paper [162] investigates the properties of concrete containing EPA considering cement types (CEM II 32.5R and CEM I 42.5R), dosages (300, 350 and 400) and replacement ratios (0, 15, 30, 45 and 60). The tests were conducted on fresh and hardened concrete. Cube, cylinder and prismatic specimens were used for destructive and nondestructive tests at 28 days. In experiments, the minimum unit weight of concrete mixture was 1800 kg/m3 at the dosage of 300, and compressive strengths of EPAC (expanded perlite aggregate concrete) were obtained between 20 and 30 MPa at the replacement ratios of 30% considering cement types, thus it was proved that EPAC can be used as lightweight concrete with adequate replacement ratios, despite some losses in mechanical properties.

Structural lightweight concretes produced with pumice (LWC) and normal-weight aggregate concretes (NWC) were investigated in [163]. Compressive strength and weight loss of the concretes were determined after being exposed to room and high temperatures (20, 100, 400, 800, and 1000 °C). SF replaced PC in the ratios of 0, 5 and 10% by weight. Unit weight of LWC was 23% lower than that of NWC. The LWC containing 2% superplasticizer retained 38% of the initial compressive strength. Rate of deterioration was higher in NWC than in LWC. The loss of compressive strengths increased depending on the SF ratio at ~ 800 °C and over.

**3.11. Properties of hardened SCC**

Self-compacting (self-consolidating) concrete (SCC) is a relatively new type of concrete with high flowability and cohesiveness, when compared to conventional concrete. The intensive publications growth on properties of hardened SCC has been observed in the last 12 years (Fig. 1), which demonstrates superior properties of this type of concrete—not only in fresh, but also in hardened state.

Data from more than 70 recent studies on the hardened mechanical properties of SCC have been analyzed and correlated to produce comparisons with the properties of equivalent strength normally vibrated concrete (NVC) [164]. Relationships were obtained between cylinder and cube compressive strength, tensile and compressive strengths, and elastic modulus and compressive strength. It is found that limestone powder, a common addition to SCC mixes, makes a substantial contribution to strength gain. Bond strength of SCC to reinforcing and prestressing steel is similar to or higher than that of normally vibrated concrete. It is demonstrated that variation of in situ properties in structural elements cast with SCC is similar to that with NVC, and the performance of the structural elements is largely as predicted by the measured material properties.

The study [165] aimed to develop a new method for proportioning SCC. This method is capable of proportioning SCC mixtures with specified compressive strength, contrary to previous SCC proportioning methods that emphasized the fulfillment of fresh properties requirements more than strength requirements. In addition, no previous method considered the grading of aggregate in SCC mixtures (fineness modulus of fine aggregate and maximum size of coarse aggregate) as in conventional concrete (CC) proportioning methods, making a need for numerous trial mixtures to adjust the fresh and hardened properties of SCC. Two well-known concrete mixture proportioning methods were adopted to develop the new method. The requirements of these methods were combined with certain modifications and a new method was proposed. In this new method, the actual range of compressive strength of the ACI 211.1 method was widened from 15–40 to 15–75 MPa, covering both normal- and high-strength SCC mixtures. Concrete strength was in agreement with the nominal design strength, except for mixtures with strength of 75 MPa; these mixtures required a slight adjustment in the w/c ratio.

CC mixtures for use in prestressed concrete applications were made under laboratory conditions with varying water-to-cementitious materials ratios, sand-to-total aggregate ratios, and cementitious material combinations (Type III cement, Class C fly ash, ground-granular blast-furnace slag, and silica fume) [170]. The SCC mixtures achieved prestress transfer compressive strengths between 38 and 66 MPa. The moduli of elasticity of the SCC mixtures were in reasonable agreement with the elastic stiffness assumed during the design of conventional slump concrete structures. The long-term drying shrinkage strains for all the SCC mixtures were approximately the same or less than those measured for the control mixtures. A change in sand-to-total aggregate ratio had no significant effect on the long-term drying shrinkage. At later ages of 56 and 112 days, the measured drying shrinkage corresponded reasonably well to those predicted by the ACI 209 procedure.

The research [174] investigated SCC with up to 80% cement replacement by fly ash in mixes adjusted to yield constant fresh concrete properties. The hardened concrete and the relationships between hardened properties were studied. The results show that SCC with up 80% cement replaced by fly ash is possible. To keep the filling ability constant, replacement of cement with fly ash would require an increase in water/powder ratio and a reduction in superplasticizer dosage. Fly ash had negative effects on strength. The comparison between SCC and normally vibrated concrete showed that their material properties are similar.

The effect of limestone fillers with different specific surface area on the hardened properties of SCC was studied in [175]. It was found that filler with a large area results in an increased autogenous shrinkage, decreased evaporation, lower plastic cracking tendency, and a higher compressive strength. With additional water the results were the opposite. The finding about higher autogenous shrinkage and lower plastic cracking potential sounds controversial and requires further study.

The mechanical properties of lightweight and normal-weight SCC were studied [176]. Lightweight SCC with a binder content of 500–650 kg $m^{-3}$ was made using less superplasticizer and viscosity modifying agent and a lower water/binder ratio than normal SCC. The bulk density was only 75% of normal SCC, but with a similar compressive strength. The elastic modulus was about 80% of that of normal SCC. These results indicate that lightweight SCC is excellent in workability and has a lower density, a high.

## IV. Summary and perspectives

The present paper reviews the literature related to the properties of fresh and hardened concrete published after the 12th International Congress on the Chemistry of Cement (Montreal, 2007). In the future, it can be expected that computational tools allowing for the prediction of the effect of casting on hardened properties will be developed. Research work dealing with numerical predictions of the effects of local aggregate content, local air content and local fiber orientation, starts now in different research laboratories around the globe. These tools, when associated with the recent progresses in the prediction of hardened properties as a function of mix design, shall allow for the prediction of local hardened properties and shall improve prediction of structural behavior.

It can moreover be expected that viscosity of concrete shall become more and more important. The recent trends in mix design show a reduction of the clinker content of concrete for environmental reasons. In order to keep similar properties in terms of durability, setting time and mechanical strength, the water amount in the system is also reduced. Viscosity shall increase because of the relative increase in solid content. Contacts between particles shall play an increasing role. Although we know how to tune yield stress by using super plasticizer, the knowledge on how to reduce viscosity is far less developed. This increase in viscosity shall moreover be increased by the use of lower quality aggregates. Around the globe, natural aggregate resources are decreasing. More and more crushed aggregates or even recycled aggregates are used. Their shape and their low packing fraction strongly increase viscosity. Finally, again for environmental reasons, new binders shall be developed in the future and shall generate new needs in knowledge and understanding. For instance, clay particle interactions in geopolymer system have nothing in common with clinker grains. Most superplasticizers become useless and anyhow do not resist to the high pH of the interstitial solution needed to activate the clay particles. Some of the tools developed for clinker could be transferred to these new cements but is doubtful that it will be the case for most of our clinker based knowledge.

A certain number of works addressing specific properties of fresh and hardened concrete have been published recently with the goal to develop new methods of testing, interpret test results, model and predict the development of properties in time or their changes under specific mechanical or environmental loading. However, most of the papers on concrete properties published in the last 4 years dealt rather with the influence of numerous factors (such as different type of loading, environmental conditions and introduction of chemical/mineral admixtures, recycled aggregates, etc. into concrete mixes) on properties of concrete, or with the properties of certain types of concrete, such as lightweight, self-compacting, fiber-reinforced, high-strength, high-performance and other types of concrete. It seems that the number of such publications will be growing further. In several works an attempt to find a correlation between the properties of hardened concrete, fresh concrete and durability, was undertaken, and sometimes such correlations work well. It can be expected that more focus will be made on studying controversial effects on concrete properties, when a positive change in one property causes an adverse effect in another one. An example of such controversial effect is an improvement of cracking resistance and durability of concrete by introduction of special components, such as internal curing agents or shrinkage-reducing admixtures. Such introduction is often accompanied by a certain strength loss at early age. Another example is introduction of a special component to improve concrete ductility, which can simultaneously lower concrete stiffness.

As was noticed before, the lack of virgin aggregates and the environmental considerations based on the needs to reduce CO2 emissions and global warming result in the necessity to apply wider low-quality aggregates and low-clinker cements in concrete manufacture. This trend obviously influences the properties of concrete, while some of them may decrease.

Both controversial and adverse effects described before make vital the development of new effective technologies aimed to compensate negative effects on the concrete properties. Another approach is an optimization of the properties, taking into account the environmental and economical considerations, in addition to the purely technical and technological aspects. Speaking about optimization, we assume that the property changes should be translated into the changes of the common parameter (such as life-cycle costs or carbon footprints), which serves to compare different technological and design solutions. The advanced models which can reliably predict the properties of concrete in both fresh and hardened states as a function of concrete composition, structural geometry, loading and environmental conditions are required for the better design and maintenance of concrete structures based on the sustainability approach.

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