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# Active Control of Properties of Fresh and Hardening Concrete

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## Abstract

Concrete mixtures have an optimized mix design in view of attaining desired properties. However, after mixing, during further processing, it is typically not possible to further adjust the performance of the fresh and hardening concrete. A new and emerging approach is to actively control the concrete properties by means of responsive particles or polymers triggered by an externally applied signal. Active control of properties of concrete refers to the concept of on-demand changes of one or more properties of the concrete after mixing by triggering a response to one or more of the constituents using a specific trigger signal (e.g. thermal, chemical, electrical, magnetic…). The on-demand control of properties can focus on the processing stage (including e.g. pumping, casting, 3D printing), the curing and hardening stage (including e.g. control of capillary pressure, shrinkage, setting, and hardening) and even on the hardened stage during service life (e.g. active corrosion control, active crack healing…). Addressing specific obstacles in cementitious environments, ensuring responsive material stability, controlling signal applicability, cost, logistics, and on-site safety is crucial for successful implementation. A RILEM technical committee has been initiated in 2023, working on the concept of Active Control of Properties of Concrete (RILEM TC 317-ACP). The committee will focus on active control of properties of fresh and hardening concrete. This paper gives a short introduction to scope and activities of TC 317-ACP.

**Keywords:** Active control; Fresh concrete; Hardening concrete; Rheology; Concrete properties

## 1 Introduction

In view of the desired performance of concrete, the mix design needs to be studied and optimized. Basic technological parameters such as water-to-cement ratio and cement content are typically considered, as prescribed by standards. Furthermore, adjustments of the properties can be obtained by means of admixtures and additions, typically commercially available chemicals and minerals that are added in small quantities but have a significant effect on e.g. workability, setting, and hardening.

This classical mix design approach, while leading to appropriate mixtures for a well-defined set of performance requirements, falls short when the requirements change along the production process of the concrete element or structure. A clear example is the case of 3D concrete printing (3DCP), requiring different rheological behaviour of the concrete in the different stages of the 3DCP process: pumpability, extrudability, and buildability [1,2]. One mixture cannot be optimized to show all of these properties without any further intervention after the mixing process. As soon as the concrete leaves the mixer, it typically shows its passive evolution of properties, largely influenced by the hydration process and environmental conditions.

A new approach is to provide adjustable constituents within the concrete mixture, e.g. chemicals or minerals that can respond to an external trigger signal, showing a significant modification of at least one of their features (e.g. shape,

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conformation, clustering, release of agent), inducing a macroscopic effect on the overall concrete behaviour. Some examples of switchable superplasticizers and magneto controllable particles can be found in [3], enabling active adjustment of rheology and setting on demand. Other examples include active curing control and shrinkage control.

Active control of properties of concrete thus refers to the concept of on-demand changes of one or more properties of the concrete after mixing by triggering a response to one or more of the constituents using a specific trigger signal, e.g. thermal, chemical, electrical, magnetic, mechanical, hygral, microwave. The on-demand control of properties can focus on the processing stage (including e.g. pumping, casting, and 3D printing), the curing and hardening stage (including e.g. control of capillary pressure, shrinkage, setting, and hardening) and even on the hardened stage during service life (e.g. active corrosion control, active crack healing…). Active control of concrete enables real-time quality control and improved concrete properties, ensuring better sustainability and environmental impact as well as resource management.

Within RILEM, a technical committee has been initiated in 2023, working on the concept of Active Control of Properties of Concrete (RILEM TC 317-ACP). The committee will focus on active control of properties of fresh and hardening concrete. This RILEM Technical Letter gives a short introduction to the scope and the activities of TC 317-ACP.

## 2 Brief literature review

Active Control of Concrete Properties is a recently identified subfield within concrete technology. A first (p)review paper was published in 2018 [4]. Concrete properties to a large extent depend on mix design and processing, leaving only limited options to actively modify concrete properties after mixing or during casting. The new concept of Active Control of concrete properties is based on the application of external signals to trigger an intended response in the material. Some current practices in concrete industry could be considered as active control, e.g. mechanical vibration, steam curing, cooling of mass concrete… More advanced active control mechanisms can be inspired by methodologies in other fields, e.g. based on hydrogels and other functional polymers. A specific approach recently studied in more detail focuses on active rheology control [3]. Active rheology control of cementitious materials can be based on magneto-responsive mineral particles, and/or triggerable functional polymers in combination with an external trigger signal.

Recent scholarly articles have explored similar methodologies aimed at actively controlling the properties of cement-based materials in both fresh and hardened states. These methods include traditional approaches such as vibration, electromechanical techniques, and stiffening control strategies [5–7], active control strategies utilizing magneto-responsive particles such as carbonyl iron powder [8], iron oxide nanoparticles [9–11], and/or fly ash [12], as well as non-magnetic particles [13]. Some active control techniques based on responsive polymers have also been reported [14–16]. In addition, by applying a surrounding magnetic field, the mineralogical compositions of hydrated cement pastes are changed [17], and mechanical properties such as compressive strength might be improved [18,19]. The literature also delves into the potential applications of innovative active control methods, such as those applicable during pumping [20–23], formwork casting [24], and 3D printing [22,25–29]. Nevertheless, various limitations and challenges persist in all the aforementioned strategies, which require more studies.

In the context of active rheology and stiffening control by magnetic field, several studies showed that the direct addition of nano magnetite could obtain controllable fresh properties in concrete [30,31] or utilizing some mineral admixtures containing magnetic phases such as fly ash [32] and fayalite (iron-silicate) slag [33]. The presence of nano, sub-micron, or micron-size magnetic mineral particles in concrete turns the fresh concrete mixture into a magnetorheological mixture with controllable rheological properties under magnetic field application.

Regarding mechanical methods for concrete active control, the studies by Sanjayan et al. [7] and Zhao et al. [34] contribute to the understanding of optimizing concrete properties through the application of vibration, albeit in different contexts. Sanjayan et al. [7] focused on the active control of rheological properties during 3D printing. They found that vibration significantly influences extrusion pressure and yield stress, potentially reducing these parameters, especially in mixtures with high thixotropy, such as those containing nanoclay particles. Including nanoparticles doubled the reduction in extrusion pressure and yield stress, highlighting their impact on active rheology control. The application of vibration improved buildability, leading to enhanced flowability and reduced extrusion pressure, ultimately improving the quality and mechanical properties of 3D printed structures.

Zeyad et al. [6] explore the impact of steam curing on concrete behaviour, focusing on early compressive strength, steam curing temperature, period, heat transfer, and microstructure. The researchers conduct a comprehensive review, highlighting how controlled steam curing significantly enhances early compressive strength, providing insights into optimal curing conditions, investigating heat transfer mechanisms, and delving into changes in the microstructure, namely pore structure and gel formation induced by steam curing. The study emphasizes the potential of steam curing to enhance early strength, optimize curing conditions, and improve the overall performance of concrete structures.

As for active control based on responsive polymers, Guo et al. [15] focused on enhancing the durability performance of cementitious materials by utilizing a pH-responsive Superabsorbent Polymer (SAP) synthesized with acrylic acid (AA)-methyl acrylate (MA) precursors. The study employed three types of SAP samples with varying crosslinking levels to investigate their swelling capacity under different pH conditions. The synthesis process involved sonication, polymerization, and lyophilization to obtain the SAP for further evaluation.

Autogenous shrinkage can be mitigated due to internal curing by superabsorbent polymers (SAP) or hydrogels. These materials also influence rheology by enhancing viscosity or showing a lubrifying effect depending on the type of SAP used. Thermo-responsive crosslinked hydrogels such as poly(*N*-isopropylacrylamide) can influence workability and partly mitigate autogenous shrinkage [35]. However, not entirely active but influenced by hydration heat, analogous types of hydrogels can be used in an active, controlled way. For example, thermal-responsive gelatin can be used for 3D printing applications [36]. Using a low temperature of 5°C allowed to have a highly thixotropic behaviour, while at room temperature the modified pastes show similar rheological properties. The former will provide a sufficient yield stress to withstand the weight of the printed material, using this low temperature.

Korda et al. [37] studied the prospect of controlling the internal curing process of SAP concrete based on real-time Acoustic Emission (AE) data in order to ensure desirable curing conditions. The study takes advantage of the increased AE activity that is generated as the SAPs release their entrained water, shrink, and detach from the pore wall. The results showed that by applying a curing agent on the concrete surface, at the moments dictated by the increased AE activity, the water provision by the SAPs could be postponed. This indicates that AE can be used to deactivate and reactivate multiple times the SAP action during curing, resulting in a prolonged internal curing period and thus, improved hydration and mechanical properties.

Drying of fresh concrete can result in plastic shrinkage cracking during the period between casting and the final setting time. These cracks can be prevented by keeping the surface of the concrete sufficiently moist by spraying water or other means. There is however little work done to determine when and how often this is required. The study by Deysel et al. [38] showed that it is possible to use the signal (indication of the capillary pressure) from a tensiometer imbedded in the concrete to determine when and how often the surface of the concrete has to be moistened to prevent cracking and ensure more durable concrete.

Deshmukh et al. [39] investigate the rheological response of cement mixtures doped with magnetic materials for potential 4D printing applications. The study designs ink systems incorporating Portland cement, fly ash, nanoparticles, and magnetite powder. The effect of a magnetic field on the rheological behaviour of the ink systems was investigated to understand the potential for active control in digital construction, and a new rheological model for the ramp-down response of the ink systems was proposed, with a Sticky Particle Model based on the inverted Papanastasiou equation. Important findings reveal the influence of fly ash on superplasticized Portland cement ink by increasing plastic viscosity and reducing yield stress to zero, resulting in a Newtonian fluid response suitable for pumping operations but not ideal for 3D printing. The application of a magnetic field demonstrated an increase in yield stress and stiffness in the ink systems, showing the potential for active control in digital construction.

Jiao et al. [28,40] described the theoretical foundations of magneto-rheology control in 3D concrete printing, and a conceptual examination was presented by rheological experiments. It was found that cementitious paste with magnetic particles shows higher structural build-up after removing the magnetic field due to the possible residual magnetic clusters because of the remanent magnetization characteristic of the magnetic particles. These findings clear the path to actively improve the buildability of cementitious materials for 3D printing by introducing a short-pulsed magnetic field during extrusion [3].

In another study, Muthukrishnan et al. [22] provide a systematic review of strategies to enhance buildability in 3D concrete printing. Acknowledging the importance of interventions at the print-head, such as mixing accelerators and magneto-rheological control, the study emphasizes the need for rapid transformation in rheological properties. The findings underscore the significance of innovative approaches and interventions at the print-head to improve buildability in 3D concrete printing. The authors also investigated set-on-demand geopolymer concrete, which offers both environmental benefits and enhanced flexibility during printing [41,42].

Stiffening control using chemical reaction based methods also gained attention recently in the purview of digital fabrication. Tao et al. [43] developed a twin-pipe pumping technique in which two streams of mortars get intermixed near the print head using a static mixer. Mohan et al. [44] proposed a system to re-activate the hydration in the retarded calcium sulfoaluminate cement-based concrete using the twin-pipe pumping technique. The resulting 3D printed elements had significantly higher early-age mechanical properties in comparison to the conventional one-component 3D printed concrete.

Furthermore, Chibulu et al. [24] explore magnetic field-based active stiffening control (ASC) to reduce formwork leakage in cement pastes. The study investigates the effects of $Fe_3O_4$ nanoparticle concentration, paste rheology, and applied pressure on flow behaviour under magnetic influence. Results indicate increased yield stress and viscosity with $Fe_3O_4$ nanoparticles, and the ASC methodology shows promise in reducing flow rates and preventing leakage in cement pastes, providing innovative solutions in construction material technology. In another study, Chibulu et al. [45] studied the effect of the volume fraction of fine sand on the magnetorheological response and blocking mechanisms of nano-magnetite incorporated cementitious mixtures for formwork leakage control. It was revealed that the filtration of the interstitial fluid caused by the clogging effect at high aggregate contents could be reduced or prevented by magnetic field application.

As for steel fibers for control of orientation and mechanical performance of concrete, Chen et al. [46] and Pham et al. [47] both focused on the impact of fiber-related parameters on mechanical properties. The study of Chen et al. delves into the influence of fiber orientation on the mechanical behaviour of steel fiber-reinforced concrete (SFRC). Through experimental tests and numerical simulations, the research emphasizes the importance of optimizing fiber distribution for enhanced performance. Controlling fiber orientation, particularly at a 60° angle, is highlighted as a key factor in boosting SFRC's ductility and toughness. Pham et al. [47] explore the effects of fiber sizes on the mechanical properties of 3D printed concrete, adapting a steel fiber-reinforced mixture for traditional casting to suit the 3D printing process. The study reveals that the strategic incorporation of steel fibers, varying in length and volume fractions, significantly enhances both compressive and flexural strengths. The findings underscore the importance of fiber parameters, such as alignment, length, and volume content, in achieving optimal mechanical performance in 3D-printed concrete. Proper alignment and distribution of steel fibers within the concrete matrix are crucial for achieving the desired mechanical properties. Active control of fibre orientation could be a helpful option to improve the performance of the final structure.

Wijffels et al. [48] experimentally studied the effect of magnetic orientation of steel fibres in transparent silicone oil and in fresh, self-compacting concrete (SCC) beams. The energy absorption capacity of SCC beams subjected to three-point bending scales approximately proportionally with the number of “well oriented fibres” bridging the catastrophic failure crack, which emphasizes the importance of adequately orienting steel fibres with the magnetic orientation technique. Also Mu et al. [49] studied the effect of steel fiber alignment using electro-magnetic field. The test results show that the splitting tensile strength and flexural strength can increase by more than 100%, which is attributed to the increase in reinforcing efficiency of aligned steel fibers.

Abavisani et al. [50] conducted a study on the practicality of using an alternating magnetic field (AMF) to enhance the compressive strength of fine aggregate based concrete. They also suggested a new actuator system for smart structures. An AMF with a density of 0.5T (Tesla) and a frequency of 50 Hz is applied to fresh and hardened concrete samples for the purpose of improving their compressive strength.

## 3 Remaining challenges and questions

The cited studies collectively demonstrate the potential of active control techniques, incorporating responsive particles and smart materials, to enhance the performance, durability, and flow behaviour of concrete structures, showcasing innovative applications in civil engineering and construction technology. However, the challenges identified in the research papers collectively emphasize the intricacies of implementing magneto-electric and magneto-rheological control in concrete structures. In the pursuit of enhancing concrete performance by enabling active control, common obstacles include limited exploration of direct applications of magnetic fields and electric currents, the need for real-time control of concrete behaviour, and difficulties in sensor installation for active control techniques. Furthermore, the issue of large space occupancy by active devices, negative consequences, such as ineffectiveness at early damage stages and increased risk of premature failure, pose additional hurdles. Addressing these challenges require further investigation and development of cost-efficient technologies, including the optimization of magneto-electric active control for large-scale structures with and without fiber reinforcement. In the context of specific applications like 4D printing, challenges arise in achieving the desired rheological properties of magneto-rheological cementitious inks. This includes issues like yield stress reduction with fly ash addition, fluidization challenges with certain types of nanoparticles, and limited stiffening enhancement under a magnetic field.

Although theoretically a wide range of potential trigger signals could be considered, the specific properties of cementitious materials jeopardize the success of some active control options. Concrete is not an easy material in this respect, with poor electrical conductivity, not transparent, high pH buffer, high thermal capacity… Furthermore, many polymers that have shown good options in other fields, are not applicable to cementitious materials because of incompatibility with high pH environments.

In short, several challenges remain, like the stability and functioning of the responsive material in a cementitious environment, the applicability of the control signal in a cementitious material, and the cost, logistics and safety of a control system on a construction site or in the precast industry. Finding solutions to these challenges will lead to marvelous opportunities in general, and for concrete 3D printing more particularly.

## 4 Scope of RILEM TC 317-ACP

The main purpose of Technical Committee 317-ACP is to create a State-of-the-art report on Active Control of Properties of Cementitious Materials, not only focussing on rheology but also on other properties in fresh state and during hardening. The committee work will not focus on active control in hardened state, but major hardened material characteristics will be referred to as potentially influenced by active control in fresh and hardening state.

The committee will organize a general discussion on the potential use of different kinds of trigger signals (magnetic, electric, redox, UV, temperature, light, mechanical…) in combination with different kinds of responsive components (nanoparticles, macroparticles, polymers…). First, a short overview will be given of traditional methodologies to actively modify concrete properties in fresh state (e.g. vibration as active control to achieve compaction, shear-induced behaviour…), at very early age (e.g. stiffening control by microwave, by electric current (Joule effect)…), and during hardening (e.g. moist and heat curing, cooling…).

Working principles and mechanisms will be discussed for different cases, including control based on responsive mineral particles as well as on responsive polymers. Some laboratory proofs of concept and potential applications of innovative active control techniques will be documented, e.g. active control during pumping, formwork casting including formwork leaking, 3D printing, setting, curing…

Finally, TC 317-ACP will discuss potential benefits of active control for concrete practice, remaining challenges, and recommendations to industry, including aspects of raw materials (production, storage, transport, quality control…).

## 5 Summary

This RILEM Technical Letter introduced the activities of the recently created RILEM Technical Committee 317-ACP 'Active Control of Properties of Fresh and Hardening Concrete'. Active Control of properties of concrete refers to the concept of on-demand changes of one or more properties of the concrete after mixing by triggering a response to one or more of the constituents using a specific trigger signal, e.g. thermal, chemical, electrical, magnetic. The on-demand control of properties can focus on the processing stage (including, e.g. pumping, casting, printing), the curing and hardening stage (including, e.g. control of capillary pressure, shrinkage, setting, and hardening) and even on the hardened stage during service life (e.g. active corrosion control, active crack healing…).

A very brief introduction was presented, pointing to some insights into the complexities and potential solutions related to active control in cement-based materials during the fresh and hardened state. It is important to understand the mechanisms and challenges of different methods such as vibration technics, the incorporation of magneto and non-magneto responsive particles, responsive particles for rheology and curing control, in addition to innovative applications namely, active control during additive manufacturing (pumpability, printability and buildability control). Overcoming the challenges demands a multidisciplinary approach, emphasizing continuous research, material-specific optimization, and innovative strategies to successfully implement the different techniques in the field of active control of concrete properties, paving the way for advancements in smart construction technologies.

## Authorship statement (CRediT)

**Geert De Schutter:** Conceptualization, Writing-original draft, Supervision. **Imene Abidi**: Writing – original draft. **Eleni Korda:** Writing – original draft. **Billy Boshoff:** Writing – original draft. **Kolawole Adisa Olonade:** Writing – review & editing. **Didier Snoeck:** Writing – review & editing. **Shravan Muthukrishnan:** Writing – review & editing. **Yiyuan Zhang:** Writing – review & editing. **Yaxin Tao:** Writing – review & editing. **Swapnil Balasaheb Ghodke:** Writing – review & editing. **Manu Kurungod Mohan:** Writing – review & editing. **Mert Yücel Yardimci:** Writing – review & editing. **Dengwu Jiao:** Writing – review & editing. **Jay Sanjayan:** Writing – review & editing, Supervision.

This letter is approved by RILEM TC 317-ACP.

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