

Magneto-rheology control of cementitious materials: principles, current status, and opportunities

Dengwu Jiao^{1,*,*}

¹Department of Architecture and Civil Engineering, City University of Hong Kong, China

*Dengwu Jiao was invited for submission of this letter as an awardee of the Gustavo Colonnetti Medal granted by RILEM in 2025

Received: 06 May 2025 / Accepted: 27 June 2025 / Published online: 04 July 2025

© The Author(s) 2025. This article is published with open access and licensed under a Creative Commons Attribution 4.0 International License.

Abstract

Magneto-rheology control, an advanced active rheology control (ARC) technique, is achieved by applying an external magnetic field to a cementitious mixture with responsive additives. It is a promising method to address the contradicting rheological requirements of cementitious materials during the placing process, enabling the development of smart and reliable concrete structures. This article reviews recent advances in magneto-rheology control for cementitious materials. The fundamental principles of magnetic particle movement and cluster formation in cementitious suspensions are first examined. Afterwards, the typical magneto-rheological responses and the key factors influencing the responsive behaviors are discussed. Finally, the potential applications and challenges of this technology in modern construction practices, including smart casting process, 3D/4D concrete printing, and the development of sustainable and multifunctional concrete, are provided.

Keywords: Rheology control; Magnetic field; Magneto-rheology; 3D concrete printing; Smart casting.

1 Introduction

The rheology of fresh cementitious materials significantly influences their processing, placement, and eventual properties in construction applications [1]. Unfortunately, opposing requirements of rheological properties often exist in different placement processes, such as pumping versus casting [2, 3], and extruding versus layer-building [4, 5]. This highlights the need for rheology control. Traditional strategies to adjust the rheology of fresh cementitious materials typically rely on optimizing material compositions and incorporating mineral or chemical admixtures [6-8]. However, these approaches often lack real-time adaptability and precise control, particularly once the mixture is prepared. This poses great challenges for advanced concrete applications such as self-compacting concrete, ultra-high performance concrete, and 3D printing concrete. To address this, the concept of active rheology control achieved by applying an external trigger signal was proposed as a promising solution for reversible and real-time control of flow behavior of cementitious materials [9, 10].

Magneto-rheological (MR) fluids are characterized by their ability to undergo rapid and controllable changes in yield stress and viscosity when exposed to a magnetic field [11, 12].

Recent studies [13-15] have explored the incorporation of magnetic particles to prepare MR cementitious materials and assessed their rheological responses under external magnetic fields. This technology offers the potential for on-demand adjustments of fresh properties during pumping, casting, and 3D printing processes [16-18], which is beneficial to mitigate the aforementioned challenges, supporting the development of more sustainable and efficient construction practices. Despite these efforts, the magneto-rheology control of cementitious materials is in its infancy, and its practical applications necessitate advancements such as responsive material design and equipment development.

This article aims to understand the magneto-rheology control of cementitious materials by discussing the fundamental principles and analyzing the key influencing factors. The challenges and opportunities associated with the integration of magneto-rheology control into modern construction practices, including smart casting process, 3D/4D concrete printing, sustainable and multifunctional concrete, will be provided. This paper is hopefully beneficial to advancing innovative construction techniques and developing smart concrete structures through the application of magneto-rheology control.

*Corresponding author: Dengwu Jiao, E-mail: dengwu.jiao@cityu.edu.hk

2 Principles: Particle movement and cluster formation

The changes in viscosity and yield stress of conventional MR fluids are driven by the reversible alignment of magnetic particles within the matrix under the application of a magnetic field [19]. Unlike traditional MR fluids, which typically exhibit Newtonian flow behavior, fresh cementitious materials possess viscoelastic properties, leading to distinct microstructural and rheological responses under magnetic stimuli. Besides, pure Portland cement paste exhibits limited response to an external magnetic field due to the inherently low magnetic properties of cement particles [13, 20]. Therefore, specialized magnetic additives are incorporated to enable the magneto-responsive behavior. Commonly used responsive additives include carbonyl iron powders [13], polymers [21], Fe_3O_4 particles [22, 23], steel fiber [24], and mineral particles [25, 26]. Using magnetic particles as the responsive additives as an example, the principles of magneto-rheological responses of cementitious materials are discussed from the perspectives of particle movement and cluster formation.

Upon applying an external magnetic field to a responsive cementitious material, the magnetic particles will be polarized, tending to move to contact with each other in the suspension under the magnetic forces. The moving particles create a micro-agitation effect, disturbing the hydration product connections and colloidal networks between solid particles or clusters, depending on the degree of the particle motion. Unlike the linear chain structures observed in conventional MR fluids, the magnetic particles in high-viscosity cementitious suspensions can agglomerate into clusters or form cluster-chains [27], relying on the behavior of the suspension, the properties of magnetic particles, and the magnetic field strength. These changes induce both micro- and macro-scale rheological transformations in the cementitious materials. It should note that the magnetically induced particle movements in cementitious suspensions occur rapidly, often within few seconds, as predicted by theoretical calculations of magnetic force and movement velocity of magnetic particles [20, 28]. When the magnetic field is removed, the dipolar forces diminish and the magnetic clusters will de-agglomerate under the influence of Brownian motion, resulting in a reversible alteration in the rheological behavior [14]. However, due to the viscoelastic properties of cementitious materials and remnant nature of magnetic particles, some residual clusters may persist in the suspension, differentiating the behavior from the complete reversibility to Newtonian flow observed in conventional MR fluids.

3 Current status

In this section, the typical magneto-responsive rheological properties of cementitious materials are first described from viewpoints of structural evolution, variations in yield stress, viscosity, and flowability. Subsequently, the recent advancements regarding the influence of material compositions, magnetic field parameters, and temperature on the responses will be discussed.

3.1 Typical magneto-rheology responsive behavior

For cementitious paste containing magnetic particles, whether nano- or micron-sized, these particles will move within the suspension upon the application of a magnetic field. From the perspective of structural build-up, as measured using small amplitude oscillatory shear (SAOS) test, storage modulus shows an immediate drop (e.g., from 500 kPa to 20 kPa) [14, 29]. This is followed by a pronounced increase at a higher growth rate, i.e., enhanced stiffness, due to the formation of magnetic clusters. This indicates a temporary improvement of liquid-like behavior immediately after magnetic field application, before the formation of magnetic clusters that increase the stiffness. Note that this phenomenon can only be captured using non-destructive SAOS test, provided magnetic particles are used as the responsive additives. In contrast, under continuous shearing at a low shear rate of 10 s^{-1} , the apparent viscosity increases significantly (e.g., from 2-5 Pa.s to 20-25 Pa.s) after an external magnetic field application [30]. Similarly, when responsive superplasticizers are incorporated as the magnetizable additives, the storage modulus of cementitious paste also shows a notable increase immediately upon exposure to a magnetic field, with no reduction observed [21], in contrast to cement pastes containing magnetic particles.

Regarding the yield stress and plastic viscosity measured from flow curve tests, both of them increase under the influence of a magnetic field [23], resulting in a significant reduction in the flowability [31]. It is important to mention that magnetic particles tend to agglomerate under the combined effects of magnetic force and high-rate shearing [32]. Therefore, caution is required when evaluating rheological responses using dynamic shear curves. The responses of cementitious materials with steel fibers to magnetic field differ significantly from that of suspensions with magnetic particles due to the distinct effects of fiber shape. Specifically, after short-term exposure to a magnetic field for 10 s, the flowability exhibits a directional behavior relative to the magnetic field. This is characterized by a reduced flow velocity and spread diameter in the direction parallel to the field and an increased flowability in the perpendicular direction [24, 33]. Despite this directional flow behavior, the overall average flowability is only slightly reduced compared to those without magnetic field exposure. These phenomena are primarily attributed to the flow-restricting effects of residual fiber aggregations.

3.2 Influencing factors

3.2.1 Material compositions

The theoretical calculations in [20] reveal that under a constant magnetic field, the attractive force between neighboring magnetic particles in cementitious suspensions relates to the viscoelastic properties of the suspension, and the volume fraction and magnetization properties of magnetic particles, while the movement velocity further depends on the size of magnetic particles. Therefore,

magneto-rheological response is determined by a combination of the properties of the paste medium and the parameters of the magnetic particles. Generally, higher concentration of magnetic particles contributes to more obvious magneto-rheological responses [34]. At fixed magnetic particles, cementitious suspensions with solid volume fractions below 0.3 ($w/c > 0.74$) exhibit an inapparent response to magnetic fields due to large interparticle distances and weak magnetic attractive forces. However, in denser particle systems with higher solid volume fractions (e.g., 0.45 corresponding to $w/c = 0.33$), the movement of magnetic particles is restricted, limiting the formation of magnetic clusters despite the strong magnetic forces between particles [35]. As a result, the overall response of such suspensions remains limited.

Chemical admixtures affect magneto-rheological behavior by altering the viscoelastic properties of the medium. Under an external magnetic field, the storage modulus of highly flowable superplasticizer-containing cementitious paste is always higher than that of paste without superplasticizers [36]. This suggests that the early-age enhancement of liquid-like properties by a magnetic field is less pronounced. Instead, the primary effect is an increase in stiffness. Notably, compared to the reference cement paste, the superplasticizer-containing pastes exhibit a significantly higher relative increase in storage modulus under a magnetic field (e.g., 1422% vs 86%) due to their initially high flowability, although the absolute increase is slightly lower (e.g., 327 kPa compared to 760 kPa). This may be attributed to the improved dispersion and higher mobility of magnetic particles in well-plasticized cement pastes. At the same time, the entanglement of superplasticizer molecular chains can restrict particle motion, limiting the extent of magnetic clustering. Moreover, the magnetic clusters formed may not effectively fill the interstitial voids between solid particles due to the increased particle separation [36]. The addition of 0.485 vol.% air-entraining agent, based on the volume of water, has a minor influence on the early-age magneto-rheological response of cementitious paste containing micron-sized carbonyl iron particles, possibly due to the bubble-bridging effect [37]. However, the magneto-rheological response tends to decrease as the concentration of magnetic particles increases, likely because of the increased alignment of more magnetic particles. Further works exploring the coupled effects of different chemical admixtures, such as air-entraining agent, viscosity-modifying agent, and superplasticizers, on magneto-rheological response are required.

The physical properties of magnetic nanoparticles play distinct roles in influencing the behavior of cementitious paste. The size of the nanoparticles mainly affects the evolution of storage modulus without magnetic field, while the structural build-up under a magnetic field is primarily determined by the magnetization properties of the particles [34]. The particle shape also influences the magneto-rheological responses. For example, irregular magnetic fly ash particles even with low magnetization properties can behave obvious response to external magnetic field due to the

stronger interparticle contacts [25]. A comparative analysis of the responsive structural evolution of magnetic nanoparticles, fly ash, and calcium aluminate cement indicate that particles with higher magnetization properties induce more pronounced rheological responses, which agrees with the findings in [38], reporting that carbonyl iron particles with greater magnetization have stronger response than Fe_3O_4 particles. Besides, the enhancement in early liquid-like behavior induced by a magnetic field is primarily observed in more flowable cementitious pastes (i.e., higher w/c but without superplasticizers), whereas for pastes with high initial stiffness, applying an external magnetic field mainly contributes to strengthening the solid-like properties.

A combination of magnetic particles in various sizes can improve rheological responses. For instance, the incorporation of magnetic fly ash (with an average particle size of $8 \mu m$) alongside magnetite nanoparticles with 100 nm has been shown to significantly improve the MR response, as evidenced by an approximate 300% increase in yield stress [23], more obvious early-age liquid-like properties, and greater relative increase in stiffness with storage modulus rising by up to 1400% [39]. When upscaling to mortar levels, the yield stress of cement mortars containing magnetic fine aggregates exhibits an increase under an external magnetic field, and the response becomes more pronounced with increasing the particle size possibly due to the increased contact area between neighboring aggregates [15, 40], although this may be partially offset by the reduced number of particles at a given volume fraction. Our recent results further indicate that both the yield stress and plastic viscosity of cement mortars containing micron-sized Fe_3O_4 particles increase upon the application of a magnetic field, aligning with the observations reported in [41]. Moreover, there is a synergistic interaction between steel fibers and steel slags on the magneto-rheological properties, as evidenced by notable increases in the yield stress and plastic viscosity after subjecting to an external magnetic field [42]. Nevertheless, due to the distinct geometry of steel fibers, new methods to evaluate the magneto-rheological response of steel fiber-containing cementitious materials are required.

3.2.2 Magnetic field parameters

Magnetic field strength has an influence on the particle interactions, thereby determining the degree of rheological response. From the evolution of storage modulus by SAOS test, a weak magnetic field like 0.08 T cannot induce significant rheological response [43]. However, this is not universally applicable. A study reported that a 0.1 T magnetic field can induce noticeable rheological responses in stiff cementitious paste [23]. Similarly, another recent study using permanent magnets with flux densities in the range of 0.06-0.1 T demonstrated a clear responsive flow behavior in cementitious paste [31]. This variation is largely attributed to the differences in the magnetic particles utilized. In addition, the micro-structural strength measured through SAOS test increases from 300 kPa to 900 kPa as the magnetic field intensity approaches 0.76 T, with no saturation threshold observed within the tested range [43]. This behavior contrasts

with that of conventional MR fluids, which typically show saturation at relatively high magnetic field strengths [19, 44]. The absence of saturation in cementitious suspensions is likely attributed to their highly viscoelastic properties.

The magnetization time, or time-varying magnetic field, also affects the responsive behavior of cementitious paste, exhibiting a history-dependent response [14]. A sudden increase in magnetic field strength typically leads to an initial drop in storage modulus, followed by an increase in stiffness as the field continues to apply. Conversely, a linear increasing magnetic field increases the storage modulus of the paste. Similarly, a sudden decrease in field strength causes a reduction in storage modulus because of the reversible nature of magnetic clusters. However, a gradual decrease in the strength can paradoxically lead to increased stiffness. After the magnetic field is removed, some residual magnetic clusters may persist in the suspension, resulting in a higher growth rate of structural build-up compared to that obtained in the absence of magnetic field [14]. Note that these residual clusters can be completely destroyed by giving a low-rate shearing, such as at 10 s^{-1} [30]. However, for responsive fine magnetic aggregates with irregular shapes and high remnant magnetization, the field-induced agglomerations can persist within the cementitious materials, leading to a higher development of yield stress [45]. Besides, the micro-agitation and redistribution effects of magnetic particles when subjected to a pulse magnetic field can potentially reduce the shear stress of cementitious paste [46].

3.2.3 Temperature

If a magnetic field is generated by electromagnetic flux, simultaneous thermal heating will occur. Indeed, subjecting a cement slurry with w/c of 0.44 and iron oxide nanoparticles to an alternated magnetic field for 6 min increases the temperature from 26°C to 49°C [47]. This temperature increase may influence the rheological response of cementitious materials. Recently, we examined the impacts of temperatures ranging from 10°C to 40°C (controlled by a water bath connected to the rheometer) on the responsive structural evolution of cementitious paste with magnetic nano- Fe_3O_4 particles. Under a 0.5 T magnetic field, the paste demonstrates enhanced fluid characteristics, whereas elevated temperature promotes faster evolution from viscous to elastic-dominated behavior. The rheological response of the cementitious paste diminishes significantly when temperature falls below 20°C , due to the high initial viscous properties of the suspension, or exceeds 30°C , as a result of increased chemical hydration rates. By analyzing the effect of temperature on cement hydration kinetics, thermodynamic forces, and magnetic properties of Fe_3O_4 particles, it is suggested that temperature primarily influences the rheological response by affecting the hydration rate of the cementitious paste. The detailed findings on this subject have been submitted to a journal and are currently under review [48].

4 Opportunities and challenges

The emerging concept of magneto-rheology control presents exciting opportunities and unique challenges for advancing novel applications in concrete construction. This section explores the potential integration of magneto-rheology control into various domains, such as smart casting processes, 3D/4D concrete printing, sustainable materials, and multifunctional concrete. It is important to note that some opinions presented here are derived from our own experiences and have not yet been supported by published studies.

4.1 Smart casting

Concrete pumping is an essential technology for the efficient placement of concrete. The magneto-rheology control offers potential advantages in regulating pumping pressure and flow velocity of concrete materials within pipelines. De Schryver et al. [17] designed a specialized control unit using permanent magnets to investigate the magnetically induced pumping behavior of cementitious pastes. When a magnetic field is applied perpendicular to the flow direction, magnetic clusters form inside the pipe, hindering material flow and thus increasing pressure loss. A magneto-induced structural build-up model was also developed and validated by experiments and numerical simulations [17]. However, while the current findings about magneto-induced stiffness control highlight significant potential, they may be less applicable to real-world concrete pumping applications, where reduced pumping pressure is generally desired. Nevertheless, if we could accelerate particle movement by aligning the magnetic field parallel to the flow direction, it is possible to facilitate material flow within the pipe. This necessitates the development of advanced magnetically controlled pumping devices. Besides, further research is required to understand the flow behavior of cementitious materials under such conditions, focusing on parameters such as flow velocity, lubrication layer properties, and pumping pressure. Moreover, addressing the challenges of achieving rheological responses in large-diameter pipes and upscaling to mortar and concrete materials is critical for practical applications.

While the magneto-induced stiffness poses challenges for concrete pumping, it presents significant potentials in the formwork casting process. Chibulu et al. [16, 49] developed a test setup to examine the pressure-driven flow of cementitious paste through a confined geometry. The findings reveal that the application of an external magnetic field reduced the flow rate due to the magnetic particle agglomerations, demonstrating applicability at both the cement paste and mortar levels [50]. The results indicate that magneto-stiffness control serves as an effective approach for minimizing formwork leakage and reducing lateral formwork pressure, particularly in high-flowable concrete materials such as self-compacting concrete. However, the efficiency of this method can be compromised under high pressures caused by the inherent gravity of the material and large gaps between formworks. Further research is needed to explore the integration of magnetic devices into large-scale formworks and to investigate the effects of incorporating

responsive particles on the overall properties of concrete structures. Moreover, the magneto-stiffening control can also be effectively utilized in plugging and abandonment process for oil and gas wells, with added advantage of having no significant impact on compressive strength [51].

4.2 3D/4D printing concrete

The 3D printing process for concrete requires the material that are sufficiently flowable during pumping and extrusion while maintaining adequate stiffness in layer building to preserve their shape without deformation. The magneto-rheology on-demand control offers a potential approach to meet the opposing rheological requirements. By applying a specialized controllable magnetic field at the print head or nozzle, the induced movement of magnetic components can possibly improve the extrudability, depending on the direction of the field. Additionally, the residual magnetic clusters within the cementitious suspension contribute to enhanced buildability of the printed layers [18, 52]. However, relying solely on residual magnetic clusters may not provide significant buildability enhancements [53]. Therefore, the development of cementitious materials with enhanced responsiveness to external magnetic fields, along with more robust and precisely controlled magnetically assisted printing systems, is essential for further advancing this technology. When using steel fibers as responsive additives and applying a 0.034 T magnetic field perpendicular to the flow direction at the nozzle, the fibers can align more efficiently along the printing direction, thereby improving flexural strength in the vertical (Z) direction [54]. However, the compressive strength in the printing direction is decreased significantly, and steel fibers tend to agglomerate easily in the nozzle, potentially blocking extrusion and diminishing extrudability.

Another possible solution of applying magneto-rheology control in 3D concrete printing is magnetizing the print bed by exposing the first few printed layers to a magnetic field. Due to the continuous magnetic stimulation, the buildability can be increased, as reflected by an approximate 50% increase in yield strength [53]. This will transform 3D printed concrete into a smart material, capable of on-demand microstructural changes, laying the foundation for four-dimensional (4D) concrete printing technology. Despite its promise, this method has certain limitations, such as the magnetic field being applicable only to the initial printed layers, restrictions on the gap between magnets (layer width), and limited improvement in interlayer bonding. To address these challenges, our group recently developed an innovative magnetized print bed that enhances the extrudability, printability, and interface bonding properties. This technology is undergoing the patent application process, with experimental results expected to be disseminated in the near future.

4.3 Sustainable and multifunctional concretes

Beyond specialized magnetic particles, traditional mineral powders such as fly ash and blast furnace slag also contain a minor fraction of magnetic particles. This inherent property makes them promising candidates as responsive additives in

magneto-rheology control [25]. Alkali-activated concrete, an alternative to traditional cement-based materials, is synthesized by activating aluminosilicate-rich industrial by-products, such as fly ash, blast furnace slag, or natural pozzolans, using highly alkaline solutions [55]. By integrating magneto-rheology control into alkali-activated concrete, it offers a promising pathway to enhance the tunable rheological properties of such materials, achieving properties tailored to specific construction demands. This capability is particularly advantageous for advanced construction technologies such as 3D concrete printing, where precise control over material properties during extrusion and layer formation is crucial.

Another interesting possible application of magneto-rheology control is the development of intelligent concrete or self-sensing concrete, which includes electrically conductive fillers such as carbon fibers, carbon black, and graphene nanoparticles, to enable functionalities like strain sensing and structural health monitoring. Magneto-rheology control offers the potential to enhance the orientation and distribution of these conductive fillers, thereby increasing the sensitivity and efficiency of the functional concrete. Research has demonstrated that applying a magnetic field to cementitious composites containing nickel particles or nickel-coated carbon fibers can improve their mechanical properties and electrical conductivity by aligning the fillers or fibers more effectively [56, 57]. Nevertheless, the relationships between paste rheology, filler characteristics, self-sensing properties, and magnetic field parameters remain insufficiently understood. Similarly, the alignment of steel fibers along specific directions in concrete using a magnetic field is well-known to enhance the flexural performance [58-60]. However, an unexplored yet promising area is the application of magnetically induced fiber alignment along the flow direction in potentially improving the pumping efficiency, which warrants further investigation.

In a recent preliminary study, the controlled orientation of graphene nanoplatelets within cementitious matrix was explored, facilitated by the inclusion of Fe_3O_4 particles. The results indicate that both compressive strength and electrical properties exhibit directional behavior along the magnetic induction direction, providing significant promise for advanced structural health monitoring applications. Despite these advancements, the challenges, such as high viscosity of cement medium and relatively low responsiveness, should be addressed to fully realize the potential of magneto-rheology control in functional concrete technologies.

5 Summary

This article provides an overview of active rheology control of cementitious materials using external magnetic fields. To achieve this, magneto-responsive additives should be first incorporated into the cementitious matrix, and the rheology is manipulated on-demand based on the movement and distribution of these additives under the influence of magnetic forces. The degree of the rheological response depends on the material compositions, such as paste medium properties, additive characteristics, and chemical admixtures,

along with magnetic field parameters and external factors like temperature and shear rate. The magneto-rheology control can be potentially used in various applications, such as facilitating smart casting processes, improving the printability of 3D printed concrete, and developing sustainable and multifunctional concretes. Despite these promising advancements, challenges remain, such as the optimization of highly responsive materials, the design of magnetizable equipment setups, and the assessment of long-term properties.

Acknowledgements

The financial supports from National Natural Science Foundation of China (52408295), Guangdong Basic and Applied Basic Research Foundation (2025A1515012809), Research Grants Council of Hong Kong SAR (21211024), and ERC (693755) are highly acknowledged. Appreciation is also given to Shengming Hu and Feng Hu for their valuable suggestions.

Authorship statement (CRediT)

Dengwu Jiao: Conceptualization, Writing – Original Draft, Funding acquisition.

References

- [1] Yuan, Q., Shi, C., Jiao, D., Rheology of Fresh Cement-Based Materials: Fundamentals, Measurements, and Applications, CRC Press (2022).
<https://doi.org/10.1201/9781003265313-9>
- [2] De Schutter, G., Feys, D., Pumping of Fresh Concrete: Insights and Challenges, RILEM Tech Lett (2016) 1: 76-80.
<https://doi.org/10.21809/rilemtechlett.2016.15>
- [3] Roussel, N., Rheology of fresh concrete: from measurements to predictions of casting processes, Mater Struct (2007) 40(10): 1001-1012.
<https://doi.org/10.1617/s11527-007-9313-2>
- [4] Roussel, N., Rheological requirements for printable concretes, Cem Concr Res (2018) 112: 76-85.
<https://doi.org/10.1016/j.cemconres.2018.04.005>
- [5] De Schutter, G., Lesage, K., Mechtcherine, V., et al., Vision of 3D printing with concrete - Technical, economic and environmental potentials, Cem Concr Res (2018) 112: 25-36.
<https://doi.org/10.1016/j.cemconres.2018.06.001>
- [6] Jiao, D., Shi, C., Yuan, Q., et al., Mixture design of concrete using simplex centroid design method, Cem Concr Compos (2018) 89: 76-88.
<https://doi.org/10.1016/j.cemconcomp.2018.03.001>
- [7] Marchon, D., Kawashima, S., Bessaies-Bey, H., et al., Hydration and rheology control of concrete for digital fabrication: Potential admixtures and cement chemistry, Cem Concr Res (2018) 112: 96-110.
<https://doi.org/10.1016/j.cemconres.2018.05.014>
- [8] Zheng, Q., Yang, E.-h., Jiang, Z., Autolytic microsphere capsules using in cement composites: A self-healing enhancement via hydration control and secondary cracking mode alteration, Constr Build Mater (2025) 463: 140128.
<https://doi.org/10.1016/j.conbuildmat.2025.140128>
- [9] De Schutter, G., Lesage, K., Active control of properties of concrete: a (p)review, Mater Struct (2018) 51(5): 123.
<https://doi.org/10.1617/s11527-018-1256-2>
- [10] De Schutter, G., Lesage, K., Active Rheology Control of Cementitious Materials, CRC Press (2022).
<https://doi.org/10.1201/9781003289463>
- [11] Li, W.H., Chen, G., Yeo, S.H., Viscoelastic properties of MR fluids, Smart Mater Struct (1999) 8: 460-468.
<https://doi.org/10.1088/0964-1726/8/4/303>
- [12] Rich, J.P., Doyle, P.S., McKinley, G.H., Magnetorheology in an aging, yield stress matrix fluid, Rheol Acta (2012) 51(7): 579-593.
<https://doi.org/10.1007/s00397-012-0632-z>
- [13] Nair, S.D., Ferron, R.D., Set-on-demand concrete, Cem Concr Res (2014) 57: 13-27.
<https://doi.org/10.1016/j.cemconres.2013.12.001>
- [14] Jiao, D., El Cheikh, K., Shi, C., et al., Structural build-up of cementitious paste with nano-Fe₃O₄ under time-varying magnetic fields, Cem Concr Res (2019) 124: 105857.
<https://doi.org/10.1016/j.cemconres.2019.105857>
- [15] Zhang, Y., Tao, Y., Godinho, J.R., et al., Active rheology control of cementitious materials: New insights from magneto-responsive aggregates, Cem Concr Res (2025) 189: 107707.
<https://doi.org/10.1016/j.cemconres.2024.107707>
- [16] Chibulu, C., Jiao, D., Yardimci, M., et al., Magneto-rheology control of cement paste containing Fe₃O₄ nanoparticles in view of reducing or preventing formwork leakage, Cem Concr Compos (2023) 142: 105176.
<https://doi.org/10.1016/j.cemconcomp.2023.105176>
- [17] De Schryver, R., Jiao, D., Yardimci, M.Y., et al., A conceptual model for numerical simulation of Active Rheology Control validated for cementitious pumping, Cem Concr Res (2024) 179: 107471.
<https://doi.org/10.1016/j.cemconres.2024.107471>
- [18] Jiao, D., Shi, C., De Schutter, G., Magneto-rheology control in 3D concrete printing: A rheological attempt, Mater Lett (2021) 309: 131374.
<https://doi.org/10.1016/j.matlet.2021.131374>
- [19] Ahamed, R., Choi, S.-B., Ferdaus, M.M., A state of art on magneto-rheological materials and their potential applications, J Intell Mater Syst Struct (2018) 29(10): 2051-2095.
<https://doi.org/10.1177/1045389X18754350>
- [20] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Rheological behavior of cement paste with nano-Fe₃O₄ under magnetic field: Magneto-rheological responses and conceptual calculations, Cem Concr Compos (2021) 120: 104035.
<https://doi.org/10.1016/j.cemconcomp.2021.104035>
- [21] De Schutter, G., Ezzat, M., Lesage, K., et al., Responsive superplasticizers for active rheology control of cementitious materials, Cem Concr Res (2023) 165: 107084.
<https://doi.org/10.1016/j.cemconres.2022.107084>
- [22] Jiao, D., Active rheology control of cementitious materials using magnetic field, Ghent University, 2021.
- [23] Deshmukh, A.S., Heintzkill, R.T., Huerta, R.A., et al., Rheological Response of Magnetorheological Cementitious Inks Tuned for Active Control in Digital Construction, ACI Mater J (2021) 118(6): 263-274.
<https://doi.org/10.14359/51733128>
- [24] Guo, X., Hu, S., Jiao, D., Flowability responses of cement paste containing steel fiber to external magnetic field, J Build Eng (2025) 103: 112220.
<https://doi.org/10.1016/j.jobe.2025.112220>
- [25] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Possibilities of fly ash as responsive additive in magneto-rheology control of cementitious materials, Constr Build Mater (2021) 296: 123656.
<https://doi.org/10.1016/j.conbuildmat.2021.123656>
- [26] Yardimci, M.Y., Jiao, D., De Schutter, G., Magnetorheological properties of fayalite slag incorporated cement mixtures, RILEM Spring Convention and Conference, Springer, 2024, 238-246.
https://doi.org/10.1007/978-3-031-70281-5_27
- [27] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Quantitative assessment of the influence of external magnetic field on clustering of nano-Fe₃O₄ particles in cementitious paste, Cem Concr Res (2021) 142: 106345.
<https://doi.org/10.1016/j.cemconres.2020.106345>
- [28] Jiao, D., Shi, C., De Schutter, G., Estimation of Magnetic Force between Micrometer-Sized Fly-Ash Particles in Cementitious Suspensions, J Mater Civ Eng (2023) 35(2): 04022421.
[https://doi.org/10.1061/\(ASCE\)JMT.1943-5533.0004594](https://doi.org/10.1061/(ASCE)JMT.1943-5533.0004594)
- [29] Nair, S.D., Ferron, R.D., Real time control of fresh cement paste stiffening: Smart cement-based materials via a magnetorheological approach, Rheol Acta (2016) 55(7): 571-579.
<https://doi.org/10.1007/s00397-016-0923-x>
- [30] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Flow behavior of cementitious-like suspension with nano-Fe₃O₄ particles under external magnetic field, Mater Struct (2021) 54: 209.
<https://doi.org/10.1617/s11527-021-01801-y>
- [31] Hu, F., Wu, H., Jiao, D., Effect of magneto-rheological response on early hydration and microstructure of cement paste, Constr Build Mater (2025) 474: 141161.
<https://doi.org/10.1016/j.conbuildmat.2025.141161>

- [32] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Rheological Properties of Cement Paste with Nano-Fe₃O₄ under Magnetic Field: Flow Curve and Nanoparticle Agglomeration, *Mater* (2020) 13(22): 5164. <https://doi.org/10.3390/ma13225164>
- [33] Cao, G., Li, Z., Jiang, S., et al., Experimental analysis and numerical simulation of flow behavior of fresh steel fibre reinforced concrete in magnetic field, *Constr Build Mater* (2022) 347: 128505. <https://doi.org/10.1016/j.conbuildmat.2022.128505>
- [34] Jiao, D., Lesage, K., Yardimci, M.Y., et al., Structural evolution of cement paste with nano-Fe₃O₄ under magnetic field - Effect of concentration and particle size of nano-Fe₃O₄, *Cem Concr Compos* (2021) 120: 104036. <https://doi.org/10.1016/j.cemconcomp.2021.104036>
- [35] Jiao, D., Yardimci, M.Y., De Schryver, R., et al., Effect of Solid Volume Fraction on the Magnetorheological Response of Nano-Fe₃O₄ Incorporated Cementitious Paste, *J Mater Civ Eng* (2022) 34(11): 04022280. [https://doi.org/10.1061/\(ASCE\)MT.1943-5533.0004440](https://doi.org/10.1061/(ASCE)MT.1943-5533.0004440)
- [36] Jiao, D., Shi, C., De Schutter, G., Magneto-responsive structural build-up of highly flowable cementitious paste in the presence of PCE superplasticizer, *Constr Build Mater* (2022) 327: 126925. <https://doi.org/10.1016/j.conbuildmat.2022.126925>
- [37] Kim, J., Ferron, R.D., Effect of Air-Entraining Agent on Rheology of Cement-Based Magnetorheological Pastes, *ACI Mater J* (2024) 121(5): 3-12. <https://doi.org/10.14359/51742113>
- [38] Zhang, Y., Lesage, K., Zhang, Y., et al., A comparison of magneto-responsive particles and testing protocols for active rheology control of cementitious materials, *Cem Concr Compos* (2024) 146: 105390. <https://doi.org/10.1016/j.cemconcomp.2023.105390>
- [39] Jiao, D., De Schutter, G., Enhancing magneto-rheology control of cement paste through synergistic effect of nano-Fe₃O₄ particles and fly ash, *Mater Lett* (2024) 367: 136630. <https://doi.org/10.1016/j.matlet.2024.136630>
- [40] Zhang, Y., Tao, Y., Zhang, Y., et al., Active rheology control of responsive mortar with low slump value: Effect of magnetic field properties, *Constr Build Mater* (2025) 458: 139450. <https://doi.org/10.1016/j.conbuildmat.2024.139450>
- [41] Zhang, Y., Tao, Y., Zhang, Y., et al., Upscaling active rheology control to cement mortar with the intervention of an inline magnetic field, *Constr Build Mater* (2024) 425: 135853. <https://doi.org/10.1016/j.conbuildmat.2024.135853>
- [42] Kang, D., Moon, D., Kim, W., Changes in rheological properties of mortars with steel slags and steel fibers by magnetic field, *Mater* (2021) 14(14): 4005. <https://doi.org/10.3390/ma14144005>
- [43] Jiao, D., El Cheikh, K., Lesage, K., et al., Structural Build-Up of Cementitious Paste Under External Magnetic Fields, *Rheology and Processing of Construction Materials*, Springer, 2020, 36-42. https://doi.org/10.1007/978-3-030-22566-7_5
- [44] Genç, S., Phulé, P.P., Rheological Properties of Magnetorheological Fluids, *Smart Mater Struct* (2002) 11(1): 140-146. <https://doi.org/10.1088/0964-1726/11/1/316>
- [45] Zhang, Y., Zhang, Y., Tao, Y., et al., Active rheology control of cementitious materials containing hard magnetic particles: Sustained response after magnetic intervention, *Cem Concr Compos* (2025), 160: 106024. <https://doi.org/10.1016/j.cemconcomp.2025.106024>
- [46] Zhang, Y., Tao, Y., Sun, Y., et al., Active control of thixotropy of magneto-responsive cementitious materials with the intervention of time-varying magnetic fields, *Cem Concr Res* (2024) 181: 107520. <https://doi.org/10.1016/j.cemconres.2024.107520>
- [47] Alvim, T., Maranhão, F.d.S., Batista, J.H.G., et al., Effect of inductive heating on the properties of a cement slurry blended with magnetic iron oxide nanoparticles, *Rio Oil & Gas Expo and Conference*, Rio de Janeiro, 2020.
- [48] Jiao, D., Hu, S., De Schutter, G., How does ambient temperature affect the magneto-rheological response of cementitious paste?, *Construction and Building Materials*, 2025, 142543. <https://doi.org/10.1016/j.conbuildmat.2025.142543>
- [49] Chibulu, C., Yardimci, M.Y., Jiao, D., et al., Active stiffening control by magnetically induced blocking in confined flow of fly ash pastes, *Constr Build Mater* (2021) 313: 125485. <https://doi.org/10.1016/j.conbuildmat.2021.125485>
- [50] Chibulu, C., Yardimci, M.Y., De Schutter, G., Effect of volume fraction of fine sand on magnetorheological response and blocking mechanisms of cementitious mixtures containing Fe₃O₄ nanoparticles, *Appl Sci* (2022) 12(19): 10104. <https://doi.org/10.3390/app121910104>
- [51] Krezinski, C., Panchmatia, P., Genedy, M., et al., Magnetorheological cements for plug setting control in oil and gas wells, *J Pet Sci Eng* (2021) 200: 108257. <https://doi.org/10.1016/j.petrol.2020.108257>
- [52] Yue, H., Zhang, Z., Hua, S., et al., Solid waste-based set-on-demand 3D printed concrete: active rheological control of cement-based magneto-rheological fluids, *Constr Build Mater* (2023) 404: 133269. <https://doi.org/10.1016/j.conbuildmat.2023.133269>
- [53] Kanagasuntharam, S., Ramakrishnan, S., Muthukrishnan, S., et al., Effect of Magnetorheological additives on the buildability of 3D concrete printing, *J Build Eng* (2023) 74: 106814. <https://doi.org/10.1016/j.jobbe.2023.106814>
- [54] Huang, J., Peng, Z., Tan, X., et al., Mechanism analysis of the magnetic field assisted 3D printed steel fiber reinforced concrete, *Constr Build Mater* (2025) 458: 139737. <https://doi.org/10.1016/j.conbuildmat.2024.139737>
- [55] Provis, J.L., Alkali-activated materials, *Cem Concr Res* (2018) 114: 40-48. <https://doi.org/10.1016/j.cemconres.2017.02.009>
- [56] Tian, W., Liu, X., Wang, X., et al., Improving electrical-thermal-mechanical functional performance of intelligent conductive cementitious composites: Through fiber orientation by magnetic field, *J Build Eng* (2025) 104: 112374. <https://doi.org/10.1016/j.jobbe.2025.112374>
- [57] Tian, Z., Li, Y., Li, S., et al., Influence of particle morphology and concentration on the piezoresistivity of cement-based sensors with magneto-aligned nickel fillers, *Meas* (2022) 187: 110194. <https://doi.org/10.1016/j.measurement.2021.110194>
- [58] Mu, R., Li, H., Qing, L., et al., Aligning steel fibers in cement mortar using electro-magnetic field, *Constr Build Mater* (2017) 131: 309-316. <https://doi.org/10.1016/j.conbuildmat.2016.11.081>
- [59] Al Rifai, M.M., Sikora, K.S., Hadi, M.N.S., Magnetic alignment of micro steel fibers embedded in self-compacting concrete, *Constr Build Mater* (2024) 412: 134796. <https://doi.org/10.1016/j.conbuildmat.2023.134796>
- [60] Gou, H., Zhu, H., Zhou, H., et al., Reinforcement mechanism of orientally distributed steel fibers on ultra-high-performance concrete, *Constr Build Mater* (2021) 281: 122646. <https://doi.org/10.1016/j.conbuildmat.2021.122646>