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Magneto-responsive structural build-up of highly flowable cementitious paste in the presence of PCE superplasticizer

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ABSTRACT

Magneto-rheology control, by means of adding magnetizable particles and applying magnetic field, is a potential approach to satisfy the contradicting requirements of fresh properties in different casting processes. Poly-carboxylate ether (PCE) superplasticizer is an essential component of modern cement-based materials, which significantly affects the viscoelastic properties of cementitious suspensions, and hence the movement and distribution of magnetic particles after applying an external magnetic field. This present research focuses on the following two aspects: whether highly flowable cementitious paste containing both magnetic particles and PCE shows rheological response to an external magnetic field, and if yes, is there a difference of magneto-responsive structural evolution of cementitious pastes with and without PCE? For these purposes, the magneto-responsive structural build-up of highly flowable cementitious pastes with various magnetic particles (two nano-Fe 3 O 4 particles and one magnetic fly ash) in the presence of PCE, described by the evolution of storage modulus over time, is evaluated. Experimental results show that highly flowable cementitious pastes containing both magnetic particles and PCE indeed exhibit obvious magneto-rheological (MR) responses. The incorporation of PCE significantly increases the relative MR effect while slightly decreases the absolute MR effect. By comparing the magneto-responsive structural build-up of cementitious pastes with and without PCE, it is revealed that the application of an external magnetic field to a highly flowable cementitious paste with PCE mainly plays a significant role in the increase of solid-like properties.

1. Introduction

Ready-mixed concrete generally follows the engineering construction processes of transporting, pumping, and formwork casting. Each process is a significant factor influencing the workability and rheological properties of fresh concrete [1, 2]. Most importantly, the requirements of concrete properties in different casting processes usually contradict with each other [3, 4]. For example, a higher structural build-up is recommended to reduce the formwork pressure while a lower one is required to improve the efficiency of multi-layer casting process [5–7]. This phenomenon also occurs in extrusion-based 3D concrete printing regarding pumpability (or extrudability) and buildability [8–10]. One potential approach to overcome these opposing property requirements is active rheology control by external vibration, with a typical example presented in [11]. Another alternative way to achieve the active rheology control of cementitious materials is adding magnetic particles (or responsive polymers [12]) together with applying a magnetic field [13–15]. The signal is generally applied post-mixing, which means that it can be used to adjust the rheological properties of the same concrete mixture on-demand or in real-time. Predictably, active rheology control has a potential to make casting processes and 3D concrete printing more reliable and smarter.

In the case of particles as responsive additives, after employing an external magnetic field, the magnetic particles will move to form clusters in cementitious suspensions if the magnetic force overcomes the resistance of the suspension [16]. The movement of the magnetic particles and the formation of clusters significantly influence the early liquid-like behavior and the later stiffness of the cementitious paste, respectively, and thus the magneto-rheological (MR) response. Experimental results and theoretical calculations reveal that the MR responses of cementitious paste containing magnetic nano-Fe 3 O 4 particles are dependent on the paste medium [17, 18], the concentration and physical...
nature (such as particle size and magnetic properties) of the magnetic particles [19,20], and the applied magnetic field [21,22]. Particularly, the viscoelastic properties of cementitious paste have significant influences on the movement and distribution of magnetic particles when applying an external magnetic field, which determines the degree of the rheological response directly.

Polycarboxylate Ether (PCE) superplasticizer has been widely practiced in construction engineering of cement-based materials to improve workability, mechanical properties and durability [23–25]. PCE with steric repulsive dispersing effect exerts a critical significance on the particle interactions and thus the viscoelasticity of cementitious paste [26,27]. The movement of magnetic particles in a cement paste under external magnetic force could be possibly altered by the presence of PCE, and thus the MR behavior. Previous results in [17] concluded that very stiff cementitious pastes containing nano-Fe$_3$O$_4$ (20–30 nm) and low PCE additions show unapparent response to an external magnetic field due to the excessive movement resistance by the high viscoelasticity, and paste with high PCE dosage seems to show a slight response. However, no further refining studies on the MR behavior of cementitious paste with PCE are available. Given that PCE is an essential component of modern cement-based materials (e.g., SCC and UHPC) and the rheological response of highly flowable cementitious paste with PCE to a magnetic field is still doubtful, further study on the MR behavior of cementitious materials with various magnetic particles in the presence of PCE is required to enrich the fundamental knowledge of active rheology control by magnetic field.

This current study is a continued research of [17], aiming at finding answers to the following two questions: whether highly flowable cementitious paste containing PCE shows rheological response to an external magnetic field, and if yes, is there a difference of the magneto-responsive structural evolution of cementitious pastes with and without PCE? For these ends, the responses of highly flowable cementitious pastes with PCE to an external magnetic field are examined from rheological viewpoint. Two types of nano-Fe$_3$O$_4$ particles and one magnetic fly ash are selected as the magneto-responsive additives. The rheological response is characterized by the structural build-up obtained from small amplitude oscillatory time sweep test. The experimental observations are analyzed and explained by the particle interactions, and the magnetic field parameter evaluating the relative magnitude of magnetic force and resistance induced by the viscoelasticity of the suspension is also calculated to provide a theoretical support.

2. Experimental program

2.1. Materials and mix proportions

CEM I 52.5 N Portland cement (OPC), fly ash (FA), and spherical nano-Fe$_3$O$_4$ particles were utilized. The particle size distribution of the cement and fly ash is presented in Fig. 1. The two types of nano-Fe$_3$O$_4$ particles with an average particle size of 20–30 nm (MNP1) and 100 nm (MNP2) were purchased from US Research Nanomaterials, Inc. The chemical composition and physical properties of the raw materials are summarized in Table 1. Further details about the physical nature of the fly ash and nano-Fe$_3$O$_4$ particles can be found in [20,28]. A commercial polycarboxylate ether (PCE) superplasticizer (MasterGlenium 51) was employed. All cementitious pastes were prepared using de-ionized water.

Four batches of cementitious paste were prepared, with the mix proportions presented in Table 2. The first two batches have the same concentration of magnetic particles (i.e., 3% MNP1 by mass of cement paste) but different water-to-cement (w/c) ratios (0.67 for B1 and 0.40 for B2). The nanoparticles concentration and w/c of B3 are similar to that of B2, and the only difference is that MNP2 was used as the magnetic additive. With regard to B4, cement paste with 50% fly ash (by volume of cement) and w/c of 0.35 was selected. Each batch includes two mixtures, i.e., no-PCE paste and PCE-containing paste. The amount of PCE was determined to achieve a highly flowable cementitious paste without the risks of bleeding and segregation. All the mixtures were prepared by using a rotational rheometer equipped with a helix geometry [21].

2.2. Determination of responsive structural build-up

The magneto-responsive structural build-up of the cementitious pastes was obtained from oscillatory time sweep test by using a parallel plate rotational rheometer (MCR 102, Anton Paar) with a magnetorheological device (MRD). The diameter of the plate is 20 mm. During the entire test, the gap between the two parallel plates was set as 1 mm, and the temperature was fixed at 20°C by a water bath.

The protocol for measuring the structural build-up is presented in Fig. 2. An external magnetic field with 0 T or 0.5 T is only applied in the oscillatory time sweep test. The pre-shearing is used to eliminate the residual stress during the gap adjustment and destroy the possibly agglomerated structures. The strain sweep test is to determine the viscoelastic yield stress of cementitious suspension, according to Eq. (1), as well as the linear viscoelastic region (LVER).

$$\tau_{c,300s} = \gamma_{c} \cdot G'$$

where $\gamma_{c}$ is the critical strain (%), $G'$ is the storage modulus in LVER (Pa), and $\tau_{c,300s}$ is the viscoelastic yield stress of cementitious suspension (Pa), representing the intensity of early hydration product bridges between cement particles [7,17]. During the oscillatory time sweep test, the shear strain was fixed at 0.005%, which is within the LVER. Each rheological test was performed repeatedly, and one representative result will be presented.

The storage modulus at the end of the time-sweep test, denoted as $G'_{t=300s}$ (0 T) or $G'_{t=300s}$ (0.5 T), is selected to illustrate the structural build-up quantitatively. The degree of MR response is characterized by the difference of $G'_{t=300s}$ (Absolute MR response, kPa) and the relative change of $G'_{t=300s}$ (Relative MR response, %), as calculated by Eq. (2) and Eq. (3), respectively.

$$\text{Absolute MR response} = G'_{t=300s}(0.5T) - G'_{t=300s}(0T)$$

$$\text{Relative MR effect} = \frac{G'_{t=300s}(0.5T) - G'_{t=300s}(0T)}{G'_{t=300s}(0T)} \times 100$$
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3. Results and discussion

3.1. Magneto-responsive structural evolution of cementitious pastes with PCE

The representative evolution of storage modulus of the considered cementitious pastes in the absence and presence of an external magnetic field of 0.5 T is shown in Fig. 3. Table 3 summarizes the main magneto-responsive parameters of the cementitious pastes. The cementitious pastes without PCE show obvious magneto-rheological responses, represented by a higher structural evolution after applying an external magnetic field of 0.5 T. It can be observed from Fig. 3 (a) and (b) that the cementitious pastes with PCE show higher values compared to that without PCE, despite the reduced absolute increase in the stiffness for the highly flowable cementitious pastes with PCE after applying a magnetic field of 0.5 T, the storage modulus in Fig. 3 (a) and (b) is in agreement with the observations in [30], which is due to the increase in the bridging distance between cement particles [7,31,32]. In the presence of an external magnetic field of 0.5 T, the highly flowable cementitious pastes indeed show higher evolution of storage modulus compared to the pastes without magnetic field. Specifically, applying an external magnetic field of 0.5 T exerts less influences on the storage modulus of the paste 3MNP1_0.67_0.5%PCE during the first tens of seconds. Subsequently, the cementitious paste shows an apparent bifurcation under the continuous magnetization. A longer bifurcation time corresponds to a more obvious response to a magnetic field of 0.5 T probably due to the enhancement in the interactions and networks between particles. The results indicate that the absolute increase in the magneto-rheological responses of the cementitious paste 3MNP1_0.67_0.5%PCE during the first tens of seconds and the cementitious paste with high stiffness always shows a high MR response. Indeed, the findings in [17] showed that cementitious paste with w/c of 0.4 had a more obvious response compared to paste with w/c of 0.35. Furthermore, cementitious paste with extremely low w/c cannot show a noticeable rheological response to an external magnetic field due to the very dense particle packing [29]. The comparable relative MR effect of the two suspensions can be attributed to the difference of the initial stiffness, indicating that the selected MNP1-incorporated cementitious pastes have similar MR response if taking the stiffness without magnetic field into account.

Compared to the cementitious pastes without PCE, the addition of 0.5% PCE slows down the structural build-up of cementitious paste in the absence of external magnetic field, as reflected by the low magnitudes of storage modulus in Fig. 3 (a) and (b). This is in agreement with the observations in [30], which is due to the increase in the bridging distance between cement particles [7,31,32]. In the presence of an external magnetic field of 0.5 T, the highly flowable cementitious pastes indeed show higher evolution of storage modulus compared to the pastes without magnetic field. Specifically, applying an external magnetic field of 0.5 T exerts less influences on the storage modulus of the paste 3MNP1_0.67_0.5%PCE during the first tens of seconds. Subsequently, the cementitious paste shows an apparent bifurcation under the continuous magnetization. A longer bifurcation time corresponds to a higher liquid-like property of the paste. More details about the different evolution trends of the storage modulus of cementitious paste with and without PCE will be presented in Section 3.2. After magnetization under 0.5 T for 300 s, the absolute MR effect is 10 kPa and 100 kPa for the cementitious pastes with w/c of 0.67 and 0.40, respectively, as presented in Table 3. The results indicate that the absolute increase in stiffness for the highly flowable cementitious pastes with PCE after applying a magnetic field of 0.5 T is lower than that of pastes without PCE. From the viewpoint of the relative MR effect, however, the cementitious pastes with PCE show higher values compared to that without PCE.

The aforementioned results show that the selected highly flowable MNP1-incorporated cementitious pastes with PCE, regardless of the initial viscoelasticity, can exhibit rheological responses to an external magnetic field of 0.5 T, despite the reduced absolute increase in the
stiffness. A question arises: Does highly flowable cementitious paste with PCE still show rheological response if we change the type of the magnetic particles? In order to get the answer, the cementitious pastes with different nano-Fe$_3$O$_4$ particles and magnetic fly ash were prepared, and their magneto-rheological response was examined in the absence and presence of PCE, as presented in Fig. 3 (c) and (d).

Under an external magnetic field of 0.5 T, the paste 3MNP1$_{0.40}$ _No PCE shows a more obvious MR response compared to 3MNP1$_{0.67}$ _No PCE due to the higher magnetic properties of MNP2 (see Table 1), which is consistent with the results in [20]. Similar to the MNP1-incorporated cementitious pastes, the addition of 0.4% PCE reduces the absolute MR effect of the MNP2-incorporated cementitious paste from 760 kPa to 327 kPa, but the relative MR effect increases significantly due to the extremely high initial liquid-like properties (i.e., low $G'_t$ at 0 T). The results indicate that highly flowable cementitious pastes with PCE can exhibit apparent MR responses from the perspective of structural build-up, irrespective of the type of the nano-Fe$_3$O$_4$ particles.

In the case of cementitious pastes containing magnetic fly ash, obvious MR response can be observed from Fig. 3 (d), regardless of the presence of PCE. The absolute increase of stiffness of 50%FA$_{0.35}$ _No PCE is lower than that of cementitious pastes with nano-Fe$_3$O$_4$ particles (no PCE). This can be attributed to the low magnetic properties of the fly ash particles, as can be observed from Table 1. Another possible reason is that only a small part of the fly ash particles is magnetic and most ones are non-magnetic [28]. Unlike the nano-Fe$_3$O$_4$ incorporated cementitious pastes, the addition of 0.2% PCE increases both the absolute MR effect and the relative MR effect of the fly ash–cement pastes. This to a certain extent indicates that the formation of magnetic clusters of micron-sized fly ash particles is less sensitive to the viscosity of the interstitial solution. Although further research is required, the highly flowable cementitious paste containing magnetic fly ash indeed shows responsive structural build-up to an external magnetic field after incorporation of PCE.

It can be summarized from Table 3 that the addition of PCE evidently increases the relative MR effect of cementitious pastes with magnetic particles, while the absolute MR effect shows a slight reduction, except for the fly ash cement paste. Overall, highly flowable cementitious pastes containing both magnetic particles and PCE superplasticizer can exhibit obvious rheological responses to an external magnetic field of 0.5 T.

### 3.2. Comparison of structural build-up of cementitious pastes with and without PCE under magnetic field

The aforementioned results allow to conclude that cementitious pastes containing both PCE and magnetic particles indeed show obvious MR response to an external magnetic field. However, the development of the storage modulus after the addition of PCE and application of the magnetic field seems to be different, as may be observed from Fig. 3. In this section, the magneto-responsive evolutions of storage modulus of cementitious pastes with and without PCE are compared.
Fig. 4 presents the influence of PCE on the evolution of storage modulus, loss modulus, and phase angle of cementitious pastes with w/c of 0.4 and MNP1 of 3%. In the absence of external magnetic field, the addition of PCE significantly decreases the magnitude of storage modulus, i.e., stiffness. The evolution trend of the storage modulus is slightly altered by the PCE, where it increases during the first seconds and then reaches a steady increase for the paste without PCE, while in the presence of PCE, it shows a gradual increase at the beginning and a slightly higher increase rate at longer resting time. The percolation time, when the phase angle starts to stabilize [21], decreases with the addition of PCE, indicating the faster formation of elastic network. This is consistent with [30], which can be attributed to the increased particle–particle separation distance by the dispersing effect of PCE [23,32,33]. After applying an external magnetic field of 0.5 T, the cementitious paste without PCE exhibits typical MR responses, i.e., increased liquid-like behavior at very early age and enhanced solid-like properties after longer magnetization time. This is represented by the reduced storage modulus and the increased phase angle immediately after applying the magnetic field, the presence of a peak for the loss modulus, and the increased storage modulus at later age. For the highly flowable cementitious paste containing PCE under 0.5 T, the storage modulus gradually increases over time, and its magnitude is always higher than that without the magnetic field. The early significant increase in the phase angle is not clear, and no peak of loss modulus is observed. This indicates that applying an external magnetic field cannot obviously improve the liquid-like properties of highly flowable cementitious paste with PCE. Instead, the stiffness of the cementitious paste is gradually enhanced with magnetization time.

However, the magnitude of the storage modulus in Fig. 4 is distinctly different due to the direct addition of PCE. This may lead to less comparability of structural build-up between these two mixtures. In this case, the magneto-response of storage modulus of different highly flowable cementitious pastes without and with PCE, represented by 3MNP1_0.67_No PCE and 3MNP1_0.40_0.5%PCE respectively, is compared, as shown in Fig. 5. It can be observed that the storage modulus of both the cementitious pastes is within the range of 0–300 kPa, regardless of the application of the magnetic field. For the Paste 3MNP1_0.67_No PCE, the storage modulus increases steadily without magnetic field. In the presence of the external magnetic field, the storage modulus is relatively low at very early age and subsequently, it increases significantly and then reaches a stable increase. By contrast, the paste 3MNP1_0.40_0.5%PCE shows a higher storage modulus immediately after applying the magnetic field, and the storage modulus gradually increases with magnetization time in an increased growth rate. The results are consistent with Fig. 4, revealing that the application of an external magnetic field to a PCE-containing cementitious paste mainly plays a significant role in the increase of solid-like properties. The improvement of very early liquid-like behavior by an external magnetic field is less obvious in PCE plasticized cementitious pastes.

3.3. Discussion

The measured viscoelastic properties of the studied cementitious pastes without magnetic field are listed in Table 4. The addition of PCE reduces the storage modulus in LVER but increases the critical strain, independent of the cementitious composition. As a result, a significant increase in the viscoelastic yield stress of cementitious pastes containing PCE is obtained. The increase of critical strain with the addition of PCE is also observed in [30,34], which indicates that the suspension tends to be more stable. PCE molecules have a tendency to be absorbed onto the surface of cement particles, with the attractive interaction even higher than the van der Waals forces [35]. This, on the one hand, leads to a stronger steric hindrance effect, increasing the particle–particle separation distance and declining the colloidal interactions between solid particles, which decreases the rigidity (i.e., \(G'\) in LVER) of the cementitious paste. On the other hand, owing to the entanglement of PCE chains with each other [33,36], the cohesive bonding between cement particles is probably improved. In addition, the C-S-H bridges are possibly enhanced due to the Ca-Si enriched colloidal surface [37,38]. This improves the elasticity of internal network and increases the deformation capacity of interparticle connections. Consequently, a relatively high oscillatory shear strain is required to facilitate the particles to move or rotate, and thereby an increase in critical strain is observed. As the product of critical strain and storage modulus, the viscoelastic yield stress increases with the incorporation of PCE due to the dominance of the increase of critical strain, at least for the selected dosage in this study.

In the presence of an external magnetic field, the magnetic dipoles in magnetic particles tend to contact with each other, and therefore, a magnetic force is formed immediately. In the case of viscous cementitious suspension, if the magnetic force between adjoining magnetic particles is larger than the resistance of the suspension, the magnetic particles will move to connect with each other to form chains and/or clusters. Certainly, not all the nanoparticles will contribute to the formation of magnetic clusters even in PCE-free cementitious paste due to the viscoelastic properties of the suspension, as presented in the schematic diagram in Fig. 6 (a). After incorporating PCE, the viscoelastic yield stress of the cementitious paste increases, as shown in Table 4. The viscosity of the interstitial solution also increases due to the presence of remaining polymers [27,39]. Even though the magnetic force can overcome the resistance of the paste, the entanglement of PCE chains probably hinders the movement of nanoparticles and thus the formation of large magnetic chains and/or clusters. Instead, it is speculated that the neighboring nano-Fe\(_2\)O\(_4\) particles accumulate to small clusters under the external magnetic force, as shown in Fig. 6 (b). Therefore, the obvious increase in the liquid-like behavior immediately after initiation of the magnetic field is not observed in highly flowable cementitious paste containing PCE. Besides, the formed smaller clusters possibly cannot connect adjoining cement particles due to the larger particle–particle separation distance, and therefore the cementitious paste
shows less influence on the very early structural evolution. However, with increasing magnetization time, the increased interactions between magnetic particles and clusters pose an increasing domination on the structural build-up. This is reflected by the bifurcation behavior of storage modulus at tens of seconds under external magnetic field. Furthermore, the theoretical magnetic force between neighboring nanoparticles derived in [17] is adopted to explain the MR behavior of the studied pastes. For cementitious paste with magnetic nanoparticles, the relative magnitude of the magnetic force against the viscoelasticity of the suspension can be evaluated by the magnetic yield parameter $Y_M$, as calculated by:

\[
Y_M = \frac{\mu_0 (\rho M)^2}{24 \tau_{c,ys}} \left( \phi_{\text{MNPs}} \pi \right) \frac{4}{3}
\]

where $\rho$ and $M$ are the density (kg/m$^3$) and magnetization (Am$^2$/kg) of the nanoparticles, respectively, $\mu_0$ is the magnetic permeability of the vacuum ($4\pi \times 10^{-7}$N/A$^2$), $\tau_{c,ys}$ is the viscoelastic yield stress (see Eq. (1)), and $\phi_{\text{MNPs}}$ is the volume fraction of nanoparticles against the voids between cement particles, which can be calculated as:

\[
\phi_{\text{MNPs}} = \frac{V_{\text{MNPs}}}{V_{\text{Total}}} \cdot (1 - \phi_C)
\]

where $V_{\text{MNPs}}$ and $V_{\text{Total}}$ are the volume of magnetic nanoparticles and total cementitious paste (kg/m$^3$), respectively, and $\phi_C$ is the volume fraction of cement particles (%). When the magnetic yield parameter is

---

**Table 4**

<table>
<thead>
<tr>
<th>Mix.</th>
<th>Critical strain (%)</th>
<th>$G'(LVER)$ (kPa)</th>
<th>$\tau_{c,ys}$ (Pa)</th>
<th>$Y_M$</th>
</tr>
</thead>
<tbody>
<tr>
<td>3MNP1_0.67_No PCE</td>
<td>0.0084</td>
<td>63.5</td>
<td>5.33</td>
<td>5.12</td>
</tr>
<tr>
<td>3MNP1_0.67_0.3% PCE</td>
<td>0.0719</td>
<td>15.3</td>
<td>11.02</td>
<td>2.46</td>
</tr>
<tr>
<td>3MNP1_0.40_No PCE</td>
<td>0.0047</td>
<td>209.4</td>
<td>9.84</td>
<td>4.28</td>
</tr>
<tr>
<td>3MNP1_0.40_0.5% PCE</td>
<td>0.0401</td>
<td>41.4</td>
<td>16.59</td>
<td>2.50</td>
</tr>
<tr>
<td>3MNP2_0.40_No PCE</td>
<td>0.0032</td>
<td>243</td>
<td>7.78</td>
<td>5.41</td>
</tr>
<tr>
<td>3MNP2_0.40_0.4% PCE</td>
<td>0.1060</td>
<td>9.9</td>
<td>10.44</td>
<td>3.98</td>
</tr>
<tr>
<td>50%FA_0.35_No PCE</td>
<td>0.0147</td>
<td>6.9</td>
<td>1.01</td>
<td>/</td>
</tr>
<tr>
<td>50%FA_0.35_0.2%PCE</td>
<td>0.0999</td>
<td>4.6</td>
<td>4.57</td>
<td>/</td>
</tr>
</tbody>
</table>

---

Fig. 5. Evolution of storage modulus of highly flowable cementitious pastes under external magnetic field.

Fig. 6. Schematic diagram illustrating the distribution of solid particles in nano-Fe$_3$O$_4$ incorporated cementitious paste without and with PCE. Note that for reasons of clarity of the illustration, the PCE molecules are not drawn at the same scale as the solid particles.
higher than 1, theoretically, the cementitious suspension will show MR response.

The calculated magnetic yield parameter of the studied cementitious pastes under an external magnetic field of 0.5 T is listed in Table 4. Obviously, all the calculated magnetic yield parameters are higher than 1, indicating that all the prepared cementitious pastes could respond to an external magnetic field. The highly flowable cementitious paste containing PCE shows relatively lower magnetic yield parameter compared to the corresponding paste without PCE, regardless of the paste medium and type of nano-Fe3O4 particles. Theoretically, a higher magnetic yield parameter means a higher predominance of the magnetic force over the resistance of the suspension, and thus the magnetic particles can move in the cementitious suspension to form clusters more easily. This, to a certain extent, can be used to explain the slight reduction of the absolute increase of the stiffness after applying an external magnetic field. In a word, the theoretical calculations are consistent with the rheological experimental results in Fig. 3. In the case of fly ash cement pastes, the relatively low magnitudes of storage modulus in LVER and viscoelastic yield stress provide useful indicators to support the ease of mobility of magnetic fly ash particles in cementitious paste under an external magnetic field.

4. Conclusions

As a continuation of [17], the presented research discusses whether highly flowable cementitious pastes containing both magnetic particles and PCE superplasticizer show response to an external magnetic field from rheological viewpoint. Based on the experimental results and discussion, the following conclusions can be drawn:

(1) The addition of PCE reduces the storage modulus in LVER of cementitious paste but increases the critical strain, independent of the cementitious composition, probably because of the improvement of deformation capacity of internal networks by PCE. The calculated viscoelastic yield stress, which is the product of the critical strain and the storage modulus, increases with the incorporation of PCE.

(2) After applying an external magnetic field, the highly flowable cementitious pastes containing PCE and magnetic particles indeed show obvious magneto-rheological responses. They exhibit an increased relative change of stiffness due to the significant decrease of initial solid-like behavior by the dispersive effect, while the absolute increase of the stiffness shows a slight reduction possibly due to the resistance to moving magnetic particles by the entanglement of PCE chains and the high particle–particle separation distance.

(3) After comparing the magneto-responsive structural build-up of cementitious pastes with and without PCE, it can be concluded that the application of an external magnetic field to a PCE-containing highly flowable cementitious paste mainly plays a significant role in the increase of solid-like properties, and the improvement of very early liquid-like behavior is less obvious.

Acknowledgements

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