Active stiffening control by magnetically induced blocking in confined flow of fly ash pastes

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ABSTRACT

Formwork leakage has become one of the important challenges of modern construction parallel to the increase in use of self-compacting cementitious materials. Excessive formwork pressure coupled with the highly flowable nature of these materials could lead to increased formwork leakage. This paper introduces a magnetic field-based active stiffening control methodology that could be beneficial for reducing formwork leakage during casting. As a demonstration of formwork leakage, pressure-driven flow through a narrow slit was investigated on magnetisable pastes containing 40% fly ash. The active stiffening control was incorporated by applying an external magnetic field at the outflow. The mass of the outflowing material was continuously recorded, and the flow rate and final net mass loss evaluated. Experimental results showed reduction in flow rate after applying the external magnetic field due to the agglomeration of magnetisable particles contained in the fly ash at the outflow region. It is concluded that the confined flow of pastes containing magnetisable particles can be actively controlled by the application of a magnetic field. The effectiveness of the introduced methodology is mainly dependent on the introduced magnetic field strength, paste viscosity, flow width to magnetisable particle size ratio and pressure level.

1. Introduction

The rheological behavior of concrete during the casting process plays a significant role at each stage of processing. During pumping, the concrete must be flowable enough to avoid high pumping pressure and pipe blockages, as well as to facilitate good form filling. However, once the concrete is cast in the formwork, a higher flowability could result in increased formwork pressure and excessive leakages of formworks, especially in the case of self-compacting concrete (SCC). This can further be driven by placing the concrete using the bottom-up pumping method in which formwork pressures can reach hydrostatic levels. It is clear that the rheological properties required for pumping and good form filling and those required for low formwork pressure and minimal leakage are in contradiction. Active rheology control or active stiffening control of the concrete could be a means to resolve this conflict [1,2]. This study thus forms part of research centered on the leakage of formworks under pressure and explores a method of active stiffening to mitigate excessive leakages. Once the concrete is placed in the formwork, a localised approach to minimize leakage of formworks by applying active stiffening control measures in the vicinity of the formwork joints is studied.

Fresh concrete, mortar or even cementitious pastes can be considered as a suspension, with rigid particles of various sizes suspended in the bulk fluid. Rigid particles that are forced to flow through a narrow constriction are known to exhibit different modes of flow depending on the conditions experienced. The particles may either flow steadily, intermittently, or not at all. This can be seen in numerous systems such as granular flow out of a silo, microfluidic systems, or flow through membranes [3]. The same behaviour can thus be expected during formwork leakage. As the fresh concrete attempts to flow through the joints, the rigid particles in the medium lead to blocking of varying degrees depending on the ratio of these particles to the flow width. For smaller gaps, only water, cement, and fine fractions leak out due to liquid migration, leaving the larger particles at the surface of the concrete. As the size of the gap increases, larger aggregate particles are also able to flow out (Fig. 1) [4].

Blocking or clogging mechanisms of rigid particles in materials such as suspensions and granular material, are primarily ruled by the ratio
between the flow width (D) and the particles size (d). In fact, there tends to be a threshold D/d ratio at which full flow transitions into intermittent flow or blocking. At low D/d, the particles are able to form stable arches across the constriction thereby causing interruption of flow [3,5-7]. This was also found to be the case in mortar extrusions where aggregate blockage was mainly affected by the D/d ratio [8]. By effectively controlling this D/d ratio, blocking can thus be induced, and formwork leakage can be minimised. This could be achieved by formulating the concrete in a way that makes it magnetically responsive, similar to a magnetorheological (MR) fluid in the magnetic gradient pinch (MGP) mode in which the outflow diameter is magnetically controlled by inducing deposition of particles that pinch the flow [9]. MR fluids form part of a set of fluids that are categorized as smart or actively controllable fluids. In the presence of an externally applied magnetic field, MR fluids can be transformed from a liquid to a semisolid [10,11]. MR fluid technology is widely used in automotive and industrial applications [12] as well as numerous environmental and biomedical applications [13]. MR technology is fortunately not only limited to commercially available packages, MR fluids can, moreover, be tailor-made to meet the specific requirements of different applications [12]. In fact, magnetic control of fresh properties of cementitious materials has become a subject of study in the recent years [14-18].

MR fluids are formulated using three basic components: a base fluid, magnetically polarizable particles suspended in the base fluid, and stabilizing additives to overcome sedimentation of the particles [10,11]. The resulting magnetorheological behavior is strongly dependent on the material selection. The selection of base fluid and magnetisable particles is in turn dependent on the specific application [10]. For the current application, the cementitious paste forms the base material. Magnetisable particles would then need to be added to the paste to make it magnetically responsive. Fly ash is known to possess magnetic properties [19,20]. The magnetic fraction of fly ash is largely due to iron minerals present, i.e., magnetite and hematite, and to a less extent mullite and quartz. The iron oxides are formed during the combustion of coal and their concentration can vary depending on the content of iron in the coal [21-23]. The viability of fly ash as a source of magnetisable particles for magnetically controllable cementitious pastes was already reported and showed that fly ash can indeed be used as a responsive additive [20]. Superplasticizer or other additives can be added to the paste to fine-tune or stabilize the paste and prevent sedimentation.

Despite recent interests in investigating the possibilities to magnetise cementitious materials, tailoring cementitious pastes to invoke or even actively control blockages in formwork leakage has not been undertaken. As such, the current study introduces a new concept of active stiffening control based on magnetic field application to magnetically induce blocking by using tailor-made magneto-responsive cementitious pastes. In this case, pastes containing fly ash as the responsive additive.

A small-scale study on confined flow of cementitious pastes was favoured before advancing to a real formwork situation. A simple test that mimics formwork leakage was thus developed to study pressure-driven flow of cementitious pastes through a confined geometry [24]. The test setup was then modified for this study to include the application of a constant magnetic field by means of static magnets. The influence of an externally applied magnetic field on pressure-driven flow of fly ash incorporated pastes through a confined geometry was experimentally investigated. Previous studies show that pure Portland cement pastes exhibit negligible magnetic response under an external magnetic field, with negligible effects to the rheological properties [14,17,25]. As such, tests on pure Portland cement pastes were omitted from the current study.

To maximally illustrate this new concept of magnetically induced blocking, a high volume of fly ash was selected. As such, three pastes containing 40% fly ash (by volume of the total binder) were considered. According to the Belgian Standard NBN B15-001 (Belgian National Application document to the European Standard EN 206), the maximum permissible amount of fly ash replacement is 50% mass replacement. In this case, 40% volumetric replacement is equivalent to approximately 46% mass replacement, within the permissible limit.

To this end, the experimental programme to study the effect of the magnetic field on fly ash incorporated pastes for active stiffening control of formwork leakage is depicted. Then, the results are summarised and discussed in terms of viability and effectiveness of the aimed application of active stiffening control. Lastly, conclusions and perspectives from this investigations are briefly drawn. It is concluded that active stiffening control of confined flow of pastes containing magnetisable particles can be achieved by the application of a magnetic field.

2. Experimental programme

2.1. Materials

The basic materials used in this study include cement, limestone powder, fly ash, and superplasticizer. The cement was a Portland cement, CEM I 52.5 N, containing Portland clinker (at least 95%) as its main constituent. The cement had a median particle size of 7.2 μm and specific density of 3.2. The limestone powder used is a finely ground, pure calcium carbonate with a median particle size of 3.7 μm and specific density of 2.7. Fly ash with median particle size of 9.0 μm and specific density of 2.22 was used as a partial replacement of cement or limestone powder in order to introduce magnetic particles into the paste material. The saturation magnetization of the fly ash obtained from a vibrating sample magnetometer (VSM-550, Dexion Magnet) was 1.74 emu/g. Table 1 shows the chemical composition of the used raw materials. The particle size distribution of the powders is presented in Fig. 2.

A polycarboxylate ether (PCE) superplasticizer (MasterGlenium 27) was

Fig. 1. Leakage of concrete through formwork joints (originating from [4]).
The mixture proportions of pastes in this study are shown in Table 2. The water content and the total volume of powder were kept constant. Three pastes were selected to study the effect of fly ash content in Table 2. The water content and the total volume of powder were kept constant throughout testing at 20°C. The sample was first pre-sheared at a shear rate of 100 s⁻¹ for 30 s. This was immediately followed by a flow curve test as shown in Fig. 3. The flow curve test was carried out through a 20 s⁻¹ step-wise decrease in the shear rate from 100 s⁻¹ to 20 s⁻¹ (i.e. 100, 80, 60, 40, 20 s⁻¹). Typically, the shear rate in the sheared part of the concrete during pumping can reach up to 60 s⁻¹ or even higher at high discharge rates [28,29]. Shear rates beyond 120 s⁻¹ were however avoided to prevent dynamic segregation of the paste in the rheometer. After the test, the surface of the parallel plate was checked, and no obvious bleeding was observed. For each mixture composition, tests were carried out on three separate batches of paste and the average values are as reported in Table 3.

### Table 2

| MixNo. | Water (g) | LP (g) | CEM (g) | FA (g) | W/P* | SP (g) |
|--------|-----------|--------|---------|--------|------|-------|
| LF40   | 900       | 1519   | 0       | 825    | 0.38 | 1.5   |
| CF40L  | 900       | 0      | 1800    | 825    | 0.34 | 7.0   |
| CF40H  | 900       | 0      | 1800    | 825    | 0.34 | 13.0  |

*W/P = water to powder mass ratio

### 2.3. Rheological characterisation of paste materials

#### 2.3.1. Mini-slump flow test

Mini-slump tests were performed to make an initial flow characterization of the material. A truncated steel cone (mini-slump cone) having the dimensions of 70 mm (upper diameter), 100 mm (bottom diameter) and 60 mm (height) was positioned on a flat steel plate. After mixing, the fresh paste was immediately poured into the mini-slump cone without any compaction and then the cone was gently lifted to allow the fresh paste to spread on the steel plate. The spread diameter was recorded as the average diameter of two measurements taken in perpendicular directions. The tests were carried out on three separate batches of freshly mixed pastes for each mixture composition.

#### 2.3.2. Flow curves

Rheological properties of yield stress fluids are typically described using the yield stress and plastic viscosity. The yield stress gives an indication of the shear stress required to initiate flow, and the plastic viscosity is a measure of the (remaining) resistance to flow [26,27]. Flow curves were thus obtained to provide a relative comparison of the yield stress and viscosity of the paste materials. A rotational parallel plate rheometer (Anton Paar – MCR 102) with 20 mm disc diameter was used to perform the rheological measurements. A fixed gap of 1 mm between the top and bottom plates was used and the temperature was kept constant throughout testing at 20 ± 0.5°C. The sample was first pre-sheared at a shear rate of 100 s⁻¹ for 30 s. This was immediately followed by a flow curve test as shown in Fig. 3. The flow curve test was carried out through a 20 s⁻¹ step-wise decrease in the shear rate from 100 s⁻¹ to 20 s⁻¹ (i.e. 100, 80, 60, 40, 20 s⁻¹). Typically, the shear rate in the sheared part of the concrete during pumping can reach up to 60 s⁻¹ or even higher at high discharge rates [28,29]. Shear rates beyond 120 s⁻¹ were however avoided to prevent dynamic segregation of the paste in the rheometer. After the test, the surface of the parallel plate was checked, and no obvious bleeding was observed. For each mixture composition, tests were carried out on three separate batches of paste and the average values are as reported in Table 3.

### 2.4. Pressure-driven flow test

To study the flow of pastes through a confined geometry in an...
attempt to imitate the flow of paste through formwork joints, the device shown in Fig. 4 was previously developed [24]. The test setup consists of a pressurized test cylinder, with a flow outlet at the bottom. The net mass of outflow was measured in real time using a digital balance connected to a data logger, and the overhead pressure supplied to the system was monitored using a pressure sensor situated at the top of the column. Two outflow areas of \(A_1\) (20 mm\(^2\)) and \(A_2\) (40 mm\(^2\)) (corresponding to slit sizes of 1 mm \(\times\) 20 mm, and 2 mm \(\times\) 20 mm dimension respectively) were used in the experiments. Hydrostatic pressure is normally assumed when SCC is placed by bottom-up pumping. Formwork pressure can reach up to 100 kPa or more depending on factors such as the casting rate or casting height [30]. Taking into account that the current study is limited to purely paste material and not concrete, the formwork pressures studied were kept in the lower range. Five overhead pressure levels of approximately 0.1, 0.2, 0.25, 0.3, and 0.5 bar were used in this study.

To test the hypothesis that the application of a static magnetic field perpendicular to the direction of flow could help minimise flow, two sets of experiments were conducted for each pressure level: Firstly, pressure-driven flow test with magnetic field \([B \approx 0.65 \text{ T or } 0.8 \text{ T}]\), and secondly, pressure-driven flow test without magnetic field \([B = 0 \text{ T}]\). The magnetic field was applied by externally attaching two block magnets (dimensions 20 \(\times\) 5 \(\times\) 5 mm) on opposite ends of the outflow slit (see Fig. 5). As observed from Fig. 5, these static magnet blocks generate an external magnetic field approximately perpendicular to the flowing direction through the slit. To maintain the same geometry in the case of no magnetic field, two aluminium blocks (with the same dimensions as the magnets) were attached to another bottom plate of the same geometry. Prior to testing, the space between the magnets/aluminium blocks was temporarily filled with a rubber filling to prevent the paste from prematurely forming chains before the bottom lid was opened. In doing so, the ability of the paste to form chains under pressure can be more accurately assessed and is in fact more representative to the actual case in formworks where the material would not be allowed to sit between the joints before flow is initiated.

The test cylinder was filled with paste to a height of approximately 250 mm, and secured onto the testing frame. The desired pressure was then applied for approximately 15 s before unscrewing the bottom lid and removing the non-absorbent plug to allow the paste to flow out. The experimental programme for the cement-based pastes is summarised in Table 4. Each measurement was repeated twice on a different batch of paste. Tests on LF40 paste were only conducted at 0.1 bar \([0 \text{ T and } 0.65 \text{ T}]\) and flow area \(A_1\).

### Table 3

| MixNo. | Density \(\text{[g/cm}^3]\) | Spread diameter \(\pm 5\text{mm}\) | Yield stress \(\text{[Pa]}\) | Plastic viscosity \(\text{[Pa} \cdot \text{s]}\) |
|--------|-----------------|-----------------|--------------------|-----------------|
| LF40   | 1.722           | 300             | 55                 | 0.9             |
| CF40H  | 1.938           | 300             | 2                  | 1.8             |
| CF40L  | 1.907           | 200             | 33                 | 3.3             |

3. Results and discussion

Flow tests results for the limestone-fly ash paste (LF40) are firsts briefly discussed, followed by a more extensive analysis and discussion of the results from the cementitious pastes (CF40H and CF40L). Thirdly, a verification that blocking effectively occurs due to formation of magnetic agglomerates by the application of an external magnetic field is outlined. This illustrates the potential of active stiffening control by means of addition of magnetisable particles.

#### 3.1. Effect of magnetic field on pressure-driven flow – LF40 paste

As outlined in the experimental programme, tests were first performed on a limestone-based paste (LF40). This gives the advantage of clearer observations since the base material contains only pure calcium carbonate, and no iron elements. Any effects due to the application of a magnetic field would thus be solely due to the addition of fly ash. Fig. 6 shows the mass evolution of the net outflow with time from the pressure-driven flow test, under the pressure of 0.1 bar and flow area of 20 mm\(^2\). The difference in curves of mass vs. time graphs of the same paste when a magnetic field of 0.65 T was applied, i.e. perpendicular to the direction of the fluid flow. When no
magnetic field was applied across the flow area, the paste flowed out of the test column uninhibitedly, and maintained an almost linear evolution. This resulted in almost complete emptying of the test cylinder, with the exception of a negligible amount of fluid corresponding to the dead zones at the bottom of the column. In contrast, when a static magnetic field was applied across the same flow area, a significant reduction in not only the flow rate (65%) but also the net mass of the outflow (87%) was observed. This difference in flow behaviour can be attributed to the formation of chains or agglomerates of the magnetic particles of the fly ash [20].

Like in an MR fluid, when a static magnetic field is applied across the flow width, some of the magnetic fly ash particles align along the magnetic field lines thereby forming chains and agglomerates. These chains and agglomerates give the fluid an additional yield stress component that is dependent on the magnetic flux density [31]. In this particular case, there is an even larger effect because of the dynamic nature of the problem in which the number of magnetic particles reaching the constriction increases with time. As the fluid flows through the slit, the magnetisable particles are attracted by the magnetic field and can deposit on the walls of the slit. The deposition of particles creates a dense network, pinching the flow path closer together, as shown in Fig. 7. Thus, it is evident that agglomeration of particles occurred, contributing to the blockage of flow. This can be linked to the clogging mechanisms observed in microfluidic channels. Clogging of the microchannel is attributed to the deposition of particles due to the presence of attractive forces. If the local interactions at the constriction are attractive in nature, it leads to the deposition of particles and to the formation of agglomerates. Through collisions, adhesion, or more importantly (magnetic) attractive forces, these agglomerates can further grow, contributing to clogging of the flow channel [32,33].

The attractive forces acting on the magnetisable particles due to the presence of the magnetic field has two consequences: (1) formation of chains or clusters that lead to formation of agglomerates of magnetisable particles, thereby decreasing the D/d ratio due to the increased particle sizes d; and (2) deposition of magnetisable particles on the walls of the slit leading to the constriction of the flow area similar to the MGP valve, thereby decreasing the D/d ratio by decreasing the flow width D. Of the two, it is not yet clear which is the more dominant effect. What is clear is that in combination, both mechanisms have the effect of reducing the D/d ratio below the critical value, moving the flow behaviour from full flow to partial or complete blocking.

3.2. Effect of magnetic field on pressure-driven flow – CF40 pastes

Following the experimental programme summarized in Table 4, the

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

| Pressure [bar] | Magnetic Field Strength |
|---------------|------------------------|
| 0.1           | 0 T                    |
| 0.3           | 0 T                    |
| 0.5           | 0 T                    |

Two repetitions carried out for each test

Fig. 6. Evolution of mass vs time for LF0 paste flowing under 0.1 bar overhead pressure.
The evolution of the net mass of outflow with time was recorded for the cement-based pastes and plotted in the graphs shown in Fig. 8. These figures show the evolution of the mass outflow of the pastes at different pressure levels, with and without the application of the magnetic field. Three main aspects were studied: the influence of flow area, magnetic field strength, and rheological properties, on the flow rate and blocking phenomenon. Fig. 8(b) shows the mass evolution of CF40H paste through a 1 mm gap ($A_1 = 20 \text{ mm}^2$) and magnetic field strength of 0 T, 0.65 T, and 0.8 T while Fig. 8(b) and (c) correspond to the results obtained for CF40H and CF40L pastes respectively (with gap width 2 mm or $A_2 = 40 \text{ mm}^2$, and $B = 0.65 \text{ T}$).

The first clear observation is that for the 1 mm slit width (Fig. 8(a)), at all three pressure values, blocking of the flow was observed even without the application of the magnetic field. As a result, only a fraction of the flow was able to pass through the gap. The graphs in Fig. 8 show how the mass of the paste outflow changes with time under different conditions.

Fig. 7. Deposition of magnetisable particles as visible after gently rinsing off the paste from the bottom plate.

Fig. 8. Graphs showing the evolution of the net mass on the scale vs time. (a) CF40H – $A_1$, (b) CF40H – $A_2$, (c) CF40L – $A_2$. 

CF40H – Cement/Fly ash 40%-High slump; CF40L – Cement/Fly ash 40%-Low slump.
of the mass of fluid in the column was emptied (2–6% of the total mass). This is shown by the 0 T curves in Fig. 8(a) that all deviate from a linear behaviour and show a decreasing slope with time. The slope eventually decreased to zero, indicating blockage of flow. For the same paste, when the slit width was increased to 2 mm (A2), there was no clogging and thus no blocking at all pressure levels when no magnetic field was applied (Fig. 8(b)). The curves showed a relatively constant flow rate throughout and the test cylinder was almost completely emptied at the end of the test. When a magnetic field was applied, blocking occurred in some instances, and to varying degrees. This is discussed in the following sections.

The data obtained from the mass vs. time graphs was analysed to quantify and compare the differences in flow rate due to the application of a magnetic field. The mass flow rate \( m \) was determined during the initial stage, when the slope of the mass-time graphs were approximately purely linear (example in Fig. 9). In addition to the flow rate, the net mass of the outflow (total mass lost from the test cylinder) was compared with or without the applied magnetic field. This difference in mass loss \( \Delta M \) was calculated as: \( \Delta M = M_{\text{out}} - M_{\text{in}} \), where \( M_{\text{in}} \) and \( M_{\text{out}} \) are the final mass on the scale at the end of the test with and without magnetic field respectively. The results from this analysis are presented and discussed in the following sections.

### 3.2.1. Influence of flow area on magnetically induced blocking

The D/d ratio is one of the most important factors that dictates whether the resulting flow will be uninterrupted, partially, or completely blocked. This ratio can be adjusted by either changing the particle sizes suspended in the fluid or by altering the flow area. In this study, the ratio was adjusted by increasing the flow width from 1 mm to 2 mm. The likelihood of blocking due to magnetically induced agglomerates was found to be directly related to the amount of pressure exerted on the fluid and the size of the flow area in relation to the particle sizes. This is illustrated in Fig. 10 which shows the effect of decreasing the flow width on the flow rate and Fig. 11 which shows the net loss of mass of the high slump CF40H paste. There is a very significant reduction in flow rate and the total mass of paste lost when the flow width is decreased from 2 mm to 1 mm.

#### 3.2.1.1. Low D/d value – Blocking observed

As previously mentioned, blocking occurs even without the application of the magnetic field when the flow width is reduced to 1 mm. This can be attributed to the D/d ratio. A more pronounced constriction by a reduced slit width, in relation to the particle sizes, effectively reduces the D/d ratio. Furthermore, while the suspension is flowing, particles can continue to agglomerate. Even without magnetic field, this can happen to some extent due to inter-particle collisions [33]. This further reduces D/d, potentially leading to blocking. To visually illustrate the agglomeration, examination of the bottom plate (Fig. 12) revealed that a dense plug of particles was formed at the outflow in case of the 1 mm slit, while no agglomeration was visible for the case of the 2 mm slit.

When rigid particles flow through a constrained path like in this case, there is a convergence in flow towards the gap and many particles arrive at the outflow area simultaneously. Conversely, because of this constriction, the rate of particles exiting through the outflow can be lower than the rate of particles arriving at the outflow. This could then lead to an accumulation of particles and the formation and growth of agglomerates that in time block the flow. The larger the particles in relation to the flow area, the easier it is for these agglomerates of particles to form and consequently block the flow [34]. This aggregate build-up is said to be rather complex to analytically or numerically describe, due to changing conditions at the constriction with time. There is a continuous modification of the local geometry of the wall, the flow field and the nature of the interactions due to the presence of previously deposited particles [32]. This could explain the increase in repeatability of the tests in comparison to the case where full flow is observed. When a magnetic field was applied, it further reduced the flow rate and loss of mass (Figs. 10 and 11). The magnetically induced clustering enhances the formation of agglomerates, driving the flow to block quicker. In contrast to the A2 case, the magnetic field is still seen to have an effect even at higher pressures and the reduction in flow rate due to the applied magnetic field is also higher.

#### 3.2.1.2. High D/d value – No intrinsic blocking

The pastes flowed uninterrupted at all pressure values when the flow width was 2 mm and no magnetic field was present. This resulted in almost complete emptying of the test cylinder, with the exception of a small height of fluid corresponding to the dead zones in the fluid column. The magnetic field was applied across the flow area, blockage of flow was observed at lower pressure values. As the pressure increased, the flow rate and mass loss curves of both with and without magnetic field cases converged and the magnetic field ceased to have an effect on the outflow (Figs. 10 and 11). In the current study, the pressure threshold where both curves with and without magnetic field converged ranged approximately between 0.25 and 0.3 bar. We refer to this point as the flow converging point \( X_{\text{c}} \). It is hypothesised that this converging point is characteristic to the set of variables selected in this study. The converging point is assumed to be dependent on the concentration of magnetisable particles, as well as the magnetic field strength applied. Lower concentration of magnetisable particles as well as lower magnetic field strength could shift the converging point to lower pressure values. Further studies are required. At low pressure (0.1 – 0.25 bar), the force exerted on the fluid due to the overhead pressure was not sufficient to resist formation of cluster and chains induced by the magnetic field. This resulted in the formation of a clog. Clogging of rigid particles flowing in a constricted channel is said to be dependent on the balance between structuration and fragmentation mechanisms which in turn are caused by the particle-fluid and inter-particle interactions. These two mechanisms occur simultaneously but a dominance of structuration could lead to clogging [33]. Application of the magnetic field works in favour of structuration. Clustering of magnetisable particles acts as an initiator for the formation of larger agglomerates which eventually block the flow. Beyond the converging point, it is assumed that either no clusters are formed or that any clusters that may have formed are fragmented due to the high pressure.

During the form-filling process, formwork pressure gradually increases from 0 kPa to the maximum value as the height of the fluid increases. If blocking is magnetically induced during this initial form-filling stage when the pressure is still sufficiently low (i.e., when the pressure is still below the \( X_{\text{c}} \) value), and the blockage is able to withstand the increasing pressure, this could be beneficial for formwork leakage. An extension of the test was carried out on the high slump

Fig. 9. Example of extrapolation of initial mass flow rate – CF40H-A1 at 0.3 bar.
CF40H paste at 0.1 bar for the 2 mm gap to check the resistance capacity of the blockage formed to flow re-initiation. Once the magnetically induced plug was formed, additional pressure was applied in a stepwise manner to determine at what pressure level the blockage would be

*Repetition on different batch of paste

**Fig. 10.** Influence of flow area on (a) initial mass flow rate with/out magnetic field, (b) decrease in initial flow rate due to magnetic field.

**Fig. 11.** Decrease in mass loss due to applied magnetic field.

**Fig. 12.** Image of the bottom plate after the test with variation in flow area and without magnetic field (a) A1 – agglomeration of particles leading to blocking, (b) A2 – no agglomeration of particles at the slit resulting in full flow.

CF40H paste at 0.1 bar for the 2 mm gap to check the resistance capacity of the blockage formed to flow re-initiation. Once the magnetically induced plug was formed, additional pressure was applied in a stepwise manner to determine at what pressure level the blockage would be

*Repetition on different batch of paste

**Fig. 13.** Determination of the pressure value at which the magnetically induced plug formed at 0.1 bar is unable to withstand the applied force – CF40H paste, 2 mm gap.

**Fig. 10.** Influence of flow area on (a) initial mass flow rate with/out magnetic field, (b) decrease in initial flow rate due to magnetic field.

**Fig. 11.** Decrease in mass loss due to applied magnetic field.

**Fig. 12.** Image of the bottom plate after the test with variation in flow area and without magnetic field (a) A1 – agglomeration of particles leading to blocking, (b) A2 – no agglomeration of particles at the slit resulting in full flow.

**Fig. 13.** Determination of the pressure value at which the magnetically induced plug formed at 0.1 bar is unable to withstand the applied force – CF40H paste, 2 mm gap.
unable to resist the applied force. The results (Fig. 13) indicate that the magnetically induced blockage is able to withstand pressure above the pressure value at which it was formed as well as above the $X_p$ value. Additional pressure can be applied before flow is reinitiated, in this particular case, up to approximately 1 bar (100 kPa).

### 3.2.2. Influence of rheological properties on magnetic response

In addition to the D/d ratio, the rheological properties of the fluid also play an important role in confined flow of cementitious pastes. The stress exerted on the pastes must first exceed its yield stress for the material to flow. Once the yield stress is exceeded, the viscosity provides an additional resistance to flow [35]. In the situation of bottom-up pumping of self-compacting concrete, the concrete is constantly being sheared as the material fills the forms. The yield stress of the fluid is thus already exceeded and the continuous shearing does not allow the material to experience the benefits of its thixotropic nature [36]. If gaps are present at the formwork interface during this form-filling phase, as far as rheological properties go, the ease with which the material will flow out will thus largely be influenced by the viscosity. For the same flow area, it is thus expected that increased viscosity and yield stress results in increased resistance to flow. This is clearly shown in Fig. 14 which shows the differences in flow rate and the net mass loss due to decreased fluidity. The flow rate vs. pressure curves (Fig. 14a) of the CF40L paste (lower slump flow value) are shifted downwards from those of the CF40H pastes, i.e. towards lower flow rates at all pressure levels. This is because the CF40L paste requires more stress to initiate flow than the CF40H paste which has a lower yield stress. Once that stress is exceeded, the CF40L paste still requires higher stress to maintain flow due to increased resistance provided by its higher viscosity.

At lower pressure (0.1–0.25 bar), the flow rates of both CF40L and CF40H pastes decrease with the application of a magnetic field. The degree of reduction in flow rate decreases with increasing pressure (Fig. 14b). From approximately 0.3 bar, the curves of 0 T and 0.65 T merge and the effect of the magnetic field is no longer observable for both CF40H and CF40L pastes. The relative loss of the total mass is shown in Fig. 15. At 0.65 T, the total loss in mass is reduced by the application of the magnetic field, until the converging threshold.

In a study by Jiao et al. (2021) [25], the formation of agglomerates of magnetic nanoparticles in stiffer mediums was found to be poorer than in more fluid pastes. This was evaluated by measuring the storage modulus of different pastes containing nanoparticles and evidenced by quantitatively mapping the clusters of Fe elements. Cement pastes with lower stiffness were found to have a higher response to the magnetic field and therefore higher increase in storage modulus due to magnetic field. The viscoelastic properties (yield stress and viscosity) of the suspensions were reported to have the ability to prevent the initial movement of nanoparticles in the paste medium. The magnetisable particles in the CF40H paste can thus be expected to have a higher response to the magnetic field due to the lower viscosity of the “base fluid” and therefore greater degree of freedom for the particles to move and form agglomerates. With this logic, one would thus assume that the CF40H paste would have a larger reduction in initial flow rate due to the magnetic field in comparison to the CF40L paste. However, this is not the case, the CF40L paste shows a higher magnitude of reduction in initial flow rate under magnetic field as seen in (Fig. 14b). This difference between expectation and reality comes from the hydrodynamic nature of this particular problem. The fluid is flowing out of the column at a certain velocity due to the applied overhead pressure. At the same time, a magnetic force is applied across the slit that offers resistance to this pressure-driven flow. There is a direct competition between the magnetic force exerted on the magnetisable particles and the force exerted due to pressure. The resultant movement of the magnetisable particles due to the magnetic force is dependent on the fluidity of the paste (a
larger area around the magnet, as well as stronger interaction between magnetic particles [25], thereby increasing the density of the agglomerates. The same principle could apply to the CF40L pastes. The increase in viscosity may have decreased the ability of the magnetisable particles to move in response to the magnetic field, but on the other hand, it increased the resistance to flow (lowering the velocity of magnetisable particles). This could have potentially increased the probability for the magnetisable particles to participate in the agglomeration of particles leading to a higher reduction in flow rate. The downward force increases as the overhead pressure is increased, however, the force due to the magnetic field remains constant, explaining why there is a threshold pressure at which the magnetic field is no longer effective.

3.2.3. Effect of magnetic field strength on magnetic response

To study the effect of the magnetic field strength, flow tests were carried out for the CF40H paste under magnetic fields of 0 T, 0.65 T, and 0.8 T. The flow width was kept constant at 1 mm, and tests were carried at approximately 0.1 bar, 0.3 bar, and 0.5 bar. Increasing the magnetic field strength increased the degree of blocking (Fig. 16). By increasing the magnetic field strength from 0.65 T to 0.8 T (23% increase), the initial flow rate was decreased by 100%, 24%, 16% at 0.1, 0.3, and 0.5 bar respectively. The increase in magnetic response is expected since a higher magnetic field strength implies a higher attraction force over a residual pressure, which in turn may have inhibited the magnetisable particles from forming agglomerates. The same principle could apply to the CF40L pastes. The increase in viscosity may have decreased the ability of the magnetisable particles to move in response to the magnetic field, but on the other hand, it increased the resistance to flow (lowering the velocity of magnetisable particles). This could have potentially increased the probability for the magnetisable particles to participate in the agglomeration of particles leading to a higher reduction in flow rate. The downward force increases as the overhead pressure is increased, however, the force due to the magnetic field remains constant, explaining why there is a threshold pressure at which the magnetic field is no longer effective.

3.3. Verification of magnetically induced blocking

To quantitatively verify whether magnetisation and consequently the agglomeration of magnetic particles is the primordial cause of blockage of flow, the magnetic properties of the cement paste near the slit were measured using a Vibrating-Sample Magnetometer (VSM). After blocking occurred under magnetic field, approximately 10 mm height of fluid near the bottom plate was left to solidify and further sliced into smaller sections (S2, S3, S4, S5, S6) as illustrated in the top figures of Fig. 17. The solidified material in the slit (S1) was also collected for analysis. The sections were then ground into powder for the VSM analysis. The results of the VSM analysis give an indication of the magnetic properties of the different sections. The higher the saturation magnetisation ($M_s$), the higher the number of magnetisable particles present in the section [15,38]. The curves in Fig. 17 show a significant difference between the $M_s$ value of section S1 (5.59 emu/g) and the $M_s$ values of the rest of the sections. This means that the saturation magnetisation of the sample from the slit is approximately 87% higher than that of the samples taken from the other sections. This corresponds with the theory that the magnetisable particles accumulate in the slit due to the magnetic field. The second highest $M_s$ value (0.88 emu/g) is from S2, just above the slit and the magnets. The saturation magnetisation is then seen to slightly decrease further away from the centre (~14% reduction at S3 and S4, and ~23% reduction at S5 and S6 compared to section S2). Based on these results, it is clear that there is a non-uniform distribution of magnetisable particles near and at the slit caused by the magnetic field, with the highest concentration in the slit. This supports the theory that cluster formation and agglomeration of magnetisable particles leads to blockage of flow, and thereby could provide a means of actively controlling stiffening of formwork leakage.

4. Conclusions

In this study, pressure-driven flow tests were carried out to replicate confined flow of cementitious pastes through formwork gaps. The influence of magnetically induced agglomeration in pastes containing fly ash on the mass flow output was investigated. Based on the results and preceding discussion, the following conclusions can be drawn:

1. When a static magnetic field was applied across the slit width, it induced the agglomeration of magnetisable particles. By inducing this agglomeration, the flow width to particle size ratio $D/d$ is
assumed to decrease, which would increase the probability of blocking. The D/d ratio is very important in determining the likelihood of blocking. Similar to flow convergence of rigid particles in other applications, there exists a threshold value - referred to as the converging point - or range of values of D/d that separates between interrupted and uninterrupted flow.

(2) At sufficiently low D/d values, blockage of flow was observed even without magnetic field. Under magnetic field, a further reduction in flow rate and mass loss was observed. The magnetic field had an effect even at higher pressure, and no converging threshold pressure was observed in the range of values investigated. The clusters due to magnetic field had the effect of enhancing the naturally occurring blocking.

(3) At sufficiently high D/d values, the pastes flowed uninterruptedly when no magnetic field was applied. Under magnetic field, blocking was observed at low pressures, with decreasing effect as the pressure was increased. A threshold pressure was observed, the so-called converging point, at which fragmentation of magnetically induced clusters exceeds agglomeration. Lower concentration of magnetisable particles as well as lower magnetic field strength could shift this converging point to lower pressure values. Beyond this threshold, there is no blocking effect of magnetic field on the confined-flow of cementitious pastes. However, the blockage formed at pressure values below the converging point is sufficiently stable to withstand pressure levels well beyond this converging point before flow is reinitiated. Further studies are required.

(4) The viscosity of the paste has counteractive effects on the magnetic response. The lower the viscosity, the higher the degree of freedom of the magnetisable particles to move and form clusters. On the other hand, the lower the viscosity, the higher the residual pressure and thereby velocity of the fluid (including magnetisable particles) which consequently opposes the formation of clusters.

(5) Increasing the magnetic field strength from 0.65 T to 0.8 T increased the attraction force of the particles towards the magnet as well as the attraction forces between magnetic particles, resulting in a higher decrease in flow rate and mass loss. Although higher magnetic field strengths increase the magnetic response, a threshold value at which no further benefits of increasing the magnetic field can be seen is expected. Further investigations with a larger variety of magnetic field strengths need to be carried out.

In view of active stiffening control based on magnetic field application, it is concluded that tailoring cementitious pastes to include magnetisable particles, e.g. fly ash, is a means to minimize or actively control confined-flow of cementitious pastes. The presented methodology shows promising results for the larger initiative which is to ultimately actively control formwork leakage. The novel concept however requires further verification on mortar- or concrete-scale tests using a more representative test set-up.
CRediT authorship contribution statement

Chizya Chibulu: Methodology, Formal analysis, Investigation, Writing – original draft, Visualization. Mert Yücel Yardımcı: Supervision. Dengwu Jiao: Writing – review & editing. Robin De Schryver: Writing – review & editing. Karel Lesage: Supervision. Geert De Schutter: Conceptualization, Methodology, Formal analysis, Writing – review & editing, Supervision, Project administration, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this study.

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