

# Understanding the role of rheology in the plastic settlement and shrinkage cracking of early age concrete

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## Abstract

Understanding the plastic (settlement/shrinkage) cracking phenomena of early-age concrete is important in-order to establish a holistic approach to minimise its occurrence. One of the factors associated with early-age concrete is the rheo-related behaviour which occur simultaneously within the timeframe known for plastic cracking. It is therefore useful to establish their links to broaden the knowledge of plastic cracking. This study is a novel evaluation of the influence of rheo-physical and rheo-viscoelastic behaviour on the plastic cracking behaviour by systematically altering these behaviours of formulated concrete mixes and extensively characterising them. The theory and frameworks for linking the behaviours were presented and established via statistical and analytical approaches. Significant rheo-related parameters found to influence plastic cracking phenomena include yield stress, structuration, creep and stress relaxation. The rheo-mechanics modelling suggests that the plastic cracking initiation tends to be a ductile failure that is pressure insensitive and sufficiently represented by von Mises criteria. This study opens up a consciousness to start evaluating mitigation strategies directed towards the materials optimisation of concrete mixtures to minimise the occurrence of plastic cracking in early-age concrete.

**Keywords:** Plastic settlement; Plastic shrinkage; Yield stress; Structuration; Viscoelasticity; Early age cracking

## 1 Introduction

Cracking is an undesirable defect in concrete as it impairs the finished product and reduces the serviceability of the structure, hence, measures must be taken to minimise its occurrence. One of such cracking defects is termed plastic cracking that occurs during the early age of concrete. The early age refers to the time of mixing up to around the final setting time; during this period, the concrete has fluid or viscous properties that allows for easy mouldability or shaping, that is plastic properties.

Plastic cracking refers to the cracking that occur from fresh state up to the end of plastic state. The exact time of the change of concrete state from plastic to solid is unknown but is generally believed to be around the final setting time [1, 2]. Plastic cracking takes two forms – plastic settlement and plastic shrinkage cracking – which cumulates into the plastic cracking behaviour of concrete.

Plastic settlement often precedes shrinkage and occurs due to the settlement of concrete's solid particles under gravity, displacing water to the surface as bleeding during the process. Any form of restraint (such as steel reinforcement or change of formwork section) to the free settlement leads to cracking due to differential settlement [3, 4]. Evaporation is the major source of plastic shrinkage cracking. The evaporation dries up

the bleed water from settlement and afterwards starts evaporating pore water which leads to internal capillary pressure build-up [5, 6]. This leads to the water surface in the pores to form concave menisci due to adhesive forces and surface tension that leads to shrinkage. The presence of restraints causes internal stress build-up that cause plastic shrinkage cracking. All these plastic cracking processes (bleeding, evaporation, capillary pressure build-up, settlement, and shrinkage) are interwoven.

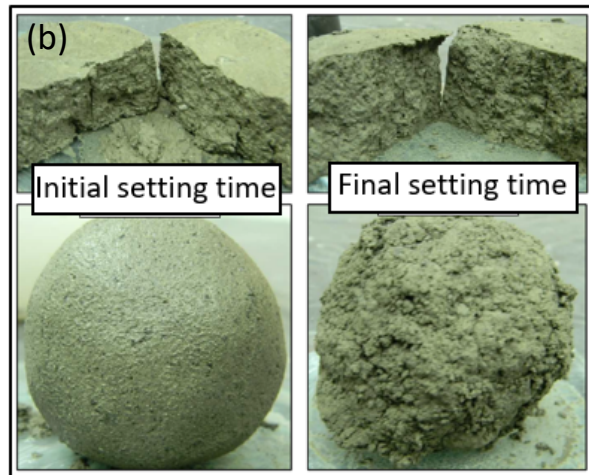
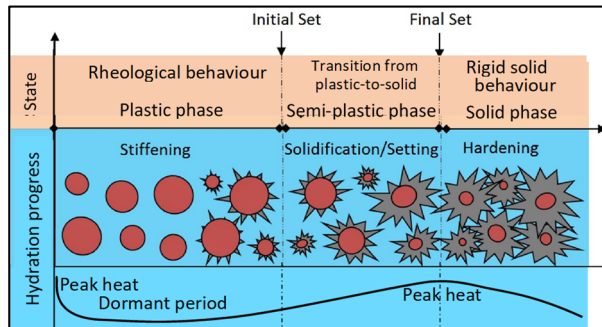
Plastic cracking, due to its nature, aggravates the durability problems at an early and premature time. These necessitate the need for measures to minimise the occurrence of plastic cracking as best as possible. To formulate and adopt the right strategy to reduce the occurrence of the cracking, its causes, process, and all influencing factors must be understood. By implication, this means that other properties known to be inherent to early age concrete must be investigated to understand their influence and relation to plastic cracking behaviour. One of such concurrent properties is rheo-related behaviours.

Fresh concrete flows and behaves like a fluid/viscous material with pronounced rheological properties (yield stress and viscosity) until it stiffens and solidifies by hydration [7]. Hence, the term “plastic” concrete which comes from the Greek word “plastikos” meaning mouldable [8]. Though concrete

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tends to hold onto these properties up to the final setting time, the setting (hydration) mainly becomes pronounced from the initial setting time that marks the end of the dormant period. Hence, concrete start losing significant amount of mouldability from the initial set. These are illustrated in Fig. 1.

(a)



**Figure 1.** (a) Setting phases of plastic concrete, (b) Pictures of moulded concrete at initial and final setting times [9].

The dormant part of the setting (stiffening in Fig. 1) is dominated by thixotropy and rigidification – a reversible and time-dependent increase in yield stress and modulus, respectively – and is characterizable by rheometry. These stiffening reduces the fluid-like (viscous) behaviour while increasing the solid-like (elastic) behaviour. It can, therefore, be said that plastic concrete possesses significant viscoelastic properties that is readily characterised by rheometry due to rheological tendencies; that is, rheo-viscoelasticity. Such consequences include dissipation of energy due to sustained strains and relaxation of associated stresses, for more details please refer Kolawole et al. [10]. These rheo-related responses and behaviour simultaneously occur with the plastic cracking processes during the plastic phase; therefore, it is reasonable to say that there is bound to be interactions among them. The source, timeframe, extent, magnitude, and links of such interactions are nearly non-existent in the literature. Only few studies [11, 12] have endeavoured to elucidate the plastic cracking processes with rheo-related microscopic phenomena.

Mechanical approaches to the plastic cracking phenomena of concrete have been reported in the literature [13–16] with no tribute to its rheological/viscoelastic behaviour; the current study combines both to form a systematic rheo-mechanics approach to the plastic cracking phenomena. For the mechanical and viscoelastic properties, the target plastic phase and rheological tendencies make rheometry preferable than the mechanical tests (such as uniaxial dog-bone test) often advocated and used in the literature. Only after initial set does the concrete's solid skeleton develops rapidly to withstand the application of mechanical test known for solid materials, though the application of these on a semi-plastic material is still questionable [17–19].

As shown later in the study, early plastic cracking initiation is dominated by a shear process; making shear rheometry a suitable tool for characterising the plastic phase of concrete for its resistant shear properties and rheo-viscoelasticity; such methodological approach and characterisation of plastic concrete are also scarce in the literature. This scarcity stems from the difficulty of measurement of a material that is still wet, plastic, poly dispersed with coarse aggregates and time dependent.

In-order to cover all these identified rheo-related properties of plastic concrete, its plastic cracking behaviour and how they are interwoven, this study was carried out in four phases and the report is structured in a similar pattern. Section 2 gives an overview of the proposed framework for the study and the adopted methodology. Section 3 details the exhaustive characterisation of the fresh concrete using rotational rheometry with focus on thixotropy/structuration and the rheo-viscoelastic behaviour of fresh and plastic-state concrete using dynamic rheometry (small amplitude oscillatory shear – SAOS).

In Section 4, the complete plastic cracking behaviour of the formulated concrete mixes are presented and linked to the rheology as an initial step towards conceptualising rheological approach to plastic cracking. Section 5 describes the novel rheo-mechanics approach and model developed to incorporate the rheo-related properties of concrete for the early-age micro-cracking occurring during the plastic phase. In Section 6, the study was summarised with key findings and conclusions provided.

It is acknowledged that there are complex phenomena adopted in the execution of the study that exceeds the limit of an article. For a detailed explanation and simplified understanding of the frameworks, methodologies and results, please refer to earlier published works [10, 19–22]. This article brings together these phenomena, from experimental and modelling approaches, to explain and showcase how rheology influences the plastic settlement and shrinkage cracking of concrete.

## 2 Framework and methodology

The role of rheology in the plastic cracking of concrete can be idealised to be in two forms – rheo-physical and rheo-viscoelastic influences. Rheo-physical influence refers to the role of rheology related to quantifiable rheological physical parameters such as yield stress, yield strain, viscosity, shear

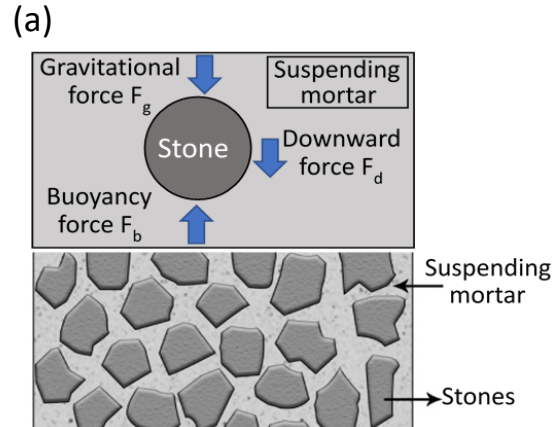
modulus, thixotropy (reversible time-dependent increase in yield stress), and rigidification (reversible time-dependent increase in elastic shear modulus). Thixotropy, rigidification and their irreversible component is referred to as structuration in this study. The rheo-viscoelastic influence refers to the role of rheology related to the plastic nature of concrete such as creep and relaxation. They emanate from the pronounced viscous nature of the plastic concrete but are also time-dependent, reducing due to increasing stiffening and hydration. It is noted that the rheo-viscoelasticity here does not refer to linear viscoelastic response.

## 2.1 Rheo-physical influence

Concrete can be idealised as the suspending mortar and coarse aggregates (stones) and the stones idealised to shear through the suspending mortar by settling under their self-weight. The sole gravitation-driven settlement is hereafter termed “self-settlement”. The settlement of a single ideal stone in a suspending mortar is shown in Fig. 2a, and the governing equations given in Fig. 2b. From the equations, a single stone will settle depending on the yield stress and thixotropy/structuration of the suspending mortar [23, 24]. Due to the numerous and irregularly shaped stones in concrete, direct frictional contacts due to converging solid volume fraction will reduce the continuing stones settlement. Note that the viscosity of the suspending fluid mainly influences the aggregates’ settlement velocity after the start of settlement [25]. The mechanisms of these have been studied and reported by Spangenberg et al., [24], Roussel [25] and Saak et al., [26].

From the last paragraph, it is expedient to rheologically characterise the suspending mortar of the plastic concrete. However, Mehdipour and Khayat [27] and Mahaut et al. [28] have shown that the yield stress and structuration of concrete is dictated by the yield stress and structuration of the suspending mortar and coarse aggregate packing fraction. The physicochemical interactions of the interstitial fluid, which are majorly responsible for structuration, is not influenced by the presence of the coarse aggregates. Therefore, there is a direct link between the rheological parameters of the suspending fluid and that of the concrete by a factor related to the aggregate packing fraction [29]. Therefore, it is sufficient to evaluate the rheological behaviour of the concrete. This is the case for this study.

While the starting source of plastic cracking is the settlement, the shrinkage is interwoven with the settlement. Furthermore, capillary pressure build-up is influenced by the rise of pore water to the surface as bleeding which emanates from plastic settlement that is influenced by yield stress and structuration. Only very few studies have given rheo-related description of these processes [11, 12]. The interconnectivity of these plastic cracking process (settlement, shrinkage, and capillary pressure) suggests that they are linkable to the rheo-physical parameters, this was statistically explored.



(b)

$$F_d = F_g - F_b;$$

$$F_d = g\rho_s V_s - g\rho_m V_s = g\Delta\rho V_s$$

For settlement not to occur,

$$\tau_m A_s \geq g\Delta\rho V_s (F_d)$$

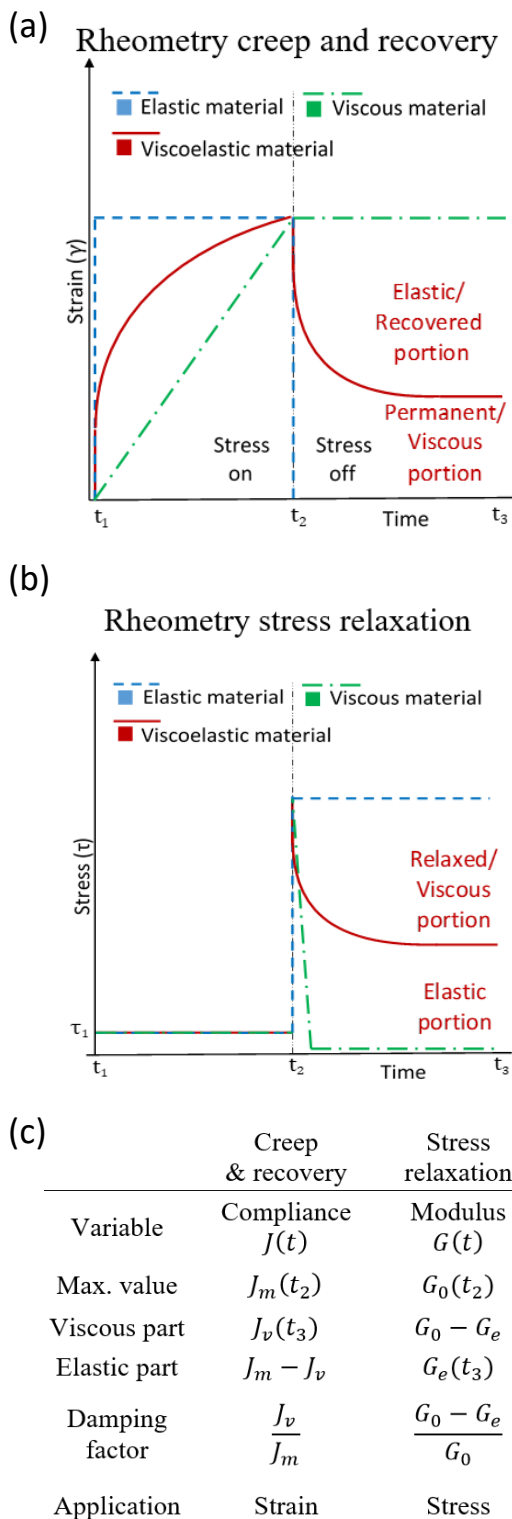
Where  $g$  – acceleration due to gravity,  
 $\rho_s$  – stone density,  $\rho_m$  – mortar density,  
 $\Delta\rho$  – density difference,  $V_s$  – stone volume,  
 $\tau_m$  – mortar yield stress,  $A_s$  – stone cross-sectional area

**Figure 2.** (a) Settlement of stone(s) in the suspending mortar, and (b) the governing equations (reproduced with permission from [20]).

## 2.2 Rheo-viscoelastic influence

Under the application of sustained loading such as cumulative restrained settlement and shrinkage strains/stress, the pronounced rheo-viscoelastic creep and relaxation of plastic concrete can influence its response. The plastic cracking strains can be dampened/dissipated due to the creep of the concrete in its plastic state (viscoelastic dissipated energy). For the purpose of this study, the dissipation ability was obtained from the rheometry creep and creep recovery test in Figure 5, and expressed as the damping factor in Figure 5c. The dissipation can allow plastic materials to absorb considerable energy by plastic deformation (ductility) before damage [30]. Furthermore, the induced stresses from the plastic cracking behaviour can also be relaxed due to the viscoelastic response of the plastic concrete (stress relaxation). The degree of stress relaxation (damping factor) was obtained from the rheometry stress relaxation test in Fig. 3b and expressed as shown in Fig. 3c.

In this study, the damping factors were formulated as the unique contribution of the rheo-viscoelastic behaviour of plastic concrete to the plastic cracking strains and stresses from restrained settlement and shrinkage. These constitute the roles of the rheo-viscoelastic behaviour of concrete in its plastic cracking behaviour and its proposed implementation for this study. There’s nearly no study incorporating viscoelasticity in the plastic cracking behaviour of concrete. More details are in Section 6. This novel approach formulates a systematic rheometry solution for obtaining the viscoelastic properties of plastic concrete that is otherwise tricky to obtain by the non-adaptability of classical mechanical instrumentation.



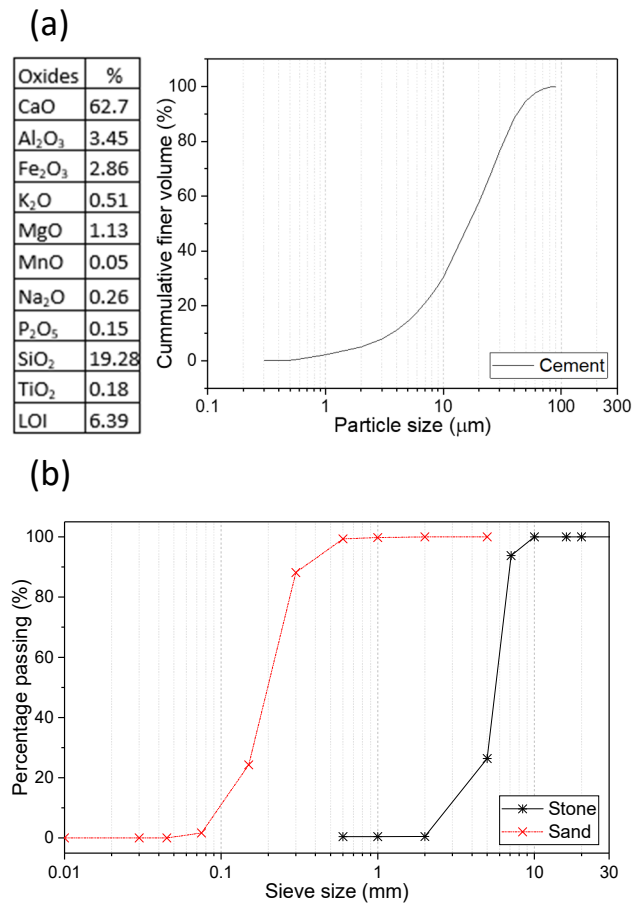
**Figure 3.** (a) creep and creep recovery test and response, (b) stress relaxation test and response, (c) rheo-viscoelastic damping parameters ( $t$  – time,  $J(t) = \frac{\gamma(t)}{\tau_0}$ ,  $G(t) = \frac{\tau(t)}{\gamma_0}$ ) (reproduced with permission from [10]).

### 2.3 Materials and test methods

Five concrete mixes were formulated for this study as shown in Table 1. The control mix (C) (consisting of water, cement, sand and stone) was rheologically modified using commonly available admixtures – superplasticiser (SP), viscosity modifying agent (VMA), and water. The rheology modification was done in-order to achieve a robust approach and understand the influence of rheology without drastically affecting the mixes’ setting times and compressive strength (Table 1). The admixtures were Chryso’s Quad 20 polysaccharide-based liquid viscosity modifying agent (VMA), and Chryso’s optima 206 polycarboxylate ester liquid superplasticiser (SP). The admixtures were added by weight of the cement to the mixing water before adding the mixing water to the dried-mixed cement-based constituents in a pan mixer. Dry materials were initially mixed for 1 minute before adding the mixing water and thereafter mixed for 2 minutes. Properties of the dry constituents are shown in Figure 4.

The rheometry testing protocols were formulated using both rotational and oscillatory shear rheometry of two commercially available rheometers with different scales of applications. An ICAR rheometer from Germann Instruments A/S [32] was used for the rotational rheometry of the concrete. A Physica MCR 501 rheometer from Anton Paar equipped with a normal force sensor [33] and a special building material cell (BMC 90) [34] was used to undertake the SAOS and viscoelastic tests. The MCR 501 configuration is mainly suitable for micro- to milli-scales of applications (min/max Torque of 0.02μNm/230mNm) while the ICAR configuration is fit for centi- to deci-scales of applications (min/max Torque of 1cNm/200dNm). This combination forms a robust testing approach for consistency and reliability of results.

As noted earlier, this study was consecutively carried out in four phases – rotational shear rheometry characterisation of the mixes, dynamic shear rheometry characterisation of the mixes, plastic cracking processes and behaviour of the mixes, and using the obtained results to analytically model the initiation of cracking in plastic concrete. The objectives of these phases towards achieving the goal of the study and the test methods involved are summarised in Table 2. More details on the test methods can be found in the references provided in the table [9, 35–37]. It should be noted that the application of the framework and methodology of this study was limited to the initial setting time ( $\approx 2$  hours) since this point marks the significant increase in the hydration/stiffening of concrete and consequently, the loss of rheo-related properties [9, 37] (see Figure 1).



**Figure 4.** Properties of the dry constituents: (a) Cement composition and size distribution; (b) Sand and stone size distribution.

### 3 Rheological characterisation

The low resolution of the rotational torque of the ICAR rheometer was found to limit its sensitivity to adequately capture the rheo-physical parameters of the plastic concrete beyond 1-hour age; hence, its use was limited to 30 minutes concrete age. The lower torque capacity of the MCR rheometer was found to limit its ability to handle the stiffness of the concrete mixes. It was therefore necessary to reduce the stone volume fraction of the mixes in Table 1 by 60%. However, its fine resolution allowed it to adequately capture the rheo-physical parameters up to the initial setting time (2 hours). To confirm that the stone content reduction does not negatively influence the variability of the rheological behaviour between the mixes, similar mixes with 60% reduced stone content were tested with the ICAR rheometer and were found to yield similar result with the MCR

rheometer as shown in Fig. 5. As noted earlier, the rheo-physical parameters of concrete are dictated by that of the suspending mortar and the stone packing fraction; hence, the results meet expectation. Therefore, a factor related to the aggregate volume fraction was estimated and used to scale the yield stress and modulus results of the MCR [28, 29].

### 3.1 Rheo-physical properties

Fig. 6 shows typical result output of the rheo-physical characterisation of the concrete mixes using ICAR (rotational) and MCR (oscillatory) rheometers, respectively. The static yield stress and strain correspond to the resistant shear strength and strain capacity of the concrete mixes (for the rheo-mechanics modelling) as shown in Fig. 7. The shear modulus in Fig. 7c emanates from  $G^* = G' + iG''$ , where  $G'$  is the storage modulus and  $G''$  is the loss modulus (Figure 8c). This complex modulus ( $G^*$  - from the MCR) was found to be similar to that of the tangent modulus (obtained from the ICAR – Fig. 6b) as shown in Fig. 5 (right). Fig. 8a shows the yield stress of the concrete mixes up to 30 minutes concrete age which was combined with that in Fig. 7a for evaluating the yield stress evolution or structuration shown in Fig. 8b. The yield stress evolution up to the initial setting time (2 hours) was estimated using the Ma-Qian-Kawashima model [39] given in Equation 1 & 2.

$$\tau(t) = \tau_0 + m\lambda_{thix} + A_{thix}t \quad (1)$$

$$\lambda_{thix} = 1 + (\lambda_0 - 1)e^{-\frac{t}{\theta}} \quad (2)$$

$\tau(t)$  is the increasing static yield stress,  $t$  is the considered time,  $\tau_0$  is the initial yield stress,  $m$  is the yield stress at a fully structured state,  $A_{thix}$  is the linear rate of evolution of yield stress,  $\lambda_{thix}$  describes the structured state (values between 0 and 1) at the considered time,  $\lambda_0$  is the initial structured state,  $\theta$  is the relaxation time required to reach fully structured state.

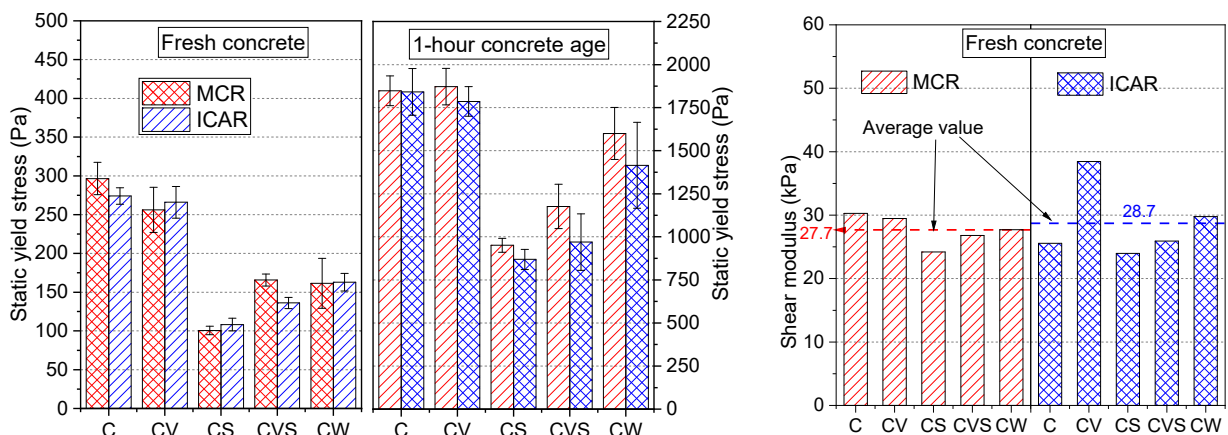
**Table 1.** Mix proportions and properties of the concrete mixes.

| Notations   | Material constituent (kg/m <sup>3</sup> ) |      |      |      |      |
|---|---|------|------|------|------|
|   | C   | CV   | CS   | CVS  | CW   |
| Water   | 217                                       | 217  | 217  | 217  | 223  |
| Cement - CEM II 52.5N                                 | 395                                       | 395  | 395  | 395  | 374  |
| Malsmebury sand                                       | 774                                       | 774  | 774  | 774  | 796  |
| Water absorption                                      | 8.57%                                     |      |      |      |      |
| Greywacke stone (6 mm nominal size)                   | 1029                                      | 1029 | 1029 | 1029 | 1018 |
| Water absorption                                      | 1.65%                                     |      |      |      |      |
| VMA   | -   | 0.6% | -    | 0.4% | -    |
| Superplasticiser                                      | -   | -    | 0.6% | 0.4% | -    |
| Other properties                                      |   |      |      |      |      |
| w/c ratio   | 0.55                                      | 0.55 | 0.55 | 0.55 | 0.6  |
| Slump (mm)  | 100                                       | 100  | 175  | 170  | 185  |
| Plastic cracking conditions<br>(10% RH and 40°C temp) | IST (min)                                 | 120  | 120  | 120  | 150  |
|   | FST (min)                                 | 165  | 165  | 165  | 195  |
| BS EN 196-3 [31] conditions<br>(65% RH and 20°C temp) | IST (min)                                 | 360  | 360  | 420  | 420  |
|   | FST (min)                                 | 420  | 420  | 510  | 420  |
| Compressive strength (7 days, MPa)                    |   | 36   | 39   | 35   | 42   |
|   | (28 days, MPa)                            | 47   | 51   | 47   | 50   |

C – control mix; CV – control mix + VMA; CS – control mix + SP; CVS – control mix + VMA + SP; CW – control mix + water; RH – relative humidity; temp – temperature IST – initial setting time; FST – final setting time

**Table 2.** Phases of the study, their objectives and test methods

| Phase | Tests & methods  | Objectives  |
|-------|--|---|
| 1     | Stress growth test (low rate rotational shearing – LRS at 0.02 rev/s) at 0, 10 & 30 mins concrete age & flow curve tests with the ICAR rheometer [19, 35]  | Resistant shear properties, structuration rate  |
| 2     | Strain sweep (at 10 rad/s), rate sweep (at 10 <sup>-2</sup> %), creep & creep recovery, stress relaxation at 0, 1 & 2 hours concrete age, and three interval thixotropy tests with MCR501 + BMC90 rheometer using small amplitude oscillatory shearing – SAOS [19, 36] | Resistant shear properties, rheo-viscoelastic properties, structuration rate  |
| 3     | Plastic cracking processes (at 10% RH, 40°C & 4 km/hr) – bleeding, evaporation, capillary pressure, plastic settlement & shrinkage; and crack areas by ASTM C1579 [9, 38]  | Plastic cracking behaviour & relationship to rheo-physical parameters by statistical methods  |
| 4     | Modelling shear crack initiation using Von Mises-Hencky (vM-H) and Bresler-Pister (B-P) failure criteria with the implementation of the viscoelastic behaviour [37]  | Shear rheometry results forms the resistant shear properties and viscoelastic behaviour; settlement and shrinkage results formed the strains/stresses and the crack areas helped to verify the prediction |



**Figure 5.** Relationship between results of ICAR and MCR501 rheometers at 60% reduced stone content.

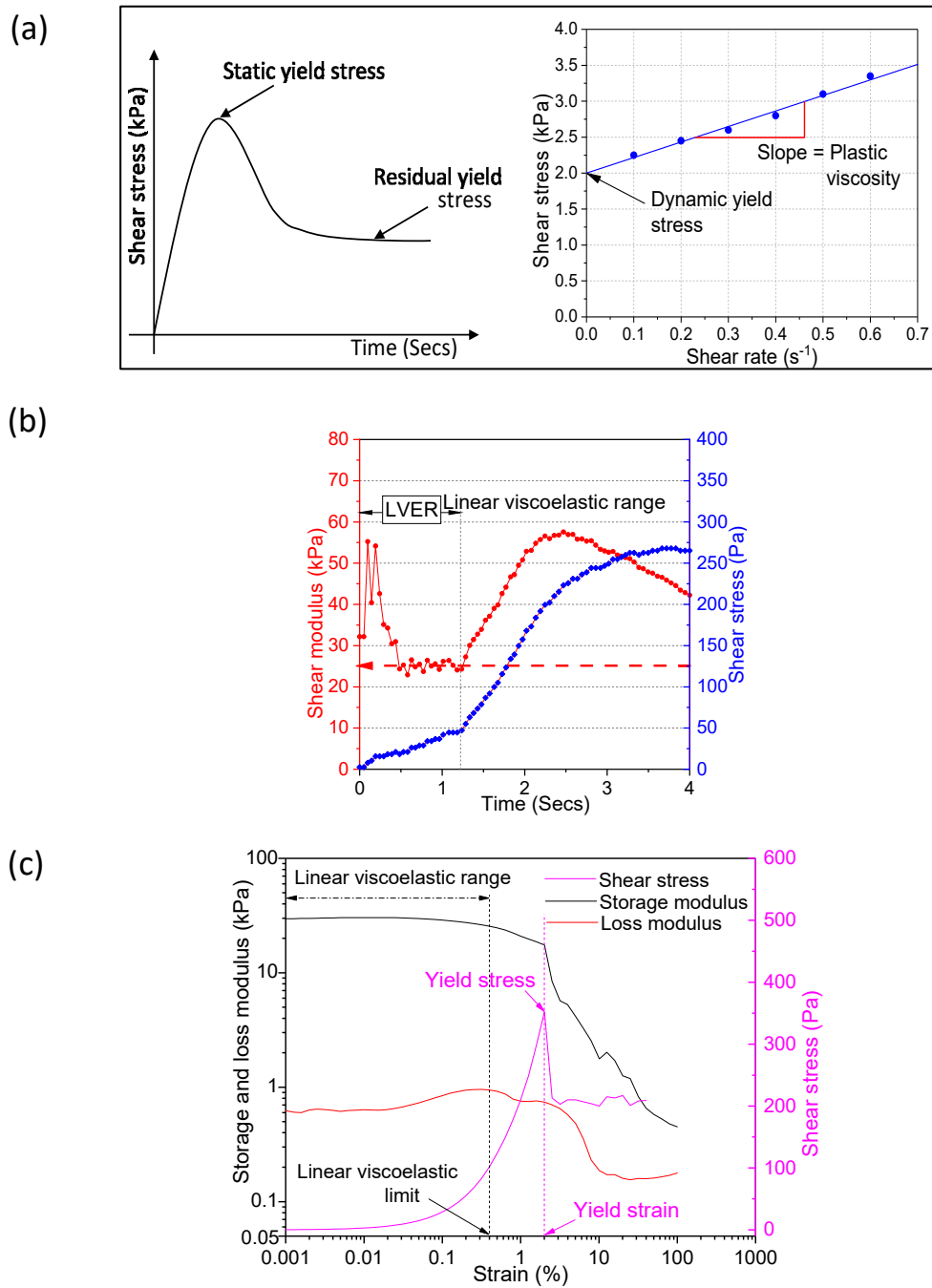
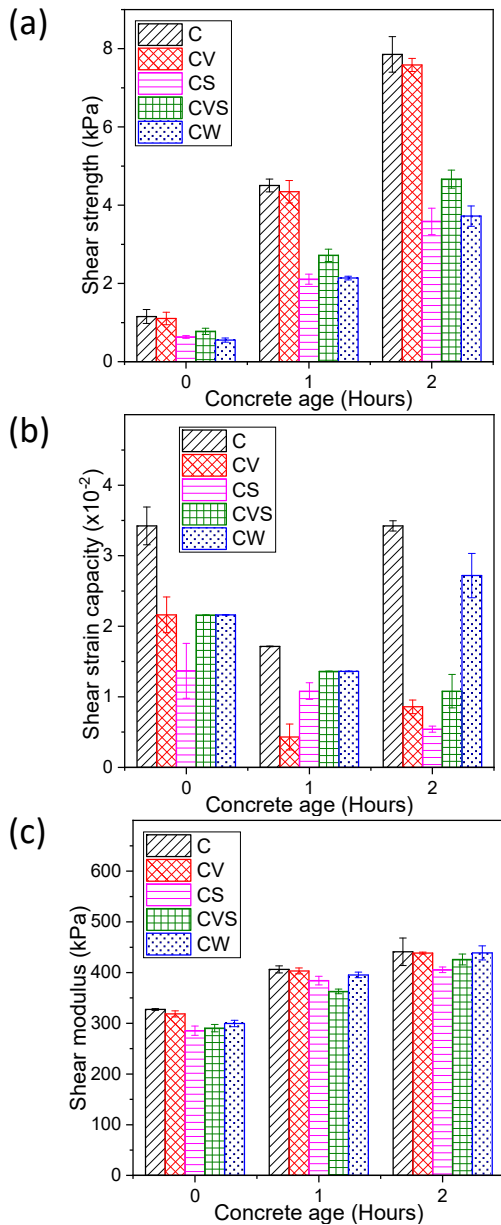
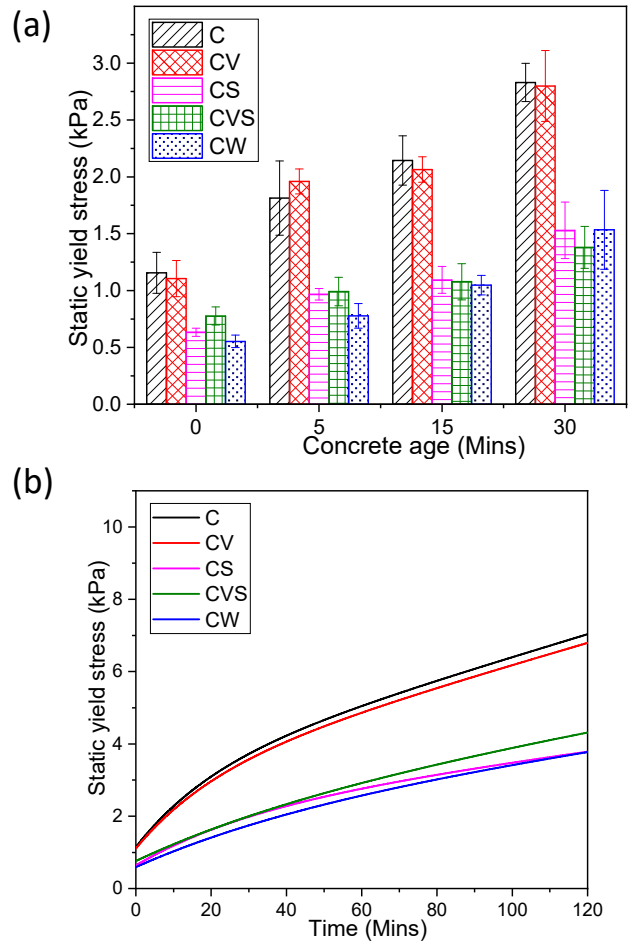


Figure 6. Typical results from (a, b) rotational shear rheometry, (c) dynamic shear rheometry.



**Figure 7.** Rheo-physical properties (a – yield stress, b – yield strain, c – modulus) of the concrete mixes measured at 0, 1 and 2 hours concrete age.

From the Fig. 7 and Fig. 8, the intent of the admixtures to variedly influence the rheo-related properties of the concrete was achieved. As shown later, the employed admixtures also differently influenced the plastic cracking behaviour of the concrete; this creates an avenue to directly correlate the plastic cracking process of the mixes to their rheo-physical parameters. These correlations are highlighted in Section 4.

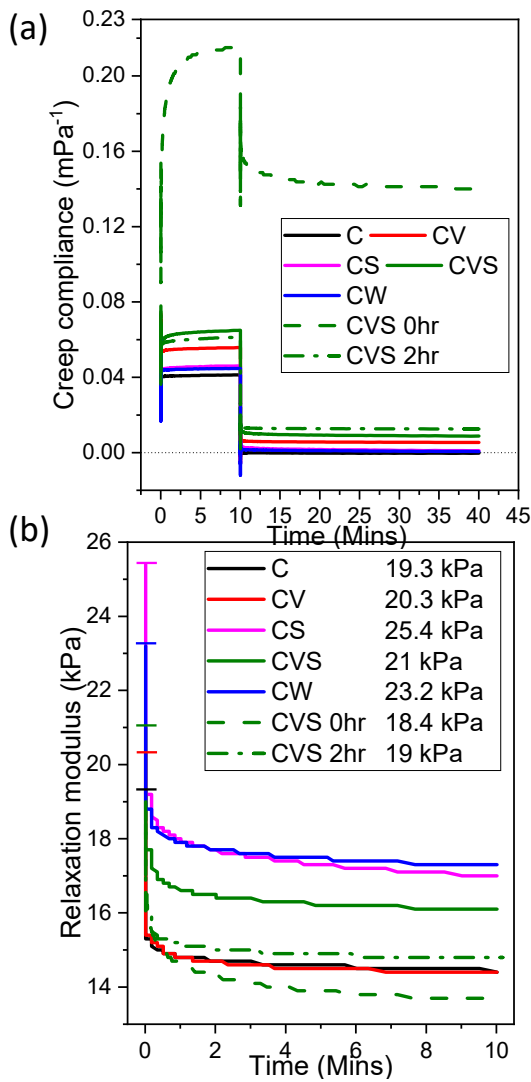


**Figure 8.** (a) Yield stress of the concrete mixes up to 30 minutes concrete age, and (b) the yield stress evolution.

### 3.2 Rheo-viscoelastic properties

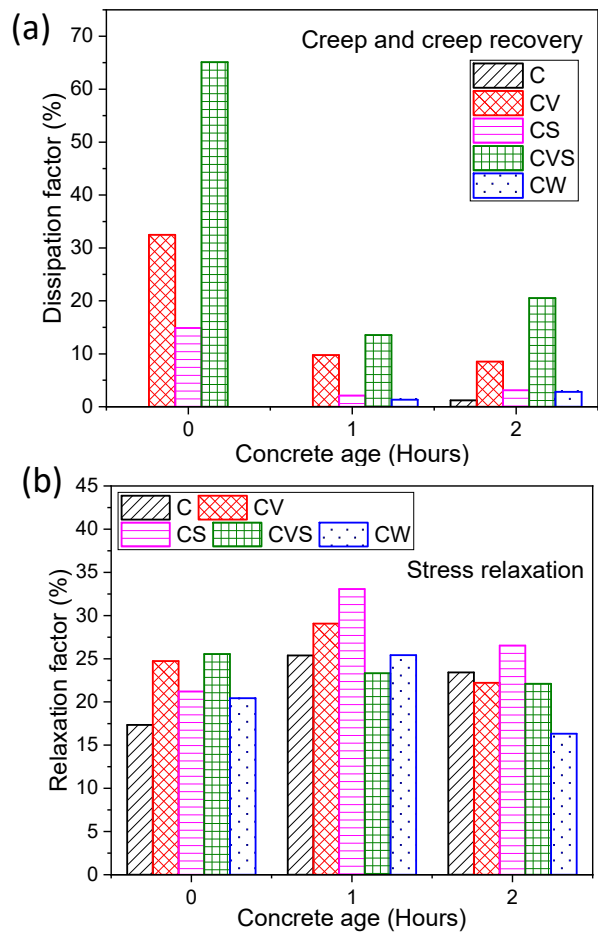
Fig. 9 shows the creep and creep recovery results of the concrete mixes while Fig. 10 depict the stress relaxation results. Similar to the rheo-physical properties, the admixtures influenced the rheo-viscoelastic properties. From the figures, the ability of plastic concrete to absorb/dissipate sustained strain energy is time limited. This ability is quantified as the damping or dissipation factors shown in Fig. 10a. The combination of VMA and SP tends to improve the dissipation ability of the concrete (with a dissipation as high as 65% after mixing the concrete); as shown later, this ability manifest in mix CVS delayed cracking.





**Figure 9.** Typical results for (a) Creep and creep recovery and (b) stress relaxation of the concrete mixes at 1 hour concrete age and those of mix CVS at 0 & 2 hours.

The stress relaxation ability (quantified as relaxation factor in Fig. 10b) of the plastic concrete seems not to change with time nor significantly influenced by the admixtures. It should be noted that the applied stresses and strains for the creep and relaxation tests are within 50% of the yield stress and strains, respectively. These values were found to be within the range of strains measured for the settlement and shrinkage in Section 4.



**Figure 10.** Damping factors of the concrete mixes for (a) creep and creep recovery (b) stress relaxation.

#### 4 Plastic cracking behaviour and correlation to rheo-physical properties

The plastic cracking behaviour plot of the concrete (mix C) is shown in Fig. 11 with emphases on the capillary pressure, settlement and shrinkage, as earlier identified to be influenceable by rheo-physical properties. Detailed results for all the mixes can be found in Kolawole et al. [20] Generally, the behaviour can be segmented into three stages, first, the bleed water is adequate on the concrete surface to prevent significant pressure build-up. Second stage where the bleeding is totally evaporated and the pore water starts evaporating, leading to rise in pressure build-up and shrinkage due to concave water menisci in the pores. Stage 3, the capillary pressure build-up is most rapid due to ending influence of particles' self-settlement that is responsible for rising pore water. For instance, for mix C shown in Figure 12a, the first stage was up to 45 minutes when the evaporation exceeds the bleeding, and the capillary pressure cum shrinkage start to increase significantly and is identifiable as a kink on the settlement plot; the second stage lasted up to about 95 minutes with changes in the rate of capillary pressure, settlement and a shrinkage plot kink. For the third stage, the indicative end of the self-settlement can be estimated to be around 95 minutes.

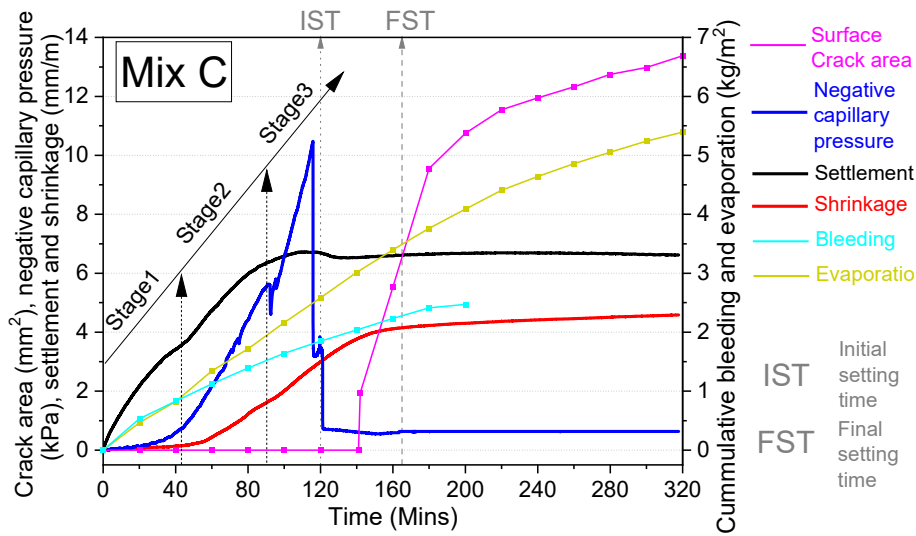


Figure 11. Plastic cracking behaviour of mix C.

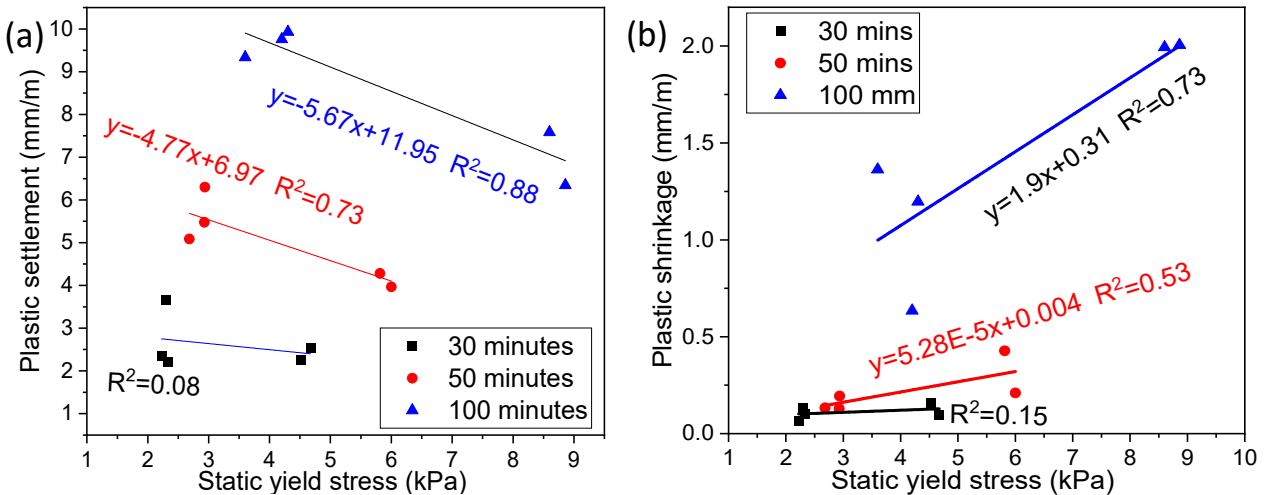
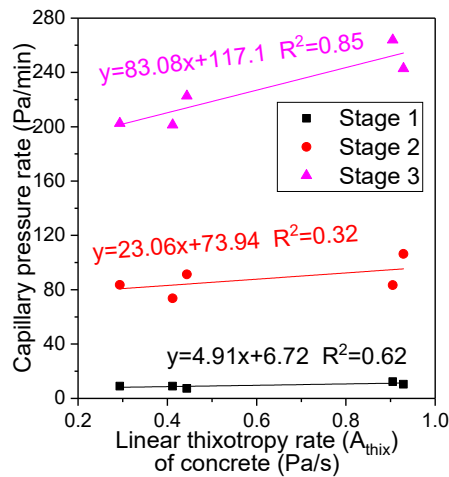


Figure 12. Relationship between the increasing static yield stress and (a) plastic settlement (b) plastic shrinkage.

Based on the framework in Section 2.1, Fig. 12a shows the correlation between the plastic settlement and static yield stress of the concrete. As noted earlier, the unique influence of each admixture on the mixes' settlement and static yield stress allows for their pairing (in time) for correlation. As expected from the framework, the yield stress shows a significant inverse relationship with the settlement except below 30 minutes concrete age. This is the average characteristic time for the concrete mixes to reach a structured state after consolidation on a vibration table (percolation time). This 30-minute duration is observable in Figure 8b where there is a rapid structuration before the start of the linear structuration ( $A_{thix}$ ). Furthermore, increasing  $R^2$  with increasing time of the correlation suggests that the structuration of the concrete impedes more settlement.

Unlike the settlement, the plastic shrinkage shows a direct relationship with the static yield stress only after 50 minutes. This is because the plastic shrinkage significantly started after

about 45 minutes (Fig. 11). The rates of capillary pressure from the stages highlighted in previous section only shows a good direct relationship with the structuration in Stage 3 (Fig. 13). This suggests that only the third stage of capillary pressure which is not influenced by self-settlement is impacted by rheo-physical properties.



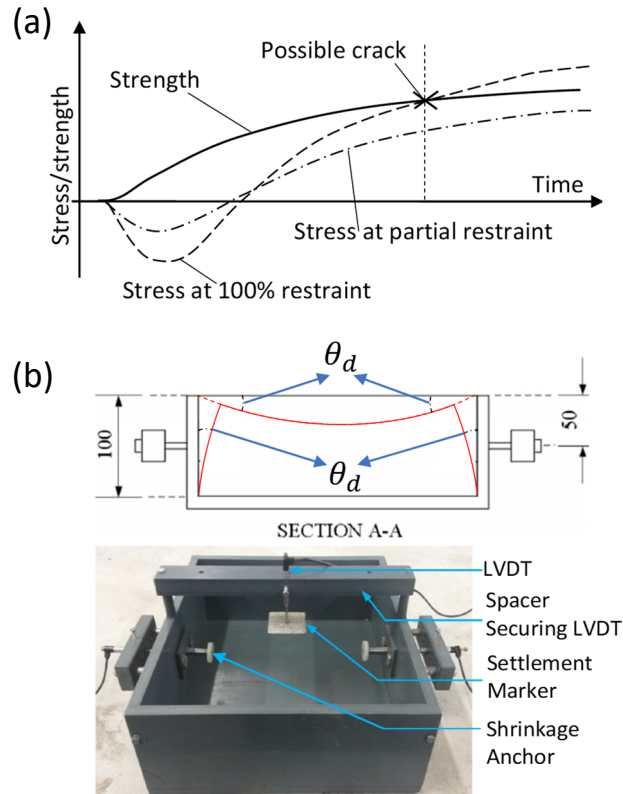
**Figure 13.** Relationship between the rate of capillary pressure build-up and rate of structuration.

These evaluated relationships help to establish the nature, timeframe, extent, and magnitude of the relationship between the rheo-physical properties and plastic cracking process. Extensive details on these are compiled in a recently published article [20].

### 5 Rheo-mechanics approach

In this section, the proposed rheo-viscoelastic influence is combined with the resistant rheo-physical properties to rheo-mechanically model the initiation of plastic cracking in early-age concrete. The measured rheo-physical and rheo-viscoelastic properties makes up the material properties while the measured settlement and shrinkage strains were used for the analyses to predict the crack initiation using Von Mises-Hencky and Bresler-Pister failure criteria. The analytical procedures were carried out with and without the rheo-viscoelastic behaviour (strain dissipation and stress relaxation) in-order to elucidate the roles of the rheo-viscoelasticity.

Measured settlement and shrinkage strains were assumed to be fully restrained as shown in Fig. 14a. Based on the vital conclusion that the self-settlement phase is majorly shear-dominated, the potential contribution of the settlement and shrinkage strains to the fully restrained shear strain ( $\gamma_{xy}$ ) was estimated from the settlement and shrinkage mould (Fig. 14b). The plane stresses were estimated with an assumed Poisson’s ratio of 0.33 and shear modulus from the SAOS. The cracking strains and stresses were thereafter estimated with and without the dissipation and relaxation factors, respectively. The plane strains and stresses were carried out in two cases. Case I, the cracking strain and stress contribute to both shear and direct deformation of the concrete. Case II, the cracking strain and stress contribute solely to shear deformation. Extensive equations and details of these can be found somewhere else [37].



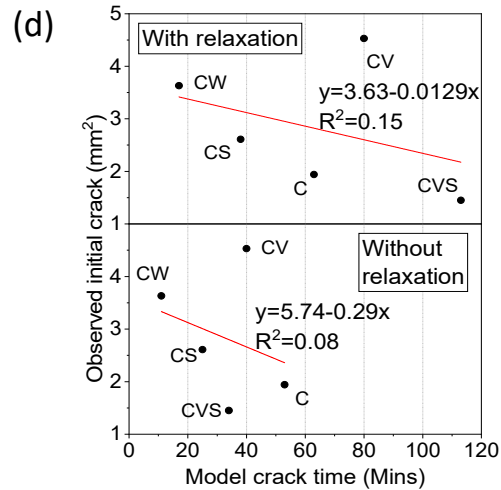
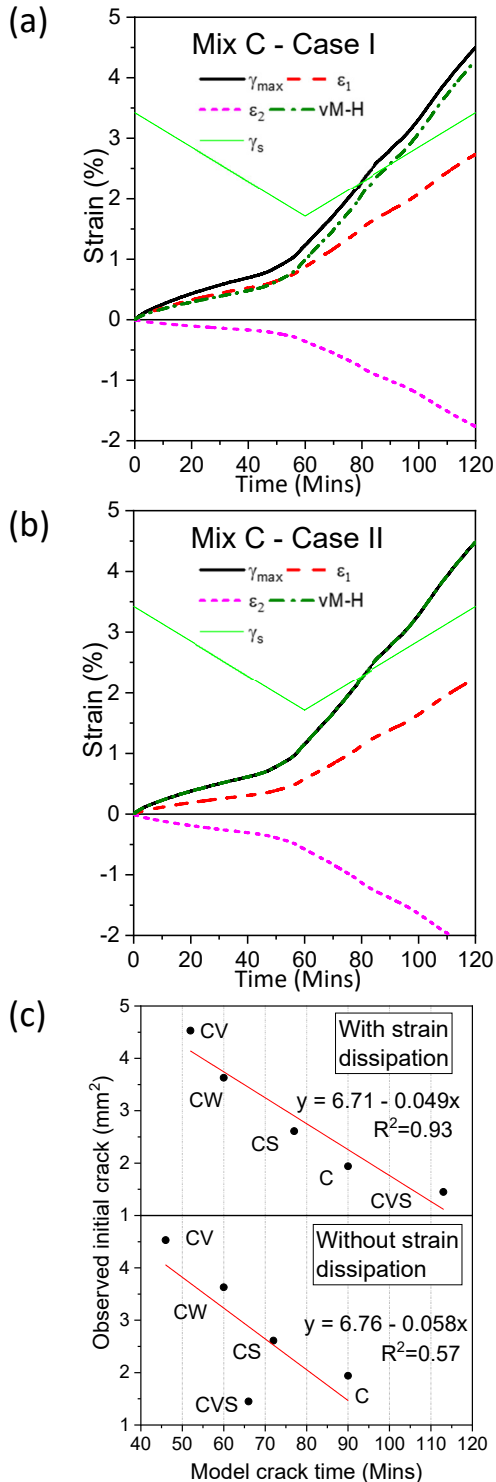
**Figure 14.** (a) Cracking risk/potential in a concrete element at partial and full restraint [40], (b) Settlement and shrinkage mould (300x300x100 mm) for estimating shear strains ( $\theta_d$ ), assuming full restraint (reproduced with permission from [10]).

As noted earlier, concrete in its plastic phase tends to exhibit ductile deformation and a plastic form of yielding [37, 41] while tending to become solid or brittle at end of hydration dormancy and start of set. These informed the choice of the two failure criteria – Von Mises and Hencky (vM-H) theory as a form of yield failure, and Bresler-Pister (B-P) theory as a form of quasi-brittle failure in Section 5.1 & 5.2, respectively. The initiation of the crack was detected, in this study, by continuously monitoring the surface and the crack progression was measured at 20 minutes intervals. Therefore, the verification of the model is delicate because the shear minute crack initiation (before the initial setting time) is difficult to detect due to the wet and plastic nature of the concrete (causing water molecules filling the microcrack). Therefore, it was proposed that the magnitude of the initial surface cracking would indicate the severity of the internal shear cracking [37].

#### 5.1 Von Mises and Hencky theory

The principle is based on the deviatoric energy component of the deformation which is responsible for the yielding and possible crack initiation. The strain and stress deviatoric energy were analysed and referred to as strain and stress paths for yielding. Fig. 15a & b show the typical results of the strain path for Case I & II analyses, respectively. The cases of analyses were quite similar which confirms that the plastic phase is majorly shear dominated. The model crack time of the mixes were correlated with the magnitude of the initial surface cracking as shown in Fig. 15c as the verification of the

model. The good fitting shows that the severity of the internal shear-induced cracking is indicated by the magnitude of the surface crack initiation (in the utilised ASTM C1579 mould [9, 38]).



**Figure 15.** (a) Strain path analysis using vM-H theory with strain dissipation, and (b) without strain dissipation; (c) relationship between the model outputs and observed cracking (d) relationship between the stress path model outputs and observed cracking ( $\gamma_{max}/\epsilon_1, \epsilon_2$  – principal shear/normal strains,  $\gamma_s$  – strain capacity, vM-H – von mises & Hencky strain path).

With the assumption of a fully restrained settlement and shrinkage, the model crack times (90, 53, 77, 113 and 60 minutes for Mixes C, CV, CS, CVS and CW, respectively) revealed that the microcracking of the concrete mixes during the plastic phase is probable. In fact, these falls within the self-settlement period of the mixes. An attempt to predict the crack initiation without the rheo-viscoelastic behaviour (strain dissipation) is also shown in Fig. 15c (lower part) and the lower correlation emphasises the significance of the influence of rheo-viscoelastic properties on the early-age cracking of concrete.

The model crack times of the stress path analyses (with and without stress relaxation) were found to not correlate well with the initial surface cracking. This reveals that the strain path analysis is a better path/criteria for modelling the cracking of early-age concrete at the plastic phase which has been experimentally noted by some other authors [17, 18, 42]. The outcome of the purpose of this study to rheologically modify the mixes in-order to achieve a robust approach and understand the influence of rheology can be observed in the results of the vM-H analytical modelling in two ways. Firstly, from Fig. 10, Fig. 11 and Fig. 15c, Mix CVS which exhibits lower plastic cracking due to incorporation of VMA and SP also exhibit good strain dissipation that helped elucidate the role of rheo-viscoelasticity in terms of strain analysis. For instance, removing the mix CVS in Fig. 15c (lower part) results in a good fit of  $R^2 = 0.96$ .

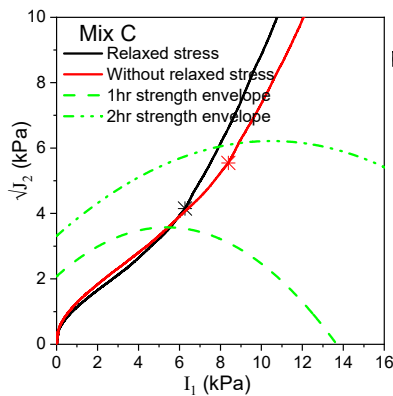
Secondly, the incorporation of VMA in Mix CV increased the plastic cracking with insignificant effects on the yield strength which helped elucidate the effectiveness of strain analysis over stress analysis in predicting cracking in the plastic state of early-age concrete. For instance, removing Mix CV in Fig. 15c yields a better fit with  $R^2 = 0.87$  and  $0.61$  (with and without stress relaxation, respectively).

The higher value of  $R^2 = 0.87$  ( $> 0.61$ ) also elucidates the significance of the stress relaxation (which was exhibited by all of the mixes unlike strain dissipation mainly exhibited by Mix CVS).

## 5.2 Bresler-Pister theory

The principle is based on a deviatoric failure plane bounded by a hydrostatic cap failure and is formulated in terms of the shear properties ( $c$  – cohesion &  $\varphi$  – angle of internal friction) and stress invariants ( $I_1, J_2$ ) as formulated in Kolawole et al. [9, 37]. It should be noted that the dynamic rheometer used for this study was equipped with a normal stress sensor for estimating the normal stress ( $N_1$ ) associated with the shear stress measurements. More details on this and its application for Mohr-Coulomb shear properties ( $c$  &  $\varphi$ ) evaluation is detailed in a companion paper [19].

The B-P theory is intended to reflect the contribution of hydrostatic/dilatant pressure on the initiation of cracking. Fig. 16 shows the typical result from the relaxed and unrelaxed stress analyses, where 1- and 2-hours strength envelope are superimposed. The markers on the stress path represent the stress points at 1 hour concrete age. The model over predicts the plastic cracking, that is, hydrostatic pressure does not necessarily contribute to the failure. This is also the case for other mixes. These results are similar to that of other studies [13, 41] that suggests that plastic concrete exhibits pressure-insensitive form of ductile failure and that the failure modes are well represented by Von Mises criterion.



**Figure 16.** Stress path analysis and strength envelopes according to Bresler-Pister theory.

## 5.3 Applications of the rheo-mechanics approach

From Section 5.1, solving the equation of the relationship in Fig. 15c ( $y = 6.71 - 0.049x$ ) yields a minimum model crack time of  $x = 136$  minutes to avoid plastic cracking initiation ( $y = 0$ ) at the concrete surface. The robustness of this estimated time and study requires further research for other forms of mixes and beyond the initial setting time. By implication of this study and within its limits, the rheo-physical properties of a concrete mix can be characterised up to 30 minutes to estimate the structuration up to initial set, and the plastic settlement/shrinkage strains measured; these can then be used to evaluate the propensity for plastic cracking. In the

context of this study, any obtained model crack time below 136 minutes would imply that there's higher propensity for surface cracking and the probable crack area can be estimated from the equation  $y = 6.71 - 0.049x$ .

By the implications of this study, strategies for reducing the propensity for plastic cracking include improving the strain dissipation and capacity (that is, ductility) of the concrete mixes, and the reduction of self-settlement by improving the yield stress and structuration. Taking cues from the differing influence of the admixtures, these strategies are related to materials optimisation of concrete mixes.

## 6 Summary and conclusions

This study sets out to broaden the understanding of the plastic cracking behaviour of concrete and the influence of rheo-related properties. This study is novel in its comprehensive investigation of concrete rheology, particularly rheo-physical and rheo-viscoelastic properties, for understanding plastic cracking in early age concrete. Important properties such as yield stress/strain, structuration, creep and relaxation, and how these are influenced by rheology modifiers (viscosity modifying agent and superplasticiser) were identified via rotational and oscillatory rheometry carefully selected over a multi-scale range of application. The processes which cumulate into the plastic cracking behaviour were investigated while identifying the physical process that links them to the rheological parameters and showing their relationship.

An attempt was also made to model plastic cracking using a rheo-mechanics approach in validating the rheo-viscoelastic influence. The limitation of this study is acknowledged in terms of its scope and application due to its rheo-related approach. That is, the theories, framework and outcomes are limited to the very early-age of concrete up to the initial setting time where significant rheo-related properties start to wean off. Further studies are required to extend the application to later ages of concrete such as final setting time and beyond.

Significant findings and conclusion emanating from this study are highlighted as follows.

- Settlement of stones in the suspending mortar of concrete is the main source of rheological link to plastic cracking behaviour. Improved yield stress and structuration reduce settlement. However, the plastic settlement is interwoven with other processes such as plastic shrinkage and capillary pressure which carries over the influence of the rheology. The plastic shrinkage is directly related to the yield stress while the capillary pressure is mainly influenced by rheology at the stage when the settlement of stones (self-settlement) has ceased.
- Another role of rheology is systematically tied to the pronounced viscoelasticity of plastic concrete due to its viscous nature. Strain dissipation and stress relaxation influence the propensity for plastic cracking initiation.

Both reduces the tendency for plastic crack initiation, but the strain dissipation can be influenced by the admixture constituent and is mainly significant during half-time of the initial set of plastic concrete.

The stress relaxation is inherent and barely influenced by the admixture constituent and occurs at least up to the initial setting time of the plastic concrete. These periods also indicate the timeframe of influence of the rheo-viscoelasticity considering the scope of this study.

- With the aid of the varied influence of the rheology admixtures, it was established that strain analyses criterion is better suited for predicting the initiation of plastic cracking in early-age concrete than stress analyses criterion. Furthermore, that the failure/cracking of early-age concrete in its plastic phase is in the form of ductile yielding which is pressure-insensitive and is well represented by Von Mises-Hencky failure criterion.
- From a materials consideration of concrete design, minimisation of one of the major processes (settlement) linking rheology to plastic cracking can be achieved by improving the structuration. And as a strategy to minimising the occurrence of plastic cracking, ductility (strain capacity and energy dissipation) of the mixes should be improved by material optimisation.

### Authorship statement (CRediT)

This paper is a summary of the first author's PhD study. John Temitope Kolawole: Conceptualisation; Methodology; Investigation; Validation; Formal analysis; Data curation, Writing – Original draft, review & editing; Visualisation; Fund acquisition. Riaan Combrinck: Resources; Methodology; Writing – Review & Editing; Supervision; Project administration. William Peter Boshoff: Resources; Methodology; Writing – Review & Editing, Supervision, Fund acquisition; Project administration.

### Declaration of competing interests

None

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