

EFFECTS OF A TWO-STAGE MIXING PROCESS ON THE CHARACTERISTICS OF CONCRETE: PART II - FRESH CONCRETE RHEOLOGY AND MEASUREMENT PROTOCOLS

AUSWIRKUNGEN VON ZWEISTUFIGEM MISCHEN AUF DIE EIGENSCHAFTEN VON BETON: TEIL II – FRISCH-BETONRHEOLOGIE UND MESSVERFAHREN

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SUMMARY

Fresh concrete properties are strongly governed by the mixing operation, yet standards still rely largely on qualitative homogeneity criteria and provide limited guidance on how specific mixing procedures affect rheology. The aim of this study is to capture and evaluate the effects of a two-stage mixing process on the workability and rheological characteristics of concrete. The experimental program includes different mix designs that cover the practical use of concrete today. The key properties of each mixture are compared with a conventional mixing process. The rheological properties are assessed using different measurement protocols to account for the shearing history. The findings disentangle measurement protocol artifacts from true material response.

ZUSAMMENFASSUNG

Frischbetoneigenschaften werden stark vom Mischprozess beeinflusst, allerdings stützen sich Normen nach wie vor weitgehend auf qualitative Homogenitätskriterien und geben nur begrenzte Hinweise darauf, wie sich bestimmte Mischverfahren auf die Rheologie auswirken. Ziel dieser Studie ist es, die Auswirkungen eines zweistufigen Mischprozesses auf die Verarbeitbarkeit, und die rheologischen Eigenschaften von Beton zu erfassen und bewerten. Das Versuchsprogramm umfasst verschiedene Mischungsrezepturen, die die tägliche Betonpraxis abdecken. Die wesentlichen Eigenschaften jeder Mischung werden einem konventionellen Mischregime gegenübergestellt. Die rheologischen Eigenschaften werden unter

Verwendung verschiedener Messprotokolle bewertet, um die Scherhistorie zu berücksichtigen. Die Ergebnisse trennen Messprotokollartefakte von der tatsächlichen Reaktion der Materialien.

1. INTRODUCTION

The mixing process takes a major role in defining the quality of the produced concrete but is often overlooked in recent research [1]. According to international standards, mixing concrete should continue until a visually homogeneous consistency is achieved [2]. However, no quantitative measures for assessing uniformity are given. It is widely known that especially for self-consolidating concrete (SCC) mixing is more challenging than for ordinary concrete mixtures [3]. Due to the high content of fines, mixers must be able to homogenize unsaturated powder as well as to disperse agglomerates [4]. In order to achieve this, mixing the cement slurry in a preliminary stage is advantageous. The selection of the appropriate mixing configuration for the specific concrete significantly impacts workability [4].

Therefore, this study investigates a two-stage mixing process, utilizing a suspension mixer for the first stage to create a homogenized dispersion of the fine aggregate contents with a grain size of < 0.125 mm. For the control group, a single stage mixing process using a common mixing pattern is applied on the same single-shaft mixer. Tests were carried out with a total of four different mix designs that represent a variety of today's concrete production.

The objectives are threefold:

- (i) Quantify how the mixing configuration alters fresh concrete rheology;
- (ii) evaluate protocol-induced bias and repeatability of rheometer measurements; and
- (iii) identify operational implications and limits of applicability.

This investigation represents a follow-up to the findings and results presented in [5]. While in the first study, the hardened concrete properties were targeted, this study focuses on the fresh concrete; specifically, yield stress and plastic viscosity, as well as their assessment.

2. MATERIALS AND METHODS

2.1 Equipment

Two types of concrete mixer were used. A compulsory single shaft mixer *AM-MANN CEM 60 S ELBA* with a double helix shaped tool geometry. This laboratory mixer is suited for concrete of all categories as well as special concretes and can apply a Froude number of 1.75 at 75 rpm.

The second mixer is a *Gertec CML30*. It is a laboratory sized colloidal mixer that is used during the first stage to produce the homogenized suspension of fines. With its very high shear gradients of 6000 s^{-1} and a Froude number of > 200 [6], this mixer is capable to disperse even fine agglomerates.

For further details on the equipment used refer to [5].

2.2 Mix Designs

A total of four distinct mix designs were considered across this study. Namely, an earth-moist concrete (EM), two self-consolidating concretes (SCC) with different additives, and a high-performance concrete (HPC). To maintain readability, some abbreviations are introduced. The designations of the different concrete mixtures are listed in Table 1.

Table 1: Overview of mixture designations

EM	EARTH-MOIST CONCRETE
SCC-L	SCC CONTAINING LIMESTONE POWDER
SCC-F	SCC CONTAINING FLY-ASH
HPC	HIGH-PERFORMANCE CONCRETE

The development of both SCCs followed the principles of Okamura [7]. The mix proportions were generally optimized using the modified Andreasen model [8] to achieve high packing density, sedimentation stability and good flowability [9,10]. The selected minimum particle size distribution was chosen as $0.2 \mu\text{m}$ with a distribution coefficient of 0.28.

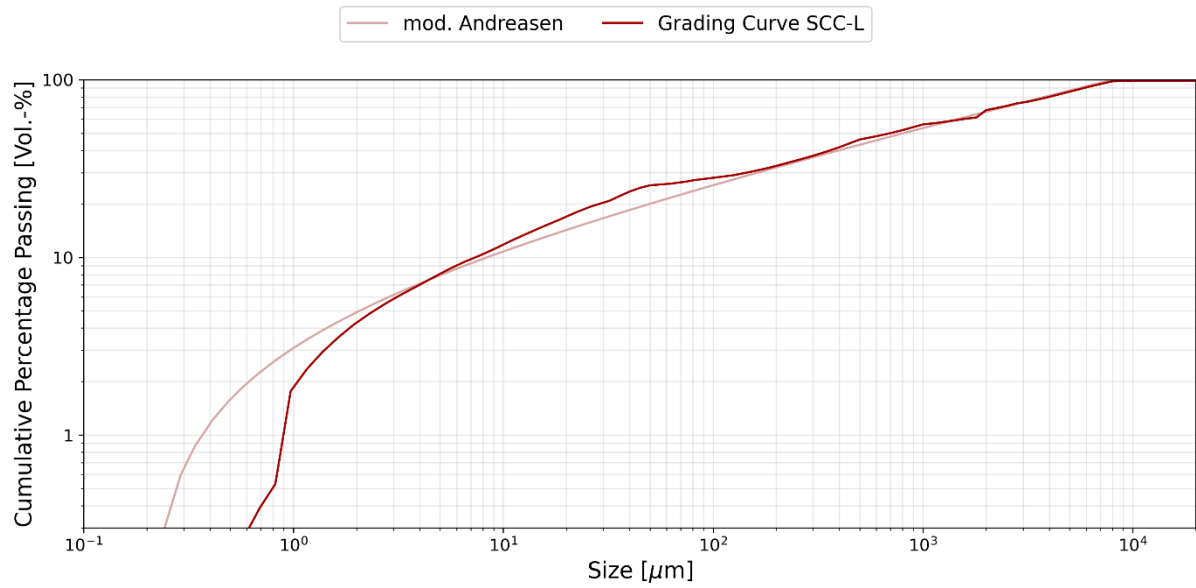


Fig. 1: Exemplary grading curve for SCC-L as reported in [5]

The grading curve of the SCC-L mixture is depicted in Fig. 1. The specific proportions of the relevant mix designs are given in Table 2.

Table 2: Mix proportions for SCC-L, SCC-F & HPC

Ingredients	Density [kg/dm ³]	SCC-L [kg/m ³]	HPC [kg/m ³]	SCC-F [kg/m ³]
Cement	3.1	400	400	400
Fly ash	2.4	-	-	200
Limestone	2.7	200	-	-
Oil shale	2.1	-	178	-
Water	1.0	195	195	195
Superplasticizer	1.09	4.0	5.3	3.0
Sand 0/2 mm	2.562	759	757	757
Gravel 2/8 mm	2.650	757	755	757
		Σ 2315	Σ 2291	Σ 2310

2.3 Mixing Configurations

Two mixing configurations were formed. Mixing Configuration A (MC-A) serves as the reference setup; Mixing Configuration B (MC-B) implements the investigated two-stage mixing concept as described in the following.

The batches of MC-A were produced by means of the compulsory mixer and a well-established laboratory mixing regime shown in Fig. 2.

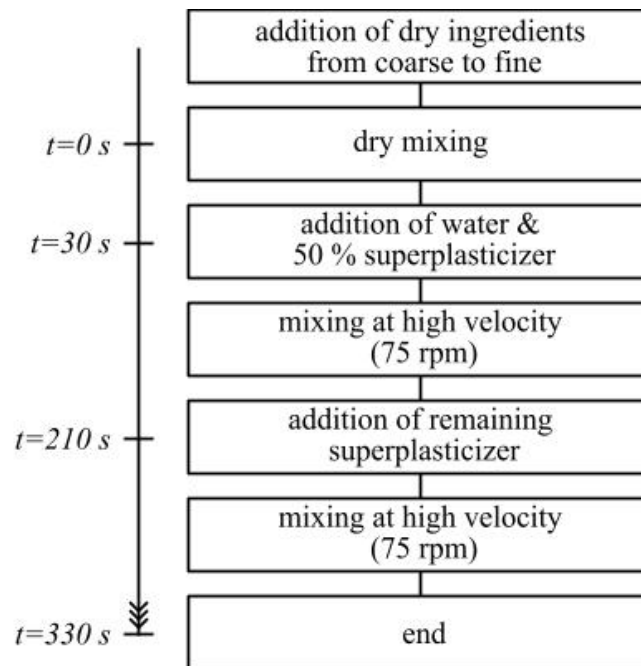


Fig. 2: Mixing regime for MC-A in the single-stage setup as reported in [5]

For MC-B, the water was given into the suspension mixer first. Afterwards, the fine ingredients $< 0.125\text{ mm}$ were added while mixing at 500 rpm, starting with the additives of the respective mixture followed by the cement. Meanwhile the mixing speed was increased over time up to 950 rpm upon completion of the addition of fines.

It should be emphasized that the mixer employed was not specifically designed to process highly viscous slurries with elevated contents of reactive cement. To ensure adequate homogenization and avoid partial clogging, cement had to be continuously dosed directly at the shear gap, as the blade-induced flow alone was insufficient for dispersion. Including the subsequent homogenization phase, the procedure required a total of 360 s, reflecting the necessity of gradual and continuous incorporation of the fine constituents (see Fig. 3).

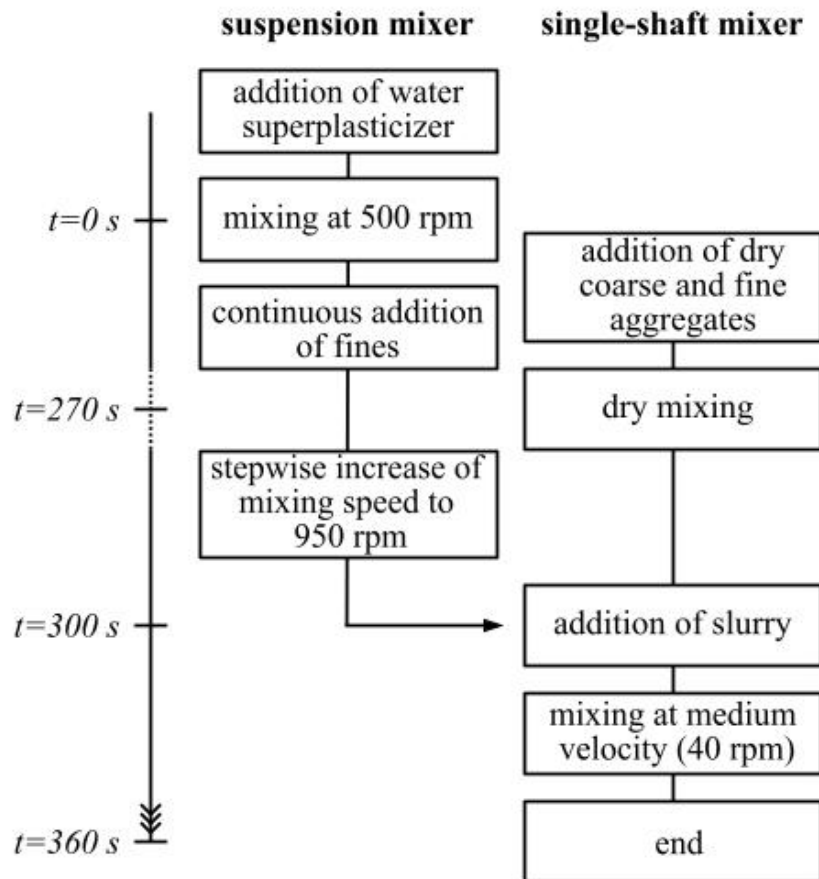


Fig. 3: Mixing regime for MC-B in the two-stage setup as reported in [5]

For the homogenization, the slurry was transferred into the compulsory mixer, where coarse aggregates and suction water had already been mixed. Residuals from the suspension mixer and transport vessel were included in the mass to ensure equivalence with the corresponding reference mixture. The function of the second stage was limited to uniformly distributing the aggregates within the slurry, a process completed within a maximum of 60 seconds.

2.4 Measurement Protocols

In this study a modified version of the ICAR Rheometer was deployed, as developed in [11]. Immediately after the mixing ended, the rheometer container was filled with the fresh concrete batch, and the vane probe with metal rods was immersed into the specimen. The yield stress and plastic viscosity were derived from each flow curve using the associated solver tool that's based on the well-known Bingham model in conjunction with the Reiner-Riwlin Equation.

In addition to the mixing configurations, two rheological measurement protocols were applied: Sequential (SEQ) and Pointwise (PW). In SEQ, rotational speed decreased from 0.45 to 0.05 rps without interruption. Measurements were taken at five data points (0.45, 0.35, 0.25, 0.15, 0.05 rps), each held for 10 s. After finishing the first SEQ protocol, the specimen was remixed with an external agitator to restore homogeneity, and a second SEQ run was performed.

PW was chosen to address pre-shearing effects, such as shear induced particle migration [11]. PW measurements used the same rotational speed levels but was interrupted to re-homogenize the concrete batch prior to each single data point, ensuring consistent conditions. This procedure was carried out twice, once before and once after the SEQ runs.

3. RESULTS AND DISCUSSION

3.1 Fresh Concrete Consistency

The measurements on fresh concrete consistency demonstrate a clear differentiation between the behavior of flowable and non-flowable concretes within the investigated mixing configurations. The SCC mixtures and the HPC consistently maintained excellent workability across both configurations, with slump flow values exceeding 70 cm. Conversely, the EM experienced partial clogging in MC-B. These outcomes prevented reliable rheological testing of the EM mixture. This observation highlights an important limitation of the two-stage mixing approach: While highly effective for flowable concretes, its applicability to stiff, low water-to-binder (w/b) systems is severely constrained. The findings underline the necessity of tailoring the mixing configuration to the mix proportions to ensure expected placement ability and reliable performance.

In addition, it became evident that concretes produced with the two-stage suspension process required higher superplasticizer dosages to achieve comparable flowability. The increase in admixture demand was negligible for SCC-L (+0.4%), more pronounced for HPC (+5.9%), and substantial for SCC-F (+19.2%).

Tests conducted without adjusting the superplasticizer dosage in MC-B demonstrated that the yield point for those batches was too high for gravitational forces to initiate flow. In contrast, excessive admixture dosage reduced the yield point beyond acceptable limits, compromising matrix stability and causing segregation of coarse aggregates.

3.2 Baseline Correction and Rheological Measurement Results

The rheological properties and the influence of the mixing regime were assessed by comparing Mixing Configuration A (MC-A) and Mixing Configuration B (MC-B). To ensure accuracy, frictional losses from bearings, seals, and other components were quantified through a no-load characterization ($T_0(\omega)$) and subsequently subtracted from the measurements ($T_x(\omega)$) as a baseline correction:

$$T_{net}(\omega) = T_x(\omega) - T_0(\omega) \quad (1)$$

Table 3 presents the processed measurement results for the SCC-L mixture in both configurations MC-A and MC-B respectively. The complete dataset is readily available online [12].

Table 3: Measurement data for SCC-L within MC-A and MC-B after Baseline Correction

SCC-L	Mixing Configuration A				Mixing Configuration B			
<u>Probe velocity</u>	<u>SEQ 1 & 2</u>		<u>PW 1 & 2</u>		<u>SEQ 1 & 2</u>		<u>PW 1 & 2</u>	
[rps]	[Nm]		[Nm]		[Nm]		[Nm]	
0.45	0.713	0.942	0.674	0.631	1.092	0.991	0.947	0.905
0.35	0.544	0.768	0.593	0.555	0.873	0.843	0.829	0.800
0.25	0.410	0.617	0.521	0.485	0.713	0.718	0.711	0.697
0.15	0.297	0.486	0.452	0.432	0.567	0.579	0.606	0.596
0.05	0.123	0.318	0.359	0.346	0.336	0.359	0.434	0.422

The tables distinguish between SEQ and PW measurement protocols. In the SEQ runs, rotational speeds were sequentially reduced from high to low, each maintained for ten seconds, which introduced pre-shearing effects and progressively lower values at later stages [11]. In contrast, the PW runs involved re-homogenization of the concrete prior to each measurement point, thereby mitigating pre-shearing and enhancing the reliability and comparability of the data.

3.3 Effects of the Mixing Configuration

The suspension mixing process is characterized by high intensity and elevated shear forces. This enhances the dispersion of fine particles, yet, also raises the slurry temperature, which promotes cement hydration and can accelerate early stiffening. Across all investigated mixes, the slurry temperature rose by 7 °C (± 0.6 °C), measured in-mixer after mixing ceased. The effect is particularly pronounced in mixtures containing pozzolanic or latent-hydraulic additives, such as oil shale in HPC and fly ash in SCC-F. In the case of EM, it was to be expected that the very low water-to-binder ratio, in combination with the shear-induced heating, would cause premature hardening. This was confirmed during the experiments, and the mixture therefore had to be excluded from rheological testing. In general, higher superplasticizer demand was observed in MC-B to maintain a workable state during mixing.

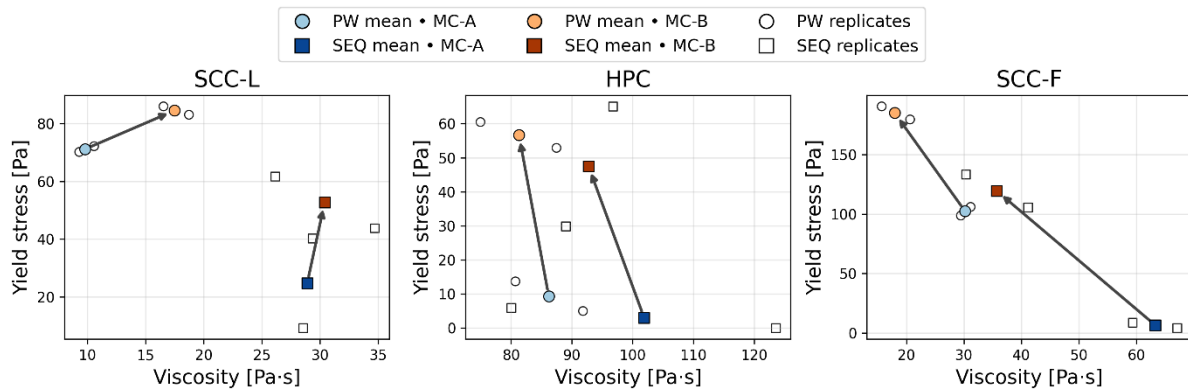


Fig. 4: Change of rheological properties with testing series by concrete mixture

Across the remaining mixtures with higher water-to-binder ratios, MC-B generally plots above and to the left of MC-A, indicating higher yield stress and lower plastic viscosity (see Fig. 4). The exception to this trend is SCC-L, which incorporates only inert limestone powder. In this case, the mixture also exhibits higher viscosity, but no general tendency can be derived, as the available data from one mixture is insufficient to support any broader conclusion.

Nevertheless, the results consistently demonstrate an increase in yield stress for any batch within MC-B, which can be attributed to an accelerated early hydration [5]. In practice this means that the external force needed to initiate material flow increases when deploying the suspension mixing process.

Within each mixture, the difference between MC-A and MC-B is more pronounced in yield stress than in plastic viscosity. This indicates that the enhanced dispersion achieved through the two-stage mixing process exerts a greater influence on the stiffness of the fresh concrete matrix than on its internal flow resistance (see Fig. 4). In practical terms, the resistance to initiate flow under gravity increases at a higher rate than the simultaneous reduction of the internal friction, which governs the speed of flow after yielding.

3.4 Evaluation of the Measurement Protocols

3.4.1 Protocol shift analysis

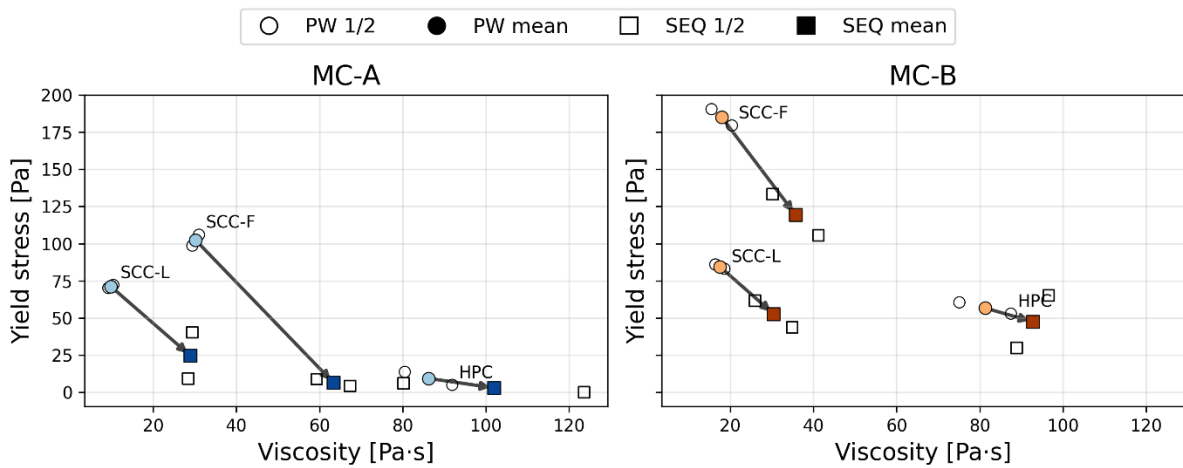


Fig. 5: Shift by measurement protocol with means (filled symbols) and contextual replicates (hollow symbols) in the plastic viscosity / yield stress space. Protocol-induced shift illustrated by the vectors drawn from the PW mean to the SEQ mean.

Each Panel in Fig. 5 plots yield stress versus plastic viscosity with the protocol-induced shift illustrated by the vectors drawn from PW to SEQ. Across all mix designs and mixing configurations, the protocol-induced shift consistently points toward higher viscosity and lower yield stress. This phenomenon is rooted in the shearing history of the Sequential Protocol. As time progresses over the course of the staircase measurement sequence, shear and thixotropic effects accumulate, resulting in an ever-decreasing resistance on the vane probe. This ultimately gives rise to a supposedly steep flow curve and a natural underestimation of yield stress. Consequently, SEQ yields less accurate estimates of yield stress while inflating viscosity.

Furthermore, the comparison between MC-A and MC-B underscores the advantage of the suspension mixing process: The difference between measurement protocols is significantly smaller in MC-B, which demonstrates the core idea behind this process. By enhancing the dispersion of fine particles, the two-stage mixing process is able to foster a more uniform fresh concrete matrix, thereby reducing uncertainty in material behavior.

3.4.2 Replicability and Accuracy

As foreshadowed in Fig. 4, measurements obtained using PW cluster more tightly compared to those obtained using SEQ across all configurations and mix designs. Fig. 6 depicts the spread between replicate measurements PW1 - PW2 and SEQ1 - SEQ2 stacked on top of each other for any pair of mixing configurations and mix designs. The values were calculated as the Euclidean distance in the yield stress/viscosity space.

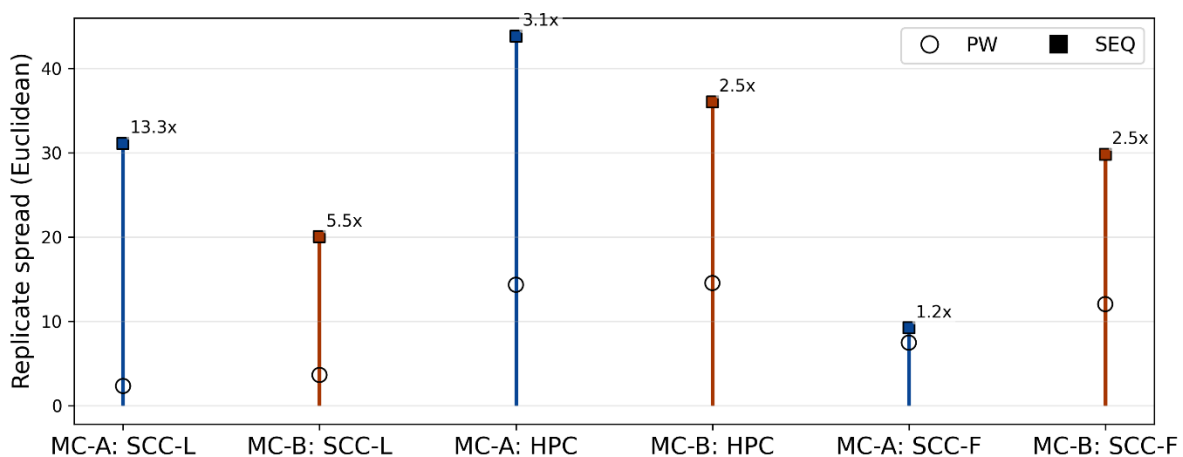


Fig. 6: Spread of PW and SEQ replicate measurement aligned for any pair of mixing configurations and mix designs

In principle, the greater the time interval between measurements, the greater the expected divergence of replicate measurements. Due to the order of testing (PW1 → SEQ1 → SEQ2 → PW2), PW measurements are expected to deviate further from one another than SEQ measurements. However, the deviations of the SEQ replicates are significantly higher, reaching up to 13.3 times the deviation of the PW replicates and averaging 4.7 times across all cases considered in this study despite almost immediate repetition.

This indicates that the re-homogenization step intrinsic to the Pointwise protocol effectively resets the material state prior to each measurement point, reducing the influence of shearing history and time-dependent structuration. Consequently, the mostly used SEQ measurement protocol demonstrates particularly higher uncertainty in the derived rheological parameter estimates.

4. CONCLUSION

The present investigation focused on two things: The effects of a two-stage mixing process on fresh concrete properties, and assessing measurement protocols for concrete rheometers. A total of four concrete mix designs were used to conduct a comprehensive evaluation across a variety of concrete types. The Mixing Configuration A (MC-A) served as control group utilizing a conventional mixing pattern, while Mixing Configuration B (MC-B) employed the investigated two-stage mixing process involving a suspension mixer for the first stage.

The main conclusions found in this research can be summarized as follows:

- The two-stage suspension mixing process enhances particle dispersion, and improves homogenization of suitable mixes, resulting in higher yield stress and lower plastic viscosity;
- Benefits are strongest in concretes with reactive fines and higher w/b ratios, indicating that the magnitude of the mixing technique effects is related to the constituent materials;
- The Pointwise protocol (PW) provides robustness and higher repeatability than the Sequential protocol (SEQ); SEQ tends to underestimate yield stress and overestimate plastic viscosity due to cumulative shear effects.
- Maintaining a workable material state during suspension mixing requires higher superplasticizer dosages for mix designs containing reactive additives.
- Although MC-B is favorable for certain mix designs, the process necessitates highly trained plant operators.
- Applicability is limited by the w/b ratio: very low w/b mixes are susceptible to premature stiffening due to shear-induced heating and thus unsuitable for the investigated suspension mixing process.

In summary, MC-B improves fresh-state homogeneity and the reliability of rheological characterization for suitable, flowable concretes. The two-stage mixing approach offers practical benefits where process control of admixture dosing is feasible; for low w/b systems, the single-stage configuration remains the better choice.

With respect to rheological parameter estimation, the PW measurement protocol should be preferred over SEQ, as it has been demonstrated to provide enhanced accuracy and replicability of results.

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