Paddle Mixer for Viscoplastic Materials and Pastes

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A modified paddle mixer suitable for the homogenization of viscoplastic fluids and pastes, such as contemporary concrete mixtures, was developed to enhance homogeneity of the product, a crucial step in ensuring desired mechanical properties. In addition to the improvement in flow characteristics, this study presents the basic dimensionless characteristics in regression form, along with the measurement of the Metzner–Otto constant. These characteristics are essential for the use of the paddle mixer as an onsite rheometer, enabling rapid and straightforward evaluation of the desired rheological properties of the prepared mixture.

The performance of the paddle mixer was assessed through homogenization experiments and power input measurements at various rotation speeds. The paddle mixer displayed creeping flow behavior up to a Re value of 50. The geometry of the paddle mixer was modified to achieve homogeneity throughout the volume, significantly influencing mixing mainly in the axial region of the mixer. To compensate for the non-Newtonian behavior, the Metzner–Otto approach was employed. Under creeping flow conditions and for pastes displaying flow index above 0.5, the paddle mixer can be characterized by a Metzner-Otto constant of 54.

Keywords
paddle mixer, concrete, Metzner–Otto, viscoplastic, non-Newtonian, paste

Introduction

Ultra-high performance concrete (UHPC) is a prospective material used in construction. Its mechanical properties (both before and after curing) are highly dependent on the distribution of the reinforcing fibers. Moreover, these suspensions often exhibit non-Newtonian behavior[1]. It was found that UHPC mixtures could be well described using either the Bingham or Herschel–Bulkley model[2]. As reported by Solomon *et al.*[3], these types of fluids tend to form well-agitated caverns surrounding the agitator; however, the remainder of the system is assumed to be stagnant. This should be mitigated by positioning the paddles in such a way as to facilitate fluid transport into and out of the cavern or—even better—to expand the cavern over the entire volume of the vessel. However, the initial configuration of the paddles in an industrial paddle mixer is not optimized to facilitate such transport.

Additionally, it has been reported that the shear stress and mixing time of concrete may influence the rheology and microstructure, depending on the concrete composition[4], as the aggregation and breakage in the paste are significantly affected by the mixing history[5,6]. The added breakage due to mixing may influence the mechanical properties of hardened concrete, such as porosity and compressive strength[7].

Consequently, improper mixing leads to an unequal distribution of particles in a poor-quality concrete mixture. The main objectives of this study were to evaluate and optimize a paddle mixer suitable for homogenizing such suspensions, and to examine its potential for onsite rheological measurements of fine-grained UHPC, as reported by Dostál *et al.*[2], utilizing the Metzner–Otto approach for non-Newtonian fluids[8]. If viable, this could enhance product quality through power input/torque measurement and contribute to a deeper understanding of the basic characteristics and rheology of the mixture (its workability, consistency, and plasticity[1]). This would allow for better quality control of the final product, potentially reducing material usage, enable more advanced designs, and enhance structural safety margins. Moreover, the homogeneity could be assessed without the need for laboratory equipment. This approach appears feasible, given

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that the current method for rapid assessment of the mixing process involves monitoring the hum of the electric motor.

The primary design criterion of optimization was to ensure thorough mixing throughout the batch volume; due to the viscoplastic nature of the suspension, only a small cavern surrounding the impeller was well mixed[9,10]. However, this could be overcome by a suitable geometric configuration of the various paddles, promoting mixing throughout the batch volume, thereby reducing mixing time, and minimizing strain within the system, resulting in better mechanical properties of the cured concrete. Nonetheless, these results need to be confirmed experimentally.

Materials and methods

The geometry of the paddle mixer was derived from an industrial-scale concrete paddle mixer, sized down to laboratory scale. Following an initial round of experiments, the geometry was modified to improve mixing in the axial region. The geometry and basic dimensions of the laboratory-scale paddle mixer are presented in Fig. 1. The paddle mixer featured an outer diameter D of 0.401 m, with the dimensions of the individual paddles listed in Table 1. Changes in the inner most paddle are represented using a wireframe model. The experiments were conducted in a flat-bottomed cylindrical vessel without baffles, possessing an inner diameter

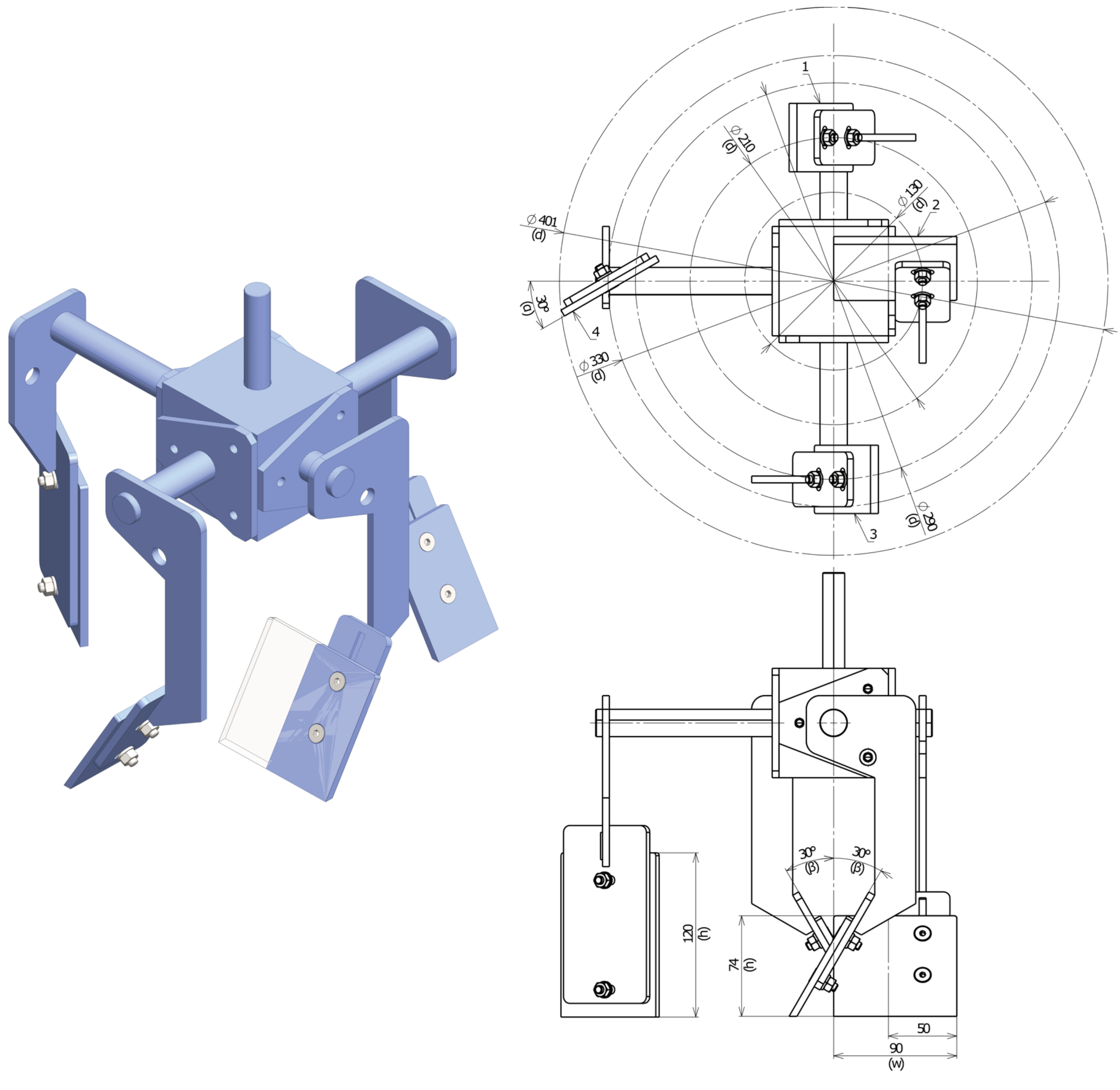

Fig. 1 – *Isometric view of the paddle mixer assembly and sketch with the main dimensions*

of 0.404 m. The bottom edges of the paddles were positioned 2 mm above the bottom of the vessel. A consistent fluid height (0.011 m) was maintained throughout the experiments, resulting in H/T = 0.027.

Firstly, the power characteristics were investigated using axial torque measurements, as suggested in the Handbook of Industrial Mixing[11]. To examine the behavior of the paddle mixer under various flow conditions, model fluids with different apparent viscosities were utilized: diluted glucose syrup (20 %v. water), glycerol (various concentrations, Newtonian), and a 9 % carboxymethyl cellulose (CMC) solution (non-Newtonian). CMC was chosen due to its rheological similarity to UHPC, as reported by Dostál *et al.*[2] The rheological properties of the model fluids are presented in Table 2. The model fluids exhibited both Newtonian and power-law behaviors. For clarity reasons, all results are presented in the style of a power-law fluid. The measurements were conducted using an Anton Paar MCR 102e rotational rheometer with a concentric cylinder system (DIN EN ISO 3219). The rotation speed range varied depending on the model fluid's apparent viscosity, from 4–26 rpm for high apparent viscosity fluids to 16–40 rpm for low apparent viscosity fluids. The upper limit was set by mixing air into the fluid, whereas the lower limit was constrained by torque measurement limitations, where friction from other sources, such as bearings and couplings, exceeded that from the paddles, resulting in imprecise measurement. Fluid temperature was continuously monitored but remained relatively constant throughout the measurements. Subsequently, the viscosity of the model fluid was measured at the experimental temperature using the rotary viscosimeter.

The homogenization experiments employed the starch indicator discoloration method, as described in the Handbook of Industrial Mixing[11]. This method was chosen for its compatibility with various model fluids and the distinct contrast it provides between colored and discolored states. Unfortunately, the iodine solution reacted with the CMC solution; hence, the homogenization experiments were conducted using only glycerol and glucose syrup. The discolored fluid was injected close to the vessel wall, positioned 1 cm below the surface. Discoloration was recorded using time-lapse photography, with images taken every 30 s. This time interval was deemed sufficiently short due to the slow homogenization process. Homogenization time was determined as the number of frames between the injection frame and the frame in which the fluid appeared uniformly colorless, multiplied by the time step. The same rotation speed range was used as for torque measurement. The homogenization experiment was performed at least three times at each rotation speed. Precise water content of the mixtures was not measured directly but was estimated based on the volume of liquid added during the initial setup. To compensate for the change in viscosity resulting from dilution of the model fluid, rheological measurements were conducted at the experimental temperature following each set of experiments.

Finally, a trial run of UHPC production was performed using a mixture with rheological properties as defined by Dostál *et al.*[2] (K = 34 Pa s^m; m = 0.89, same batch as in the article). The ingredients used and their dosages are presented in Table 3. Compared to other similar mixtures, this mixture exhibited very low viscosity, achieved through high

Table 1 – *Geometrical dimensions of the laboratory-scale paddle mixer*

Paddle	d (mm)	h (mm)	w (mm)	α (°deg)	β (°deg)
1	210	74	50	0	30
2	130	74	90 (50)	0	30
3	290	74	50	0	30
4	330	120	80	30	0

Table 2 – *Rheological properties of the model fluids with volume fraction of added water*

Model fluid	K (Pa s^m) ± 0.1	m (–) ± 0.01	T (C°) ± 0.1
power characteristics measurement			
glycerol	1.1	1	16.3
glycerol (25 %v.)	0.7	1	16.4
glycerol (75 %v.)	0.3	1	16.6
glucose syrup (20 %v.)	6.1	1	16.8
CMC 1	4.9	0.80	17.1
CMC 2	6.7	0.78	13.5
homogenization measurement			
glycerol	0.6–1.0	1	12.7–14.4
glucose syrup	5.5–5.9	1	14.6–15.2

Table 3 – *Dosages of the UHPC components used*

Component	Quantity (kg m^{-3})
Silica aggregates with sizes of 0.063–0.63 mm	486 ± 1
Silica aggregates with sizes of 0.63–1.2 mm	739 ± 1
Cem II 52.5 N	700 ± 1
Microsilica	100 ± 1
Fine-grained slag	80 ± 1
Water	210 ± 5
Superplasticizer	40 ± 1

water content; further dilution would render the recipe industrially undesirable. Firstly, the entire production process was tested, beginning with a loose premix powder, to which two-thirds of the water was added, followed by a plasticizer, and then the remaining water. However, at this scale, the agitator struggled with deagglomeration, as the clump size remained the same between the industrial and scaled-down versions, at approximately 40 mm. A run with half the dosage was also tested, but similar issues were encountered. Therefore, a homogenized mixture was prepared in the industrial-scale version, which was then poured into the scaled-down paddle mixer for comparison, as the mixture quality was deemed superior. The rheological behavior of this mixture was subsequently tested using the obtained power characteristics. The results were validated using the methodology described in reference[2] involving measurement with a screw agitator. Only four rotation speeds—4, 5, 6, and 7 rpm—were tested, due to limitations of the torque sensor and motor.

Hydrodynamic characterization of the paddle mixer

The commonly used method for evaluating an agitator involves measuring the characteristics of two dimensionless numbers: the dimensionless homogenization time (*nt*) and the power number (Po) (Eq. (1))[11]. The behavior of these dimensionless numbers is highly dependent on the flow regime within the batch. In the region of the developed turbulent flow, characterized by a high Reynolds number (Re) value (Eq. (2)), both Po and *nt* are assumed to be constant. In contrast, in the creeping flow region (low values of Re), the characteristics of Po usually follow an inverse proportionality defined by Eq. (3), while *nt* is assumed to be again constant but of a different value[11].

$$\mathrm{Po} = \frac{P}{\rho n^3 d^5} \tag{1}$$

$$\mathrm{Re} = \frac{nD^2\rho}{\eta} \tag{2}$$

$$\mathrm{Po} = \frac{A}{\mathrm{Re}} \tag{3}$$

Based on the nature of the tested paddle mixer, the rotation speed, and the viscosity of the tested fluids, predictions were made for creeping and transitional flow regimes. After plotting the measured data in their corresponding dimensionless form, they were visually analyzed, separated into regions of similar tendencies, and fitted with regression functions (Eqs. (4) or (5)). The flow regime was tested between Re values of 10 and 100. These functions were chosen according to the expected flow behavior and the relatively narrow measurement range in which they were deemed sufficiently complex. In the creeping flow region, where homogenization time should be constant, a t-test was applied to its regression to determine if parameter *B* significantly influenced the regression. If parameter *B* was found to be unnecessary, an approximation using the average value was employed.

$$nt = \frac{B}{\mathrm{Re}^C} \tag{4}$$

$$\mathrm{Po} = \frac{B}{\mathrm{Re}^C} \tag{5}$$

However, this evaluation is only suitable for fluids with Newtonian behavior. Metzner and Otto proposed a methodology for non-Newtonian fluids[8]. The method assumes that the effective shear rate is proportional to the rotation speed (Eq. (6)). By applying the power-law model (Eq. (7)) to the definition of the Reynolds number from Eq. (2), a redefined version of the Reynolds number for power-law fluids is established (Eq. (8))

$$\dot{\gamma}_{ef} = kn \tag{6}$$

$$\eta = K\dot{\gamma}_{ef}^{m-1} \tag{7}$$

$$\mathrm{Re}_m = \frac{nD^2\rho}{K(kn)^{m-1}} = \frac{D^2\rho}{Kk^{m-1}n^m} \tag{8}$$

The Metzner-Otto model has undergone extensive scrutiny over the last half-century. For shear thinning fluids, such as UHPC, it has been shown that the constant *k* is often the function of the flow index *m* [12–14], especially for highly shear thinning fluids. However, *k* can be assumed constant over a short interval of *m* or when the fluid exhibits low shear thinning properties[15]. The independence of the constant from the flow index is a widely debated topic, with most sources reporting values between 0.25 and 0.65 [12,14,16,17]. The model has been demonstrated to work well without modifications under creeping flow conditions, while further modifications are necessary to describe the behavior in transitional or turbulent regions[18]. Therefore, in this study, only the creeping flow region was evaluated, with flow indexes limited to values above 0.65. These limitations, however, should not affect most UHPC mixtures, as they exhibit similar behavior to the model fluids. Using a suitable power-number regression based on the measurements of Newtonian fluids, the characteristic agitator constant *k* of the Metzner–Otto model was determined. Thus, the Eq. (9) is derived, which was used to calculate the desired *k* parameter for the individual fluids. A weighted average value from the two tested CMC variants was then used to define the paddle mixer, with a 3 to 1 ratio favoring CMC 2, based on the ratio of the underlying datasets.

$$\mathrm{Po} = \frac{A}{\mathrm{Re}} = \frac{Ak^{m-1}}{\mathrm{Re}_m} \tag{9}$$

This result can subsequently be used to measure the rheological properties of UHPC mixtures, as reported by Dostál *et al.*[2] However, in this study, the low maximal torque allowed by the sensor resulted in an insufficient number of points to reliably measure the characteristics. Consequently, only the apparent viscosity was calculated for measurement validation using Eq. (10).

$$\frac{P}{D^3 A} = \eta n^2 \tag{10}$$

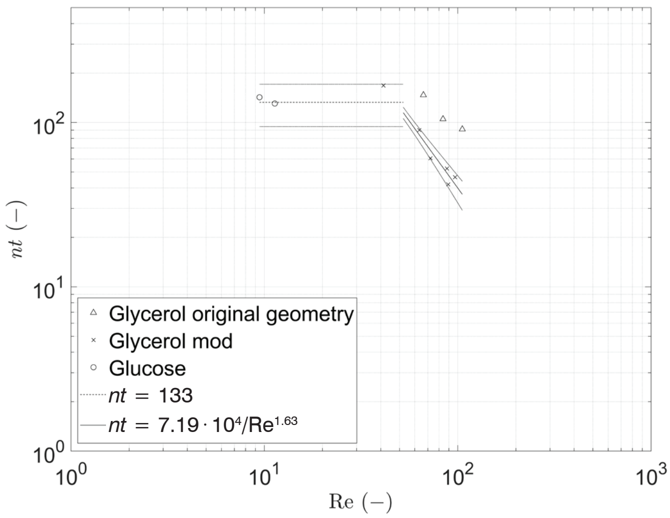

Fig. 2 – *Dimensionless homogenization time characteristics with suggested regressions and a 95 % confidence interval*

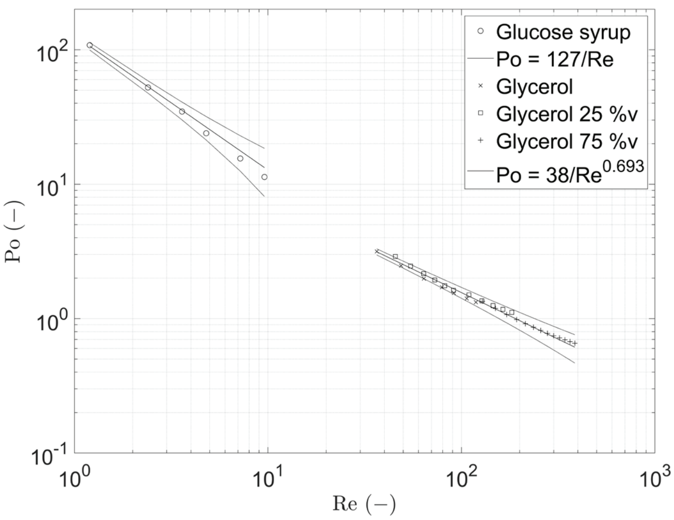

Fig. 3 – *Power number characteristics for Newtonian fluids with suggested regressions and a 95 % confidence interval*

Results and discussion

The homogenization characteristics of the paddle mixer are shown in Fig. 2. It is evident that the change in paddle positioning improved the mixing process, primarily due to enhanced mixing in the axial region, which required several times longer to homogenize compared to the rest of the vessel. Neglecting the axial region, the results with and without a change in the closest paddle did not differ significantly. However, even with this modification, the axial region appeared to be the bottleneck of the homogenization, as it remained the slowest to reach a homogenized state. Furthermore, the figure also suggests that the creeping flow was achieved with a highly viscous fluid; however, the measurement method proved unreliable for such a slow blending process. Out of five different rotation speeds, only two measurements had repeated results within 5 % of the average value. Regarding the homogenization process, the majority of micromixing occurred in the wake of the outermost paddle, as it created the most instabilities in the flow. The remaining paddles facilitated fluid transport between the mixed regions. This was confirmed during UHPC production attempts, where the system could mix dry particulates but struggled to homogenize the batch when liquids were added. This was mainly because the clumps did not scale with the system; their dimensions remained similar between the industrial and scaled-down versions, with diameters of 40 mm. At the scaled-down level, only the outermost paddle was capable of slow deagglomeration. However, this result does not necessarily reflect the mixer's capabilities; rather, it highlights the challenges encountered when dealing with concrete at this scaled-down size.

The power measurement and resulting power-number characteristics of the Newtonian fluids are presented in Fig. 3, revealing two distinct flow regimes. It appears that mixing of glucose syrup was fully conducted under creeping flow, while mixing with glycerol solutions exhibited a slight level of turbulence. The shift appeared to occur at Re value of approximately 50, corresponding to the beginning of the transition section observed during homogenization. Based on the observed trend in these two figures for the presented paddle mixer, creeping flow behavior can be expected below a Re value of 50, aligning with similar behavior observed in helical ribbon agitators by Novák and Rieger[19]. The non-Newtonian power-number characteristics are shown in Fig. 4. The obtained results can be effectively described using equation (9) from which the two Metzner-Otto constants can be calculated. However, it is important to note that this value is heavily influenced by the precision of the flow in-

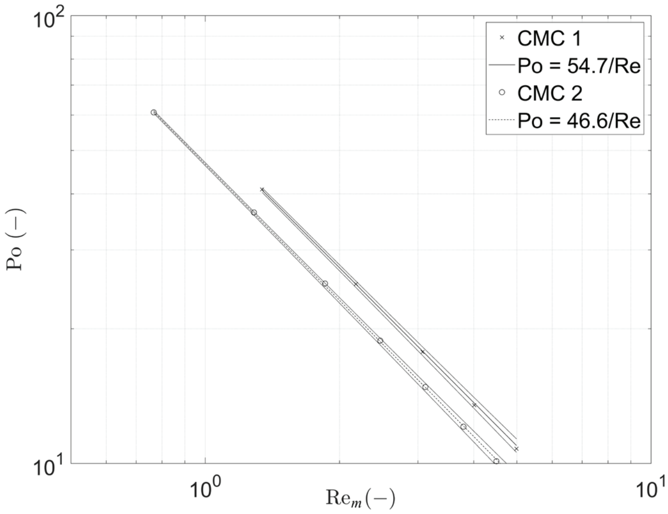

Fig. 4 – *Plot of non-Newtonian results obtained using the Metzner-Otto approach with suggested regressions and a 95 % confidence interval*

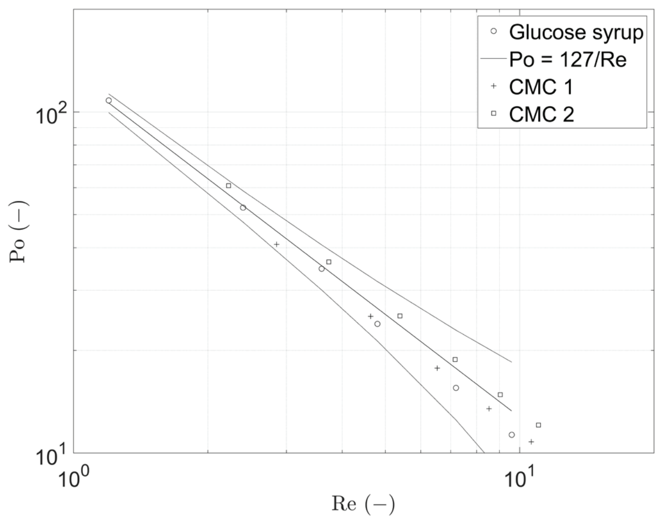

Fig. 5 – *Comparison of the non-Newtonian and Newtonian power number results, converted using the obtained Metzner-Otto constant*

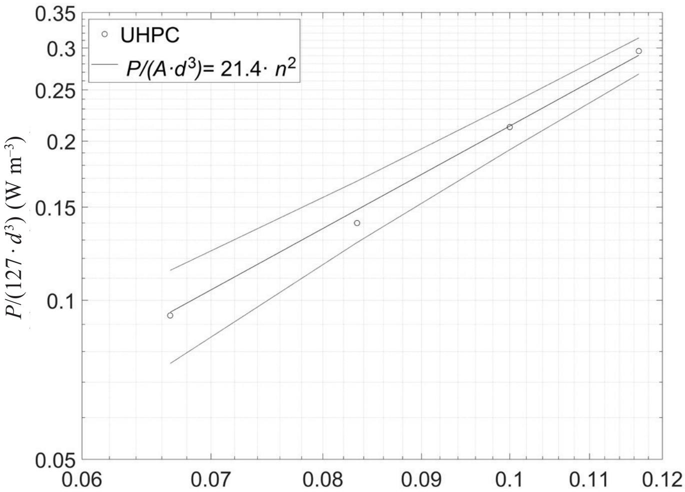

Fig. 6 – *Result of the test measurement of the real UHPC mixture (both axes in logarithmic scale)*

Table 4 – *Metzner–Otto constants published for similar agitators*

Agitator type	Constant k	Ref.
Paddle mixer	54 ± 12	This article
Screw	17–77	13,20
Helical ribbon	16–38	21,22
Anchor	25–30	16
Planetary mixer	6.6	23

dex *m,* and constrained by the underlying theory for values $m > 0.65$. To confirm that the obtained Metzner-Otto constants yield reliable results, a comparison is presented in Fig. 5. For this comparison, the non-Newtonian results were converted to their Newtonian equivalents and plotted alongside the results obtained with the Newtonian model fluids. The two datasets appeared to correspond quite well, suggesting that, at least for the given range of flow indexes and Re values below 50, the Metzner-Otto methodology produced reliable results. The mean value of the Metzner–Otto constant k is presented in Table 4, along with results from other authors for low-speed agitators. The constant appears to be of the expected order, with its value slightly exceeding that of other agitators used for mixing similarly viscous fluids. Further comparison is more challenging due to the vast difference in geometry. Typically, slow-speed agitators such as helical ribbons or screw agitators have $H/T \sim 1$, which is markedly different from the 0.027 present in our paddle mixer. However, no similar paddle mixer with a known Metzner-Otto constant was found in the literature. We believe that the high value of the measured constant can be attributed to the larger dimensions of the paddle mixer, along with the more complex geometry and larger surface area of the blades compared to other slow-speed agitators.

As mentioned previously, due to the limited torque range of both the motor and the sensor installed on the stand, only a few points were measured during the UHPC test; hence, a simple Newtonian fit was used (Eq. (10)). The regression is presented on a logarithmic scale in Fig. 6. The resulting apparent viscosity was 21.4 Pa s, which is reasonably close to the value of 22.3 Pa s obtained through measurement with a screw agitator using the methodology established by Dostál *et al.*[2] This result highlights the potential benefit of our findings, indicating that using predefined characteristics of the paddle mixer, the quality of the prepared mixture can be assessed in real time without the necessity of using external measuring tools or changing agitator geometry. However, compared to other well-established agitator types, a broader test of reliability measurements is necessary. It seems preferable to conduct these experiments on the industrial-scale mixer due to the problematic behavior of UHPC mixtures at the laboratory scale.

Conclusion

This study has demonstrated that the paddle mixer can be effectively characterized by the dimensionless homogenization time and power number, and that its behavior aligns well with established theory. Additionally, the Metzner–Otto approach for non-Newtonian fluids appears to be suitable for this type of agitator.

Regarding the homogenization process, it was observed that the majority of mixing occurred in the wake of the outermost paddle, while the remaining paddles facilitated fluid exchange between the mixed regions. Thus, enhancements in paddle geometry should aim to facilitate faster fluid exchange between these regions. However, this is suboptimal, as more efficient mixing could be achieved if all paddles contributed to the homogenization process.

The most significant finding of this study is that generic paddle mixers can be utilized for onsite rheological measurements using only simple power input and speed of rotation measurements. These measurements are straightforward and cost-effective to implement, requiring minimal expertise to operate. Through such measurements, the desired properties of UHPC used in construction applications can be explored with a reasonable degree of accuracy, replacing time-consuming rheological measurements typically performed in a laboratory. Moreover, this method appears to enhance the overall quality of the prepared mixtures, while also allowing for the prediction of the amount of energy or strain introduced into the mixture, factors often related to the quality of the cured concrete.

Nomenclature

A – agitator Po constant in the creep region, –
B – fitting parameter, –
C – fitting parameter, –
d – rotation diameter of centers of individual paddles, mm
D – outer diameter of the paddle mixer, m
h – height of individual paddles, mm
H – height of the fluid, m
k – Metzner–Otto constant, –
K – flow consistency index, Pa s^m
m – flow behavior index, –
n – impeller revolutions per second, s^{-1}
nt – dimensionless blending time, –
P – torque power input, W
Po – dimensionless power number, –
Re – dimensionless Reynolds number, –
Re_m – dimensionless Reynolds number for non-Newtonian fluids, –
t – time, s
T – diameter of the vessel, m
w – width of individual paddles, mm
α – radial angle of individual paddles, °deg
β – axial angle of individual paddles, °deg
$\dot{\gamma}$ – shear rate, s^{-1}
η – apparent viscosity, Pa s
ρ – density, kg m^{-3}

Abbreviations

CMC – carboxymethyl cellulose
UHPC – ultra-high performance concrete

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