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Mixing of concrete or mortars: Distributive aspects

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ABSTRACT

This article describes an experimental methodology offering efficiency criteria for granular materials in terms of their mixing distributive capability. The methodology is based on analyzing the distribution kinetics of colored tracer particles which were demonstrated to respond similar to cement particles during mixing. The effect of certain critical parameters such as the mixer type, the volume and the mixer speed are investigated. The influence of mix design characteristics on distribution is also presented for several mixer types. Finally, a comparison of the dispersive versus the distributive capability is achieved for several (mixer, mix design) systems, which opens opportunities for defining rules for transfer and extrapolation.

1. Introduction

The final properties of mortars and concretes are strongly affected by the quality of mixing. The quality of mixing can be divided into two main phenomena, they are: dispersion and distribution.

The dispersive task deals with the rupture of the transient particle aggregates generally formed, in the very first moments after the water addition, by the capillary forces. Distribution, on the other hand, relates directly to the homogeneity of the final product and corresponds to the ability of the mixer to spread all the particles within the product.

Dispersion has not been extensively studied for granular material and virtually no literature exists for concretes and mortars until the authors of the present paper recently presented techniques to characterize the dispersion capability of mixer/mix design sets [1]. They proposed an experimental methodology incorporating mixing efficiency criteria for granular materials in terms of their dispersion capability. This methodology is based on the analysis of the dispersion kinetics of colored, cohesive, tracer particles that progressively de-agglomerated while mixing. There is slightly more literature on distribution compared to dispersion because distribution was perceived as the most important phenomenon attributing to the material reaching its ultimate level of homogeneity in the mixing vessel. However, it is essential to note that one can distribute only what has dispersed thus, distribution and dispersion are complementary and mixing is efficient only when both processes are efficient.

In previous studies, the quality of the distribution process was evaluated through homogeneity characterization. This was measured either by evaluating the variability of the concrete composition, a very tedious task, or by observing the variations on the dependent macroscopic properties of the concrete (strength, rheological characteristics, etc...). Charonnat [2] defines the efficiency of a mixer as its capability to "uniformly distribute all its constituents in the container without favoring one or the other". Some authors [3–4] have described similar approaches, but all have also expressed concerns about the relevancy of sampling, which was extensively studied by Robin [5]. Concrete standards, such as EN-206, also provide some very basic guidelines about homogeneity. It indicates that mixing of the concrete constituents must be achieved in "compliant" mixers, and pursued until "a homogeneous aspect of the concrete is reached". In ready-mix batch plants, concrete is assumed to be homogeneous; whereas, the concrete homogeneity must be verified in field applications and controlled by means of specific procedures. If concretes homogeneity can be proven, then mixing time can be reduced; therefore, the interest of developing mixing efficiency indicators pertaining to concrete homogeneity is industrially attractive. However, assumptions between product homogeneity and the stabilization of continuously measured values are often made at the batch plant. The most often measured value is the electrical wattmeter signal (extensively studied by Chopin [6]), despite the lack of an explicit proven link between signal stabilization and concrete homogeneity.

The current study is aimed at developing a "rapid" technique enabling us to characterize the efficiency of the distributive process during mixing of granular material such as mortars or concretes. It is important to stress that this is different from characterizing the mixing efficiency directly by analyzing the final granular composition of the material throughout the mixing vessel. Clearly, the efficiency of the distribution process is particle size dependent. The distribution of the finest elements of the mix design is more difficult and longer to achieve than the distribution of the largest particles [3]. For this reason, characterizing the ultimate distribution capability of the (mixer, mix design) set is only possible through the development of methods that trace the fine particles of the mix design. In the proposed approach, small colored non-cohesive particles are considered tracers of the cement particles and the evolution of the color

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homogeneity versus the mixing time is used to easily characterize the distributive capability of the system.

2. Methodology development

2.1. Principle

2.1.1. General methodology

The methodology developed for the evaluation of the *distributive* capability of (mixer, mix design) sets is based on the addition of a minor amount of colored particles. These tracers of the smallest elements of the mix design are assumed to behave similar to the powders present in the concrete or mortar. The spreading of the particles in the bulk concrete is thus measured versus time by means of colorimetric analysis performed on small samples extracted at different locations within the mixer. The tracer of choice is a red iron oxide pigment powder by Bayer (synthesized by Lanxess®), referenced as Bayferrox 110P. Its main characteristics are both to have the same mean size as the mean cement particle size and to be virtually non cohesive. It is note worthy that the study of the *dispersive* capability of the (mixer, mix design) system [1] was achieved by means of a cohesive iron oxide pigment (Bayferrox 110G) produced by granulation of 110P particles. Thus, the former dispersive study and the present distributive study are very consistent with each other. The color parameter a^* of the CIE Lab system is used to accurately characterize the red color of each sample.

The ratio of 110P particles added to the mix is typically 0.8% of the total mass of cement particles in the mix design. This value could have been lowered because it is mainly based on the analytical capability of the colorimeter. However, it should generally remain in the range (0.4%–1.0%), which was proven to have a negligible effect on the rheological characteristics of the mix design. The selected amount of colored powder was added at a single given position on top of the free surface of the mix, right after the addition of water but prior to mixing. This position depends on the type of mixer and although this is generally not critical, it must ideally be the same position for all the experiments performed with the same mixer. After the addition of the tracer, mixing would resume for a predetermined duration and after which mixing would stop in order to achieve the sampling protocol.

The ideal characterization of the heterogeneousness of the material in the mixer can be determined by the evaluation of the so-called "segregation" [6] which covers two concepts. The *intensity* of segregation characterizes the magnitude of the heterogeneity in the mixer, whereas the *scale* of segregation is an indicator of how heterogeneity is spatially structured in the mixer. If it is possible to obtain the intensity of segregation by means of statistical data processing, it is much more difficult to obtain the scale of segregation, since the latter would require a precise location of where the samples were withdrawn from within the mixer. Moreover, since the link between the scale of segregation and the physical causes is difficult to achieve, the present study exclusively focused on determining the intensity of segregation as a means to describe the heterogeneity of the concrete mix.

A "true" measurement of heterogeneity is not possible due to the statistical bias induced by sampling. The number of samples and their size with respect to the concrete volume are critical factors for the relevancy of the whole analysis. The estimation of the mixture's heterogeneity ideally requires the extrapolation of "measured" values of the mean and variance from the examined properties (a^*) in order to obtain estimations of the "true" values of the mean and of the variance. In addition, since it is based on a sampling process, the notion of heterogeneity is not univocal and intrinsic to the state of a material submitted to mixing. It must be associated with characteristic scales.

If N is the number of samples, V_T the total volume of the mixer, and V_e the volume of one sample, we can define the different characteristic scales of the problem:

- The observation scale V_0, simply defined as $V_0 = V_e$
- The heterogeneity scale V_h, defined by the ratio $V_h = V_T/N$
- The tracer scale V_t, defined as the mean volume of the tracer particles

Typically, the tracer scale must be much lower than the observation scale; otherwise the analytical variability becomes significantly high. However, this is not a significant issue since the tracer particle size is very small. Ideally, $V_0 = V_h$, which would indicate that the total volume of concrete or mortar would be analyzed after splitting into equal sub-volume samples. Although such experiments are exceptionally described in literature [4], this would be unrealistic on a daily basis if the experimental productivity was a concern. V_h must ideally be lowered in order to evaluate the heterogeneity at the smallest possible scale. Lowering the V_h would increase the total number of samples N, thus increasing the cost associated with the analytical protocol. The comparison between the observation scale and the heterogeneity scale indicates how accurately each sample characterizes a sub-volume of the mixer. Since V_0 by definition represents the volume of the minimum accessible heterogeneity, it would also always be equal to or lower than V_h. Therefore, the material heterogeneity is only estimated at the scale V_h and the *precision* of heterogeneity (at the minimum scale V_h) is an increasing function of the ratio between V_h and V_0. It is thus important to analyze a sufficient number as well as a large quantity of samples. If the size of the sample is imposed by the analytical tools, then the choice on the number of samples remains undetermined.

Statistical values can be described for a^*. If p is the *true* mean and μ the *measured* mean then:

$$p = \frac{1}{V_T}\int_V a^*(V)dV, \tag{1}$$

p cannot be directly determined by using a sampling procedure, whereas the measured mean can be easily extracted from the experimental set of data a^*_i:

$$\mu = \frac{1}{N}\sum_{i=1}^{N} a_i^* \tag{2}$$

The *true* variance is:

$$\sigma^2 = \frac{1}{V_T}\int_V \left(a^*(V) - p\right)^2 dV \tag{3}$$

For the same number of samples N randomly "distributed" in the material, the *measured* variance S^2 is:

$$S^2 = \frac{1}{(N-1)}\sum_{i=1}^{N}\left(a_i^* - \mu\right)^2. \tag{4}$$

The total experimental variance is the addition of all the variances involved in the processes:

$$S^2 = S_M^2 + S_A^2 + S_S^2 \tag{5}$$

where:

S^2 is the experimentally measured variance,
S_M^2 is the mixing induced variance,
S_A^2 is the analytical variance,
S_S^2 is the sampling induced variance,
S_M^2 is the variance of interest. For a^* the analytical errors are small because the colorimetric analysis is precise and accurate, hence S_A^2 can be neglected as an initial approximation. Regarding the sampling induced variance S_S^2, it is quite difficult to estimate because it is not only a function of the sampling procedures but also an increasing function of the level of heterogeneity in the medium under investigation.

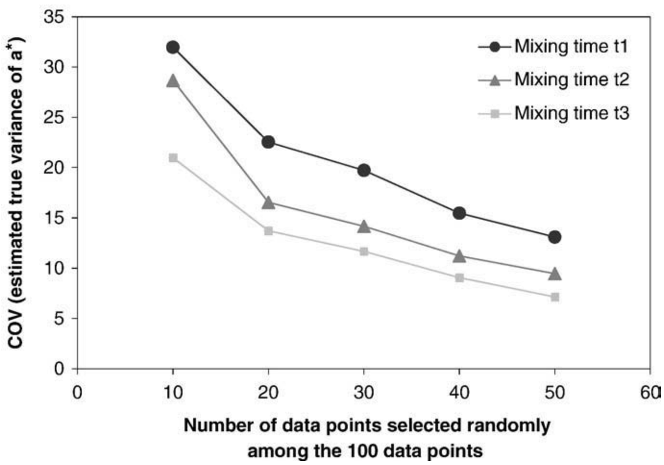

Fig. 1. Evolution of the coefficient of variation of the estimated true variance as a function of the number of data points selected randomly among 100 experimental data points. Each curve corresponds to a series of measurements at a given mixing time.

In order to gain an understanding of how the experimental sampling affects the statistical results, a series of experiments were conducted in a 50 L mixer with 100 experimental data point samples (sample $=3$ ml). These samples were obtained at several different mixing times. The data were processed subsequently, as if less than 100 data point had been generated. A hundred samples of the desired number of data points (between 10 and 50) selected randomly among the 100 data point were statistically treated and the coefficient of variation of the estimated true variance was calculated. A well-known Student correction which takes into account both the number of samples and the confidence level x% is applied according to the number of processed data point:

$$F_{\mathrm{m}} = \frac{(N-1)}{\chi^2(x\%)} \tag{6}$$

where $\chi^2(x\%)$ is the value of the Khi-2 test for a confidence level of x%.

F_{m} is the factor by which we have to multiply the measured variance S^2 to obtain an estimate of the true variance σ^2 with a level of confidence of x %. It appears from the analysis that the reduction in the number of points treated leads to a rapid deterioration in the quality of the true variance estimation. Fig. 1 exemplifies this effect for the experimental conditions typical of our study. Making the rather crude assumption that, with $N=100$, the true variance is correctly evaluated by the Student correction of the Eq. (6) applied to the experimental variance, it can be observed, even for a relatively low confidence level of only 1 sigma ($x\%\approx 66\%$), that using less than 50 data point provides an additional degradation of quality in the evaluation of the true variance by more than 5%, which increases to 15% for 20 data points. Therefore, a sampling strategy using less than 50 points does not appear relevant for determining heterogeneity and 100 data point is preferred whenever possible.

In this study, we are interested mainly by the temporal evolution of the heterogeneity in the mixer using different experimental conditions. Since the mean value of a^* may also vary with time, a straightforward comparison of the variances or of the standard deviations is poorly adapted and it is preferable to characterize heterogeneity simply by the coefficients of variation (COV) on a^* defined as:

$$\mathrm{COV}(a^*) = \frac{S}{m} = \frac{\sqrt{\dfrac{\sum_{i=1}^{N}\left(a_i^* - \bar{a}^*\right)^2}{(N-1)}}}{\sum_{i=1}^{N} a^*}, \text{with} \geq 50 \tag{7}$$

For those values of N equal or larger than 50, the Student correction is negligible and not taken into account in Eq. (7).

2.2. Experimental protocol

2.2.1. Preparation protocol

For all the experiments, the mixing protocol at the laboratory scale was as follow:

(1) Pre-wet the sand and the gravel in a drum mixer 1 day before making the mix, so that the aggregates are completely saturated (The water quantity is 5% of the sand weight and 2% of the gravel).
(2) Introduce the gravel, followed by the sand, and finally the hydraulic binders (cement or mineral additives) into the mixer.
(3) Add the rest of the water (total water − water absorbed by the aggregates) within 10 s, while mixing at nominal speed.
(4) Stop the mixer and add the pigment powder by placing it at a single position on top of the free surface of the mix (pigment amount is 0.8% of the binders mass).
(5) Resume mixing at nominal speed and mix for a variable time depending on the evolution of the colors standard deviation.
(6) Complete the sampling and analytical protocol.

This operation is reproduced for each mixing time to obtain the evolution of COV verse concrete mixing time.

2.2.2. Analytical protocol

The parameter a^* of the CIE Lab system is used to characterize the red color of each sample. A more detailed explanation of how the red color is measured is found in [1]. In this study, it is only important to note that:

(1) At least 50 samples of mixed concrete were collected within the mixer at different random locations. The samples were taken after the mixer was stopped and at a specific mixing times.
(2) Each sample is then poured in a cylindrical transparent cell. The diameter of the cell is 2 cm and the height is 1 cm.
(3) The color is analyzed by the use of a colorimeter (Spectro-color Dr Lange $d/8°$ ∅10 mm).
(4) The 50 a^* values obtained from the specific mixing times were directly recorded and are used to obtain the coefficient of variation of the red color COV(a^*).

2.3. Performance of the methodology

A typical evolution of the COV(a^*) versus the mixing time is shown Fig. 2 for a standard C25 concrete prepared in a 30 L mixer (CM3, mixer concept described in Table 5 of Appendix B).

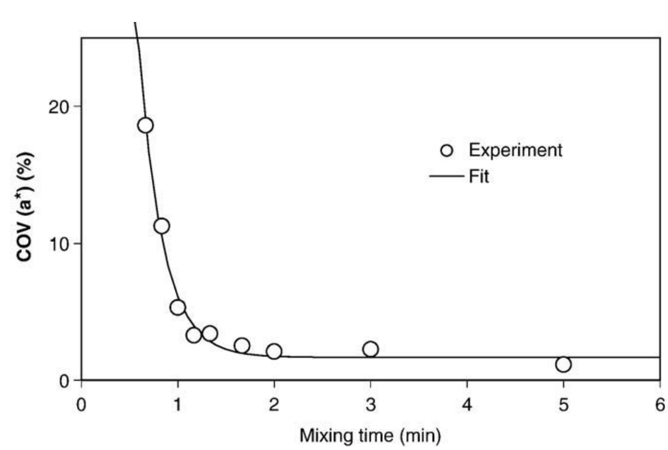

Fig. 2. Evolution of the coefficient of variation of the red color COV(a^*) vs mixing time. CM3 mixer, 20 L, 55 rpm, 0.8% 110P particles, C25/30 concrete. Mix design: mixture#1.

COV can be fitted by an exponential curve, which is consistent with the logarithmic variation of heterogeneity that is often found in literature [5].

$$\mathrm{COV}(a_t^*) = A + (B - A) \times \exp(-k \times t) \quad (8)$$

A and B are two constants which have no physical meaning for distribution since they characterize respectively the final and the initial values of COV. The initial value of COV is very high but meaningless, because it strongly depends on the way the powder is spread on the mixture's surface. COV decreases rapidly with time and reaches a plateau within moments, indicating the maximum level of distribution of the fine elements. The value of this plateau is never null and remains typically within the 1–3% range at very long times, despite a supposed perfect distribution. This is largely due to the sampling effects.

k is a constant from which a characteristic distribution time t_D can be determined:

$$k = 1 / t_D \quad (9)$$

Low t_D values indicate a greater efficiency in mixing in terms of distribution.

Reproducibility of the technique was examined. The conditions of Fig. 2 were repeated 8 times. Table 1 depicts the corresponding distribution times. Based on this set of experiments, the precision on determining the t_D values can be estimated to approximately 7% for a 1-sigma confidence level (68%) and close to 16% for a higher level of confidence (2-sigma = 95%). Obviously, this level would be reduced with shorter time intervals between each series of samples.

The companion study on the dispersive aspects of mixing [1] was done with a cohesive red tracer 110G, which is a granulated version of the tracer 110P used in the present study. Due to the fact that the characteristic dispersion times of the tracer 110 G are much larger than the characteristic distribution times of the tracer 110P, the possibility of using 110 G instead of 110P for both studies was experimentally demonstrated. In this situation, only one single experiment could be made for both characterizations; dispersion and distribution would take place simultaneously but at different kinetics. This would indicate that the mean value of a^* would increase with time, whereas COV(a^*) would be similar for cohesive or non cohesive powders.

Grey cement itself could occasionally be used instead of the pigment 110P for the distribution characterization study, providing the luminance L^* replaces the red color a^* used in CIE Lab system. However, since there are significantly minor differences in luminance at different times with cements, the method cannot be universally used. This is also mainly a means to validate that the proposed technique developed with the red tracer particles simulates the behavior of the cement particles during the mixing process. Fig. 3 displays side by side a^* for the 110P tracer and L^* for the cement particles. The similarity between the two curves and between the extracted characteristic times (respectively 2.2 min and 2.3 min) clearly demonstrates the capability of the 110P particles to mimic the behavior of the cement particles during distributive mixing.

Table 1
Reproducibility of the color kinetics method, based on the evaluation of the characteristic time t_D (in minutes).

Experiment	1	2	3	4	5	6	7	8
t_D (minutes)	0.45	0.50	0.47	0.54	0.50	0.45	0.50	0.52
Mean value: 0.49 Standard deviation: 0.03								

Mixer CM3, 20 L, 55 rpm, 0.8% 110P particles, C25/30 concrete. Mix design: mixture#1, described in Appendix A.

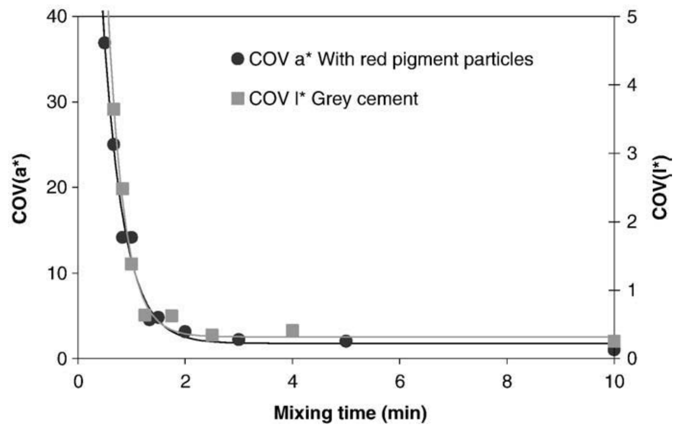

Fig. 3. Comparison between kinetics obtained with 110P pigment or with grey cement. CM1 mixer, 80 L, 30 rpm, C25/30 concrete (the continuous lines correspond to best fits). Mix design: mixture#1.

3. Experimental results

We used the methodology previously described to compare the mixing efficiency of (mixer, mix design) sets with respect to the distributive aspects. The first part is dedicated to the effects of process characteristics including the mixer geometry, mixer volume and mixer speed on the distributive performance of the same standard concrete mix design. The second part deals with changes in the mix design with a single mixer type. We eventually present some results benchmarking the dispersive and the distributive behaviors for some of the concrete formulas conventionally produced in the industry.

3.1. Influence of the process characteristics

3.1.1. Effect of the mixer's design

Fig. 4 depicts the influence of the type of mixer on the distribution kinetics curves of standard concrete mix design. Drum mixers, planetary motion mixers, and pan mixers are considered in this study. The mixing strategy for each mixer is described in detail in Appendix B. Included within the experiments of Fig. 4 are two mixes performed with the same mixer (CM1), but with varying mixing speeds. To summarize the results, the characteristic times were

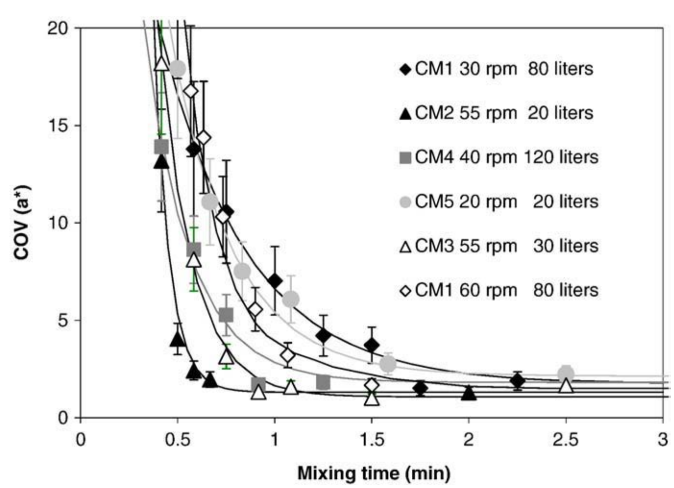

Fig. 4. Influence of the concrete mixer (the continuous lines correspond to best fits). Mix design: mixture#1.

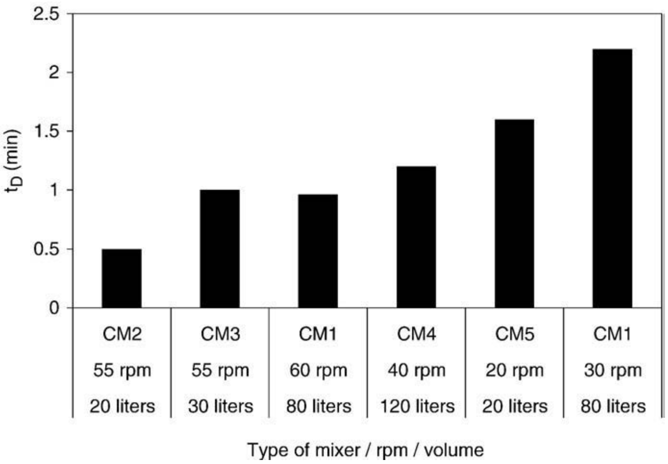

Fig. 5. Influence of the type of concrete mixer: comparison of the distribution times in several conditions (the first row in the *x*-axis legend corresponds to the type of mixer, the second to the mixer's speed, and the third to the mixed volume). Mix design: mixture#1.

extracted from the results of Fig. 4 and displayed in Fig. 5. They clearly show that the differences between mixer efficiency are quite noticeable. In a conventional use, the drum mixer CM5 is the less efficient mixer; whereas, the pan mixers CM2 and CM3 were the most efficient. The CM1 mixer was the only mixer of our panel for which the mixing speed can be adjusted. We observed that the higher the mixing speed, the faster the maximum distribution level is reached. These results can be used to provide some rules for transfer or extrapolation in order to maintain the same level of distribution in materials prepared with different equipment. Transferring a concrete formula from mixer1 to mixer2 simply requires an adaptation of mixing times. If t_{m1} is the *minimal* mixing time required for obtaining a well-distributed concrete with the reference mixer, the *minimal* time t_{m2} to do the same with another mixer is thus simply:

$$t_{m2} = t_{m1}(t_{D2} / t_{D1}) \tag{10}$$

3.1.2. Effect of the mixer volume

All mixers do not necessarily use the same operational volume; it depends on the mix design. The influence of the material's volume to be mixed on the distributive capability of the mixer is generally not known. For the sake of exemplification, we achieved such a study on the single drum mixer. The drum mixer was set to rotate at 20 rpm for 3 experiments consisting of 20, 30 and 40 L. The characteristic distribution times of Fig. 6 demonstrates the significant impact of the volume on distribution; the lower the volume, the faster the

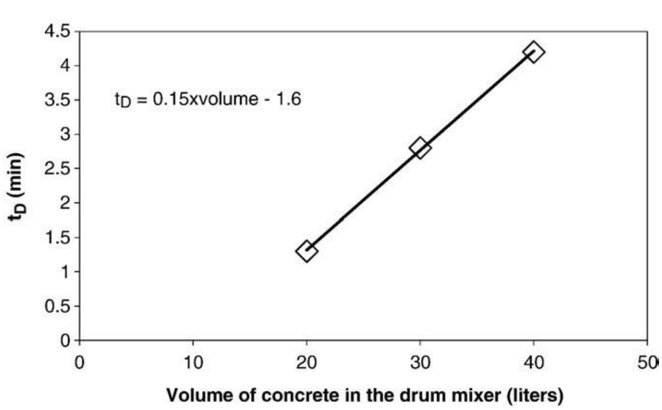

Fig. 6. Influence of the filling factor of the drum mixer CM5: comparison of the characteristic distribution times for different volumes of mixed concrete. Mix design: mixture#1.

distribution. As for the mixer type, the adaptation of the minimal mixing times to different volumes can be done with the same rule as the one of Eq. (10). The rate of evolution of the mixing time is typically 0.15 min/L for the drum mixer. In other words, changing the concrete volume by ±1 L requires the minimal mixing time to vary by ±9 s in order to maintain a constant distributive efficiency. This is very significant with respect to the mean mixing times. It is not the scope of the present study to describe the volume effect for any mixer, but this value of the slope is obviously mixer dependent.

3.1.3. Effect of the mixer speed

It is consistently observed that increasing the mixer speed is beneficial in regard to the distribution efficiency of all mixer types. However, we anticipate that the speed itself is not necessarily the critical parameter because using higher speeds would imply a greater number of revolutions within the same time span. It is therefore interesting to determine whether the material deformation n_t or the number of rounds, defined as:

$$n_t = t_m \, x \, \Omega \tag{11}$$

is the factor controlling the distribution efficiency. To validate this point, similar experiments were achieved at different rotational speeds and the characteristic color kinetic curves were expressed not only versus the mixer speed but also versus the deformation. The curves in Fig. 7a and b were achieved with the counter-current, planetary motion mixer CM1. These experimental curves are not in sync when rpm is on the *x*-axis, but they become very similar when deformation n_t is on the *x*-axis. In addition, the graph linking the

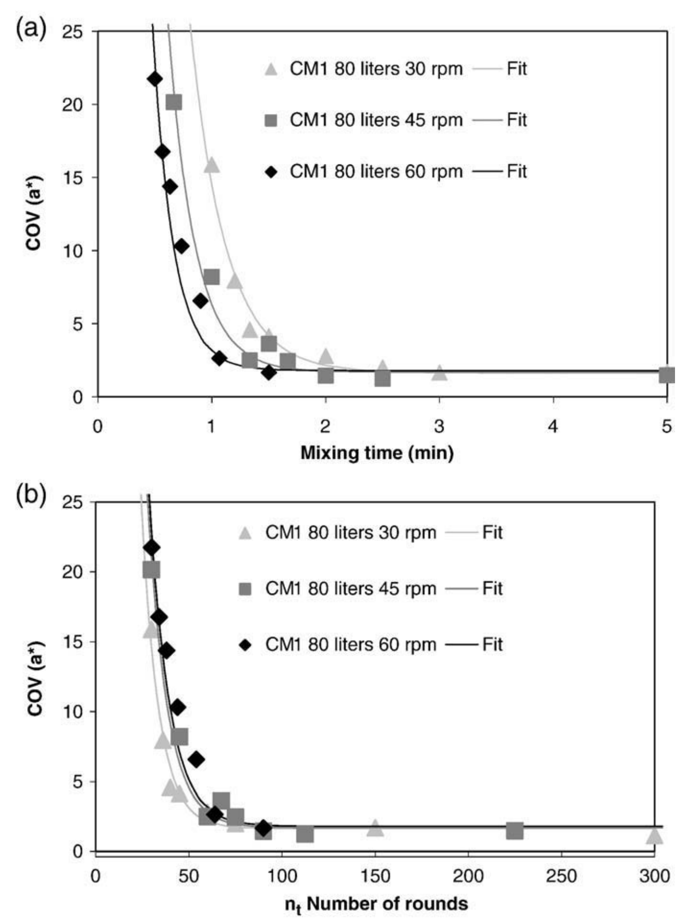

Fig. 7. a and b Effect of the mixer rotation speed on COV(a^*) (CM1 mixer, 80 L). Mix design: mixture#1. (a) COV(a^*) versus time for three mixer speeds (30, 45 and 60 rpm). (b) COV(a^*) versus deformation for three mixer speeds (30, 45 and 60 rpm).

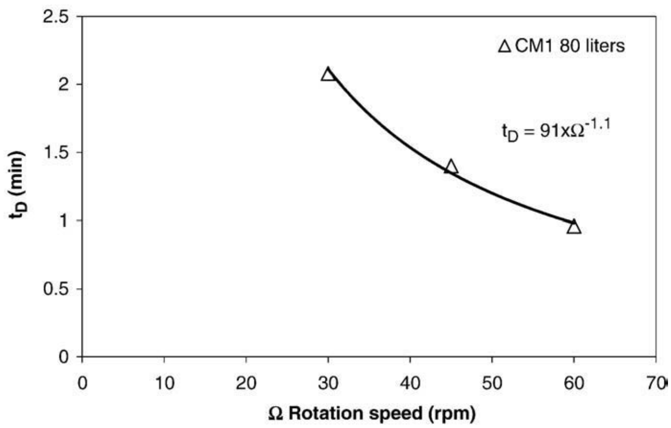

Fig. 8. Distribution times versus rotation speed. CM1 mixer, 80 L. Mix design: mixture #1.

characteristic times t_D, obtained from processing Fig. 7-a and the mixer speeds in Fig. 8, demonstrates a simple relationship. If D is a constant:

$$t_D \propto \frac{D}{\Omega^\beta}, \tag{12}$$

For the CM1 mixer, β is equal to 1.1 and therefore close to 1. This illustrates that the product $t_D \times \Omega$, which is equivalent to a deformation, must remain roughly constant in order to ensure that an identical distributive performance will be obtained at different speeds. Thanks to Fig. 8, we can extract that the value of the constant $D \approx 90$. This corresponds to the minimum number of rotations required to distribute efficiently the fine elements of the concrete, whatever the rotational speed. This value of D is mixer dependent and could increase or decrease depending on the efficiency of the mixer: the lower the value of D, the more efficient the mixer.

Deformation thus appears to be the key variable on the distribution function of each mixer and the effect of speed is almost exclusively associated to the number of rotations imposed on the concrete. In other words, it is possible to directly compensate for lower mixing speeds by increasing the mixing time or vice-versa.

3.2. Influence of the mix design

In order to determine the influence of the mix design, one mixer was selected and used to reduce any variability caused by the mixer. Therefore, the mixing conditions were essentially identical, including the mixing speed and the mix volume. While maintaining a basic reference mix design (C25), the composition of the mix design was varied in order to evaluate the role of: large aggregates; the quantity of water; and the compactness of the granular composition on the distributive capability of the mixer.

3.2.1. Effect of the large aggregates

Concrete and its equivalent mortar were both produced in the same mixer under the same operating conditions. The occasional possibility to use mortar instead of concrete was developed by the concrete industry in order to predict the rheological behavior of concrete and more specifically to detect the cement/admixture incompatibility without the need of making concrete. The formulation for the mortar was developed using a concrete mix design while maintaining the water/cement ratio and the developed surface of the aggregates.

The distribution times were evaluated for both concrete and mortar (Table 2)

Table 2 clearly highlights the significant impact of the largest particles on the distribution kinetics. It can also be induced that even the relatively large particles such as gravel (4/10 mm) or sand (0/4 mm) are not as highly efficient at distribution as larger gravels (10/20 mm). This aspect was not expected with distribution and would be more intuitive and could be experimentally confirmed for dispersion. Despite that the exact physical phenomena are not well-known, arguments related to the possibility that the local and intense, but highly unsteady, deformations brought to the intergranulate paste by the larger aggregates have greater significance to distribution than the mean deformation brought to the paste by the mixer.

Table 2
Comparison of the characteristic distribution times for concrete (mixture#1) and its equivalent mortar (mixture#4).

	Mortar	Concrete
t_D (minutes)	4.2	0.5

3.2.2. Effect of water

Intuitively, higher water contents contribute to a faster distribution of the finest elements. Three concretes were prepared at different W/C ratios (0.45, 0.60 and 0.80) with the mixer CM1 operating at 30 rpm. The strategy to determine the effect of water on the distribution was to maintain a constant quantity of cement while increasing the water quantity and adjusting the volume to 1 m^3 by reducing the quantity of sand and aggregates. The relationship between the distribution times and the W/C ratio is shown Table 3.

The experiments confirm intuition. The increase in the quantity of water causes a clear reduction of distribution time. More water means larger interparticulate distance and lower paste viscosity, which are both favorable for a "circulation" of the smaller particles.

3.2.3. Effect of the mix maximum packing fraction

Only some experiments were achieved with a binary mixture of glass beads of 66 µm and 648 µm immersed in a glucose solution. This was done to approximately determine the effect of the aggregate compactness within the mix. The solution's concentration was adjusted to mimic the viscous characteristics of a concrete paste. The mixer was a standard 1 L planetary mixer (MM1) conventionally used at the laboratory scale for mortar preparation. The relative ratio of the two populations of beads was allowed to vary for a maximum volume fraction of 40%.

The results of Table 4 show that the distribution time is constant for a wide range of small/large particle volume ratio, except for the ratio 30/70, which corresponds to the maximum aggregate compactness. These results should be analyzed in a more systematic study, but more importantly with more sophisticated mixes and higher volume fractions. However, they do give rise to some interesting phenomena and they could suggest that the maximum compactness actually degrades the capability of the mixer to distribute the finest elements, whereas these finest elements are generally used in the mix design to optimize both compactness and rheology. It would appear that a maximized compactness may limit the distributive capability of the mixer because the space accessible to the particles is minimized, whereas dispersion is favored.

3.2.4. Effect of the mix design

The capability to distribute the finest elements of several mix designs was evaluated with several mixers using operational

Table 3
Effect of the W/C ratio on the distributive characteristic times (CM1, 30 rpm, mix designs based on mixture#1).

W/C	0.45	0.60	0.80
t_D (minutes)	3.5	2.8	2.3

conditions close to the optimum. Three types of mix designs were selected: a Standard Concrete (SC), a High Performance Concrete (HPC) and a Self Compacting Concrete (SCC). For each, the mix designs are those regularly used by the concrete industry. As shown in Fig. 9, the mixer CM2 provided the best results for standard concrete; however, we observe that both HPC and SCC concretes are less efficient regarding the distribution of the finest elements. Mixer CM2 is the most sensitive to the type of concrete in respect to mixing efficiency. The ranking of efficiency is the reverse for the second largest volume mixer (CM4), which seems more adapted for fluid concretes than for standard concretes. The third mixer (CM1), which uses a planetary motion, provided similar results for the 3 types of concrete. It can be concluded that it is less sensitive to the type of concrete and it would provide a greater robustness to changes in the mix design. Finally, the drum mixer (CM5) is clearly the less efficient mixer. This is due to the low rotational speed and the flow pattern of the concrete within the drum mixer: an internal geometry with no gaps means no high shear and high deformation zones (Table 5).

3.2.5. Comparison of the distributive and dispersive capability

The distributive characteristics of several concrete types were examined with respect to their dispersive characteristics, experimentally determined with the protocol presented in [1]. As before, the same set of mixer types was used. A comparison of the distribution times t_D with the dispersion times t_C is summarized in Fig. 10. Some consistencies are apparent since all the results pertaining to the same mix design align more or less on a master straight line constructed with the data values obtained with different mixers, except for a single datum point (circled). It should be noted that there is no scientific argument about the linearity, which is used more to facilitate the understanding that as a strict rule. The relative position of the "line" in the (t_D, t_C) graph characterizes the "intrinsic capability" of the mix design to be prepared with different concrete mixers, whereas the position of a particular datum point in the "line" is an indicator of the concerned mixers capability to achieve mixing of the specific mix design. Among the classes of concrete examined the HPC curve is below the other concretes because it contains less water, which was found to be beneficial for dispersion. The SCC curve appears slightly above the curve of standard concrete, which indicates that the dispersive aspects of mixing are weakly degraded with a fluid material, whereas distribution is not. For standard concretes the "noise" appears significantly larger, which indicates that there is a relatively higher sensitivity of the mix design with respect to mixer changes. These "lines" provide mix design specific working positions for each mixer, referring to their global distributive and dispersive mixing efficiency.

4. Conclusion

The purpose of the study presented in this paper was to describe a new methodology and to exemplify its interest by means of some of the key findings obtained with it, but not to show exhaustive results related to a large range of (mixer, mix design) systems.

The interest of a new methodology to determine the capability of (mix design, mixer) systems to distribute the finest elements of the mix design was studied. This study was based on analyzing the color evolution of red pigment particles initially introduced on the top of a mix and allowed to blend over time. The red particles are tracers and behave similar to cement particles in concrete submitted to mixing. A single distribution time is sufficient to characterize the mixing efficiency regarding distribution. It was demonstrated that the deformation applied to the material, proportional to the number of rotations, is the key parameter driving the distributive aspects of the concrete. Relatively simple rules for producing identical batches under different operational conditions can be determined. For instance, using different mixer speeds with the same mixer would simply require a proportional adjustment of the mixing time. It is note worthy that there is no need to look for arguments related to the energy brought to concrete by mixing, such as the energy per volume of mixture, to predict the distributive efficiency of a particular mixer. The transfer between different mixers at any scale is also possible and rules for transfer are also identified. Those rules are obviously mix design dependent. The present study has demonstrated that a particular concrete mixer is never both efficient for any type of mix design while being excellent for all. Depending on the physical properties of the mix design, a specific mixer is excellent for a specific kind of mix design, but less adapted for others. Clearly, the drum mixer operating under conventional conditions is always less efficient than any other mixer, but we cannot exclude that particular conditions, such as the use of lower material volumes and higher speeds, could improve its distributive capability.

However, the overall efficiency of mixing comes from the concomitant actions of both dispersion and distribution, so that none of these sub-processes should be considered alone. If the proposed methodology allows for a straightforward evaluation of the distribution times, the characteristic methodology developed in [1] for the dispersion times t_C provides relevant, although overestimated, values. Nevertheless, the direct comparison of the (t_D, t_C) is well adapted for evaluating the capability of a (mixer, mix design) system with respect to mixing efficiency. But, it appears that it is quite impossible to extrapolate simultaneously t_D, which varies with $1/N$, and t_C which was found to vary approximately with $1/N^2$. Therefore, the optimal strategy for a better extrapolation between mixers, which should ideally maintain the two times constant, must always result from a compromise. Anyway, the perspective brought by the possibility to position simultaneously distribution and dispersion really opens new opportunity in the understanding of the mixing effects at the laboratory and industrial scales.

Nomenclature

β	exponent
Ω	mixer speed, rpm
Φ_v	solid volume fraction
μ	true value of the mean of a^*
σ^2	true variance on a^*
a^*	red color intensity measured as a component of the $L^*a^*b^*$ standards
a^*_t	a^* at time t
COV	coefficient of variation on a^*
D	number of rotations required to well distribute the fine elements of the concrete
F_m	Student correction
L^*	luminance measured as a component of the $L^*a^*b^*$ standards
N	number of data points
n_t	deformation
p	measured value of the mean of a^*
S^2	measured variance of a^*
t	time
t_C	characteristic dispersion time, minutes
t_D	characteristic distribution time, minutes
t_m	mixing time
V_0	observation scale
V_h	heterogeneity scale
V_t	tracer scale
V_T	total mixer volume

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Appendix A. Mix designs for mortar and concrete

The mix designs of cementitious materials require a wide range of particles. Our study is mainly devoted to concretes for which the particles were never larger than 20 mm (aggregates). The smallest were cement particles (typically 50 µm). Fillers were occasionally used to fill or complete the wide granular distribution. Water was occasionally mixed with plasticizers (lignosulfonate) or superplasticizers for SCC.

The first column of Table 4 indicates, in the composition mixture tab and unless otherwise noted, the nature of the particles, the sizes of the smallest particle and the sizes of the largest particles, and the origin of the particles. The other columns indicate the composition of the mixtures in kg/m^3 as indicated in the legend of the figures.

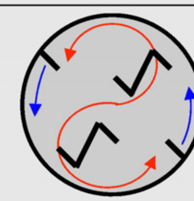
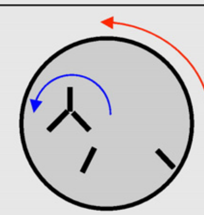
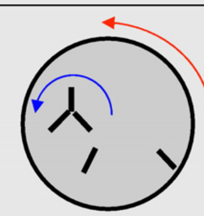
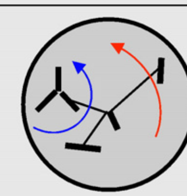
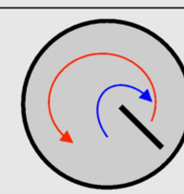
Table 4
Composition of the concrete and mortar mix designs used in the present study.

Mixture # (all units in kg/m^3)	1 SC	2 HPC	3 SCC	4 mortar
Coarse aggregates (Cassis, France) 10/20	637	726		
Coarse aggregates (Cassis, France) 6/10	425	187	700	
Coarse aggregates (Cassis, France) 3/6	297	119		
Fine aggregates (Cassis, France) 1.6/3	80	167	877	590
Fine aggregates (Cassis, France) 0/1.6	321	527		590
Cement CEMI 52.5 CP2 (Le Teil, France)	278	480	302	500
Limestone filler (Saint Béat, France)	161	161	201	296
Admixture lignosulfonate (Chryso)	1.4	2.2		1.8
Admixture PCP (Chryso)			4	
Water	170	205	193	300
Red pigment (Bayer)	2	4	2	4

Appendix B. Mixer designs

This appendix describes schematically the main features pertaining to the mixers used in this study. All are laboratory or pilot scale devices, customarily used for concretes (referenced as CM) or mortars (referenced as MM).

Table 5
Concrete and mortar mixers used in the present study.

Concrete mixers	
CM1 Counter-current mixers, "planetary" motion (pan fixed/scraper moving/shaft rotating) Usual rotation speed: 10-50 rpm Mixing capacity: 80L	
CM2 Co-current motion (same rotation direction) (pan rotating/scraper fixed) Usual rotation speed: 55 rpm Mixing capacity: 20 liters	
CM3 Co-current motion (same rotation direction) (pan rotating/scraper fixed) Usual rotation speed: 55 rpm Mixing capacity: 30 liters	
CM4 Main axial mixer, with scrapers for bottom, axis and wall. Freely rotating auxiliary mixer Usual rotation speed: 40 rpm Mixing capacity: 120 liters	
CM5 Drum mixer Usual rotation speed: 20 rpm Mixing capacity: 50 liters	(blank)
Mortar mixer	
MM1 Planetary motion Usual rotation speed: 140-280 rpm Mixing capacity: 1L	

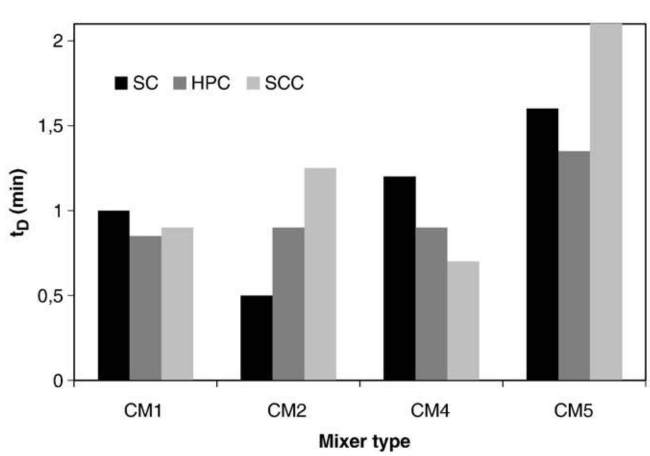


Fig. 9. Effect of the mix design on the distribution times for different mixer types.

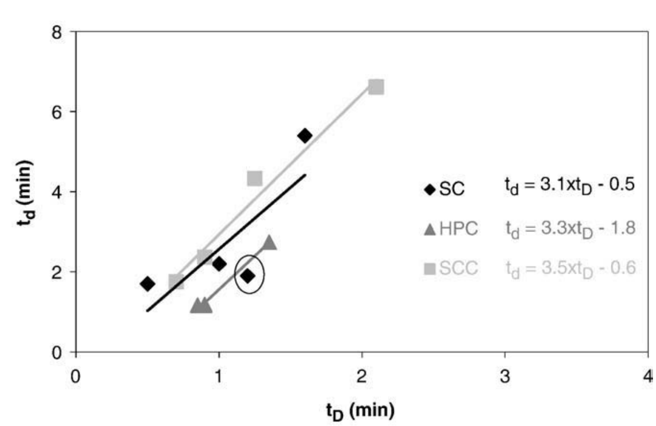


Fig. 10. Dispersive capability versus distributive capability for different mix designs.

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