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Determination of the energy consumption during the production of various concrete recipes

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ABSTRACT

This article presents a report of the mixing of concrete on the laboratory scale in a single-shaft and twin-shaft mixer. For both mixers we selected five concrete recipes that cover a broad spectrum of concrete mixing techniques. The concrete recipes differ from each other amongst other things by virtue of the aggregate-sized distribution curves, water–cement ratio, flow properties, compressive strength and mixing times. The specifically volume-related application of energy – which is necessary for the homogenization of the particular recipe in the mixer – is an essential influencing variable.

The comparison of the specifically volume-related application of energy is possible only if the concrete recipes possess the same homogeneity. The time curve of the homogeneity plotted against the necessary mixing time indicates the mixing efficiency, which in turn is determined by an imaging measurement process. Comprehensive mixing experiments show that the resulting application of energy, measured via the current composition, does not provide sufficient information in order to define the actual homogeneity in the mixture. A method was developed for the purpose of comparing concrete mixtures based on various recipes with the same homogeneity in relation to the specifically volume-related application of energy. The particular application of energy can be determined via the required mixing time and the power output process in terms of time.

1. Introduction

Mixing of dry or moisturized powders is a unit operation in process engineering industry, and can be found in the construction-, food-, and pharmaceutical industries, as well as in other fields. This paper focuses on concrete mixers, of which there are two main categories. The first type of mixer produces concrete one batch at a time, while the second type produces concrete at a constant flow rate. The paper focuses on the discontinuous concrete mixer, in a single shaft- and twin shaft execution.

The user's objective when employing a charge mixer is to attain a defined homogeneity in the solids, to be mixed within the shortest possible mixing time. The change of mixing quality during the mixing time is described by the mixing efficiency. The mixing efficiency is determined in the classical manner. Representative solid samples are taken out of the mixing chamber and are analyzed outside for their composition. The conditions during the mixing process, such as power consumption, gradients of moisture or rate per minute etc. should remain unchanged. The boundary conditions influence the mixing efficiency [1]. The operator of a concrete plant is not so much interested in the mixing efficiency, but rather the mixer efficiency related to the product. The question here is how well a mixer can produce a uniform concrete from its constituents. The properties (specific concrete parameters) for fresh concrete such as the density of fresh concrete, the air content and the compressive strength etc. are often considered. The procedural method of determination of mixing quality can be found in the norm of RILEM [2], DIN EN-459-2 [3] and in [4].

Concretes of various categories of strength and quality are mixed and used in the industry daily by the ton. The mixing times are increased from a rather short 35 second mixing time for the traditional recipes to several minutes for the special concretes when large portions of fines components are involved. The flow rate of the concrete plants will reduce dramatically for high performance concrete. The various recipes` are being studied by various research institutions of concrete with regard to strength, quality, and mixing time.

The development of the concrete recipes in the last 20 years according to [5] has developed from a four-component system (water, coarse aggregates, sand and cement) into multi-component systems since the early nineties. The addition of admixtures or synthetic micro silica makes the mixing task considerably more difficult, since these components have very large fine proportions, something that confronts some mixing processes with a difficult task. The present-day ultra high performance concrete, with compressive strengths of more than 200 N/mm^2, cf. [6], as compared to ordinary concrete with, for instance, a compressive strength of 20/25 N/mm^2, present modern mixing technique with increasing requirements. A further

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variety of concrete that has been of interest in research today is the self-compacting concrete described, for instance, in [7]. The concrete has a high flowability and can be placed without vibration.

Detailed information on the treatment and analysis of high performance concrete can be found in [8]. More specific parameters (rheology, microstructure) are available for measurement, but these simplify neither the treatment nor the analysis of high performance concrete.

The microstructure and rheological flow [9,10] of this high performance concrete is now more important than previously. In many cases the concrete quality can be recognized only in the finished product.

The quality of the concrete is critically determined by the microstructure. Based on the investigations, for instance, in [9], the microstructure of the concrete depends on the composition and the curing conditions as well as on the mixing method and the mixing conditions prevailing at the production site.

A recent publication attempts to solve this offline problem of concrete parameters by in-mixer measurements for describing mixture evolution during a concrete mixing process. The three inline measurements in [11] are power consumption, a concrete moisture sensor and a sensor for the rheology of concrete.

This paper describes an arrangement with the necessary application of energy for the purpose of concrete mixing based on various concrete recipes. The mixing time consists here of the sum of the loading period (dry mixing and wet mixing), the mixing period and a dispersion mixing period. It is well-known that the discharge and weighing periods also require energy, but these are disregarded in this paper.

In comprehensive experiments it becomes apparent that the comparison of different concrete recipes regarding the application of energy is only valid when the homogeneity of the different recipes is equal at the end of the mixing process. This is important for the integration of the power curve to determine the application of the energy. The load time of the aggregates is constant $t_{\mathrm{load}} = 10$ s during the mixing experiments with the two shaft mixers.

Cazacliu and colleagues [12,13] show further details of new kinetic models for power consumption, using rheology and dimensional analysis to enhance the description. This paper does not include these parameters. Rather, a simple method should help determine the application of energy for a concrete recipe.

The method for assuming the homogeneity at the end of the mixing process is image analysis in this case. A helpful technique for the further evolution of this method of concrete recipe is [14] in which some cement was marked with a ferrous oxide. Using this analysis method, the homogeneity of a concrete mixture is determined from a portion of the power curve and the mixing efficiency. The practical user can produce and compare concrete mixtures with constant homogeneity if he knows the percentage energy portion in the range of the stationary power consumption. In a concrete plant it is not always possible to take a representative sample for the determination of homogeneity. Therefore, the determination of the mixing time, together with the enhancement of the mixing efficiency, using image analysis, represents a considerably more precise method for the determination of the homogeneity.

The method presented here is thus suitable for the determination of the mixing time for the attainment of a previously defined homogeneity. Of course it cannot replace any further testing methods, such as the flow consistency, homogeneity determination of the aggregates size distribution and the compressive strength determination.

These statistical aids are very precisely described in [15] which studied dry powder mixtures. The physical equation that characterizes the distribution of components (dispersion) in a powder mixing experiment is the Fokker–Planck-equation [16]. More information about this equation, its application and the necessary internal and boundary conditions by determination of the mixing efficiency can be found in [17–19].

2. Theoretical considerations for determination of the homogeneity

2.1. Theoretical considerations for determination of the mixing efficiency

The concrete norms such as RILEM document the statistical sampling of concrete samples in a very detailed manner. This chapter contains further details of the mixing efficiency. The statistic regarding the coefficient of variation and the empiric variance are contained in Appendix A. Sommer and colleagues [15,20] discuss taking samples of dry powders in some detail. The theory in Appendix A is based on only one powder component (the component of interest).

According to Sommer [15], the mixing efficiency – determined via the time span of the variance $\sigma^2(c_{P,i},t_{\mathrm{M}})$, according to Eq. (1) – consists of three variances. The variance of the measurement method σ^2_{M} contains the reproducibility and can be determined by preliminary experiments. As a rule, the latter should be so small that only the variance of the uniform random mixture σ^2_{Z} will influence the system and so the variance of the measurement method σ^2_{M} is negligible ($\sigma^2_{\mathrm{Z}} >> \sigma^2_{\mathrm{M}}$). The systematic variance σ^2_{Syst} is thus a function of the time and, in its stationary state, has the value $\sigma^2_{\mathrm{Syst}} = 0$, that is to say, the mixing process is terminated. A longer mixing time does not improve the mixing quality,

$$\sigma^2\left(c_{P,i}, t_{\mathrm{M}}\right) = \sigma^2_{\mathrm{M}} + \sigma^2_{\mathrm{Z}} + \left(1 - \frac{m_{E,T}}{m_{\mathrm{P}}}\right) \cdot \sigma^2_{Syst.}. \tag{1}$$

Current spectroscopy measurement methods of [21–23], which can be employed only up to a certain sample volume, are employed in an attempt to reduce the effort required for the evaluation of the attainable mixing efficiency of continuous or discontinuous powder mixers. The difficulty inherent in all measurement methods relates to their calibration for each individual substance, something that is not possible in the case of many concrete recipes. Any missing calibration frequently leads to error sources in the determination of the concentration. Each of the referenced authors had studied powder samples and did not analyze fresh concrete samples.

Optical measurement methods with fiber-optical waveguides and CCD cameras were used by [24–28], each of which used image analysis in order to characterize the mixtures on the basis of particles with differing colors. Sampling from the mixing chamber could not always be dispensed within this case. For this purpose, however, the powder mixer had to be stopped briefly for the purpose of measuring the concentration distribution. This article therefore focuses on a method that relies on a determination of the concentration course and the mixing efficiency distribution by means of image analysis without sampling. A CCD video camera records the mixing process throughout the entire mixing time in order to thus determine the mixing efficiency. This measurement method offers the advantage that the camera can be used in a flexible manner when the structural size of the mixer or of the sample volume is changed. Furthermore, one can access the raw data as often as desired and at various times and under certain circumstances, in order to adapt the analysis method. Moving images of the mixing process, moreover, help gain an impression of the entire mixing procedure during the process.

2.2. Determination of mixing efficiency by means of image analysis

The digital images that were taken have a resolution of 720×576 pixels. The blue component (tracer) therefore cannot be resolved up to primary particle size. The tracer mass concentration is $\overline{c_{P,E}} = 0.74\%$: One can gain an impression of the mixing efficiency with a resolution of 366.8 mm^2 per sample. With increasing resolution, the details could, of course, be better recognized. However, disturbing non-homogeneities, such as reflections of particles or shadow formations caused by mixing tools and the trough edge, could then dominate the mixing efficiency. But the analyses showed that a