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# Research of Dispersion Characteristics of Screened Cements

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**Abstract:** Present day cement production is a high-technology industry requiring sophisticated technology-savvy approach at each phase of its manufacture. Given that cement, i.e., floured gray-colored powder is a principal product of any cement-manufacturing enterprise considerable attention should be paid to a degree of fineness of this binding agent. The study offers a new approach to determining of the dispersion characteristics of screened powders based on processing of data obtained be means of electronic granulometers.

**Key words:** Cement, granulometric composition, particle, grade, distribution function

## INTRODUCTION

Such construction-related and processing characteristics of cement as compression resistance, rate of strength development, water demand, water segregation, specific cost of grinding and other are determined not only by mineralogical composition but also to a great extent by Dispersion Characteristics of Cement (DCC) namely by granulometric composition indices, mean particle size, content and ratio of various fractions in cement, specific surface area of the powder under consideration, etc. (Duda, 1985; Butt and Timashev, 1974; Unland *et al*., 2003).

## MATERIALS AND METHODS

**Main part:** Cement particles are of irregular form, therefore, diameters of spherical particles with the same density are taken as the size of such particles. The volume of particles is being most often regarded as a characteristic property. In this case, a particle size equivalent to its volume will be defined as follows:

$$d = \sqrt[3]{\frac{6V}{p}} \tag{1}$$

Where, V is the volume of a real particle. The equivalent diameter (size) of cement particles may be determined by direct measurements. For example, via microscopic or optical method it is possible to find out three main dimensions of a cement grain, namely its length $d_1$, width $d_2$ and thickness $d_3$. Using these dimensions a particle volume may be approximately calculated by means of an empirical equation used in granulometry (Baron, 1960):

$$V = \frac{d_1 d_2 d_3}{2.2} \tag{2}$$

In this case, the equivalent size of a particle will be determined by the following equation:

$$d = \sqrt[3]{\frac{6d_1 d_2 d_3}{2.2f}} = 0.954\sqrt[3]{d_1 d_2 d_3} \tag{3}$$

and will almost be in line with the geometric average of the three main dimensions of cement particles. In a production environment comparison of behavior of real and exemplary particles in some testing processes is frequently used in order to research dispersion properties of cements. Previously, such processes most often involved powder screening through a set of sieves or sedimentation of the same in liquid medium. Presently, a method of laser diffraction becomes more wide spread. It has such distinctive features like wide range of sizes of the investigated particles (from thousandth parts to hundreds of microns), fast analysis and computer processing of the measurement results (Artamonova *et al*., 1996).

Granulometric composition (particle-size distribution, grain-size distribution) which determines a relative weight content $\Delta D_i$ of definite size grades, i.e. of aggregates of particles belonging to $+d_{i-1}$, $-d_i$ grade which fall within

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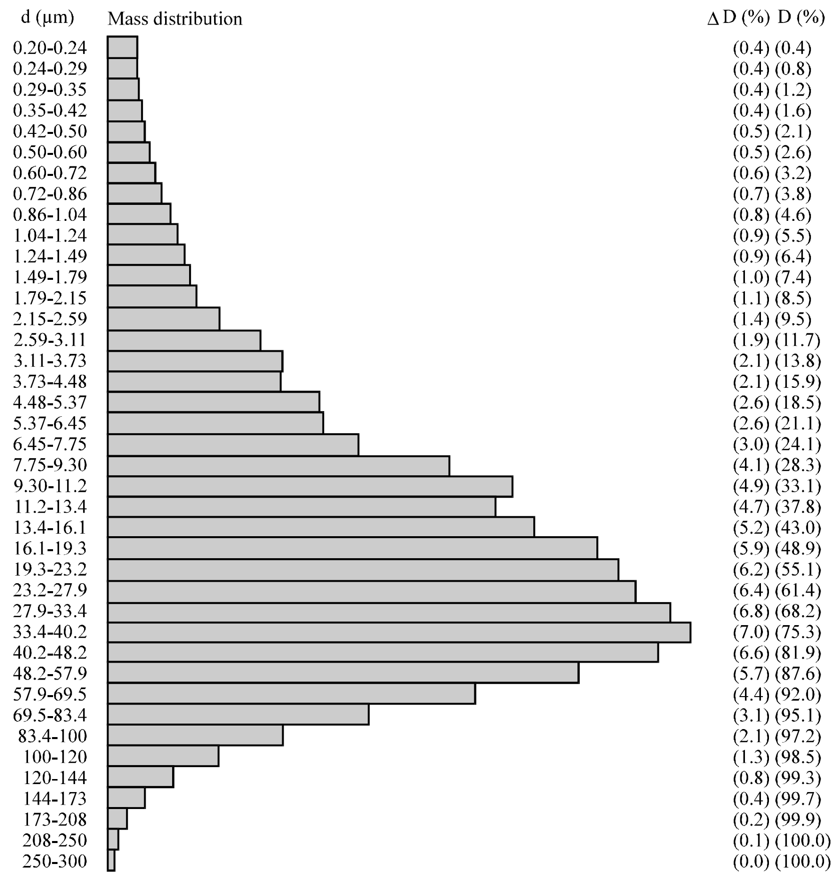


Fig. 1: Granulometric composition and dispersion characteristics of screened cement ($L_c$ = 80,000 m3/h, n = 200 rpm)

$[d_{i-1},...,d_i]$ interval is the most general and informative characteristic of cement degree of dispersion. The following formula is widely used in literature to determine the relative weight content of definite fractions $f_i \equiv \Delta D_i$. Further in our research, we'll be committed to this equation. We'll also suggest that the particles belonging to $[d_{i-1}, ..., d_i]$ fraction have the same size equal to:

$$\bar{d}_i = \frac{(d_{i-1} + d_i)}{2} \quad (4)$$

The particles smaller than $d_i$ will form $-d_i$ grade the content of which will be designated as $D(d_i)$, the particles bigger then $d_i$ will form $+d_i$ grade with the content designated as $R(d_i)$. Dependences between $D(d_i)$ and $R(d_i)$ are referred to as functions of cumulative distribution by passage and remainder in the control sieve, their values can be determined with use of the Eq. 5:

$$D(d_i) = \sum_{k \le i} f_k \quad (5)$$

The relative content of definite fractions $\Delta D_i$ may be used for calculation of the values of differential function of distribution:

$$R(d_i) = 1 - D(d_i) \quad (7)$$

Where, $\Delta d_i = d_{i-1}-d_i$. Division of cement into grades (given that d>30 µm) in a laboratory environment is performed by means of screening through a number of subsequent sieves and in a production environment by means of an aerodynamic method with use of various separator units. In recent years, the laboratories of the cement-producing factories more frequently examine cement granulometric composition by means of optical and laser particle analyzers allowing accurate determining of weight ratios of narrow fractions of cement grains. Figure 1 shows the results of laser granulometry of cements produced by grinding systems with closed grinding cycle in the various modes of a separator unit operation. It is necessary to note that the method of laser diffraction applied in such grinding

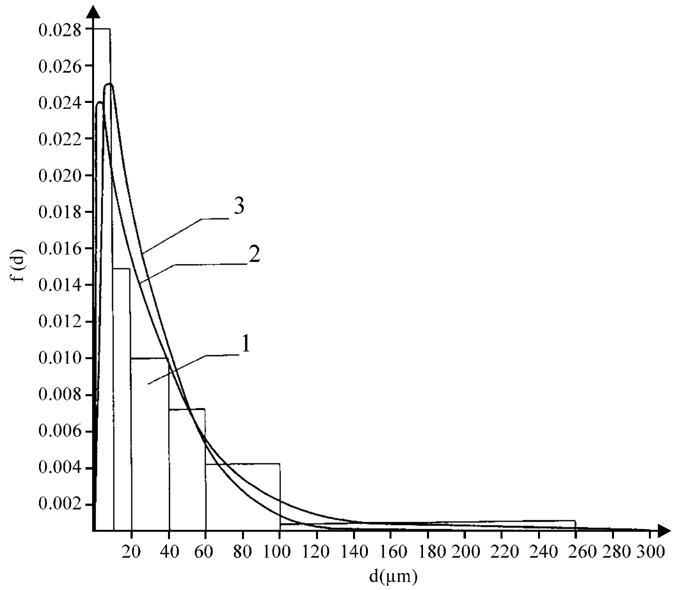


Fig. 2: The methods of description of granulometric composition of cement: 1) generalized histogram of granulometric composition of cement; 2) differential curves approximating granulometric composition and complying with RRBS rule; 3) log-normal distribution

systems gives an opportunity to determine both major and equivalent dimensions of particles belonging to various fractions.

This curve is distinguished by a distinct asymmetric maximum, i.e., abrupt decline towards small particles and flat decline towards coarse ones. This peculiarity of the differential distribution function can be described via Rosin-Rammler-Bennett-Sperling (RRBS) distribution:

$$f(d) = \frac{n}{d'}\left(\frac{d}{d'}\right)^{n-1} \exp\left(-\left(\frac{d}{d'}\right)^{n}\right) \quad (8)$$

Or via log-normal Kolmogorov-Hatch-Choate distribution (LND):

$$f(d) = \frac{\lg e}{\sqrt{2\pi}\, d \lg\sigma} \exp\left(-\frac{t^2}{2}\right) \quad (9)$$

Where:
- n = A fractions distribution factor based on RRBS
- d' = Characteristic dimension of a particle corresponding to 36.8% of screening residue with the dimension d (which corresponds to the passage of 63.2%), μm; lg e = 0.4342:

$$t = \frac{\left(\lg d - \lg d[v, 0.5]\right)}{\lg\sigma},$$

$$\sigma = \frac{d[v,0.84]}{d[v,0.5]} = \frac{d[v,0.5]}{d[v,0.16]}$$

Where:
- d[v, p] = Mesh size allowing 100% volume (mass) passage (p) of screened cement
- d[v, 0.5] = Median particle size which divides cement volume (mass) into two equal parts

Restriction n>1 is explained as follows: when n>1 and d→0 RRBS differential distribution function demonstrates increase without limits which means existence of infinite number of ultrafine particles in the finished product (Andreev *et al*., 1959).

Figure 2 shows generalized histogram of granulometric composition of cement given in Fig. 1 as well as plotted RRBS and LND distribution functions (Eq. 8 and 9) with parameters which approximately correspond to experimental data (Fig. 1) across the whole range of particle size change: n = 1.1; d' = 33 μm; d[v, 0.5] = 26.3 μm; [sigma] = 2.62 μm:

$$f(d) = 0.0333\left(\frac{d}{33}\right)^{0.1} \exp\left(-\left(\frac{d}{33}\right)^{1.1}\right) \quad (10)$$

$$f(d) = \left(\frac{0.4141}{d}\right) \exp\left(-2.851 \lg^2\left(\frac{d}{26.3}\right)\right) \quad (11)$$

For the purposes of analytical description of granulometric composition of cement as set by experimental data arrays ($d_i$-$D(d_i)$) or ($d_i$-$R(d_i)$) the following cumulative distribution functions are most frequently used:

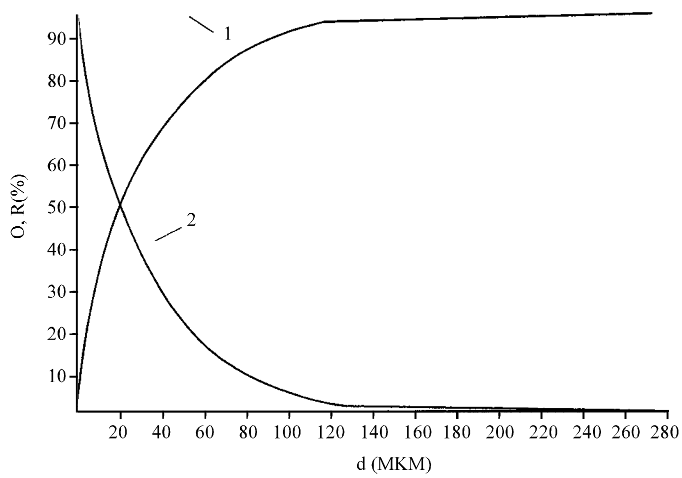


Fig. 3: Cumulative curves of granulometric composition of cement: 1) overall residue curve; 2) overall passage curve

$$R(d) = 100\exp\left(-\left(\frac{d}{d'}\right)^n\right) \quad (12)$$

For RRBS distribution and:

$$R(d) = 100(1 - F(t)) \quad (13)$$

For log-normal distribution; where:

$$F(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{t} \exp\left(-\frac{z^2}{2}\right) dz \quad (14)$$

is an error integral the value of which is determined with use of tables (Andreev *et al.*, 1959). Parameters n, d', d[v, 0.5] and lg σ contained in the distribution functions (Eq. 10-13) are identified on the basis of experimental data. The cumulative distribution function curves plotted with use of data from Fig. 1 are given on Fig. 3.

In order to check the correspondence of cement grains distribution by Eq. 12 and 13, let's transform them to a linear form by means of rearrangements and introduction of new variables:

$$Y_1 = k_1X + B_1 \quad (15)$$

$$Y_2 = k_2X + B_2 \quad (16)$$

Where:

$X$ = lg d
$k_1$ = n
$k_2$ = 1/lg σ
$Y_1$ = lgx lg (100/R)
$Y_2$ = $F^{-1}$(1-R/100)
$B_1$ = -n lg d-0.3622
$B_2$ = -lg [v, 0.5]/lg r
$F^{-1}$ (t) = Function inverse to the error integral

## RESULTS AND DISCUSSION

The results of processing of experimental data relating to granulometric composition of cement (Fig. 1) with use of new variables are given in Table 1.

The first column of table contains fraction number; the second one its limiting dimensions (fraction limits); the third one contains mean size of particle for different fractions; the fourth column is for relative weight content (in %) of individual fractions; the fifth column contains individual fraction ranges; the sixth one contains the values of cumulative function for passage (%); the seventh one the values of cumulative function for residue; the eighth column is for experimental values of differential distribution function $f(\bar{d}_i) = f_i/\Delta d_i$; the ninth to the eleventh column contain the values of new variables $X_i$, $Y_{1i}$, $Y_{2i}$.

Differential distribution line plotted along the experimental data points ($d_i, f(\bar{d}_i)$) is shown on Fig. 4. The form of this line and in particular abrupt decline of the named line when the particles size tends towards zero (Fig. 5) confirms advisability of its use for smoothing of RRBS equation at n>1 or of log-normal rule.

It follows from Eq. 15 and 16 that the overall residues line will be presented as a straight line on a log-log grid (X, $Y_1$) given RRBS rule application or on a log-probability grid (X, $Y_2$) if LND is used. The parameters of linear dependences (Eq. 15 and 16) in a first approximation are determined by two experimental data points ($d_1$, $R_1$) and

Table 1: Results of processing data on granulometric composition of cement

| Fraction $[d_{i-1}, d_i]$ | $\bar{d}_i$ | $f_i$ (%) | $\Delta d_i$ | $D(d_i)$ (%) | $R_0(d_i)$ (%) | $F(\bar{d}_i)$ | $X_i$ | $Y_{1i}$ | $Y_{2i}$ |
|---|---|---|---|---|---|---|---|---|---|
| 0.20-0.24 | 0.220 | 0.4 | 0.04 | 0.4 | 99.6 | 0.1000 | -0.6198 | -2.7604 | 2.660 |
| 0.24-0.29 | 0.265 | 0.4 | 0.05 | 0.8 | 99.2 | 0.0800 | -0.5376 | -2.4579 | -2.420 |
| 0.29-0.35 | 0.320 | 0.4 | 0.06 | 1.2 | 98.8 | 0.0670 | -0.4559 | -2.2807 | -2.260 |
| 0.35-0.42 | 0.385 | 0.4 | 0.07 | 1.6 | 98.4 | 0.0570 | -0.3768 | -2.1549 | -2.150 |
| 0.42-0.50 | 0.460 | 0.5 | 0.08 | 2.1 | 97.9 | 0.0630 | -0.3010 | -2.0356 | -2.040 |
| 0.50-0.60 | 0.550 | 0.5 | 0.10 | 2.6 | 97.4 | 0.0500 | -0.2218 | -1.9417 | -1.950 |
| 0.60-0.72 | 0.660 | 0.6 | 0.12 | 3.2 | 96.8 | 0.0500 | -0.1427 | -1.8502 | -1.950 |
| 0.72-0.86 | 0.790 | 0.7 | 0.14 | 3.9 | 96.1 | 0.0500 | -0.0655 | -1.7626 | -1.760 |
| 0.86-1.04 | 0.950 | 0.8 | 0.18 | 4.7 | 95.3 | 0.0440 | 0.0170 | -1.6798 | -1.680 |
| 1.04-1.24 | 1.140 | 1.0 | 0.20 | 5.7 | 94.3 | 0.0500 | 0.0934 | -1.5937 | -1.580 |
| 1.24-1.49 | 1.365 | 1.0 | 0.25 | 6.7 | 93.3 | 0.0400 | 0.1732 | -1.5212 | -1.500 |
| 1.49-1.79 | 1.640 | 1.0 | 0.30 | 7.7 | 92.3 | 0.0330 | 0.2529 | -1.4585 | -1.430 |
| 1.79-2.15 | 1.970 | 1.0 | 0.36 | 8.7 | 91.3 | 0.0280 | 0.3324 | -1.4031 | -1.360 |
| 2.15-2.59 | 2.370 | 1.4 | 0.44 | 10.1 | 89.9 | 0.0310 | 0.4133 | -1.3350 | -1.280 |
| 2.59-3.11 | 2.850 | 2.3 | 0.52 | 12.4 | 87.6 | 0.0440 | 0.4914 | -1.2404 | -1.160 |
| 3.11-3.73 | 3.420 | 2.2 | 0.62 | 14.6 | 85.4 | 0.0350 | 0.5717 | -1.1640 | -1.060 |
| 3.73-4.48 | 4.300 | 2.2 | 0.75 | 16.8 | 83.2 | 0.0290 | 0.6513 | -1.0976 | -0.960 |
| 4.48-5.37 | 4.920 | 2.9 | 0.89 | 19.7 | 90.3 | 0.0320 | 0.7230 | -1.0210 | -0.850 |
| 5.37-6.45 | 5.910 | 2.2 | 1.08 | 21.9 | 78.1 | 0.0200 | 0.8096 | -0.9692 | -0.780 |
| 6.45-7.75 | 7.100 | 3.0 | 1.30 | 24.9 | 75.1 | 0.0230 | 0.8893 | -0.9053 | -0.680 |
| 7.75-9.30 | 8.515 | 3.2 | 1.55 | 27.1 | 72.9 | 0.0140 | 0.9685 | -0.8624 | -0.610 |
| 9.30-11.20 | 10.250 | 3.0 | 1.90 | 30.1 | 69.9 | 0.0150 | 1.0492 | -0.8082 | -0.520 |
| 11.20-13.40 | 12.300 | 3.5 | 2.70 | 33.6 | 66.4 | 0.0160 | 1.1271 | -0.7500 | -0.425 |
| 13.40-16.10 | 14.750 | 3.5 | 2.70 | 37.1 | 62.9 | 0.0130 | 1.2068 | -0.6961 | -0.330 |
| 16.10-19.30 | 17.700 | 4.2 | 3.20 | 41.3 | 59.7 | 0.0130 | 1.2856 | -0.6497 | -0.220 |
| 19.30-23.20 | 21.250 | 5.0 | 3.90 | 46.3 | 53.7 | 0.0130 | 1.3655 | -0.5686 | -0.095 |
| 23.20-27.90 | 25.550 | 5.5 | 4.70 | 51.8 | 48.2 | 0.0120 | 1.4456 | -0.4990 | 0.045 |
| 27.90-33.40 | 30.650 | 5.9 | 5.50 | 57.7 | 42.3 | 0.0110 | 1.5237 | -0.4275 | 0.195 |
| 33.4-40.2 | 36.800 | 6.4 | 6.80 | 64.1 | 35.9 | 0.0090 | 1.6042 | -0.3517 | 0.360 |
| 40.2-48.2 | 44.200 | 6.9 | 8.00 | 71.0 | 29.0 | 0.0086 | 1.6830 | -0.2696 | 0.550 |
| 48.2-57.9 | 53.050 | 7.0 | 9.70 | 78.0 | 22.0 | 0.0070 | 1.7627 | -0.1821 | 0.770 |
| 57.9-69.5 | 63.700 | 6.4 | 11.60 | 84.4 | 15.6 | 0.0055 | 1.8420 | -0.0932 | 1.010 |
| 69.5-83.4 | 76.450 | 5.3 | 13.90 | 89.7 | 10.3 | 0.0038 | 1.9212 | -0.0056 | 1.265 |
| 83.4-100 | 91.700 | 4.0 | 16.60 | 93.7 | 6.3 | 0.0024 | 2.0000 | 0.0794 | 1.530 |
| 100-120 | 110.000 | 2.8 | 20.00 | 96.5 | 3.5 | 0.0014 | 2.0792 | 0.1631 | 1.780 |
| 120-144 | 132.000 | 1.7 | 24.00 | 98.2 | 1.2 | 0.0007 | 2.1584 | 0.2417 | 2.100 |
| 144-173 | 158.500 | 1.0 | 29.00 | 99.2 | 0.8 | 0.0003 | 2.2380 | 0.3215 | 2.420 |
| 173-208 | 190.000 | 0.5 | 35.00 | 99.7 | 0.3 | 0.00014 | 2.3160 | 0.4016 | 2.760 |
| 208-250 | 229.000 | 0.2 | 42.00 | 99.9 | 0.1 | 0.00005 | 2.3979 | 0.4765 | 3.200 |
| 250-340 | 275.000 | 0.1 | 50.00 | 100.0 | 0.0 | 0.00002 | 2.4771 | 0.6990 | 4.500 |

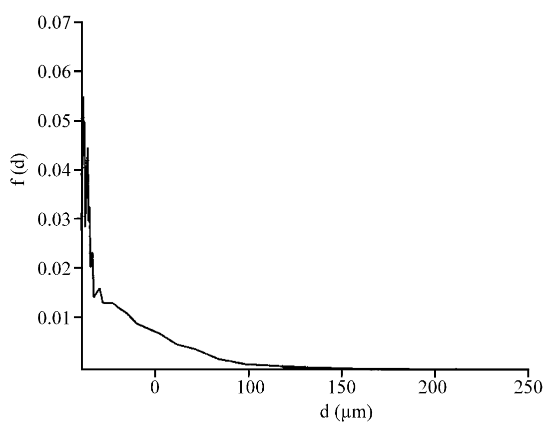


Fig. 4: Differential curve of cement particles distribution by size

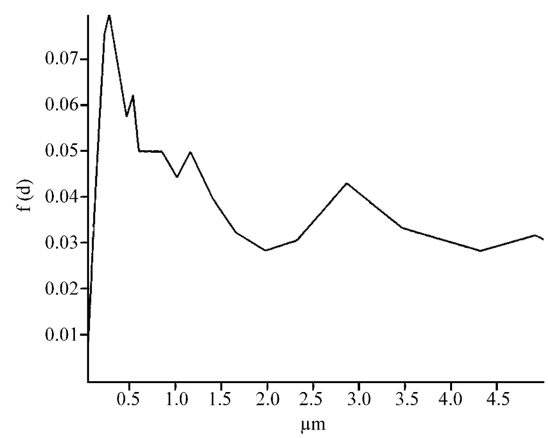


Fig. 5: Differential curve of cement particles distribution: initial section shown on Fig. 3

($d_2$, $R(d_2)$) and more accurate determination is performed by means of processing of the whole experimental data array by a Least Squares Method (Kouzov, 1971; Anonymous, 1988).

In this case, the error of the experimental data approximation by functions (Eq. 15 and 16) may be evaluated by comparing mean-square deviations of theoretical values $kX_i+B$ from the experimental value $Y_i$:

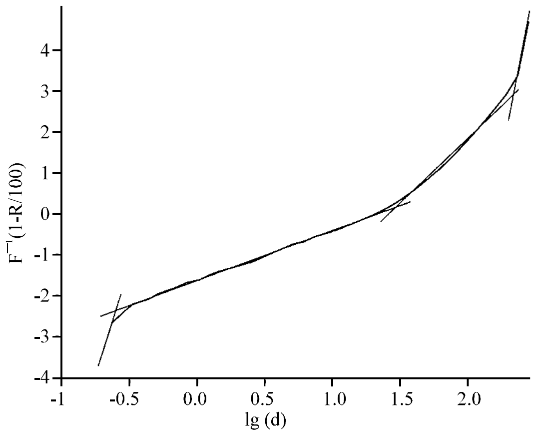


Fig. 6: Granulometric composition of cement on log-probability grid lg d-$F^{-1}$(1-R/100)

$$\Delta = \sqrt{\frac{1}{n}\sum_{i=1}^{n}\left(Y_i - kX_i + B\right)} \quad (17)$$

Figure 6 and 7 demonstrate the granulometric composition of cement given in Fig. 1 on non-uniform coordinate grids, namely the log-log grid and the log-probability grid.

Analysis of the resulting lines evidences that across the whole range of particle sizes they can not be aligned along a single line, that's why, the granular composition of screened cement with the required accuracy does not correspond both to Rosin-Rammler distribution and to log-normal rule.

The accuracy of description of cement granular composition by means of distributions (Eq. 12 and 13) may be increased by application of piecewise approximation which supposes interchange of experimental curves of particles distribution by size by polygonal lines. In which case, each section of the polygonal line will have its own set of distribution parameters which are determined by the Least Squares Method.

**Findings:** The above offered approach to research of particle size distribution characteristics of finely dispersed powders allows forecasting properties of powders such as their activity, for example, if the offered method will be applied with due account of parameters of the used equipment, it will be possible to perform a calculation for the whole finely dispersed powders production line depending on the requirements to such powders. Comparison of Figure 6 and 7 allows to come to a conclusion that both RRBS and LND distributions approximate experimental data with almost the same

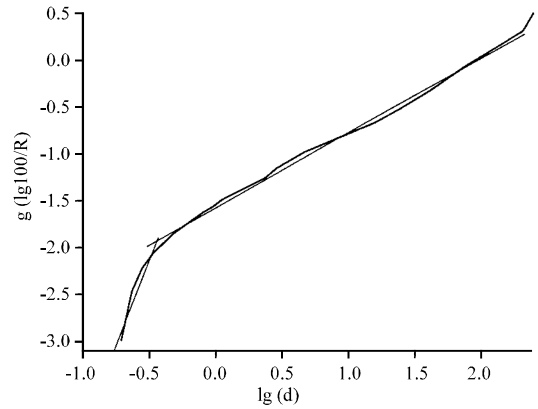


Fig. 7: Granulometric composition of cement on log-log grid lg d lg lg 100/R

accuracy. RRBS distribution gives an opportunity to get more simple description of granulometric content of cement. The log-normal distribution has another advantage, i.e., it gives clear physical meaning of its parameters and absence of limits in regard of such parameter values.

The parameters of RRBS distribution across the whole or a part of interval of particles size change ($d_k$, $d_l$) in accordance with the least squares method are determined with use of Eq. 18 and 19:

$$n = \frac{mA - CD}{G},\ d' = 10^{-(B+0.3622)/n} \quad (18)$$

Where:

$$B = \frac{(DH - AC)}{G}G\ =\ mH - C^2 \quad (19)$$

Here, m stands for a number of values $d_i$ which fall within ($d_k$, $d_l$) interval;

$$A = \sum_{i=k}^{l}(\lg d_i)\lg\times\lg\left(\frac{100}{R(d_i)}\right);\ C = \sum_{i=k}^{l}\lg d_i,$$
$$D = \sum_{i=k}^{l}\lg\times\lg\left(\frac{100}{R(d_i)}\right);\ H = \sum_{i=k}^{l}(\lg d_i)^2 \quad (20)$$
$$G = mH - A_2$$

When the granulometric composition of cement given in Fig. 1 is approximated by RRBS distribution across the whole range of particle sizes from 0.2-300 μm with the help of the Least Squares Method the result will be as follows; n = 1.075, d′ = 32.6 μm:

$$R(d) = 100\exp\left(-\left(\frac{d}{32.6}\right)^{1.075}\right) \quad (21)$$

For extra fine particles range of 0<d = 0.5 μm: n = 3.54, d′ = 1.25 μm, for the range of particle sizes of 0<d = 100 μm: n = 0.91, d′ = 33.46 μm. Piecewise approximation of the granulometric composition of cement by RRBS appears to be as Eq. 22:

$$R(d) = \begin{cases} 100\exp\left(-\left(\frac{d}{1.25}\right)^{3.54}\right) \\ 100\exp\left(-\left(\frac{d}{33.46}\right)^{0.91}\right) \end{cases} \quad (22)$$

$$0<d \le 0.5\mu m$$

The presented system of equations allows describing granulometric composition of screened cement with the acceptable accuracy which is ensured by RRBS distribution. In which case, the traditional characteristics of cement particles dispersion, namely content and ratio of various fractions as well as specific area can be expressed by the indices of the granulometric composition (n and d′).

## CONCLUSION

- There were offered the analytic expressions for determining particle dispersion characteristics of screened powders based on processing of data obtained by means of electronic granulometers
- It is demonstrated that the accuracy of cement granulometric composition description may be increased by piecewise linear approximation which supposes interchange of experimental curves of particles distribution by size by polygonal lines

The offered method for determining particles dispersion characteristics of screened powders allows establishing connection between construction-related and processing characteristics of cements through the indices of granulometric composition determined by means of RRBS distribution (n and d′).

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