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Segregation of Particulate Solids in a Horizontal Drum Mixer

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Die Entmischung von Feststoffpartikeln in einem horizontalen Trommelmischer
Ségrégation des solides en particules dans un mélangeur à tambour horizontal
Segregación de sólidos particulados en mezclador de tambor horizontal
横型ドラムミキサー内における粒状粉体の分離
卧式混料筒固体粒子的分离法
فصل المواد الصلبة الحبيبة في الخلاطات ذات الاسطوانة الأفقية. بقلم ابه. روكويكي.

Summary

Investigations of the mixing of two sieve fractions of sea sand in a horizontal drum mixer have been carried out. An appearance of the distinct axial segregation has been found and the final equilibrium state did not depend on the initial state of a mixture. An absence of the radial segregation has been also found in initial end-to-end loading as well as when the components were initially randomly mixed.

Notation

k number of spot samples in a section
w weight of particle
x weight concentration of component
$\tilde{x}$ number concentration of component
σ variance of concentrations distribution

bs between sections
is inside sections
i number of a section
j number of a spot sample in a section
l larger
m mean
s smaller
t total

1. Introduction

A mixing of particulate materials differing in sizes, densities and/or shapes is always accompanied by segregation. It may be caused by many different factors and the forms of appearance may be various, depending on properties of components, an initial loading, a mixer design and mixing conditions.

A great number of factors affecting the segregation lead to considerable difficulties. In addition problems arise, well known to the investigators of mixing of particulate solids, with defining the degree of mixing and with sampling. That is why the stress has been laid on fundamental investigations, utilising simple apparatus in order to identify the basic mechanisms of segregation. Such apparatus are shear cells [1—4] or segregation cells [5,6] and rotating drums — horizontal [7—11] or inclined [12, 13]. Other types of investigation are theoretical considerations, leading to mathematical models of segregation processes [14—16]. Such models are, up to the present time, purely empirical and do not reflect the phenomenon in its full complexity. However, they may be useful in describing the individual processes under the particular conditions for which they were derived.

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2. Theoretical Considerations

The object of this paper is the presentation of the results of investigations into the mechanism of segregation in a horizontal drum mixer. A movement of particles in such a mixer has been comprehensively described and the segregation mechanisms have been elucidated. The most detailed investigations were carried out by Donald and Roseman [8]. They explained the mechanisms of both axial and radial segregation of particles differing in size and attributed the axial segregation to the effect of end walls of a mixer. The friction between the particles and the wall produces the velocity gradient over adjacent bands of particles. The highest velocity is attained by the particles within the bands at a small distance from the end walls and it decreases to a constant value near the center of a mixer. In short mixers the wall effect spreads over the full length of a mixer. The axial segregation consists in passing the particles from one band to another, with the smaller particles being more capable of exchanging their relative positions, and the higher the velocity gradient, the easier this exchange is. The radial segregation occurs when particles change their paths of circulation in the plane perpendicular to the drum axis, due to the velocity gradient of particles over adjacent layers. This is possible in the surface layers only, where particles are slipping or rolling down into the voids below under the influence of gravity. There is a greater chance for the smaller particle to drop into the void in the layer below and as mixing proceeds, the core of smaller particles rises, surrounded by larger ones.

According to Donald and Roseman the axial mixing is slower than the radial mixing. They explained this by the fact that radial mixing is affected by gravity, whereas there are not any external forces acting in the axial direction. According to Rutgers [17], however, dispersion coefficients in both directions do not differ much and the radial dispersion

seems to be faster because the radial distance in a mixer space is, as a rule, shorter than the axial one, so that the final state in the radial direction is achieved more rapidly. Both segregation processes do not cause the components to be completely separated. Individual parts of a mixture volume are enriched in respective components; as a consequence, after a long mixing time interval, an equilibrium state is achieved between the random and the completely segregated states.

These considerations have been confirmed by Rogers and Clements [10], who have found that in all cases a core was formed in the earlier stages of mixing, followed by the band formation. In opposition to Donald and Roseman, who have attributed the band formation to the effect of end walls of a mixer, Rogers and Clements have stated that one factor affecting the band formation is the proportion of smaller components in a mixture in relation to the volume of voids provided by the larger components. When this proportion is too high, the volume of voids is too small to receive all smaller particles and in that case the bands are less noticeable. Furthermore, they have found the considerable effect of the rotational speed of a mixer on the segregation rate (the lower the speed, the higher the segregation rate) and they have also indicated that the segregration takes place with the diameter ratio of particles less than 1.2:1, as was suggested by Donald and Roseman.

Yamaguchi et al. [11] have investigated the segregation due to density in a horizontal drum mixer. They have found considerable axial segregation with ultimate bands enriched in the lighter component; this effect has decreased with increasing the mixer length. In opposition to Rogers and Clements they have stated that the rotational speed of a mixer slightly influences the segregation.

Apart from the factors mentioned above, the segregation is strongly affected by the initial loading of a mixer. According to Donald and Roseman, the radial mixing followed by the axial one occurs only if a mixer is initially loaded with the components layered horizontally. For the end-to-end loading only the axial mixing can occur and the process is considerably slow. This was supported by the investigations of Rogers and Clements (horizontally layered loading) and Yamaguchi et al. (end-to-end loading).

3. Experimental Tests

The mixer, with a length of 120 mm and an internal diameter of 74 mm, was made of polyacrylic glass, and for the purposes of loading and sampling the upper part of the mixer was removable. In order to eliminate deviations during rotation the mixer was fixed in a lathe chuck and was driven through a two-stage belt transmission. The rotational speed of the mixer was 70 rpm. Particular attention was paid to careful levelling of the mixer, mainly because it had been stated that the horizontal deviation of 0.6 % caused a significant disturbance in the motion of particles.

Two sieve fractions of the sea sand were used as mixing materials, with size ranges of 0.2 to 0.25 mm and 0.385 to 0.43 mm, respectively. The sand was washed with benzene, carefully dried and sieved three times in laboratory sieves. The microscopical analysis showed the agreement of the particle sizes with the sieve meshes for 98—99 particles by 100 within both fractions.

Two series of experiments were performed, differing in the initial state of the mixture. In the first series, materials were end-to-end loaded so that the initial state of mixture was the complete segregation. In the second series, materials were initially randomly mixed in another mixer. In both series, the mixer was half-fully loaded and the weight ratio of components was 1:1.

After the determined mixing time the mixer was stopped and spot samples were removed according to the systematic sampling scheme, similar to Rogers and Clements. The mixer has been divided into 11 sections along the axis and in the middle of them a series of sampling planes were positioned. Three spot samples from each section were randomly taken, except for the middle section (No. 6), from which ten spot samples were taken. In order to position the sampling points the templet was made with the openings for inserting the sampling device; the templet was placed instead of the mixer lid during sampling. The location of sampling points is shown in Fig. 1.

The sampling device was similar to that described by Weidenbaum and Bonilla [7]. It was composed of two thin overlapping steel tubes (Fig. 2). The longer internal tube was blinded at the bottom end and the slit was cut at the

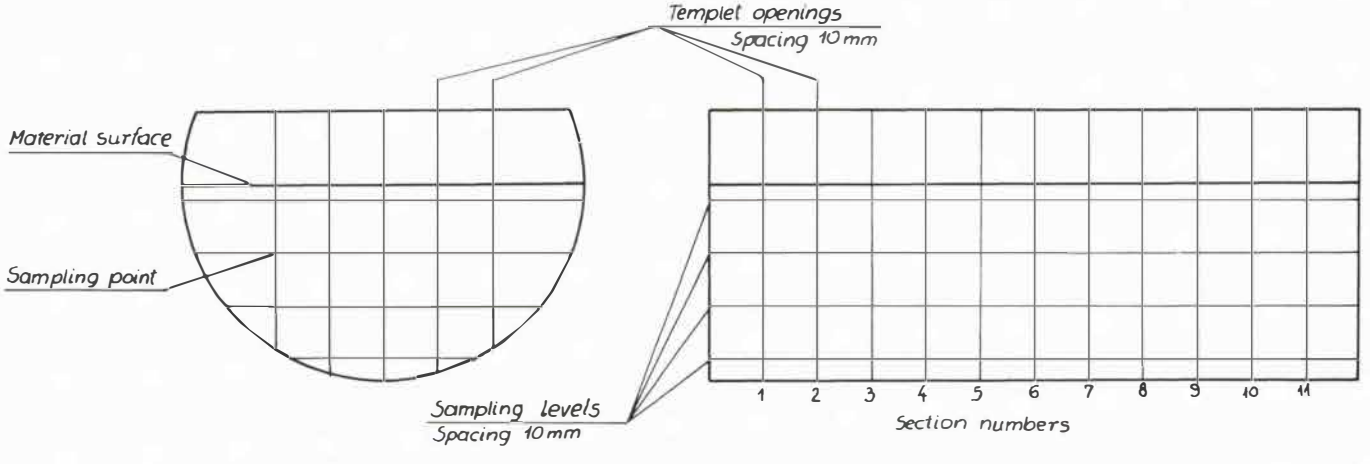

Fig. 1: Location of sampling points

distance about 3 mm above the bottom, so that 80 to 200 particles may be trapped into the sampler. The scale was cut on the external covering tube to fix the vertical location of a sampling point. The horizontal location was fixed by inserting the sampler into the appropriate opening in the templet.

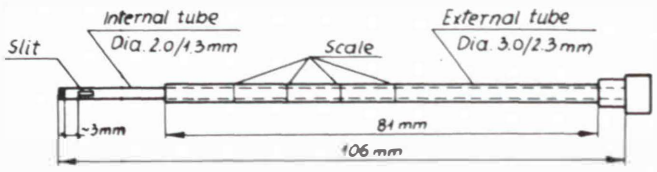

Fig. 2: Sampling device

The spot samples were poured into the measuring cells and were placed in the projection gauge with a magnification of 5:1. The samples were analysed by counting the particles of both components and calculating the number concentration of larger particles. The measurements were biased by an error of one to two particles per sample, because 2 to 3% of particles were elongated and it was difficult to include them into the proper fraction.

4. Results

Two series of experiments were carried out, differing only in the initial state of mixture. Each series consisted of three runs under identical mixing conditions, in order to estimate the repeatability of results. The samples were taken after a respective mixing time of 0, 4, 10, 20, 40, 60, 90, 120, 300 and 1080 mins (initial segregation), or 0, 2, 4, 6, 10, 420 mins (initial randomness). In order to ascertain that any horizontal deviations did not occur, in the runs of series with initial segregation the components were loaded from the left end to the right in two runs and from the right end to the left in the remaining run.

The resulting sample for each of the time periods consisted of 120 spot samples, i.e., 3 runs × (10 sections × 3 spot samples + 1 section × 10 spot samples). An analysis of spot samples gave the set of the number concentrations of the larger component. These results were worked out as follows:

1. The weight concentrations were calculated, according to the relation:

$$x_1 = \frac{\bar{x}_i w_i}{\bar{x}_i w_i + \bar{x}_i w_i} \tag{1}$$

2. Repeatability for all three runs of a given series was examined using the t test of accordance of sectional mean values of concentrations for individual runs. In all cases the differences between mean values were insignificant at 95% significance level.
3. The overall mean value for each section was calculated and the concentration profiles along the mixer axis were drawn (Figs. 3a—d and 4a—c).
4. For the middle section (No. 6), from which ten spot samples were taken in every run, the examination of core formation was performed. With this purpose the spot samples taken from the central region of the section were separated from the peripheral ones. The t test of accordance of mean concentration values between both sets of spot samples was performed. In all cases differences were insignificant at 95% significance level. This proved the absence of radial segregation in the mixer.
5. The analysis of variance of concentrations was carried out in order to compare the variances between sections with the variances inside sections. The variances were calculated as follows:

$$\sigma_t^2 = \frac{\sum_{i=1}^{11} \sum_{j=1}^{k_i} (x_{ji} - x_m)^2}{119} \tag{2}$$

$$\sigma_{bs}^2 = \frac{\sum_{i=1}^{11} k_i (x_{im} - x_m)^2}{10} \tag{3}$$

$$\sigma_{is}^2 = \frac{\sum_{i=1}^{11} \sum_{j=1}^{k_i} (x_{ji} - x_{im})^2}{109} \tag{4}$$

$$F = \frac{\sigma_{bs}^2}{\sigma_{is}^2} \tag{5}$$

The results, presented in Tables 1 and 2, show that the axial segregation in the mixer is significant. The graphs of total variance vs. time for both series, shown in Fig. 5, may be considered as the mixing curves.

5. Discussion

The examination of concentration profiles (Figs. 3 and 4) indicates appreciable axial segregation in the mixture. At the final state an almost pure larger component is situated near the end walls of the mixer, whereas in approximately half distance from the middle of the mixer the sections are enriched in the smaller component particles (sections Nos. 4 and 8). Such axial concentration profiles are consistent with previous observations [7, 8, 10, 11], as well as with Donald and Roseman's theory of axial segregation.

Very interesting conclusions may be drawn from the comparison of two processes of mixing starting from the opposite initial states. Fig. 5 demonstrates that in both cases an almost identical final degree of mixedness has been reached, and the comparison of Figs. 3d and 4c indicates that the final concentration profiles are also congruent. This may lead to the conclusion that the final (equilibrium) state of a mixture does not depend on the initial conditions.

Whereas the fact of absence of radial segregation in the end-to-end loading agrees with earlier observations [8], its absence in the random initial loading is evoking reflections. It may lead to the conclusion that a core arises only when it is introduced by initial loading. It takes place, for example, when components are initially horizontally layered and the core nucleus is being formed during the first several revolutions; a mechanism of this initiation is convectional rather than diffusional.

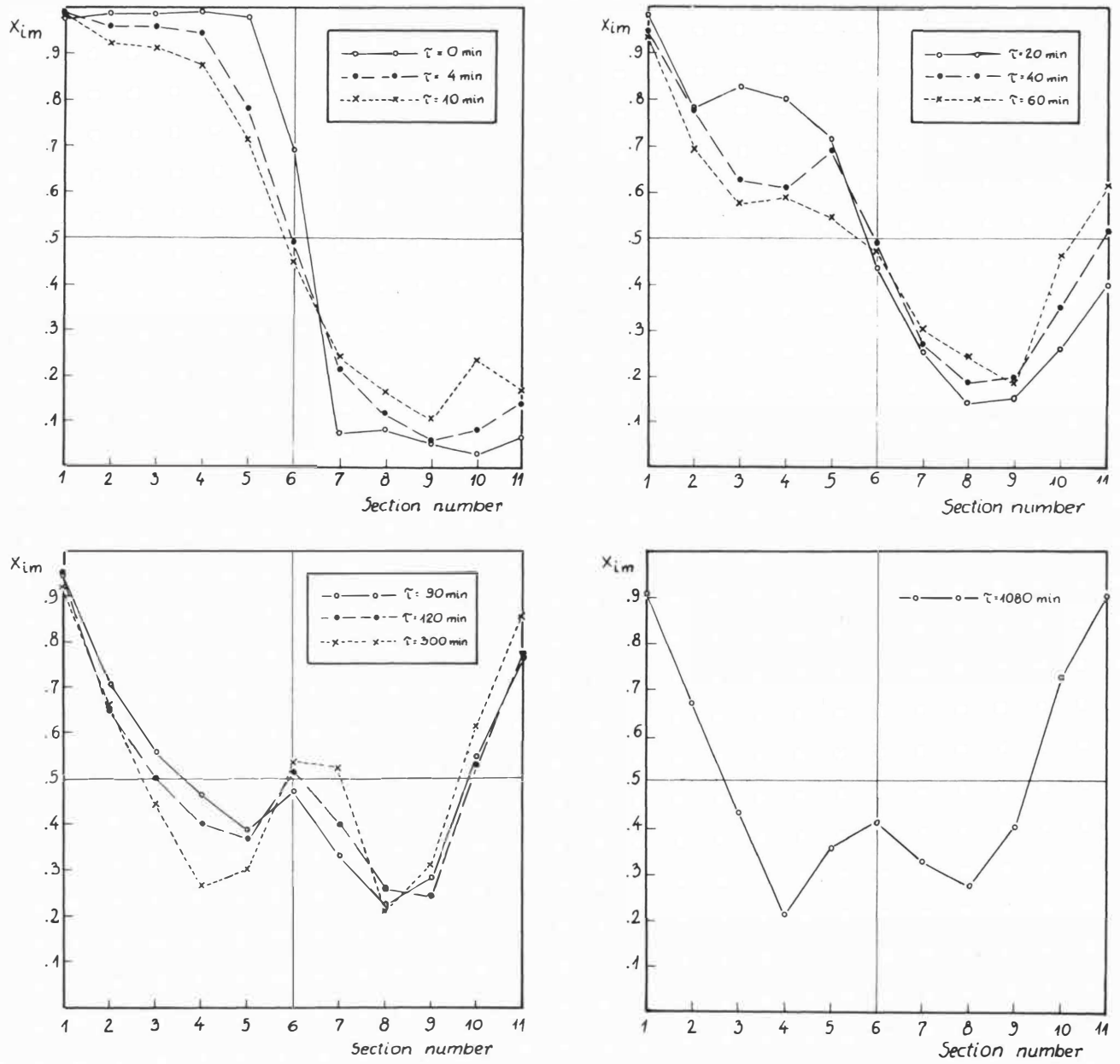

Fig. 3: Concentration profiles — initial segregation
a) τ = 0; 4; 10 min
b) τ = 20; 40; 60 min
c) τ = 90; 120; 300 min
d) τ = 1080 min (equilibrium)

The analysis of variances (Tables 1 and 2) shows a significance of inter-sectional variances in relation to those inside sections (the F values) in all cases, except for the initial random state in the second series (the critical F value, $F_{0.05;\,10;\,109}$ = 1.93). It has been also found that the distribution of mean concentrations at individual time periods, as well as the distribution of variances inside sections, are normal; this is evidence of the validity of the sampling scheme used.

Table 1: Analysis of variance — initial segregation

τ, min	0	4	10	20	40	60	90	120	300	1080
x_m	0.536	0.507	0.508	0.505	0.508	0.503	0.491	0.505	0.507	0.485
σ_t^2	0.1819	0.1352	0.1062	0.0871	0.0655	0.0590	0.0511	0.0583	0.0586	0.0584
σ_{bs}^2	1.9292	1.4832	1.1385	0.8387	0.5318	0.4287	0.4363	0.4087	0.5049	0.5687
σ_{is}^2	0.0170	0.0093	0.0097	0.0168	0.0211	0.0238	0.0148	0.0252	0.0161	0.0098
F	113.5	159.5	117.4	49.9	25.2	18.0	29.5	16.2	31.4	58.0

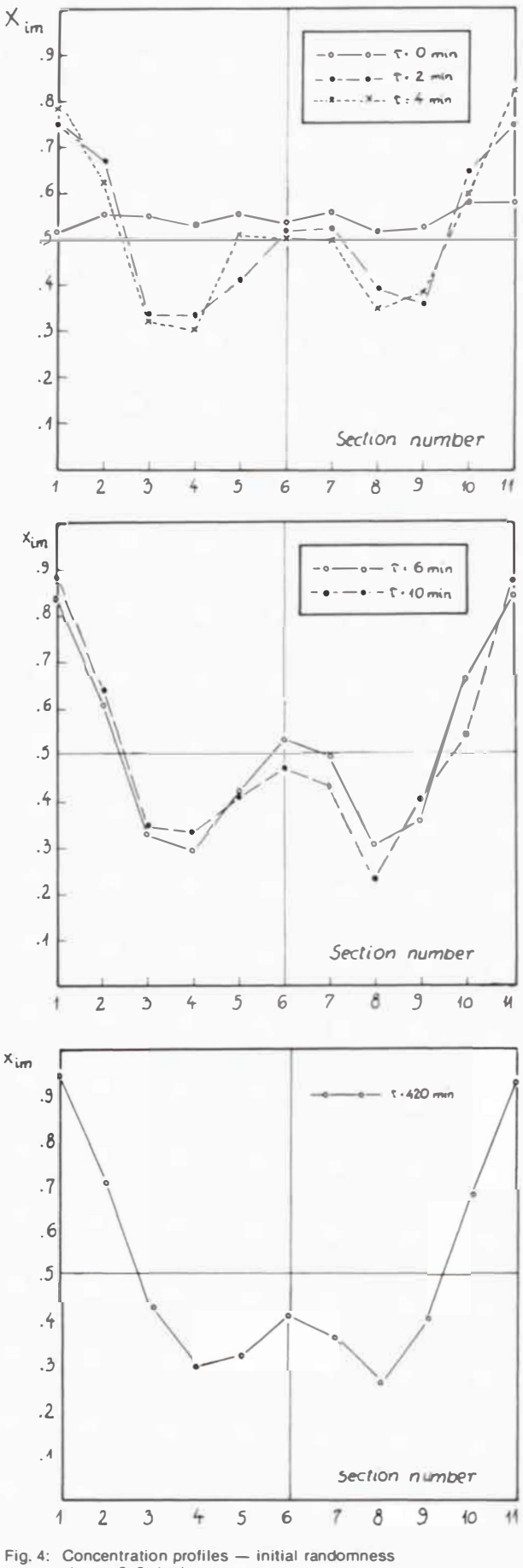

Fig. 4: Concentration profiles — initial randomness
a) τ = 0; 2; 4 min
b) τ = 6; 10 min
c) τ = 420 min (equilibrium)

Table 2: Analysis of variance — initial randomness

τ, min	0	2	4	6	10	420
x_m	0.550	0.520	0.519	0.525	0.507	0.527
σ_I^2	0.0087	0.0303	0.0372	0.0457	0.0527	0.0642
σ_{bs}^2	0.0050	0.1952	0.2813	0.3753	0.4139	0.5613
σ_{is}^2	0.0092	0.0122	0.0099	0.0085	0.0117	0.0078
F	0.54	16.0	28.4	44.2	35.4	72.0

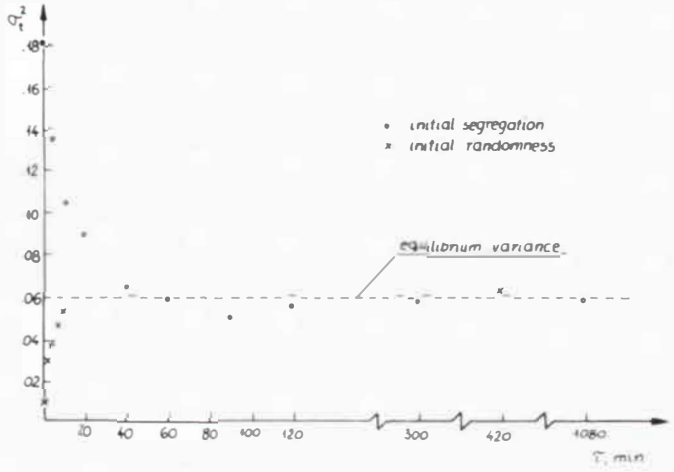

Fig. 5: Progress of mixing (σ_I^2 vs. τ)

6. Final Comments

Materials of different sizes tend distinctly to segregate when mixing in a horizontal drum mixer. The segregation is most effective near the end walls of a mixer, where almost exclusively larger particles accumulate. The segregation mechanism depends on the initial loading of components. In the end-to-end initial loading, as well as in the random one, only axial segregation occurs and the final equilibrium state is the same in both cases. Donald and Roseman's [8] theory seems to explain the axial segregation satisfactorily.

The authors believe that the systematic sampling scheme used in this work depicts properly the state of a mixture.

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