Proc. Estonian Acad. Sci. Engng., 1997, **3**, 1, 35–49
https://doi.org/10.3176/eng.1997.1.04

INNER FRICTION FACTOR OF FINE POWDERS

Jüri TADOLDER and Jaan TAMM

Department of Machine Science, Tallinn Technical University, Ehitajate tee 5, EE-0026 Tallinn, Estonia

Received 11 June 1996, revised 3 September 1996, accepted 11 December 1996

Abstract. This study discusses the measurements and dependencies of the inner friction factor of fine powders. To estimate the inner friction factor of different size groups of fine powder materials, a simple method and the well-known test rig for the determination of shear strength of soils were used. The variables investigated were: material type, powder fineness and pressure between the powder particles. Detailed test results were achieved for quartz sand and limestone, fine-milled cast iron, fillers for the paper industry, silica gel, and chalk.

Key words: powder material, inner friction factor, impact milling, disintegrator, modelling of the milling process.

1. INTRODUCTION

Impact milling and its applications, particularly disintegrator technology, have been established in Estonia. Highly productive hammer mills are being applied in the building materials industry and at Estonia´s power stations. Disintegrators operate to mill foodstuffs, to process lime and sand mixtures in the silicalcite-concrete industry and to prepare materials in laboratories. The results of research related to impact milling have spread both locally and internationally.

Estonian-made equipment was mainly imported to the former Soviet Union. In addition, Estonia can be regarded as a centre of disintegrator technology, where the impact milling theory was developed. Among the institutions in this field, *Desintegraator* and *Silbet*, research and production associations, as well as Tallinn Technical University, were dominant.

By modelling powder material movement in a disintegrator, optimum technological processing parameters of rotors and milling bodies can be determined [1]. Today, about 10% of the electrical energy produced is used for the milling process. Thus, an efficient design of the milling equipment could lead to substantial saving [2]. Accurate rotor design and proper material movement speeds on the milling bodies as well as impact speeds facilitate the formation of the self-lining of impact surfaces, thus decreasing the wear rate markedly. It could be applied to achieve wear-resistant design of the high-speed impact milling equipment [3, 4]. To obtain proper results, the study of the friction factor between the powder particles and the equipment surfaces is essential. This article discusses the measurements and dependencies of the inner friction factor of a fine powder.

By a simple method, we estimated the inner friction factor of different size groups of various fine powder materials. The well-known test rig for the determination of shear strength of soils was used. This installation is based on shifting two cylinders, filled with powder, under fixed pressure relative to each other, and on determining the shifting force.

Dependence of the inner friction factor of fine powders on different parameters was obtained. The investigated variables were: material type, powder fineness, and pressure between the powder particles. Of the variables, the pressure between the powder particles is most significant. Detailed test results were achieved for quartz sand and limestone, crushed in high-speed impact milling equipment. To investigate the properties of fine powders, the fine-milled cast iron, fillers for the paper industry, silica gel, and chalk were tested. These results can be used to calculate powder particle and layer movement in mills and classifiers [1] by a PC ROTOR program.

2. TEST RIG

According to soil mechanics, the resistance of soil to shear (shear strength) depends on the specific stress in the soil as well as on its structure. To test the soil, special equipment has been designed and manufactured (Fig. 1), and the standards have been certified according to GOST 12248-78 [5]. The function of the installation is to shift two cylinders filled with soil under fixed pressure relative to each other and to determine the shifting force. The existing test rig should be adjustable to accommodate and implement these procedures for certain powder technology applications. A more detailed instruction in GOST 12248-78 for testing conditions in the rig contains the requirements for practical adjustments and additions.

To achieve proper test results, the material being tested should not leak from the space between the fixed and the moving parts (Fig. 1). Such occurrence influences the test results quite considerably and leads to a certain systematic deviation. With coarse powders, such problem is not observed, but under higher normal pressure, in the case of fine powders (less than 150–200 μm), powder particles start moving off the above-mentioned space. To avoid that, the junction between the fixed and the moving parts, as well as the junction between the axles and rollers must be finished up.

Another requirement is that the rolling resistance of the rollers should be as minimal as possible. This means keeping the rolling surfaces clean and the position of the axles of the rollers geometrically regular. In fact, the resistance of the test rig itself can be eliminated by an idle testing.

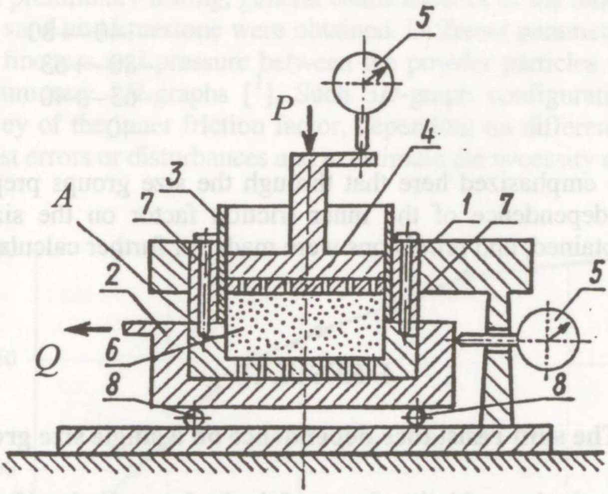

Fig. 1. Principal scheme of the test rig: *1*, fixed part; *2*, moving part; *3*, cylinder; *4*, piston; *5*, indicators; *6*, material being tested; *7*, directors; *8*, rollers; *A*, space between the fixed and moving parts.

3. SAMPLE PREPARATION

In this study, powder sample preparation involves breaking and classifying the required number and amount of material.

The whole volume of the test rig cylinders was 75 cm^3, equal to the minimal volume of the test sample. Taking into account possible losses during repeated check tests, each sample should be at least 150–200 cm^3, distributed homogeneously into the required number of test samples.

The quartz sand samples were prepared from the Männiku standard sand (Estonia). Milled in a disintegrator [6], the sand was classified by means of analytical sieves into the following seven size groups, µm:

–1250–+700 (particle size less than 1250 and more than 700 µm)
–700–+315
–315–+280
–280–+140
–140–+80
–80–+40
–40

Additionally, two extra fine groups were prepared by the help of a centrifugal classifier [7] : –20 and –10 µm.

Sample preparation in a disintegrator determines the special shape of the powder particles (typical of impact milling), as well as a more narrow granulometric composition. But using these samples and test results for a definite application – modelling of similar impact milling equipment – the particular sample preparation in a disintegrator is acceptable.

The test samples from limestone powders were prepared quite similarly to the samples of quartz sand, only without classifying eight extra fine fractions, µm:

−1250–+700 −140–+80
−700–+315 −80–+63
−315–+280 −63–+40
−280–+140 −40

It should be emphasized here that through the size groups prepared, a good review of the dependence of the inner friction factor on the size of powder particles was obtained, and provisions were made for further calculations.

4. RESULTS

4.1. The shift resistance dependence on a single size group

To determine the inner friction factor of the broken and classified quartz sand samples, about 70 separate single tests were made. To conduct limestone powder testing, first, some experience was gained. For the whole testing series, about 50 single tests were performed [8, 9]. For an increased accuracy, repetition of tests is essential.

The graph in Fig. 2 shows the shift resistance, depending on the deformation of a particular size group of the quartz sand (−140–+80 μm) under normal pressure $p = 0.147$ MPa. An analogous dependence of limestone powder is shown on the graph in Fig. 3.

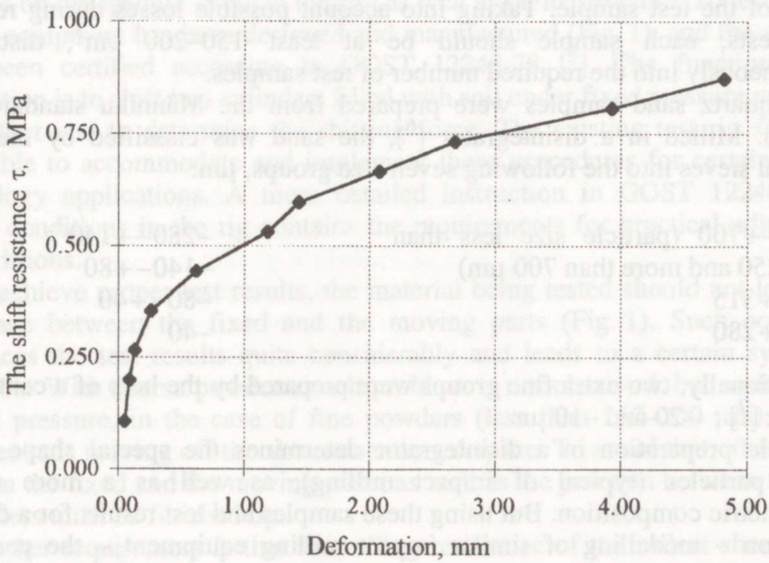

Fig. 2. Dependence of the shift resistance on deformation, quartz sand −140–+80 μm, $p = 0.147$ MPa.

During the preliminary testing, general characteristics of the inner friction factor of fine quartz sand and limestone were obtained. Different parameters like material type, powder fineness and pressure between the powder particles were studied by the help of summary *3D*-graphs [1]. Such *3D*-graph configurations provide an excellent survey of the inner friction factor, depending on different parameters, to uncover the test errors or disturbances and to estimate the necessity of repeated tests.

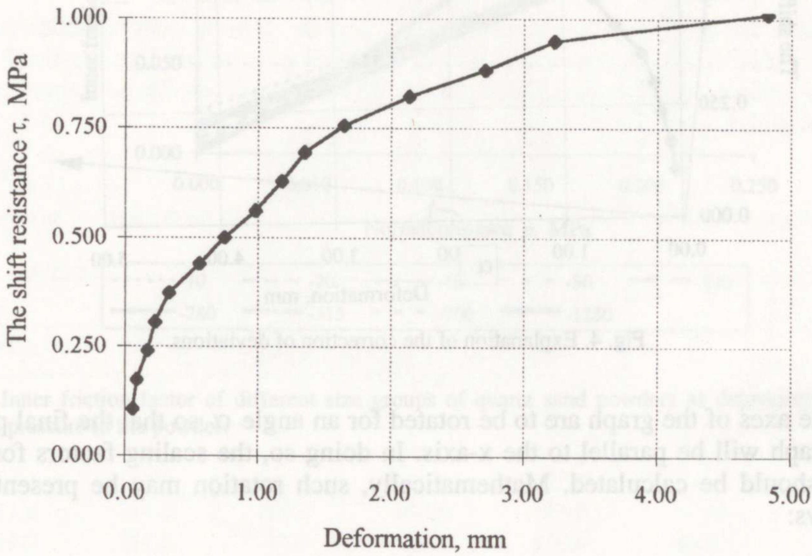

Fig. 3. Dependence of the shift resistance on deformation, limestone −140 – +80 μm, $p = 0.147$ MPa.

Besides the quartz sand and limestone tests, friction properties of various industrial fine powders were studied and compared. These include the powders processed by impact milling or used for impact milling; in addition, narrow size limits of particles were analysed. The fine-milled cast iron, fillers for the paper industry, silica gel, and chalk were tested and the results were compared.

4.2. Processing of single test results

Test results (Figs. 2 and 3) show that the shift resistance does not increase with deformation. In fact, the final value of the shift resistance is the inner friction factor of a size group of the powder material.

In practice, systematic errors or disturbances cause a systematic deviation of the results. As a result of our further analysis, such deviations were found to be regular and were eliminated. This elimination may be accomplished by means of the graphic solution described in Fig. 4.

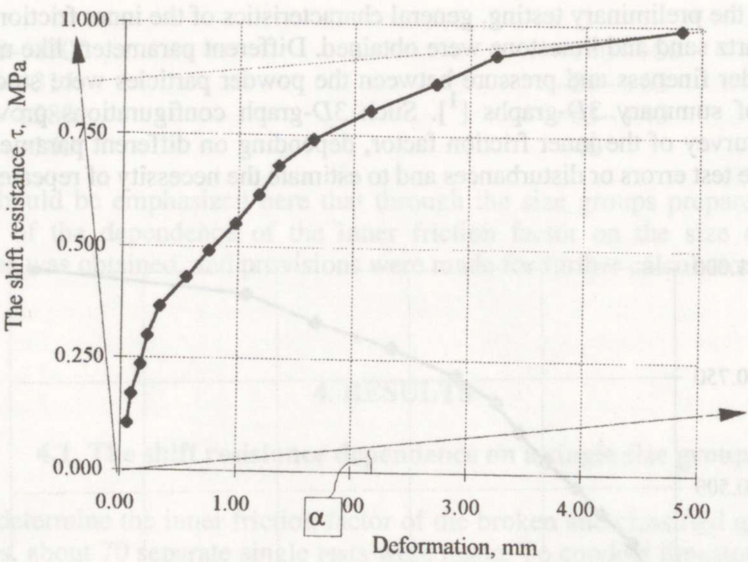

Fig. 4. Explanation of the correction of deviations.

The axes of the graph are to be rotated for an angle α so that the final part of the graph will be parallel to the **x**-axis. In doing so, the scaling factors for both axes should be calculated. Mathematically, such rotation may be presented as follows:

$$x_1 = y \cos \alpha - x \sin \alpha ,$$
$$y_1 = x \cos \alpha + y \sin \alpha , \tag{1}$$

where x, y, coordinates of a point in preliminary axes; x_1, y_1, coordinates of the same point in rotated axes.

The limit value of the shift resistance, the actual inner friction factor, may be simply determined after such turning from the "corrected" graph of dependence according to the "corrected" coordinates (1).

4.3. Inner friction factor of the narrow size group

Generally, the dependence of the inner friction factor for a narrow size group on the normal pressure, is linear (Fig. 5), which may be presented by a simple formula

$$\tau = \mathbf{A} + \mathbf{B}p , \tag{2}$$

where p, normal pressure; **A**, **B**, coefficients to be determined from the single tests.

In our analysis of different size groups of quartz sand and limestone powders, some regularities were found. For instance, the dependence of the inner resistance factor on the normal pressure in the graphs is higher for coarse powders. It means that the value of the coefficient **B** in Eq. (2) for larger size groups is greater. This rule is more evident for quartz sand powders (Fig. 5).

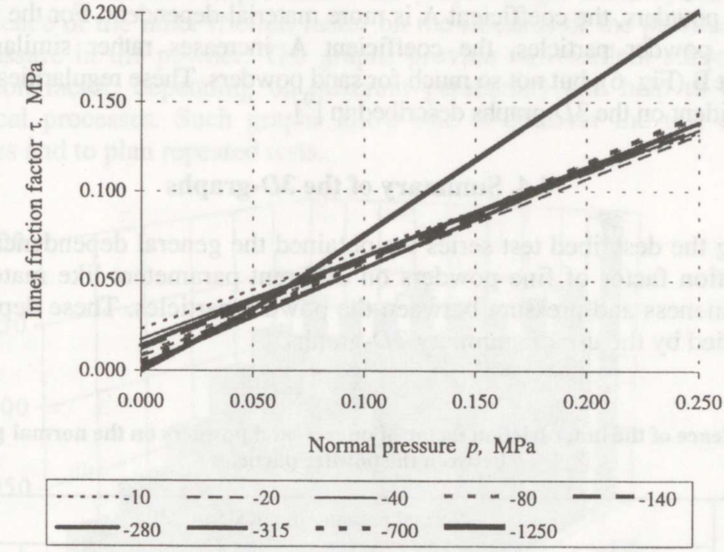

Fig. 5. Inner friction factor of different size groups of quartz sand powders as dependent on the normal pressure in the powder.

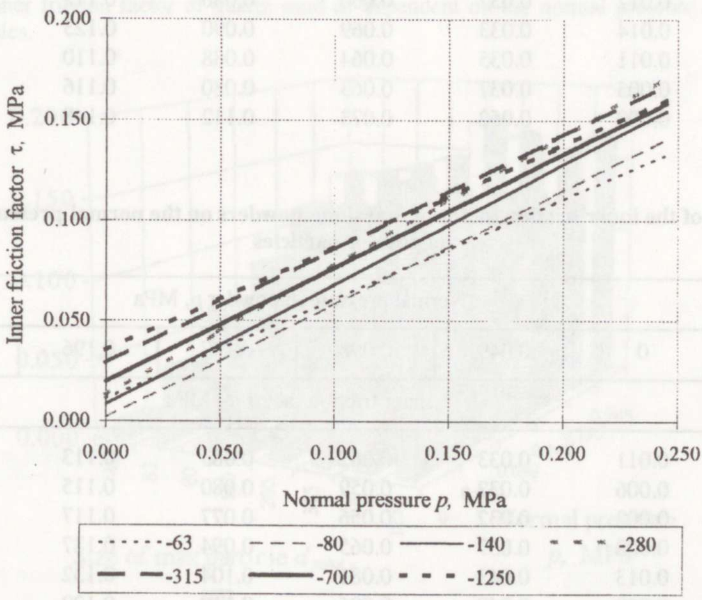

Fig. 6. Inner friction factor of different size groups of limestone powders as dependent on the normal pressure in the powder.

According to our preliminary tests and comparisons between the quartz sand and limestone powders, the coefficient **A** is more material-dependent. For the larger size limestone powder particles, the coefficient **A** increases rather similarly to the coefficient **B** (Fig. 6), but not so much for sand powders. These regularities were also clearly evident on the 3*D*-graphs described in [9].

4.4. Summary of the 3*D*-graphs

During the described test series we obtained the general dependencies for the inner friction factor of fine powders on different parameters like material type, powder fineness and pressure between the powder particles. These dependencies were studied by the use of summary 3*D*-graphs.

Table 1

Dependence of the inner friction factor of quartz sand powders on the normal pressure between the powder particles

Size of max. particle d_{max}, µm	Normal pressure in powder p, MPa					
	0	0.049	0.098	0.147	0.196	0.245
	Inner friction factor τ, MPa					
10	0.023	0.041	0.067	0.096	0.115	0.130
20	0.008	0.033	0.054	0.083	0.113	0.127
40	0.017	0.030	0.070	0.088	0.113	0.127
80	0.008	0.035	0.058	0.101	0.112	0.140
140	0.012	0.037	0.060	0.086	0.115	0.132
280	0.014	0.033	0.069	0.090	0.123	0.127
315	0.011	0.035	0.064	0.088	0.110	0.138
700	0.005	0.037	0.063	0.080	0.116	0.151
1250	0.000	0.052	0.073	0.112	0.148	0.214

Table 2

Dependence of the inner friction factor of limestone powders on the normal pressure between the powder particles

Size of max. particle d_{max}, µm	Normal pressure in powder p, MPa					
	0	0.049	0.098	0.147	0.196	0.245
	Inner friction factor τ, MPa					
40	0.011	0.033	0.062	0.083	0.113	0.129
63	0.006	0.032	0.059	0.080	0.115	0.132
80	0.002	0.032	0.056	0.077	0.117	0.138
140	0.008	0.037	0.065	0.094	0.137	0.147
280	0.013	0.043	0.081	0.104	0.132	0.177
315	0.029	0.048	0.096	0.110	0.129	0.167
700	0.020	0.047	0.078	0.096	0.133	0.157
1250	0.035	0.066	0.083	0.103	0.132	0.167

Tables 1 and 2 and the comprehensive 3*D*-graphs (Figs. 7 and 8) demonstrate the dependence of the inner friction factor on the fineness of the powder and the normal pressure in the powder. The graphs provide an excellent survey of the inner friction factor, depending on different parameters and help to calculate technological processes. Such graphs allow one to uncover the test errors or disturbances and to plan repeated tests.

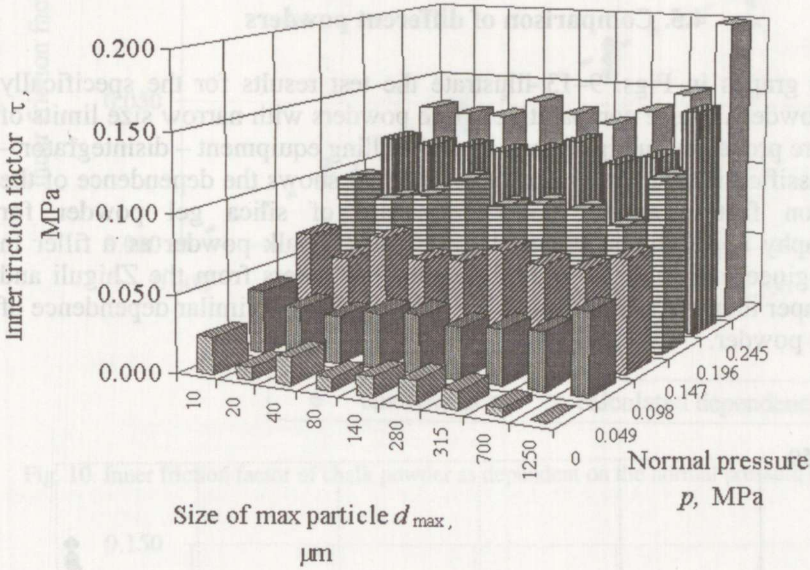

Fig. 7. The inner friction factor of quartz sand as dependent on the normal pressure between the powder particles.

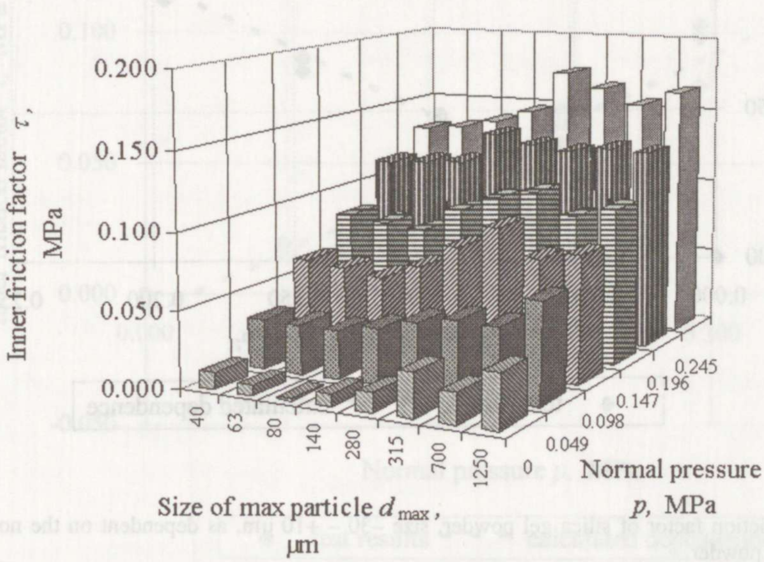

Fig. 8. The inner friction factor of limestone as dependent on the normal pressure between the powder particles.

In the future, such summary graphs would facilitate modelling of the algorithms for the determination of the inner friction factor of different fine powders, depending on the conditions of the treatment and preparation of technological equipment.

4.5. Comparison of different powders

The five graphs in Figs. 9–13 illustrate the test results for the specifically processed powders. These comparatively fine powders with narrow size limits of particles were processed in high-speed impact milling equipment – disintegrator – and then classified in an inertial separator. Figure 9 shows the dependence of the inner friction factor on the normal pressure of silica gel powder for chromatography applications. Figure 10 illustrates chalk powder as a filler in chemical engineering; Figs. 11 and 12 demonstrate fillers from the Zhiguli and Slavjansk paper industry (Russia); and Fig. 13 introduces a similar dependence of the cast iron powder.

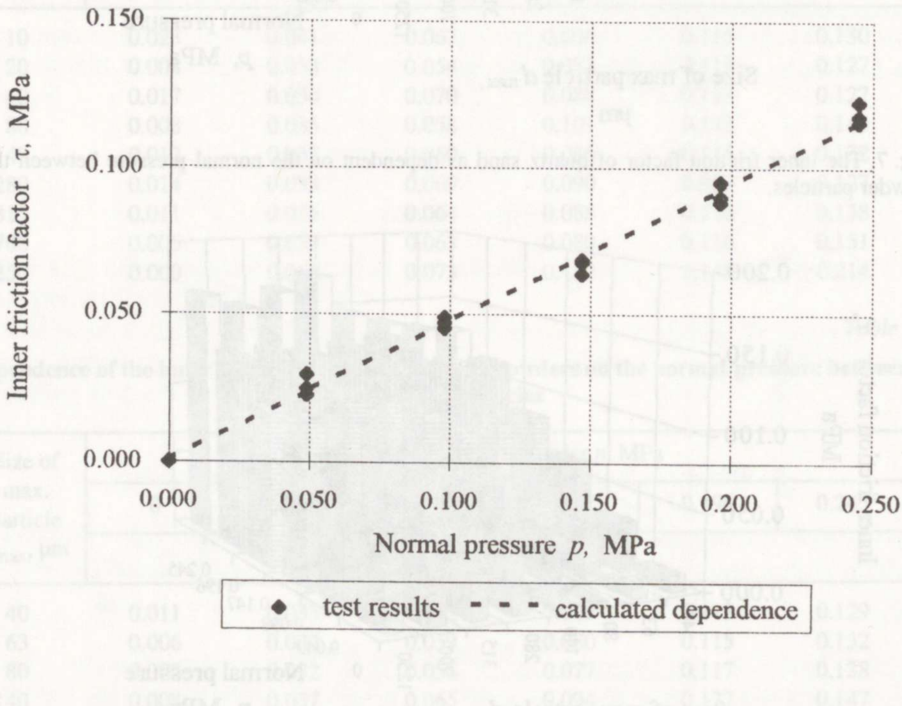

Fig. 9. Inner friction factor of silica gel powder, size −30 – +10 μm, as dependent on the normal pressure in the powder.

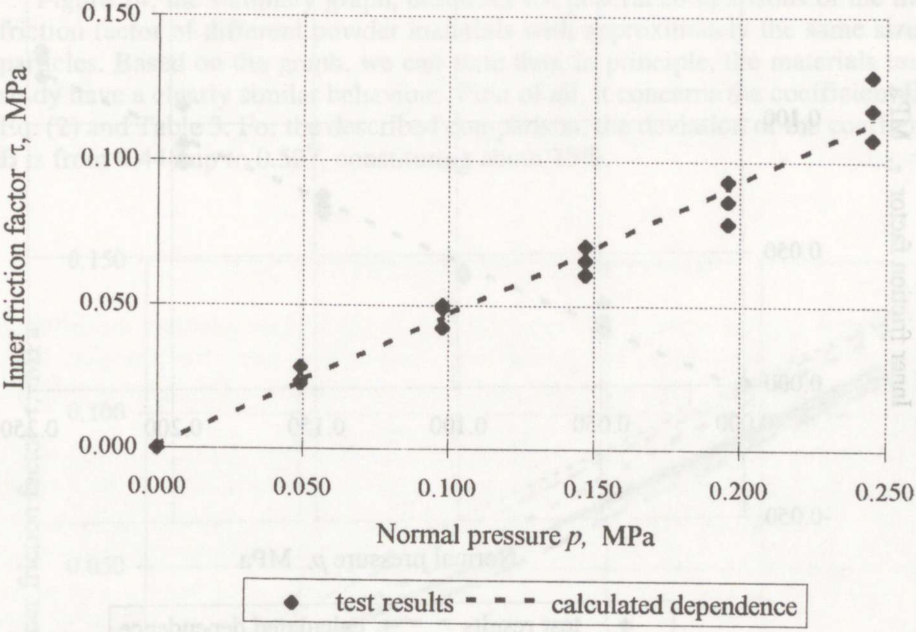

Fig. 10. Inner friction factor of chalk powder as dependent on the normal pressure in the powder.

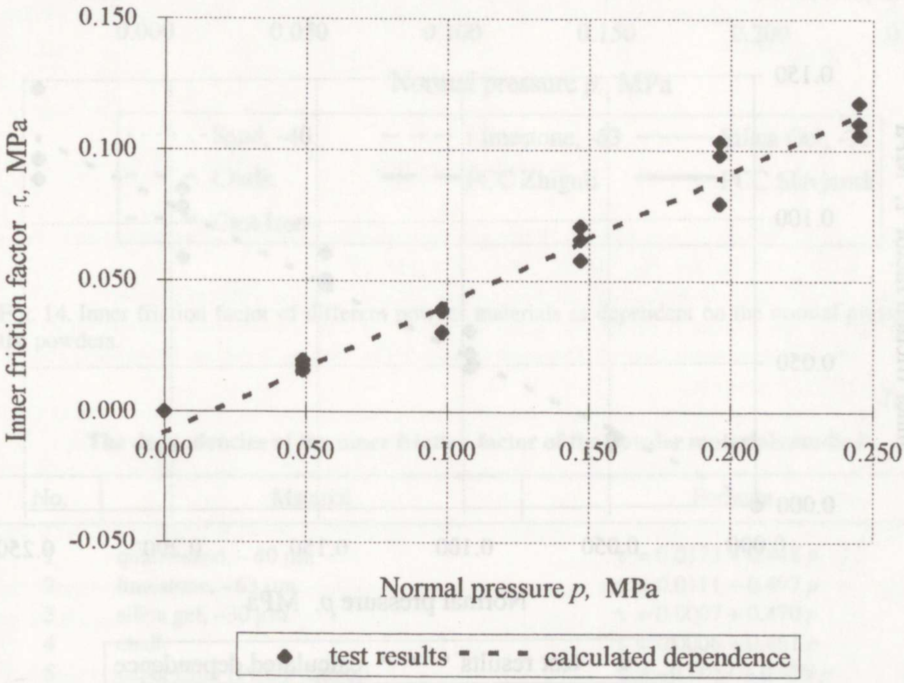

Fig. 11. Inner friction factor of paper filler (Zhiguli, Russia) as dependent on the normal pressure in the powder.

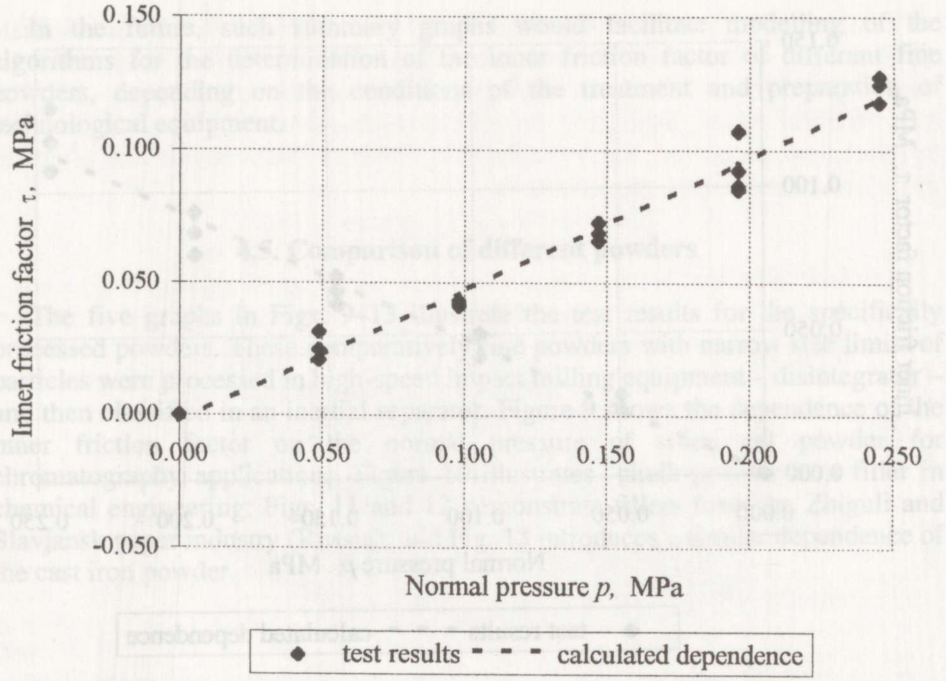

Fig. 12. Inner friction factor of paper filler (Slavjansk, Russia) as dependent on the normal pressure in the powder.

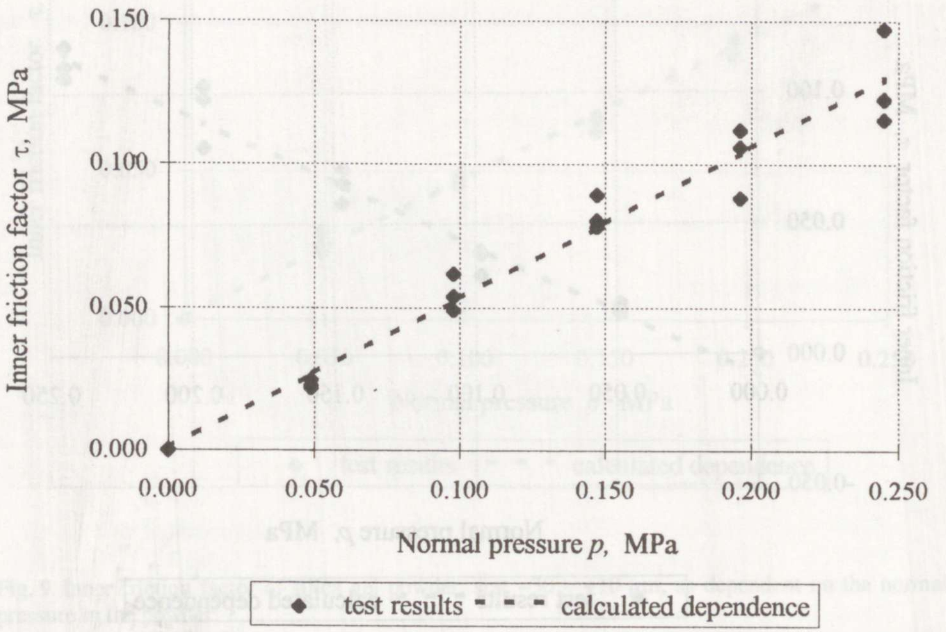

Fig. 13. Inner friction factor of cast iron powder as dependent on the normal pressure in the powder.

Figure 14, the summary graph, describes the general comparisons of the inner friction factor of different powder materials with approximately the same size of particles. Based on the graph, we can state that, in principle, the materials under study have a clearly similar behaviour. First of all, it concerns the coefficient **B** in Eq. (2) and Table 3. For the described comparison, the deviation of the coefficient **B** is from 0.448 up to 0.527, constituting about 15%.

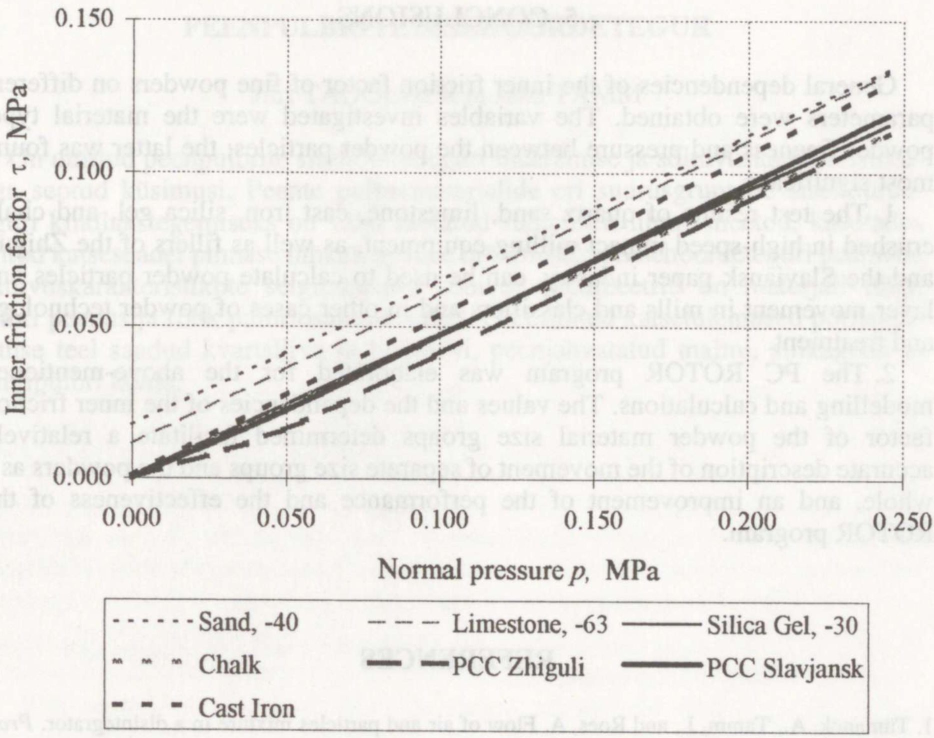

Fig. 14. Inner friction factor of different powder materials as dependent on the normal pressure in the powders.

Table 3

The dependencies of the inner friction factor of the powder materials studied

No.	Material	Formula
1	quartz sand, – 40 µm	$\tau = 0.0173 + 0.448\,p$
2	limestone, –63 µm	$\tau = 0.0111 + 0.497\,p$
3	silica gel, –30 µm	$\tau = 0.0007 + 0.470\,p$
4	chalk	$\tau = 0.0006 + 0.461\,p$
5	paper filler (PCC), Zhiguli	$\tau = -0.0087 + 0.499\,p$
6	paper filler (PCC), Slavjansk	$\tau = -0.0025 + 0.497\,p$
7	cast iron	$\tau = 0.0007 + 0.527\,p$

These formulas in Table 3 can be used to calculate the movement of powder particles and of the layer in the mills and classifiers [1] by the special PC ROTOR program. They also facilitate milling equipment design, allow us to calculate accurate material movement speeds on milling bodies, and to find the required impact speeds to break initial material properly and to create optimal milling conditions.

5. CONCLUSIONS

General dependencies of the inner friction factor of fine powders on different parameters were obtained. The variables investigated were the material type, powder fineness and pressure between the powder particles; the latter was found most significant.

1. The test results of quartz sand, limestone, cast iron, silica gel, and chalk crushed in high-speed impact milling equipment, as well as fillers of the Zhiguli and the Slavjansk paper industry, can be used to calculate powder particles and layer movement in mills and classifiers and in other cases of powder technology and treatment.

2. The PC ROTOR program was elaborated for the above-mentioned modelling and calculations. The values and the dependencies of the inner friction factor of the powder material size groups determined facilitate a relatively accurate description of the movement of separate size groups and the powders as a whole, and an improvement of the performance and the effectiveness of the ROTOR program.

REFERENCES

1. Tümanok, A., Tamm, J., and Roes, A. Flow of air and particles mixture in a disintegrator. *Proc. Estonian Acad. Sci. Phys. Math.*, 1994, **43**, 4, 280–292.
2. Tamm, J. *Separative Grinding of Solid Fuels*. Cand Dissert. Tallinn, 1987 (in Russian).
3. Tadolder, J. and Tamm, J. *Modelling of the Movement of Fine Powders in Disintegrators and Inertial Separators*. Annual Technical Report, 1993. Tallinn Technical University, Tallinn, 1993 (in Estonian).
4. Tamm, J. On aerodynamical testing and adjusting of the disintegrator-based systems with external classifier. In *Theses of the 8th All-Union Seminar Disintegrator Technology*, Kiev, Oct. 1–3, 1991, 19–20. Research and Production Association Desintegraator, Kiev, 1991 (in Russian).
5. *GOST 12248-78. Soils. Laboratory Methods for Determination of Shear Strength.* Editorial Board of Standards, 1979 (in Russian).
6. Tümanok, A., Tamm, J., and Sarandi, J. Disintegrator-separator. USSR Author´s Certificate No 1716667 (B02C23/10). Application No 4215953/29–33, March 25, 1987; decision on issue – September 7, 1987 (in Russian, not published).
7. Tamm, J. and Kangur, H. Centrifugal Classifier. Application for USSR Author´s Certificate No 5055669 from July 21, 1992; decision on issue of the patent of Russian Federation 1993 (in Russian).

8. Tadolder, J. and Tamm, J. *Modelling of the Movement of Fine Powders in Disintegrators and Inertial Separators*. Annual Technical Report, 1994. Tallinn Technical University, Tallinn, 1994 (in Estonian).

9. Tamm, J., Tümanok, A., and Tadolder, J. On inner friction factor of fine powders and application for calculation of material movement in impact mills. In *Proc. OST-95 Symp. Machine Design*, Oulu, Finland, May 18–19, 1995. University of Oulu, Oulu, 1995, 112–121.

PEENPULBRITE SISEHÕÕRDETEGUR

Jüri TADOLDER ja Jaan TAMM

On uuritud peenpulbrite sisehõõrdeteguri määramise ja sõltuvuskarakteristikutega seotud küsimusi. Peente pulbermaterjalide eri suurusgruppide sisehõõrdeteguri kindlakstegemiseks on välja töötatud suhteliselt lihtne meetod, kasutades tuntud katseseadet pinnase nihketugevuse mõõtmiseks. Sisehõõrdeteguri peamiste sõltuvuskarakteristikute selgitamiseks sobivad parameetrid on materjali tüüp, pulbri peenus ja rõhk pulbriosakeste vahel. On esitatud katsetulemused põrkejahvatuse teel saadud kvartsliiva ja lubjakivi, peenjahvatatud malmi, silikageeli ja kriidipulbri kohta.