Particle Size and Distribution of Bulk Solids as Parameters that Significantly Influence their Flow Behaviour

Velikost delcev in porazdelitev velikosti delcev kot parametra, ki pomembno vplivata na lastnosti tečenja sipkih snovi

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Abstract: Particle size and particle size distribution of bulk solids can significantly influence their flowing behaviour, and many of the handling problems that arise in practice can be ascribed to unplanned changes of particle size and/or distribution of the bulk solid being handled.

In the present paper, the experimental results of measuring the rathole index - RI by the Johanson Hang Up Indicizer for different mixtures of finegrained and coarsegrained powders are presented and discussed. By measuring the rathole index we wanted to prove the dominant influence of fine particles on the flow behaviour of bulk solids.

The main conclusion was that if all the other parameters influencing the cohesive strength are constant, the cohesive strength of bulk solids increases as the particle size decreases and/or the particle size distribution widens.

Izvleček: Velikost delcev in porazdelitev velikosti delcev pomembno vplivata na obnašanje sipkih snovi in marsikatero težavo, ki nastane v praksi pripišemo ravno nenačrtovanim spremembam velikosti delcev in/ali porazdelitvi velikosti delcev pri materialih, s katerimi imamo opravka.

V članku so predstavljeni rezultati merjenja indeksa lijakastega iztoka – RI indeksa z napravo Johanson Hang Up Indicizer za različne mešanice grobe in fine frakcije. Z merjenjem tega indeksa smo želeli prikazati dominanten vpliv finih delcev na lastnosti tečenja sipkih snovi.

Ena od pomemnejših ugotovitev je bila, da se ob vseh ostalih parametrih (konstantnih), ki vplivajo na obnašanje sipke snovi, kohezijska trdnost sipkih snovi povečuje z manjšanjem velikosti delcev in/ali s širjenjem območja velikosti delcev.

Key-words: Bulk Solids, Particle Size and Particle Size Distribution, Silo, Flow Behaviour of Bulk Solids, Johanson Hang Up Indicizer.

Ključne besede: sipke snovi, velikost delcev in porazdelitev velikosti delcev, silos, lastnosti tečenja sipkih snovi, Johanson Hang Up Indicizer.

Scientific paper

INTRODUCTION

When bulk solids are being discharged out of a silo, they flow due to gravity in one of the two flow patterns: mass flow and funnel flow. An undesired phenomenon, which often appears in the first case, is a cohesive arch forming, and in the second case, a rathole or stable pipe[1]. The probability of cohesive arch or rathole forming arises due to the cohesive strength of bulk solid when it is consolidated. If all the other parameters influencing the cohesive strength are constant, the cohesive strength of bulk solids increases as the particle size decreases and/or the particle size distribution widens.

Particle size and particle size distribution of bulk solids are two properties that can significantly influence their flow behaviour. In the past, some observations concerning these influences were made, because many of the handling problems that arise in practice can be ascribed to unplanned changes of particle size and/or distribution of the bulk solids being handled.

Especially in the seventies and eighties of the past century, several researchers studied the influence of fine particles on the flow properties of bulk solids. In 1975 for example, KURZ AND MÜNZ[2] presented the experimental results of shear tests on limestone powders with different widths of particle size distribution. They stated that even small changes in the fine particle content gave measurable changes in cohesiveness.

In the early eighties FÜRLL[3] investigated the maximum permissible fine particle content which does not affect the flow behaviour of coarse, cohesionless materials.

In the mid-eighties MOLERUS AND NYWLT[4] discussed the experimental results, which were obtained with various mixtures of finegrained, cohesive and coarsegrained, cohesionless powders. The aim of their paper was to interpret the experimental results in terms of the parameters determining particle interactions.

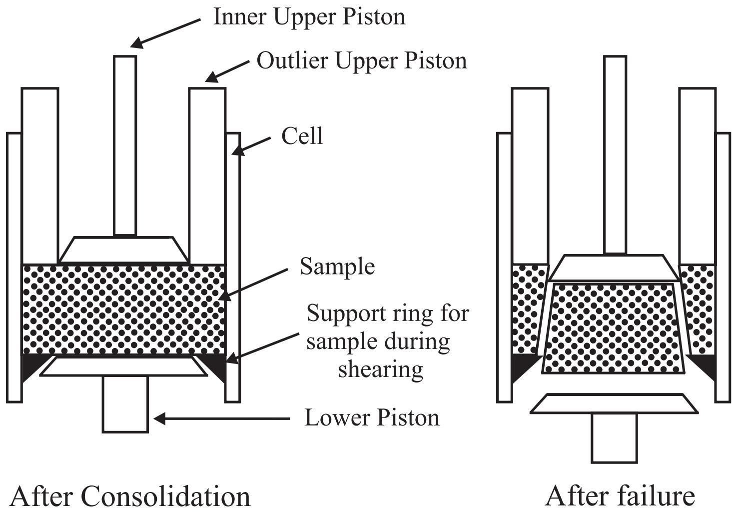

Figure 1. Measurement principle.
Slika 1. Princip merjenja.

Most investigations were performed by the Jenike cell or by testers that measure in the same way as the Jenike tester. In the nineties, a new device was placed on the market – the Johanson Hang Up Indicizer[5,6] – which can help evaluate and characterize powder materials, so that one can solve the flow problems, evaluate processes, design equipment and improve quality control programs with indices, which are quite simple to interpret and understand.

The procedure of measuring by the Johanson Hang Up Indicizer is fast, user- independent, and the device is easy to operate. The operator first fills and weighs the measurement cell with the sample to be tested. The cell is then placed in the Hang Up Indicizer where the sample is sheared or failed. An internal computer then calculates the data and immediately displays the result on the screen.

In the present paper, the experimental results of measuring the rathole index - *RI* - by the above-mentioned device for different mixtures of finegrained and coarsegrained powders are presented and discussed. By measuring the rathole index we wanted to prove the dominant influence of fine particles on the flow behaviour of bulk solids.

RI is the recommended outlet diameter to ensure rathole failure and cleanout in a funnel-flow bin. In general, a higher *RI* indicates poor flow or higher values of shear parameters, and a lower *RI* indicates better flow or lower values of shear parameters. For example, a higher *RI* indicates a greater tendency for a powder to hang up at container walls, and to form agglomerates.

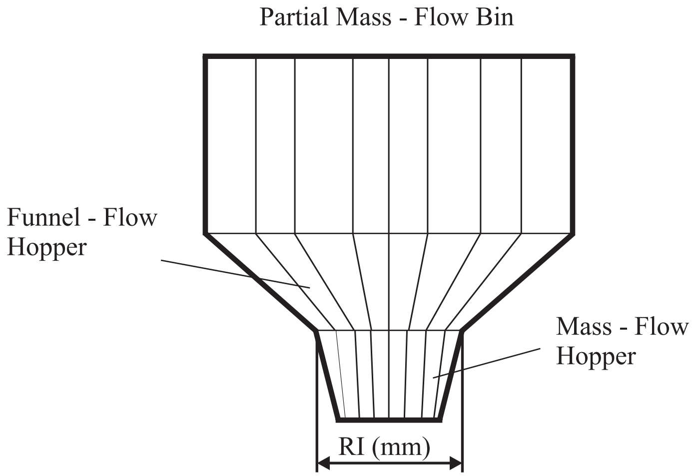

Figure 2. Rathole index, *RI*.
Slika 2. Indeks lijakastega iztoka, *RI*.

THE IMPORTANCE OF PARTICLE SIZE AND PARTICLE SIZE DISTRIBUTION

As mentioned in the introduction, MOLERUS AND NYWLT investigated into the influence of the fine particle content on the unconfined strength, f_c, of binary mixtures of limestone (mixtures of spheres were considered) with the intention to estimate the critical mass ratios of fine-grained (cohesive) and coarse-grained (cohesionless or free-flowing) particles.

They stated that the fine particle content, which defines the flow properties of the mixture, is reached when the coarse particles are completely embedded in the fine particles. It was estimated that the appropriate ratio of fine particles (m_f) to the total mass ($m_f + m_c$) of the mixture is approximately 30 %.

MOLERUS AND NYWLT used binary mixtures of limestone powder in experiments where the coarse fraction had a d_{50} = 45 µm (2 % < 20 µm) and the fine fraction had a d_{50} = 3.4 µm (2 % > 7 µm). A translational shear tester similar to the Jenike tester was applied for the shear tests of mixtures with mass contents of fine particles of 0 %, 5 %, 10 %, 15 %, 20 %, 25 %, 35 % and 100 %.

Three different yield loci were measured for each mixture, corresponding to three different load levels of consolidation, i.e. the maximum principle stresses σ_1 of 0.4, 0.8 and 1.2 [N/cm^2]. Their results are given in Fig. 3. Two different evaluation schemes are presented – the computational determination of f_c using linear regression of the measured yield loci, and the direct graphical evaluation.

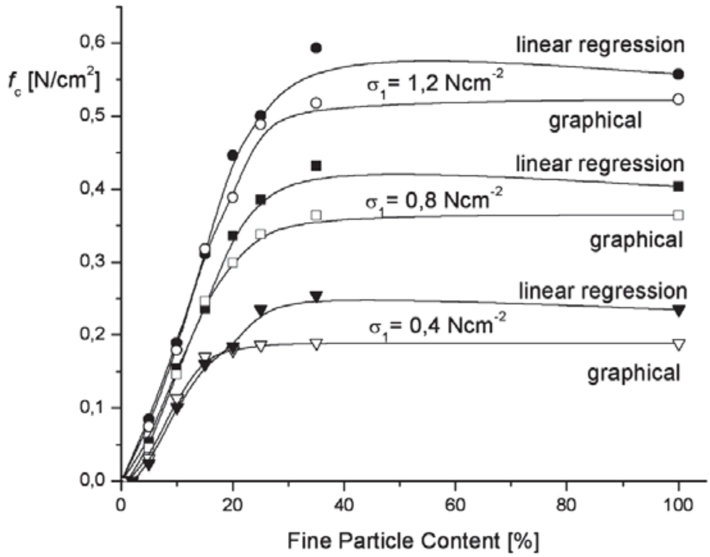

Figure 3. Unconfined yield stress f_c as a function of fine particle content and maximum principal stress during the consolidation, σ_1. Modified from MOLERUS AND NYWLT[4].
Slika 3. Strižna trdnost f_c glede na vsebnost finih delcev (σ_1 = maksimalna glavna napetost med procesom konsolidacije). Prirejeno po MOLERUS IN NYWLT[4].

Fig. 3 makes it evident that if the fine particle content is 30 % or more, the unconfined strength of the mixture is dominantly influenced by the fine component. Unfortunately, mixtures with fine particle content of more than 35 % were not prepared and investigated.

Sample Preparation and Measurements

Limestone was used for our investigations-the same material was used to prepare the fine fraction and three different coarse fractions. The fine fraction consisted of limestone powder with a parameter d_{50} as the median particle size, and was measured by three different devices:

- d_{50} = 5.8 μm measured by FRA 9200
- d_{50} = 6.8 μm measured by SRA 150
- d_{50} = 6.5 μm measured by Sedigraph 5100

Specific surface of limestone measured by Area Meter Ströhlein (BET-method): 1150 m^2/kg.

The coarse fractions were prepared in three different size ranges:

- 200 – 400 μm
- 630 – 800 μm
- 1000 – 1250 μm

When selecting between the different fractions, we followed the condition that the critical mass ratio of fine-grained to coarse-grained particles is reached when the coarse particles are completely embedded in the fine particles, which is only possible if condition $d_f / d_g \leq 0.155$ is implemented. The maximum diameter, d_f, of a sphere passing through the most dense packing of spheres of a diameter d_c is determined by $d_f / d_g = 0.155$. In our case the ratios of median particle sizes of fine fraction to coarse fraction were as follow

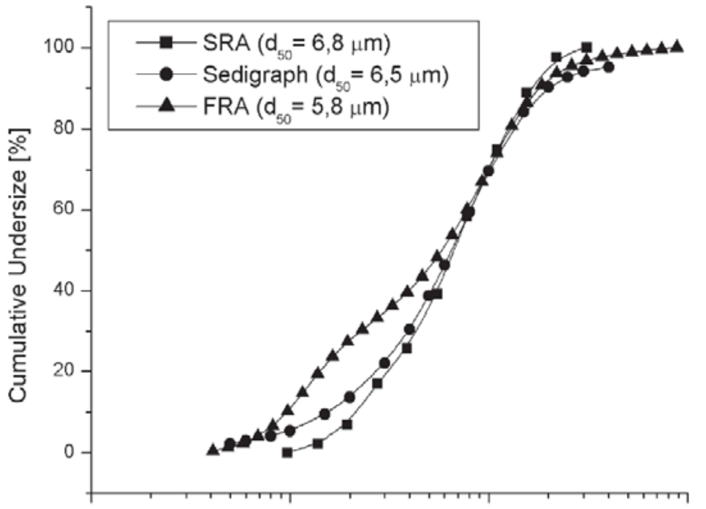

Figure 4. Cumulative particle size distribution measured by different devices.
Slika 4. Kumulativna porazdelitev velikosti delcev, merjena z različnimi napravami.

Table 1. Data of devices used for investigating median particle size.
Tabela 1. Podatki o opremi, ki je bila uporabljena za določitev srednje velikosti.

Manufacturer	Model	Particle Diameter Range (Equivalent Spherical Diameter)
Leeds and Northrup	Microtrac Particle Size Analyzer, SRA 150	0.69 – 704 μm
Leeds and Northrup	Microtrac Particle Size Analyzer, FRA 9200	0.12 – 704 μm
Micromeritics	Particle Size Analysis System, Sedigraph 5100	0.1 – 300 μm

(d_{50} values for coarse fractions are approximates):

- $d_{f50} / d_{c50} = 6.4\ \mu m/300\ \mu m = 0.021 < 0.16$
- $d_{f50} / d_{c50} = 6.4\ mm/\ 700\ \mu m = 0.009 < 0.16$
- $d_{f50} / d_{c50} = 6.4\ \mu m/1100\ \mu m = 0.006 < 0.16$

Mixtures with different proportions of fine to coarse fraction were prepared and measured. The mass contents of fine particles in the mixtures were as follow: 0 %, 10 %, 20 %, 30 %, 35 %, 100 %, and in contrast to the research performed by MOLERUS AND NYWLT, mixtures with 40 %, 45 %, 50 %, 55 %, 60 %, 65 %, 70 %, 80 % and 90 % mass content of fine particles were also prepared and measured. The results are given in Table 2.

Table 2. Rathole indices of mixtures, measured by Johanson Hang Up Indicizer.
Tabela 2. Indeksi lijakastega iztoka posameznih mešanic, ki so bili merjeni z napravo Johanson Hang Up Indicizer.

Mass Contents of Fine Particles	*RI* Index (Coarse fraction: 200 – 400 μm)	*RI* Index (Coarse fraction: 630 – 800 μm)	*RI* Index (Coarse fraction: 1000 – 1250 μm)
0 %	80	80	80
10 %	80	80	80
20 %	140	100	120
30 %	420	520	640
35 %	620	1060	1180
40 %	940	1260	1580
45 %	1200	1660	1900
50 %	1620	2160	2480
55 %	1720	2240	2520
60 %	2060	2300	2540
65 %	2120	2340	2640
70 %	1960	2180	2500
80 %	1800	2020	2240
90 %	1700	1840	1940
100 %	1360	1360	1360

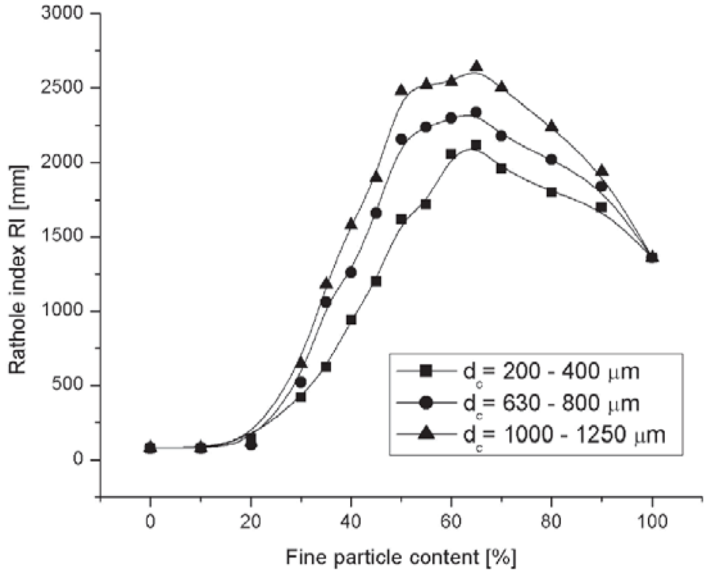

Figure 5. The influence of fine particle content on the flow behaviour of mixtures – RI comparison.
Slika 5. Vpliv deleža fine frakcije na tečenje mešanic – primerjava RI.

Conclusions

We performed the presented research with intention to demonstrate the dominant influence of fine fraction on the shear strength of a compacted mixture. Binary mixtures with different mass ratios of fine-to-coarse fraction were considered. The ratios of median particle sizes of coarse fraction to fine fraction, d_{50c}/d_{50f}, were approx. 50, 110 and 170. The data obtained lead to the following conclusions:

- In the 0-20 % fine particle content range, the fine fraction does not influence or insignificantly influences the flow behaviour of the predominating coarse fraction in the binary mixture.
- In the 20-45 % range, the influence of the fine fraction on the cohesive strength of the mixture is steeply increasing – the bigger the particles in the coarse fraction, the steeper the curve.
- The shear parameters reach their maximum values in the 45-60 % fine particle content range – the bigger the particles in the coarse fractions, the bigger the maximum value of the rathole index, and consequently, values of the shear parameters.
- Through further increasing of the fine particle content in binary mixtures (content > 65 %) the shear parameters are gradually decreasing.
- The shear parameters of the mixture reach similar values as the fine fraction itself in the 35-50 % fine particle content range.

Considering the above-stated conclusions, one can say that in industrial processes dealing with bulk solids such handling is desirable, which will not result in excessive crushing or attrition of the material and will not provide a chance for widening of the particle size distribution.

Through such approach we can prevent undesired apperances, which would consequently lead to higher values of shear strength of the material that would furthermore mean problems with silo discharging, process stagnation or higher investments into silo on account of radical solutions, such as increasing the dimensions of the silo.

POVZETEK

Velikost delcev in porazdelitev velikosti delcev kot parametra, ki pomembno vplivata na lastnosti tečenja sipkih snovi

Velikost delcev in porazdelitev velikosti delcev pomembno vplivata na obnašanje sipkih snovi. V preteklosti so bile opravljene določene raziskave, s katerimi so se preučevali ti vplivi, saj lahko marsikatero težavo, ki nastane v praksi pripišemo ravno nenačrtovanim spremembam velikosti delcev in/ali porazdelitvi velikosti delcev pri materialih, s katerimi imamo opravka.

Zlasti v 70-ih in 80-ih letih prejšnjega stoletja so različni raziskovalci preučevali vpliv finih delcev na lastnosti tečenja sipkih snovi. Leta 1975 sta na primer KURZ IN MÜNZ objavila članek v katerem sta predstavila rezultate strižnih testov z apnenčevimi prahovi. Ugotovila sta, da imajo tudi najmanjše spremembe vsebnosti fine frakcije, za posledico spremembe kohezivnosti sipkih materialov. MOLERUS IN NYWLT sta sredi osemdesetih let objavila članek v katerem razpravljata o strižnih lastnostih mešanic finih, kohezivnih in grobih, nekohezivnih materialov. Poskušala sta interpretirati rezultate v smislu parametrov, ki definirajo interakcije med delci.

Večina raziskav v tistem času je bila opravljena z Jenikejevo celico ali pa z aparati, ki delujejo na podobnem principu, v devetdesetih letih prejšnjega stoletja pa je bil razvit nov aparat, s pomočjo katerega lahko določamo strižne lastnosti sipkih materialov. Gre za Johanson Hang Up Indicizer, s katerim je možno relativno hitro določiti lastnosti tečenja sipkih materialov, in sicer s pomočjo parametrov, ki jih je možno dokaj enostavno interpretirati.

V članku so predstavljeni rezultati merjenja indeksa lijakastega iztoka – RI indeksa z omenjeno napravo za različne mešanice grobe in fine frakcije. Gre za indeks, ki posredno daje podatek o strižnih lastnostih materiala. Z merjenjem tega indeksa smo želeli prikazati dominanten vpliv finih delcev na lastnosti tečenja sipkih snovi.

Pri raziskavah je bil uporabljen kalcit, in sicer smo uporabili enak material tako za pripravo grobih kot tudi fine frakcije. Fino frakcijo je predstavljal material, s parameterom $d_{50} \approx 6$ μm.

Groba frakcija je bila pripravljena v 3 različnih območjih: 200 – 400 μm, 630 – 800 μm in 1000 – 1250 μm.
Pripravljene in raziskane so bile mešanice z različnimi razmerji fine in grobe frakcije. Utežni delež fine frakcije v mešanici je bil naslednji: 0 %, 10 %, 20 %, 25 %, 30 %, 35 %, 40 %, 45 %, 50 %, 60 %, 70 %, 80 % in 100 %.

S pomočjo pridobljenih podatkov so zaključki naslednji:

- Če so vsi ostali parametri, ki vplivajo na obnašanje sipke snovi konstantni, se kohezijska trdnost sipkih snovi povečuje z manjšanjem velikosti delcev in/ali s širjenjem območja velikosti delcev.
- V območju 0 do 20 % vsebnosti fine frakcije v binarni mešanici, fina frakcija ne vpliva bistveno na strižne lastnosti mešanice.
- V območju 20-45 % vsebnosti fine frakcije, začne vpliv fine frakcije na strižne lastnosti mešanice strmo naraščati – večji kot so delci v grobi frakciji, bolj strmo se dviguje krivulja.
- Strižni parametri dosežejo svoj maksimum v območju 45-60 % vsebnosti fine frakcije v mešanici, in sicer večji kot so delci grobe frakcije večja je maksimalna vrednost po svoji absolutni vrednosti.
- Z nadaljnjim naraščanjem vsebnosti fine frakcije v binarni mešanici (vsebnost > 65 %) strižni parametri postopoma upadajo.
- Strižni parametri mešanice dosežejo podobne vrednosti kot jih izkazuje fina frakcija sama že v območju vsebnosti fine frakcije od 35-50 %.

Glede na navedene zaključke lahko zapišemo, da je pri industrijskih procesih, kjer imamo opravka s sipkimi snovmi zaželeno takšno ravnanje s slednjimi, ki ne bo rezultiralo v pretiranem drobljenju, obribavanju ali kakorkoli vplivalo na spremembe v granulacijski sestavi materiala. S takšnim pristopom lahko zmanjšamo nezaželene pojave, ki bi lahko povzročili večje vrednosti strižnih parametrov materiala, to pa bi pomenilo probleme pri praznjenju silosov, zastoje v proizvodnji ali pa večje investicijske stroške silosov na račun radikalnih rešitev, kot je večanje dimenzij silosov.

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