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Acoustic Analysis of the Impact of Moist Spherical Particles

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***Abstract*— The impact behavior of spherical dominant elastic γ-Al_2O_3 granules and elastic zeolite 4A granules has been investigated using free fall tests. The impacts have been recorded by a high speed camera and the elastic sonic waves generated at impact within the target have been recorded by an acoustic sensor. The time interval between consecutive impacts, the impact and rebound velocities and the coefficient of restitution (CoR) have been determined.**

Moreover, the influences of impact velocity, moisture content, particle diameter and plate thickness have been investigated. Since the investigated range of impact velocity is in the elastic regime below yield velocity the CoR remains nearly constant in a wide range of impact velocities. However, at higher impact velocities the CoR slightly decreases. Furthermore, with increasing moisture content, increasing particle diameter and plate thickness the coefficient of restitution slightly decreases.

In addition, homogenous elastic glass beads have been used for the free fall tests as ideal elastic reference material.

***Index Terms*— coefficient of restitution, material behavior, moisture content, impact behavior**

I. Introduction

A short-time interaction of contacting bodies is described as impact and characterized by a change of the state of motion, momentum and energy of the involved bodies. Since only internal forces are acting the total momentum and the total energy is conserved at impact. The impact laws have been formulated by Christiaan Huygens (1629-1695) [1].

Impacts in nature arise for instance in astronomy at aggregation and agglomeration of gas, dust and particles in accretion discs and interstellar clouds. In physical geography, impacts appear in ice and stone avalanches and at weather phenomena such as tornados and dust devils and in technical processes, impacts occur at processing, transportation and storage of granular materials. Especially in fluidized beds and at pneumatic conveying, collisions occur between the granules themselves and between the granules and the walls of the apparatuses.

The coefficient of restitution (CoR) is a physical parameter characterizing the energy absorption at impact

$$e=\sqrt{\frac{E_{\mathrm{kin,R}}}{E_{\mathrm{kin,A}}}}=\sqrt{\frac{E_{\mathrm{kin,A}}-E_{\mathrm{diss}}}{E_{\mathrm{kin,A}}}}=\sqrt{1-\frac{E_{\mathrm{diss}}}{E_{\mathrm{kin,A}}}}, \qquad (1)$$

where $E_{kin,A}$ and $E_{kin,R}$ are the kinetic energies of impact and rebound and E_{diss} is the energy dissipation at impact. Generally, the CoR can be given as the ratio of relative velocities Δv of rebound v_R to impact v_A

$$e=\sqrt{\frac{E_{\mathrm{kin,R}}}{E_{\mathrm{kin,A}}}}=\sqrt{\frac{1/2m\cdot\Delta v_{\mathrm{R}}^2}{1/2m\cdot\Delta v_{\mathrm{A}}^2}}=\frac{\left|\vec{v}_{\mathrm{R},1}-\vec{v}_{\mathrm{R},2}\right|}{\left|\vec{v}_{\mathrm{A},2}+\vec{v}_{\mathrm{A},1}\right|}. \qquad (2)$$

At impact of a particle against a rigid wall Eq. (2) reduces to

$$e=\frac{\left|\vec{v}_{\mathrm{R},1}\right|}{\left|\vec{v}_{\mathrm{A},1}\right|}. \qquad (3)$$

For the experimental investigation of the CoR different experimental setups are used in the literature.

The CoR is predominantly determined by free fall tests [2], [3], [4]. In this connection, spherical particles are dropped onto a rigid target and the normal and oblique impact can be analyzed. Usually, the impact is recorded using a high speed camera [5]. From the recorded images the impact and rebound velocities can be determined and the CoR can be calculated by Eq. (3). Other measurement methods are the determination of the rebound height using a camera [2], [6] or the measurement of the time between two consecutive impacts of a single particle by evaluation of the acoustic of the impact [7], [8], [9]. In doing so, the impact and rebound velocities are determined from the time interval Δt before and after impact respectively

$$v=\frac{g\,\Delta t}{2}. \qquad (4)$$

At investigation of the normal impact, the influence of impact velocity is studied preferentially. Higa *et al.* [10], Koller [11] and Tillet [6] have been investigated additionally the influence of size of impacting sphere and target. Fu *et al.* [12] and Mangwandi [13] studied the influence of binder content, binder viscosity and moisture content on the impact behavior of granules.

Moreover, impacts between particles and a layered plate have been studied. Huang *et al.* [14] used steel spheres of different diameters impacting on a layer of microscopic steel particles. Kantak and Davis [15] carried out free fall tests of steel and Teflon spheres against a silica plate stringed by a dry or wet cotton layer.

With the free fall apparatus of Foerster *et al.* [16] particle-particle impact can be studied. At this apparatus, a

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spherical particle is released to fall freely and delayed a second particle below the first one is also released to fall freely. Through this experimental arrangement, the upper particle can catch up the lower particle and impact may happen.

Labous *et al*. [17] describe another experimental arrangement for investigation of particle-particle impact. Two particles each in one tube are accelerated by air pressure and are directly shot on each other.

TABLE I
CHARACTERISTICS OF THE MATERIALS

Property	Glass beads	γ-Al_2O_3		Zeolite 4A	
Mean diameter d_{50} (mm)	1.5; 2.0; 2.5; 3.0	1.80	2.50	2.05	3.50
Sphericity ψ	0.99	0.99	0.99	0.98	0.98
Solid density ρ_s (kg/m³)	2,500	3,372	3,368	2,179.9	2,374.7
Particle density ρ_g (kg/m³)	2,500	879	865	1,087.8	1,102.0
Porosity ε (%)	0	73.9	74.3	52.2	53.6
Modulus of Elasticity E (GPa)	65.00	12.23	19.11	2.45	3.34

Through free fall tests, the oblique impact can be investigated likewise [4], [5], [16] and [18]. In this case a plate is inclined to the direction of motion; the angle of inclination θ can be varied between 0 and 90°. The normal and tangential CoR, the angular velocity, the rebound angle and the Coulomb friction coefficient can be determined. On their experiments regarding the oblique impact, Dong and Moys [19] also investigated the influence of the initial angular velocity of the particles.

Furthermore, the normal CoR has been studied by pendulum experiments [3], [20] - [24]. In this connection, the impact velocity can be varied by the initial amplitude. In the simple way of a pendulum arrangement, the particle-particle impact can be examined as Stevens and Hrenya [23], Donahue [25] and Weir and Tallon [24] have carried out. Seifried *et al*. [22] as well as Tallon [27] have performed multiple impacts using a pendulum. Moreover, a pendulum is suitable for the investigation of low impact velocities as done by Hatzes *et al*. [21].

Another experimental arrangement is used by Poppe *et al*. [26]. By a gear microscopic spherical particles are dispersed from a dust sample, accelerated and orthogonally shot upwards against a target.

The eccentric impact can be analysed by collision of a rotatable bedded body against a rigid wall as described in the work of Adams [27] and Brach [28].

II. MATERIALS

As materials, industrial produced spherical alumina oxide (γ-Al_2O_3) and zeolite 4A granules and as ideal elastic reference material glass beads have been chosen.

The alumina oxide granules are industrially used as adsorbent, catalyzer and drying agent due to the high specific surface. The used synthetic zeolite 4A granules are non-water soluble, highly hygroscopic and are industrially used as adsorbents for water and for drying of organic liquids (solvents, oils, fuels and other saturated hydrocarbons), air, liquid gas (propane, butane) as well as technical and inert gases. The glass beads exhibit a smooth surface, a high degree of homogeneity, elastic material properties, a narrow particle size distribution and are isotropic, thus the glass beads are suitable to be used as ideal reference material for free fall experiments.

Different physical product characteristics of the materials were measured and are summarized in Table I.

III. PREPARATION

In order to examine the influence of moisture content X_W on the material behavior at impact, the dry granules (X_W = 0.0 kg_{H2O}/kg_{DS}) have been moistened using an air conditioned chamber at the relative humidity of 100 % and the temperature of 25 °C (γ-Al_2O_3: X_W = 0.52 kg_{H2O}/kg_{DS}, zeolite 4A: X_W = 0.23 kg_{H2O}/kg_{DS}). Maximum possible moisture content with totally filled inner pores has been obtained by temporarily placing the granules in water (γ-Al_2O_3: X_W = 0.85 kg_{H2O}/kg_{DS}, zeolite 4A: X_W = 0.43 kg_{H2O}/kg_{DS}).

The moisture content X_W is calculated from the mass increase during wetting

$$X_W = \frac{m_W}{m_{DS}} = \frac{m_{tot} - m_{DS}}{m_{DS}}, \quad (5)$$

where m_W is the mass of water, m_{DS} is the mass of the dry granule and m_{tot} is the total mass of the wetted granule.

IV. FREE FALL APPARATUS

A free fall apparatus, see Fig. 1, has been constructed to measure the normal CoR.

Vacuum tweezers are used to fix the granule before it is dropped so that the granule starts to fall freely without initial velocity and rotation. Different drop heights have been adjusted to ensure different impact velocities. The granule impacts onto the target (an impact plate) made of hardened steel having a thickness of 30 mm. To investigate the influence of the plate thickness a second target exhibiting a thickness of 1.65 mm has been used for several experiments. A digital high speed camera records the movement of the granule near the contact point at a single impact. The camera operates at a frame rate of 8,000 frames

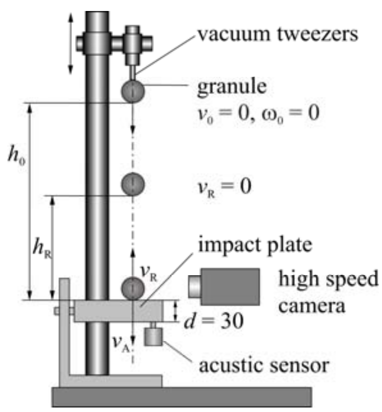

Fig. 1. Free fall apparatus.

per second and the recorded images have a resolution of 512 × 128 pixels. The impact and rebound velocities can be determined from consecutive recorded pictures just before and after impact.

To obtain accurate results, it is necessary to ensure that impacts are reproducible and that measurements of the events of impact and rebound are precise. Achieving this involves critical attention to the mechanical design, construction, alignment and calibration, the image-forming objects, the direction and uniformity of illumination. The influence of gravitation and resistance force of the air can be neglected within the small-sized area of focus of the digital high speed camera.

Moreover, elastic waves generated at each impact are recorded by a piezoelectric acceleration sensor fixed at the alternate surface of the impact plate. The impact and rebound velocities can be determined from the time interval of consecutive impacts using Eq. (4). During an experiment several impacts of each particle occur before the particle has left the plate or remains lying on the plate.

Since the CoR is a widely distributed and scattered parameter much more than 100 tests have been carried out per series and drop height to obtain representative and confident results.

V. Results

A. CoR

The normal CoR of dry γ-Al_2O_3 and zeolite 4A granules is shown for different impact velocities in Fig. 2. The figure depicts a comparison of both measurement systems – the high speed camera and the acoustic senor – having values of high accuracy in the same range.

The granules exhibit a dominant elastic material behavior and the impact velocities are obviously below yield velocity since the CoR remains predominantly constant, within the range of investigated impact velocity. However, the CoR is clearly below unity. This impact behavior results from different influences like elastic waves, rotation at rebound, yielding of surface asperities and inhomogeneity of the granules having significant effect.

Since the acoustic sensor offers the possibility to record multiple impacts of a single particle much more measurement points can be traced in a wide range of impact velocities, see Fig. 3 showing velocity and height versus time curves of a single glass bead (d = 1.5 mm) for several consecutive impacts. Moreover, low velocity impacts can be easily recorded and evaluated using the acoustic sensor.

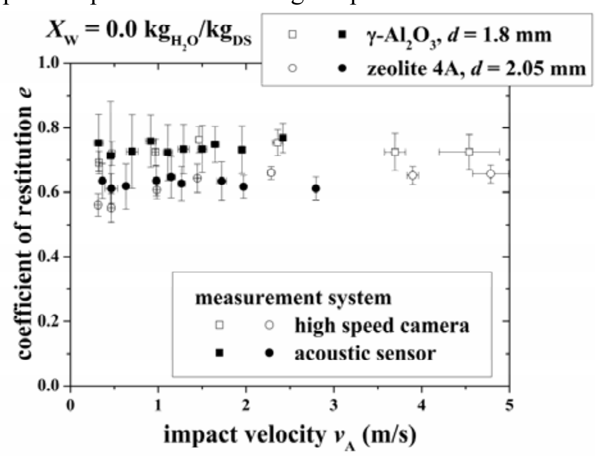

Fig. 2. Normal CoR of dry γ-Al_2O_3 (d = 1.8 mm) and zeolite 4A granules (d = 2.05 mm) recorded using a high speed camera and an acoustic sensor.

The high speed camera exhibits a limited focus and time frame and enables the record of only the first impact of a single granule. However, the camera enables the visualization of the impact procedure and in case of an inclined target the possibility of the investigation of the oblique impact and the impact on targets covered by thin layers such as water or powders.

Fig. 4 shows different probability functions of the CoR of dry γ-Al_2O_3 granules in comparison with glass beads. The experimental values are approximated by a normal distribution. The CoR is a parameter, distributed in a wide range, strongly depending on different properties like homogeneity, isotropy, shape, surface roughness etc. Therefore, every single impact is an individual process exhibiting hardly predictable properties. For example the orientation and the direction at impact of a single particle have considerable influence and deliver different CoRs respectively. The ideal glass beads clearly exhibit a narrow distribution of the CoR.

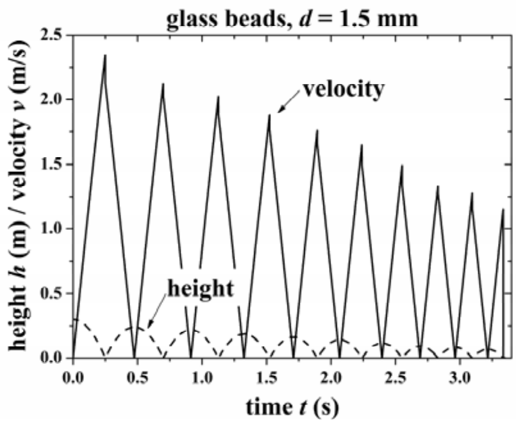

Fig. 3. Velocity and displacement versus time curves of a single glass bead (d = 1.5 mm) for several consecutive impacts measured using the acoustic sensor.

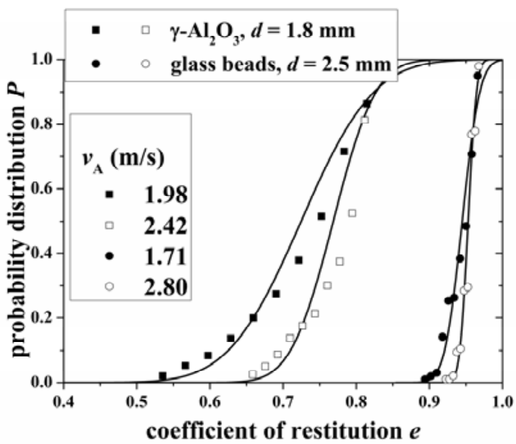

Fig. 4. Probability distribution functions of the coefficient of restitution of dry γ-Al_2O_3 granules (d = 1.8 mm) and glass beads (d = 2.5 mm) at different impact velocities measured using the acoustic sensor.

B. Moisture content

As shown in Fig. 5 and Fig. 6, with increasing moisture content the CoR of the γ-Al_2O_3 and zeolite 4A granules slightly decreases. One influence could be an increased adhesion due to water at the surface. Consequential, the CoR should decrease at lower impact velocities where the influence of adhesion would be larger. In addition, since the granules are water-insoluble no explicit viscous behavior can develop with increasing moisture content. However, further investigations have shown a considerable damage of the granules by moistening [29], [30]. Due to adsorption of water on the surface of the hygroscopic granules, the water molecules achieve an energetically favorable condition; thermal energy is released. In this connection, within the structure of the granules, stresses may arise as a consequence of thermal expansion and existing stresses may cause local dislocations and micro-cracks, whereby the structure and the inner bonds can be damaged. The fracture force and strength significantly decrease. This behavior can cause the slight decrease of the CoR.

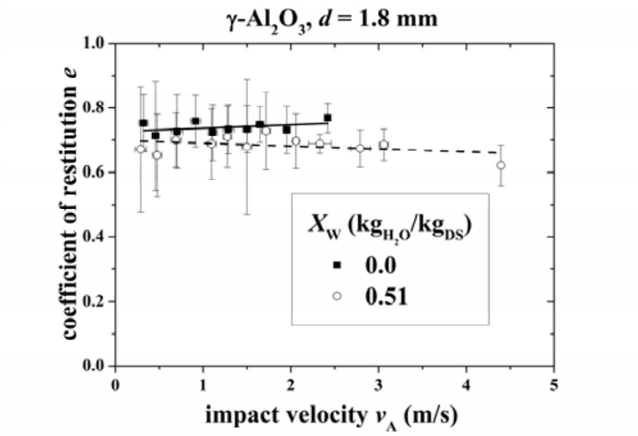

Fig. 5. Normal CoR of γ-Al_2O_3 (d = 1.8 mm) granules exhibiting different moisture contents measured using the acoustic sensor.

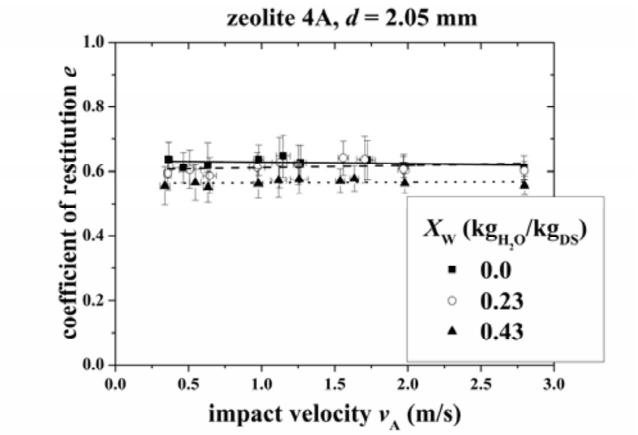

Fig. 6. Normal CoR of zeolite 4A (d = 2.05 mm) granules exhibiting different moisture contents measured using the acoustic sensor.

C. Particle size and thickness of the target

Fig. 7 shows the normal CoR of glass beads of different particle sizes versus impact velocity. The glass beads are used as ideal elastic reference material at impact. Even though, the CoRs are large, they remain below unity.

At impact, elastic waves are generated within both colliding bodies. They travel through the bodies, are reflected at discontinuities like phase boundaries and travel back into the contact region influencing the impact. Since the glass beads are very homogeneous and isotropic, they exhibit rarely discontinuities. Therefore, the elastic waves are reflected at the surface. Repeated reflections and passing through the contact region increasingly influence the impact. According to experimental results and theoretical approaches of several authors [11], [31], [32], [33], [34] at elastic impact, elastic waves within the colliding bodies are a main process for dissipation of kinetic energy.

Furthermore, as shown in Fig. 7, with increasing particle size, the CoR of the glass beads remains almost constant at impact against the thick plate. Since the ratio γ of particle size d to plate thickness d_P

$$\gamma = \frac{d}{d_P} \tag{5}$$

has a value smaller than 0.1 the thick plate can be nearly regarded as an infinitely extended elastic solid at impact of glass beads. The glass beads leave the surface of the thick plate before the first reflected elastic wave (generated in the plate) can return back into the contact region. Consequently, just a small amount of the kinetic energy is converted into elastic waves and the CoR is slightly below unity. Comparable results have been also observed by Sondergaard *et al*. [4].

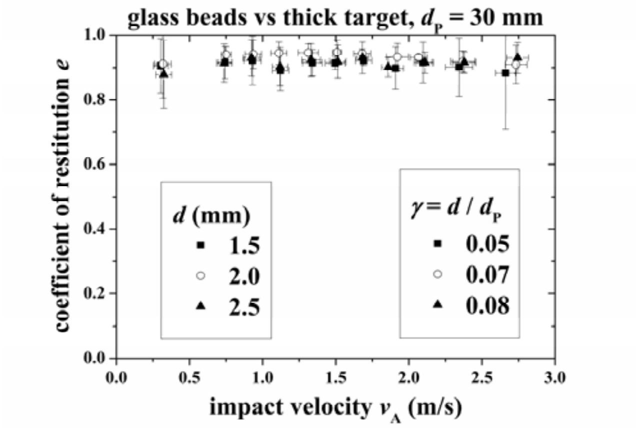

Fig. 7. Normal CoR of glass beads of different particle sizes (d = 1.5, 2.0, 2.5 mm) at impact against the thick plate (d_P = 30 mm) measured using the acoustic sensor.

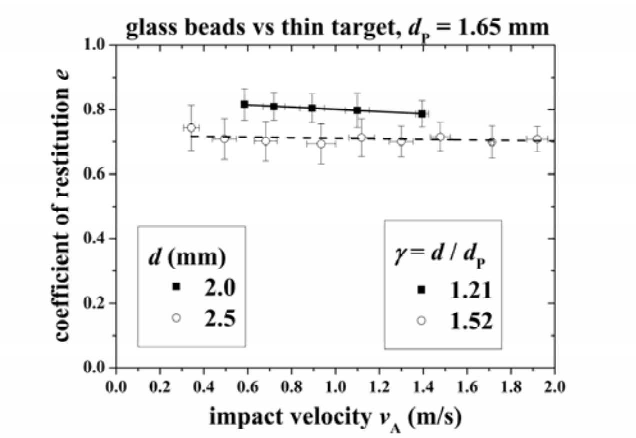

Fig. 8. Normal CoR of glass beads of different particle sizes (d = 1.5, 2.0, 2.5 mm) against the thin plate (d_P = 1.65 mm) measured using the acoustic sensor.

However, analog to Raman [31] and Sondergaard *et al.* [4] at larger values of γ, the CoR of the glass beads decreases with increasing ratio γ as shown in Fig. 8 and in comparison to Fig. 7. This trend develops due to an increasing percentage of kinetic energy converted into elastic waves especially flexural waves.

The influence of different target diameters and accordingly the ratio γ on the CoR of γ-Al_2O_3 granules (d = 1.8 mm) is shown in Fig. 9 and on the CoR of zeolite 4A granules (d = 2.05 mm) in Fig. 10. The γ-Al_2O_3 and zeolite 4A granules don't exhibit an impact behavior comparable to the glass beads. In the investigated range, a change in plate thickness and the ratio γ respectively doesn't significantly affect the impact behavior; the CoR only slightly decreases with increasing ratio γ.

Moreover, according to Johnson [35], the total time t_{el} of impact of a particle against a wall at elastic impact follows to

$$t_{e1} = 2.87\left(\frac{\left(1-\nu_1^2\right)^2}{E_1^2}\frac{m_1^2}{v_{A1}R_1}\right)^{1/5}, \qquad (2)$$

where E_1, ν_1, m_1, and R_1 are the Modulus of Elasticity, the Poisson's ratio, the mass and the radius of the particle, respectively.

The contact time of the granules is the about 31 times (γ-Al_2O_3, d = 1.8 mm) and 57 times (zeolite 4A, d = 2.05 mm) greater than the total time of impact of the glass beads (d = 2.0 mm), respectively.

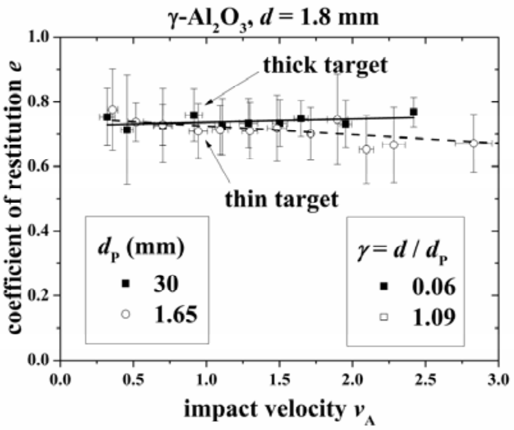

Fig. 9. Normal CoR of dry γ-Al_2O_3 (d = 1.8 mm) at impact on targets having different thicknesses measured using the acoustic sensor.

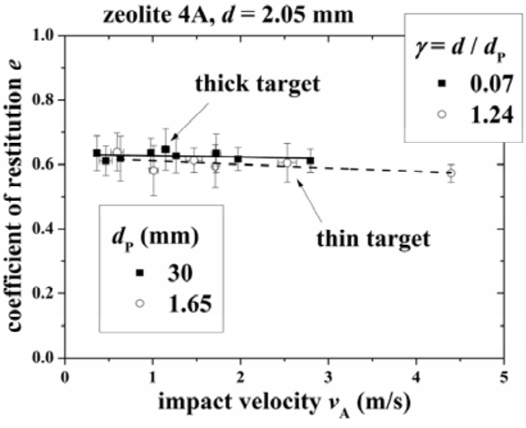

Fig. 10. Normal CoR of dry zeolite 4A granules (d = 2.05 mm) at impact on targets having different thicknesses measured using the acoustic sensor.

At impact of the granules with the thick plate, the contact time is only large enough that elastic waves (generated in the plate) can transit trough the contact region once at maximum. At impact with the thin plate elastic waves can transit trough the contact region several times.

In contrast to the ideal composed glass beads, the granules exhibit a high inhomogeneity and porosity. Generated elastic waves cannot propagate unhindered over large distances within the granules. They are nearly immediately reflected at disturbances and, hence, also at impact with the thick plate, waves (generated in the granules) may transit several times through the contact region before the granule leaves the plate. Thereby, the impact is clearly influenced by elastic waves.

In addition, the granules are soft compared to both plates and the glass beads, respectively. Thus, at impact, the granules are much more deformed than the target. According to that, much more elastic potential mechanical energy is stored in the granules and can be dissipated by elastic waves generated in the granules. Moreover, it is to be supposed that the granules slightly oscillate after leaving the plate.

Within the elastic impact regime of comparatively soft granules, the CoR usually is significantly less unity. In addition, these granules exhibit a CoR which is to be interpreted as nearly constant in a wide range of impact velocities until yield point since the scattering of the CoR is very large.

VI. Conclusions and Outlook

The impact behavior of γ-Al_2O_3 granules, zeolite 4A granules having different moisture contents and ideal glass beads against two impacts plates of different thicknesses have been investigated using an acoustic sensor and a high speed camera. The CoR has been determined and different influencing parameters have been revealed. Within the investigated range of impact velocities the granules exhibit elastic material behavior. However, the CoR is significantly below unity since especially elastic waves and also rotation at rebound, yielding of surface asperities, inter-particle friction and inhomogeneity of the granules affect the impact behavior and, hence, the energy dissipation.

Due to damage as a consequence of thermal expansion at wetting, the CoR has been found to slightly decrease with increasing moisture content. Furthermore, the ratio of particle diameter to target thickness has to be found to have no significant influence on the CoR of the granules within the investigated range. This has to be studied by further experiments. Moreover, the energy loss due to propagation of elastic waves generated at elastic impact of the materials has to be evaluated by means of suitable approaches from the literature.

References

[1] K. Fassmann, M. Bill, H. v. Ditfurth, H. Helbing, W. Jens, R. Jungk, E. Kogon, "Die Großen der Weltgeschichte", Band V, Calvin bis Huygens, Kindler Verlag AG, 1974, 996-1013

[2] S. Antonyuk, "Deformations- und Bruchverhalten von kugelförmigen Granulaten bei Druck- und Stoßbeanspruchung", Dissertation, O.-v.-G.-Universität Magdeburg, docupoint Verlag, 2006

[3] S. M. Iveson, J. D. Litster, “Liquid-bound granule impact deformation and coefficient of restitution”, *Powder Technol*. 1998, 99 (3), 234-242
[4] R. Sondergaard, K. Chaney, C. E. Brennen, “Measurement of solid spheres bouncing off flat plates”, *J. Appl. Mech*. 1990, 112 , 694-699
[5] A. H. Kharaz, D. A. Gorham, A. D. Salman, “Accurate measurement of particle impact parameters“, *Meas. Sci. Technol*. 1999, 10 (1), 31-35
[6] J. P. A. Tillett, “A study of the impact on spheres of plates“, *Imperial Chemical Industries Limited*, Butterwick Research Laboratories, Welwyn, Herts. 1954, 677-688
[7] A. D. Bernstein, “Listening to the coefficient of restitution“, *Am. J. Phys*. 1977, 45 (1), 41-44
[8] M. Higa, M. Arakawa, N. Maeno, “Measurements of restitution coefficients of ice at low temperatures“, *Planet. Space Sci*. 1996, 44 (9), 917-925
[9] Y. Yin-Chao, O. Fuat, B. R. Lynnwood, “Impact of spheres on ice“, *J. Eng. Mech. Div., Am. Soc. Civ. Eng.* 1970, 96 (5), 641-652
[10] M. Higa, M. Arakawa, N. Maeno, “Size dependence of restitution coefficients of ice in relation to collision strength“, *Icarus* 1998, 133, 310-320
[11] M. G. Koller, H. Kolsky, “Waves produced by the elastic impact of spheres on thick plates“, *Int. J. Solids Structures* 1987, 23 (10), 1387-1400
[12] J. Fu, M. J. Adams, G. K. Reynolds, A. D. Salman, M. J. Hounslow, “Impact deformation and rebound of wet granules“, *Powder Technol*. 2004, 140 (3), 248-257
[13] C. Mangwandi, Y. S. Cheong, M. J. Adams, M. J. Hounslow, A. D. Salman, “The coefficient of restitution of different representative types of granules“, *Chem. Eng. Sci.* 2007, 62 (1-2), 437-450
[14] H. Huang, M. P. Dallimore, J. Pan, P. G. McGormick, “An investigation of the effect of powder on the impact characteristics between a ball and a plate using free falling experiments“, *Mater. Sci Eng. A* 1998, 241, 38-47
[15] A. A. Kantak, R. H. Davis, “Collision of spheres with wet and dry porous layers on a solid wall“, *Chem. Eng. Sci*. 2006, 61 (2), 417-427
[16] S. F. Foerster, M. Y. Louge, H. Chang, K. Allia, “Measurements of the collision properties of small spheres“, *Phys. Fluids* 1994, 6 (3), 1108-1115
[17] L. Labous, A. D. Rosato, R. N. Dave, “Measurement of collision properties of spheres using high-speed video analysis“, *Am. Phys. Soc., Phys. Rev*. E 1997, 56 (5), 5717-5725
[18] A. H. Kharaz, D. A. Gorham, A. D. Salman, “An experimental study of the elastic rebound of spheres“, *Powder Technol*. 2001, 120 (3), 281-291
[19] H. Dong, M. H. Moys, “Experimental study of oblique impacts with initial spin“, *Powder Technol*. 2006, 161 (1), 22-31
[20] J. Coaplen, W. J. Stronge, B. Ravani, “Work equivalent composite coefficient of restitution“, Int. J. Impact Eng. 2004, 30 (6), 581-591
[21] A. P. Hatzes, F. G. Bridges, D. N. C. Lin, “Collisional properties of ice spheres at low impact velocities“, *Mon. Not. R. Astron. Soc*. 1988, 231, 1091-1115
[22] R. Seifried, W. Schiehlen, P. Eberhard, “Numerical and experimental evaluation of the coefficient of restitution for repeated impacts“, *Int. J. Impact Eng.* 2005, 32 (1-4), 508-524
[23] A. B. Stevens, C. M. Hrenya, “Comparison of soft-sphere models to measurements of collision properties during normal impacts“, *Powder Technol*. 2005, 154 (2-3), 99-109
[24] G. Weir, S. Tallon, “The coefficient of restitution for normal incident, low velocity particle impacts“, *Chem. Eng. Sci*. 2005, 60 (13), 3637-3647
[25] C. M. Donahue, C. M. Hrenya, A. P. Zelinskaya, K. J. Nakagawa, “Newton's cradle undone: Experiments and collision models for the normal collision of three solid spheres“, Phys. Fluids 2008, 20, 113301
[26] T. Poppe, J. Blum, T. Henning, “Analogous experiments on the stickiness of micron-sized preplanetary dust“, *Astrophys. J.* 2000, 533 (1), 454-471
[27] G. G. Adams, “Imperfectly constrained planar impacts – a coefficient-of-restitution model“, *Int. J. Impact Eng*. 1997, 19 (8), 693-701
[28] R. M. Brach, “Classical planar impact theory and the tip impact of a slender rod“, *Int. J. Impact Eng*. 1993, 13 (1), 22-33
[29] P. Müller, M. Seeger, J. Tomas, “Compression and breakage behavior of γ-Al2O3 granules“, *Powder Technol*. 2013, 237, 125-133
[30] Müller, P.; Tomas, J., “Compression behavior of moist spherical zeolite 4A granules“, *Chem. Eng. Technol*. 2012, 35 (9) 1677-1684
[31] C. V. Raman, “On some applications of Hertz’s theory of impact“, *Phys. Rev*. 1920, 15, 274-284
[32] C. Zener, “The intrinsic inelasticity of large plates“, *Phys. Rev. 1941*, 59, 669-673
[33] S. C. Hunter, “Energy absorbed by elastic waves during impact“, *J. Mech. Phys. Solids* 1957, 5 (3), 1957, 162-171
[34] J. Reed, “Energy losses due to elastic wave propagation during an elastic impact“, *J. Phys. D: Appl. Phys.* 1985, 18 (12), 2329-2337
[35] K. L. Johnson, “Contact mechanics“, Cambridge University Press, 1992