MECHANICAL COMPACTION OF COKING COALS FOR CARBONIZATION IN STAMP-CHARGING COKE OVEN BATTERIES

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Abstract: The density of the coal charge plays an important role in the coke quality. The increase of the bulk density usually improves the coke strength due to increased coal particle contact and increased coke density. There are a few possibilities to increase the coal charge bulk density: adjusting the grain size distribution or moisture content (drying), oil addition and mechanical treatment (e.g., partial briquetting or stamping). A renewed interest in stamp charging cokemaking technology has been observed in recent years, especially in Asia, but also in Europe (Poland, Germany and Ukraine). The paper presents the results of studies on the effects of selected factors on the coal cake density and mechanical strength i.e. stamping energy, coal type, water content and crushing fineness. There is possibility to influence these parameters in industrial conditions. The investigations were carried out with use of mechanical stamping apparatus and strength testing machine specially designed for this purpose.

Keywords: coke making, stamp charging, compaction, mechanical strength, bulk density, coal stamping

Introduction

Density of coal charge influences the quality of the received coke and production capacity of the coking chambers (Karcz, 1991; Vander et al., 1996; Karcz and Strugala, 2008). There are a few possibilities to increase the coal charge bulk density (Karcz and Strugala, 2008; Czaplicki and Janusz, 2012): adjusting the grain size distribution, moisture content (drying), oil addition and mechanical treatment (e.g. partial briquetting or stamping). A renewed interest in stamp charging cokemaking technology has been observed in recent years, especially in Asia, but also in Europe, e.g. in Poland, Germany and the Ukraine (Gural et al., 2008; Kurunov et al., 2010; Loddo et al., 2011). This situation results from the decreasing supply and increasing price of prime coking coals. A stamp charging system enables the enhancement of the bulk density of the coal charge. Consequently, it has a positive influence on the mechanical strength of the coke, particularly on abrasion index - Micum 10 (Loison et

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al., 1989; Chatterjee et al., 2001) The coke produced from blends with higher densities is less porous which is beneficial for mechanical strength (Loison et al., 1989; Herman, 2002; Strugala, 2002). What is important, it also allows using a higher amount of weaker coals in the coking blend (Chatterjee et al., 2001; Krishnan et al., 2004; Kuyumcu and Sander, 2014). The stamp charged coke ovens (Fig.1) differ little from the conventional top charged ovens, but the battery equipment is clearly different. The coking blend is compacted in a metal box with dimensions that are slightly smaller than the coke oven (20 to 30 mm). The stamping process is accomplished by a row of mechanical stampers that produce a durable coal cake. The prepared coal cake is charged into the chamber through the oven door after the compaction process. This method allows obtaining coal charge bulk density of 1100 kg/m^3 (wet basis) and higher, whereas for top charged coke ovens this value is on the order of 800 kg/m^3.
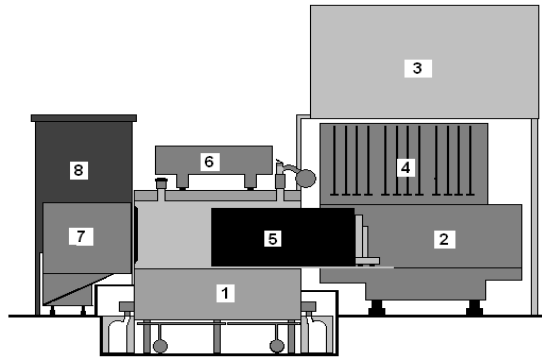

Fig. 1. Stamp – charged coke oven battery: 1 – battery refractory brickwork, 2 – SCP (Stamping-Charging-Pushing) machine, 3 – coal tower ,4 – stamping units, 5 – coal cake, 6 – CGT (Charging Gas Transfer) car, 7 – coke guide car, quenching car, 8 – quenching tower

In industrial practice the stamped cakes are characterized by the following dimensions: c.a. 3.5–6 m height, 12–16 m length and 0.4–0.5 m width. The goal is to prepare the coal cake with a certain density which provide its proper mechanical strength necessary to trouble-free oven charging and enable to achieve adequate productivity of ovens and coke quality (Kuyumcu and Sander, 2014). In aspect of productivity, process should be realized in a short time. Failure of the cake during charging causes operational and environmental problems (fugitive emission). Factors that directly affects both the cake density and mechanical strength are cumulative stamping energy (stamping time) and physicochemical properties of coal. The uniform distribution of density and coal charge properties (i.a. moisture content, crushing fineness) of the whole volume of the cake is essential.

The paper presents the results of studies on the effects of selected factors on the coal cake density and mechanical strength i.e. stamping energy, coal type, water content and crushing fineness. There is possibility to influence these parameters in industrial condition.

Materials and methods

For the investigation purposes, five coking coals and one coking blend were selected. The coals used for the preparation of the blends originate from the mines of the Upper Silesian Coal Basin (USCB). These coals are used as the basic components of the coking blends used in Polish coke plants for the production of metallurgical coke. The properties of selected coals are presented in Table 1.

Table.1 Properties of investigated coals

Parameters	A	B	C	D	E
Moisture content, M^a %	0.6	0.7	0.9	1	1,1
Ash content, A^d, %	4.8	10.5	7.9	4.6	5.6
Volatile matter, VM^{daf}, %	22.32	27.87	24.82	35.92	34.06
Carbon content, C^{daf},%	90.2	88.4	89.3	85.4	86.3
Nitrogen content, N^{daf},%	1.3	1.5	1.4	1.5	1.5
Hydrogen content, H^{daf},%	4.7	5.0	4.8	5.3	5.24
Sulfur content, S_t^{daf},%	0.12	0.52	0.47	0.49	0.3
Oxygen content, O^{daf},%	3.8	4.5	4.0	6.4	6.6
Roga index, RI	64	74	71	77	62
Free swelling index, FSI	7.5	8	8	7.5	7
True density, ρ^t, g/cm^3	1.373	1.401	1.389	1.344	1.341
Crushing fineness, %<3,15mm			93		

The analyses of single coals were performed following the Polish Standard procedures for moisture M (PN-G-4512:1980), ash content A^d (PN-ISO 1171:2002), and volatile matter content VM^{daf} (PN-G-04156:1998). Carbon, hydrogen and nitrogen contents were determined according to procedure PN-G-04571:1998 and sulfur content according to PN-G-04584:2011. Oxygen content was calculated from the difference of mass balance. Polish Standard procedures were also followed to determine the Roga Index, RI, PN-G-04518:1981, the Free Swelling Index, FSI, PN-ISO 501:2007. True density was determined with use of helium pycnometer AccuPyc II 1340 which works on the basis of gas-displacement method, made of Micromeritics, USA. During the measurement of absolute density the temperature were remained constant at value of 25 °C by means of refrigerating/heating circulator.

Stamping test were performed with use of mechanical stamping apparatus (Fig.2). The installation was equipped with a digital shift sensor that enabled the control of the charge height. Weighted portion of coal is charged into cylindrical mold (with diameter of 95 mm and 150 mm nominal height) and then compacted by means of series of stamper dropping (11 kg) from the same height (0.64 m). Cumulative stamping energy is calculated from the potential energy of the stamper. Volume of the obtained coal cake is determined based on its diameter and height. Bulk density of the coal charge is determined from the quotient of mass and the volume of compacted coal.

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The mechanical strength tests were conducted with use of strength testing machine equipped with bidirectional load cell with maximum load of 5 kN (Fig. 4). Prepared sample was placed between compression plates and then pressed with speed of 2 mm/min. Value of the measured force increases until the destruction of sample takes place and later decreases (Fig.5). The measurement is conducted until the value drops below 80% of its maximum. Value of compressive strength was determined from the quotient of maximum force recorded and surface of stamped coal sample. In case of shear test, the coal sample is placed in a mold where it is divided into two symmetrical parts. For one of them, a force is exerted, which is perpendicular to the cross-sectional area of sample. Value of shear strength was determined from the quotient of maximum exerted force and sheared section area.
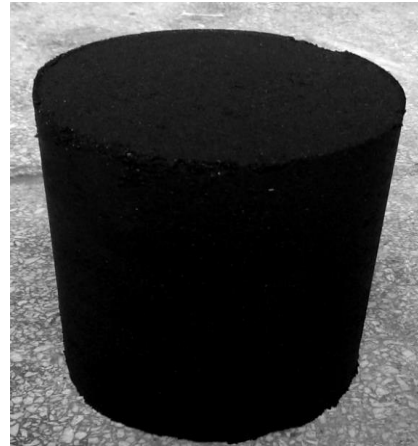

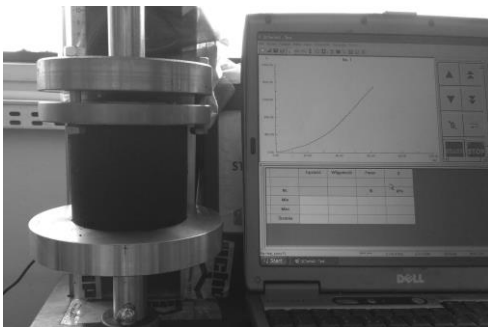Fig. 2. Mechanical stamping apparatus

Fig. 3. Prepared coal cake

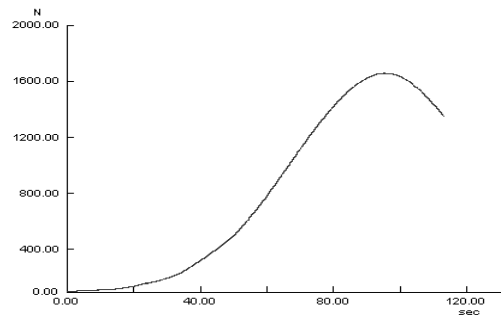Fig. 4. Strength test device

Fig. 5. Screenshot of compressive strength test

Results and discussion

Influence of stamping energy on coal cake density and its compressive strength

The influence of cumulative stamping energy on coal cake density is presented in Fig. 6. Investigation was carried out for coal blend with composition similar to the one used in one of the Polish coking plants. The crushing fineness was 93% below 3.15 mm (d' RRSB = 1.31 mm) and water content was 10%. Fifteen stamping steps were performed which corresponds to stamping energy of approximately 1780 J/kg coal. It can be clearly observed that density increases together with the increase of stamping steps. Relationship between stamping energy and cake density is logarithmic. Coal particles under the influence of impact energy move between themselves, small particles consecutively fill voids between particles and create dense agglomerate. Movement of particles is facilitated by surface moisture which reduces the friction forces. At the beginning of the process, the density rapidly increases, but further, the increase is noticeably lower. With increase in charge density, porosity decreases which causes growth of water saturation index (Fig. 7). Stamping of coal enables obtaining bulk density at the level of approximately 75–80% true density of coal (ρ^d/ρ^t). Increase in charge bulk density positively influence the mechanical strength of coal cake due to enhanced particle-particle contact area and increased capillary forces caused by pore saturation growth (Fig. 8). Increase in charge bulk density from approximately 990 to 1063 kg/m^3 caused significant enhancement of coal cake compressive strength. The values of strength increased from approximately 151 to 462 kPa i.e. for each 10 kg/m^3 rise of bulk density, the increase of compressive strength was 43.8 kPa. At industrial scale the stamping energy of 450-800 J/kg coal charge is applied and the stamping process takes about 4.5 to 8 minutes. The obtained coal cake density is around 1000 kg/m^3 (db – dry basis). The density of coal cakes obtained at laboratory scale is similar.
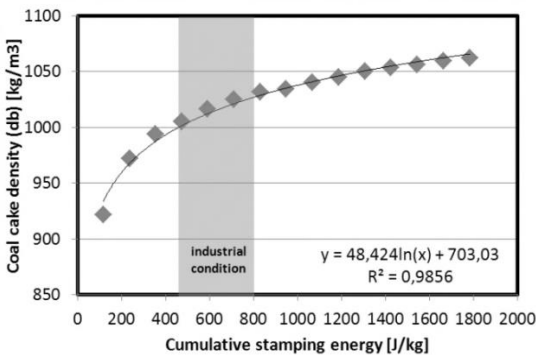

Fig. 6. Coal cake density vs. cumulative stamping energy (coal blend)
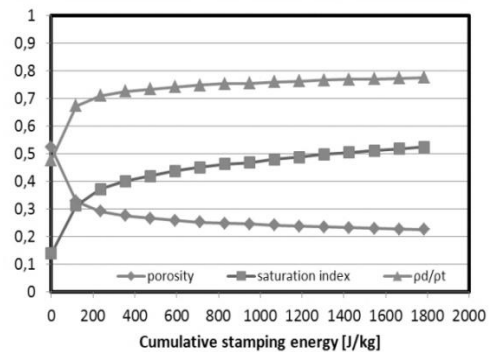

Fig. 7. Changes of porosity, saturation index and ratio of cake density/coal true density (coal blend)
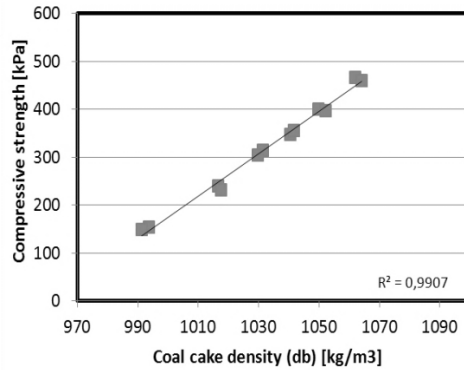
Fig. 8. Compressive strength vs. coal cake density (coal blend)

Influence of coal type and moisture content on coal cake density and its mechanical strength

The tests were carried out for 5 single coals mentioned in Table 1. The range of moisture content was 7-13%. For each test 5 stamping steps were carried out, i.e. the cumulative stamping energy was constant. The water in coal charge acts as a lubricant which reduces the forces between coal particles, facilitating their rearrangement and acts as a binder that provides proper mechanical strength of compacted coal (Kuyumcu and Sander, 2014). This is due to the presence of capillary forces (liquid bridges, capillary pressure) between coal particles. From the other hand, water is unfavorable in aspect of both thermal (higher energy demand to evaporate water) and ecological balance (greater quantity of wastewater) of carbonization process. Additionally, water can negatively affects the ceramic lining of the coke ovens.

In Figures 9 and 10 the influence of coal type and moisture content on coal cake has been presented. As can be seen, the moisture has a large effect on wet bulk density of coal, but a slight effect on bulk density calculated on dry state (dry coal charge - important for the productivity of coke ovens). The higher level of bulk density for coal B was achieved. Increase in moisture content from 7 to 13% caused growth of wet bulk density from 1096 to 1200 kg/m^3 (9.5%) while dry bulk density increased from 1020 to 1044 kg/m^3 (only 2.4%). In case of coal C, wet bulk density increased by 8.2% (from 1088 to 1177 kg/m^3) while dry density only by 1.7% (from 1009 to 1026 kg/m^3). For coal A similar relationships was noticed. Wet bulk density increased by 9.3% (from 1068 to 1167 kg/m^3) whereas dry bulk density increased by 2.4% (from 991 to 1015 kg/m^3). In the case of coal D and E a slightly different relationship was noted. While wet bulk density increased by 7.1% and 6.9% respectively (for D from 1008 to 1088 kg/m^3 and E from 1012 to 1082 kg/m^3), the level of dry density remained largely unchanged. The dry bulk density is approximately 940 kg/m^3 for both coals.
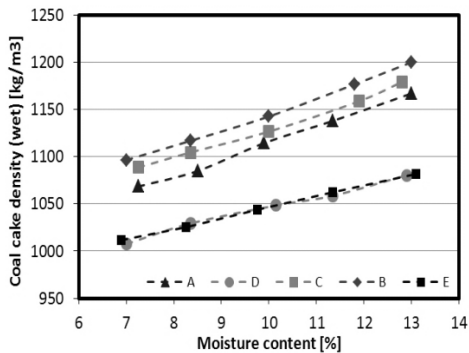
Fig. 9. Influence of coal type and moisture content on coal cake density (wet basis)
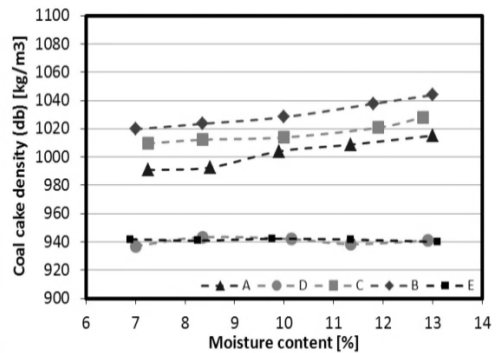
Fig. 10. Influence of coal type and moisture content on coal cake density (dry basis)

As can be seen from Figs. 9 and 10, the coals have different level of density obtained for constant stamping energy (5 stamping steps). A varied level of coal cake density (depending of coal type) can result from several causes. Firstly, due to different true density of coals resulting from various degree of coalification and ash (mineral matter) content. Generally, the higher the degree of coalification and the ash content, the higher is the true density of coal. The second reason may be varied mechanical (grindability, hardness of coal structure) and surface (wettability) properties of selected coals. The wettability of coals depends on various factors i.a. coalification degree, ash content and maceral composition (Orumwense, 1998; Laskowski, 2001; Gosiewska et al., 2002). Less coalified coals contains more oxygene and hydrophilic functional groups than more coalified coals (Fuerstenau et al., 1983; Gutierrez-Rodriguez and Aplan,1984). The coal A is the most coalified from the selected coals (VM^{daf} = 22.32%, O^{daf} = 3.8%) while coal D is the lowest coalified (VM^{daf} =35.92, O^{daf} = 6.4%). Higher wettability of surface of coal grains is associated with higher works of adhesion (reversible work to separate the interfaces of two coal grains) which can adversely affect rearranging of coal particles and prevent creating of dense coal cake. For the coals D and E (potentially characterized by the lowest wettability) increase in moisture content did not improve the dry density which can be related to the described effect. In the case of different mechanical properties, higher density can be obtained due to spalling of coal particles. For coking coals, the grindability which reflects coal structure hardness, decrease with increase of volatile matter content. During the stamping process plastic-elastic deformation takes place. Locally the mechanical strength of the particles may be exceeded thus some parts of coal grains can be crushed and fill particle-particle voids. For the low rank coals with lower grindability this phenomena might be limited. From the other hand, excessive particles breakage during stamping can negatively affect bulk density of coal cake.

As was aforementioned, the moisture play important role in preparation of stamped coal cakes. From the practical point of view, proper amount of water is essential to

provide required strength of industrial coal cake. For all samples, the increase in water content from 7% to 8.5-10% improves the mechanical strength (both compressive and shear strength) of the stamped cake (Figs.11 and 12). Increase in strength is caused by increased density and surface forces between coal particles (i.a. increasing the number of particle-particle contacts points with capillary bridges). With further increase in moisture content, the strength decreases despite of higher cake density. This may be due to that excessive moisture inside the pore an between coal particles can prevent the formation of surface forces (Dash et al., 2005). Therefore, it can be concluded that there is an optimal level of moisture content which provides suitable strength of coal cake. In the case of compressive strength the higher values was obtained for 10% of moisture content and for D, C, and A coals respectively. For coals B and E, the optimum moisture content was 8.5%. Similar relationships was noticed for shear strength measurement, with the exception of coal B for which the maximum values of shear strength was obtained for 8.5% of moisture.
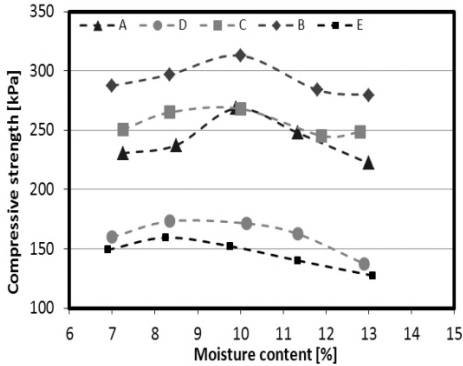

Fig. 11. Influence of coal type and moisture content on coal cake compressive strength
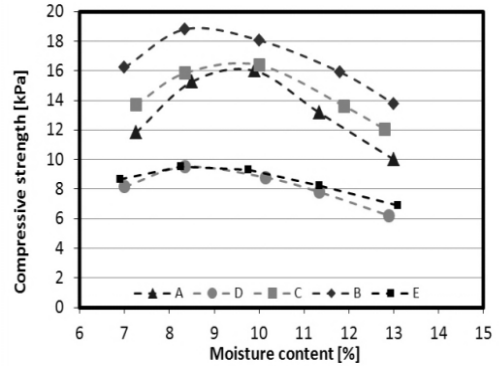

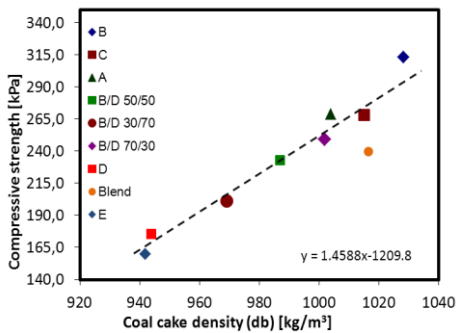Fig. 12. Influence of coal type and moisture content on coal cake shear strength

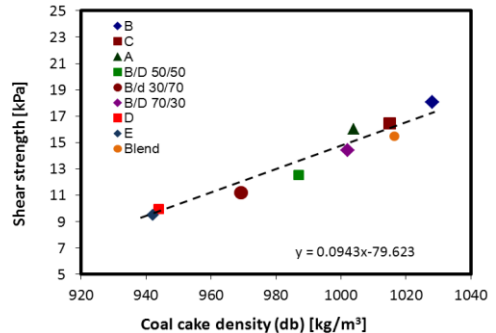Fig. 13. Influence of coal type on coal cake compressive strength (constant stamping energy)

Fig. 14. Influence of coal type on coal cake shear strength

In Figures13 and 14 the influence of coal type on bulk density and compressive and shear strength has been presented. Additionally, three binary blends with various proportion of coals B and D were prepared (50/50, 30/70 and 70/30). As is apparent from Figs.13 and 14, the relationship between coal cake density and compressive and shear strength is linear. The determination coefficients are R^2=0.898 and R^2=0.947 respectively. As was previously mentioned it is due to enhanced particle-particle contact points resulting greater cohesion of coal cake.

Influence of crushing fineness on coal cake density and its mechanical strength

Apart from coal type and moisture content, bulk density of stamped cake can be influenced by crushing fineness. In industrial scale coals which are used for stamp charging batteries are crushed with use of hammer mills to the level of 90-96% below 3.15 mm. For classic top-charged batteries, the crushing fineness of 75-85% below 3.15 mm is used. Higher crushing fineness enables to obtain proper mechanical strength of coal cake, but it can affect the bulk density. As is presented on Fig.15, increase in crushing fineness of coal charge from 87 to 99% below 3.15 mm causes reduction of bulk density from 1036 to 991 kg/m^3. The main advantage of a greater degree of crushing is undoubtedly higher strength of stamped coal cake (Fig.16). With increase in crushing fineness from 87 to 99%, the compressive strength linear increases from 231 to 253 kPa (for constant stamping energy) despite of lower density. The improvement is much higher for constant cake density (Fig.17). In that case, the compressive strength of stamped cake increased from 231 to 359 kPa. The strength growth mechanism is similar to that obtained for density increase. Greater crushing fineness is related to higher number of particle-particle contact points (higher surface of contact between particles, stronger total bonding forces) which positively influences cake strength. Additionally, crushing fineness has an impact of quality of produced coke also, which should be taken into consideration while choosing its level.
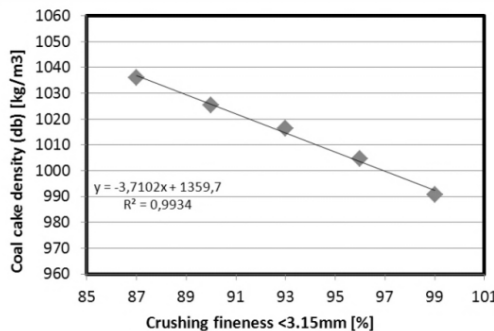

Fig. 15. Influence of crushing fineness on coal cake density (constant stamping energy)
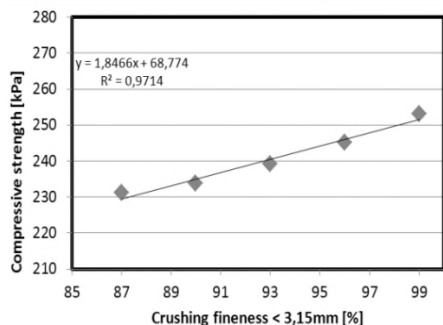
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Fig. 16. Influence of crushing fineness on coal cake compressive strength (constant stamping energy)
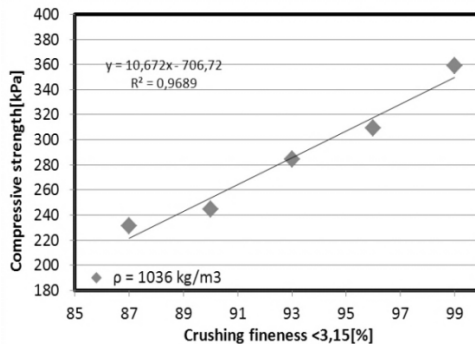
Fig. 17. Influence of crushing fineness on coal cake compressive strength (constant cake density)

Conclusions

The aim of the investigation was to evaluate the influence of selected parameters (i.e. stamping energy, coal type, moisture content and crushing fineness) on coal cake density and mechanical strength. The results are summarized as follows.

- Increase of stamping energy causes increase of density of coal cake.
- Increase in moisture content positively influences both wet and dry bulk density of coal cake. Changes of wet bulk density was from 6.9 to 9.5% (depending on the coal type). In the case of dry bulk density the differences were lower (from 1.7 to 2.4%) except for two coals D and E for which there was no significant differences.
- Coal type has an impact on density of stamped cake. For constant stamping energy, the density of stamped cake is greater for higher rank coals.
- The density of coal cake influences mechanical strength of stamped coal cake. The higher the density, the higher the strength of coal cake.
- There is an optimum level of moisture content in coal charge which provide maximum strength of cake. For the investigated samples, this level was 8.5-10%.
- Increase in crushing fineness reduces the coal cake density while mechanical strength is improved.

Acknowledgements

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