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EFFECT OF MOISTURE CONTENT OF CEREAL GRAINS LAYER ON PRESSURE DISTRIBUTION ON SILO WALL *

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A b s t r a c t. The paper presents the results of measurements of silo wall pressure during the storage of wheat, barley and oats grain. The study was conducted on a test station. The test silo was filled with two layers of grain of different moisture content levels. The difference in the grain moisture content caused moisture diffusion and grain swelling, the result of which was an increase in grain pressure against the silo wall. It was found that the value of the initial wall pressure and its increase was related to the type of cereal (its physical properties), the moisture content of the grain layers, and the duration of storage. The greatest increase in the value of silo wall pressure was obtained for wheat (in the boundary layer the increase was 2.24-fold over 10 days with bottom layer moisture content of 16% and upper layer moisture of 7%), and the smallest one for oats (1.87-fold). The changes in the values of the silo wall pressure were described by means of regression equations.

K e y w o r d s: silo, grain, pressure distribution, moisture content

INTRODUCTION

Numerous studies relating to the pressure on bin walls and bottom have been conducted primarily for raw materials whose physical properties were constant and did not change in the course of the experiment. In many cases the physical properties of materials are subject to change even during short periods of storage. Moisture diffusion may be one of the fundamental causes of such changes. Grain stored in a silo never has uniform moisture. Cereal grain is a capillary-porous material with a propensity to absorb water and to secrete water in the form of vapour. Under the conditions of moisture concentration gradient inside a silo chamber, moisture migration occurs causing the swelling of grains and changes in the pressure exerted by the cereal grain on the silo wall. This phenomenon has been studied by means of a model test station.

DISTRIBUTION OF PRESSURE AGAINST THE WALLS AND BOTTOM OF SILO DURING THE STORAGE OF LOOSE MATERIALS

Most cereal grain is stored in silos. This method of grain storage carries numerous problems (e.g., grain blockages in the storage chambers of silos, cracking of silo walls and ceilings, and sometimes even more serious problems). Analysis of actual instances of such problems shows that the cause of damage to the silo can be an erroneous design assumption related to the shape of the silo and to the properties of its structure or to its operational usage (manner of filling or discharge). The parameters of the materials stored also have a considerable effect on the level of strain in storage silos.

The basic method for the calculation of the pressure exerted by a loose medium on the walls of a bin is the theory of Janssen [7]. On the basis of modifications to that theory numerous design standards have been developed for the design

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and construction of bins for the storage of loose materials. The modifications of Janssen's equations consist in applying, to the calculations, material constants for the loose medium, at different stages of storage bin filling and discharge. Alternatively, they consist in assessing bin loading during discharge and multiplying this by empirical factors (constant or varying along the height of the bin), experimentally selected so that the pressure values calculated be close to actual values. Experimental and practical studies show that the distributions of pressure calculated according to recommended methods do not reflect the true status of storage bin loading with sufficient accuracy. Borcz *et al.* [1] conducted, on real objects, a study of pressure exerted by loose materials on silo walls, and compared the results obtained with data proposed by the relevant Polish Standard. He found considerable differences between results obtained according to the standard method and experimentally. In many cases the values of pressure measured on the experimental objects were higher than those calculated on the basis of the Polish Standard.

Thompson *et al.* [12] measured the pressure against the bottom of two bins made of corrugated sheetmetal, with different geometric dimensions. Bin A had a diameter of 12.8 m and a height of 17.1 m, while bin B had a diameter of 11 m and a height of 14 m. Strain gauges were located in the bins along two different radii. In both cases Thompson *et al.* found significantly lower values of pressure against the bottom close to the bin wall than at other distances from the bin axis. The values of pressure against the bottom of bin A were on the average 1.2 times higher than those in bin B. Appropriately processed measurement data were then compared with data calculated for the recommended parameters of maize grain according to ASAE EP433 and DIN 1055 standards. The values measured in bins A and B were 1.04 and 1.29 times higher than those calculated according to ASAE and 1.19 and 1.55, respectively than those calculated according to DIN for those bins.

A probable cause of the discrepancy lies in the physical properties of the medium which are not directly included in Janssen's equations or else are adopted as constant, while in reality they are functions of other parameters. In the case of cereal grain, apart from parameters traditionally taken as determining the pressure exerted by grain against the walls and the bottom of silos, the effect of properties characteristic for materials of plant origin should be taken into consideration as well. For cereal grain, the most significant parameter is its moisture content. Clower *et al.* [3] determined experimentally the effect of vertical stress, moisture and particle size on the value of Janssen's constant and on the density of grain materials.

Boruszak and Sygulski [2] conducted studies on the effect of the manner of filling a bin with rapeseed on the distribution of pressure on the bin wall and bottom. They found that sprinkle filling of a bin with rapeseed resulted in a decrease in the pressure against the bin walls, both after the filling and during discharge, as compared to stream filling. Horabik and Molenda [5], on the basis of a model study on rapeseed, put forth a thesis that the most favourable distribution of pressure is achieved in the case of circumferential filling of a bin. Circumferential filling creates a structure of the medium which transmits the highest vertical normal pressures within the area of the axis of symmetry of the bin. Other experiments conducted by Horabik [4] and Molenda *et al.* [10] show that sprinkle filling of a bin with wheat grain generates lower static load on smooth bin wall than is the case with centre filling. In the case of rough or corrugated sheetmetal walls sprinkle filling causes higher static loads on the wall as compared to centre filling. The lower static load on the wall is usually accompanied by higher values of the ratio of the dynamic to static loads of the bin wall.

Borcz *et al.* [1] and Kamiński [9] presented pressure distribution for various loose and granular materials (cereal grain, oil plants seed, loose mineral materials). Kamiński [9] on the basis of the results of model studies, found that the highest values of lateral pressure occur with stream filling, and the lowest with bin filling along the wall.

Studies on the effect of eccentric discharge of silos on lateral pressure were conducted by Kamiński [9]. He used sugar and wheat grain of known physical properties as the material exerting pressure on the bin walls and bottom. In his report he also presented the Polish and foreign standards relevant for the subject matter.

Horabik [4], Horabik *et al.* [6] also worked on determining of the effect of discharge orifice eccentricity, and of the coefficient of material friction against the bin wall, on the value of the moment of force exerted by the grain on the wall and the bottom of a model bin in the course of its discharge.

Schwab *et al.* [11] monitored for 6 h the vertical load exerted by wheat grain on the bin bottom. He showed that the value of the load is related to the duration of storage. He developed linear regression equations for the calculation of changes in the load of the bin bottom. He found that the pressure distribution during the storage period varied radially in a manner similar to that observed in the course of the bin filling.

MATERIALS AND METHODS

The study was conducted using a test station presented in Fig. 1. The basic element of the station was a silo (1) of an inner diameter of 600 mm and 1200 mm in height. The silo was provided with a thermostatic jacket, supplied

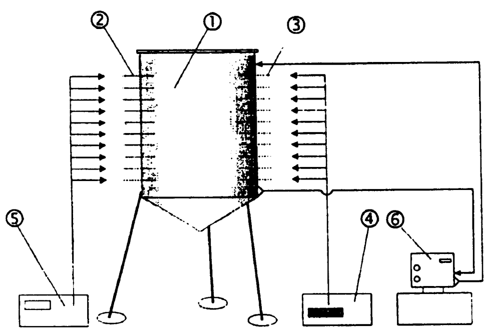

Fig. 1. Schematic diagram of the measurement apparatus: 1 - silo, 2 - strain gauge, 3 - thermocouple, 4 - digital temperature gauge, 5 - electronic wall pressure indicator, 6 - ultrathermostat.

with water from an ultrathermostat (6). Silo wall pressure was measured at eight levels (located at 175, 275, 375, 475, 575, 675, 775 and 875 mm from the bottom edge of the cylindrical part of the silo) by means of strain gauges (2) and an electronic indicator (5). At the same levels grain temperature was measured at five distances from the silo axis, by means of thermocouples (3) connected to a temperature gauge (4). The temperature measurement points were located at the following distances from the silo axis - 0, 75, 150, 225 and 300 mm.

The lower part of the silo was filled with grain of 16% moisture content, up to the level of 500 mm, and then the silo charge was supplemented with a layer of grain of 7% moisture, up to 1000 mm.

Grain of 16% moisture content was obtained by wetting grain of 7% moisture using distilled water. Wetted grain was stored for 3 days in tightly sealed plastic barrels placed in a controlled climate chamber at 15°C. The grain was thoroughly stirred every 8 h to obtain uniform moisture distribution.

Three types of cereal grain were used in the study-Henika wheat, Ars barley, and Dragon oats. The study was conducted in three ten-day cycles at a constant temperature of the water jacket - 15°C. The pressure exerted by the cereal grain on the silo wall, and the grain temperature and moisture content at particular points within the silo were measured once a day.

Prior to the measurements in the silo, for each of the cereals with moisture content levels of 7% and 16% the following physical properties were determined: heaped density, packed density, mass of 1000 grains, and the natural repose cone. The results of the determinations are presented in Table 1. The highest values of the heaped density, packed density and mass of 1000 grains were those for the wheat, while the lowest values characterized the oats. The increase in grain moisture content from 7% to 16% caused a decrease in the heaped and packed densities for all the types of cereal grain under study, and an increase in their mass of 1000 grains. Increased moisture content also caused an increase in the natural repose cone. The highest values of the natural repose conce were those for the oats.

Table 1. Characteristics of the physicasl properties of cereal grain under study

Type of cereal	Moisture content (%)	Heaped density (kg/dcm^3)	Packed density (kg/dcm^3)	Mass of 1000 grains (kg)	Natural repose cone (^{o})
Wheat	7	0.848	0.925	0.0425	23.5
Henika	16	0.768	0.778	0.0440	29.0
Barley	7	0.653	0.651	0.0392	24.0
Ars	16	0.591	0.648	0.0423	32.0
Oats	7	0.603	0.609	0.0351	26.0
Dragon	16	0.522	0.572	0.0310	37.0

RESULTS AND DISCUSSION

Figure 2 presents the results of measurements of pressure exerted on the silo wall by the wheat, barley and oats grain at the end of the first, fifth and tenth days of the storage cycle. After one day of storage the highest values of wall pressure were obtained for barley and wheat. Considerably lower values were obtained for the oats which had the lowest heaped density. With increasing duration of storage the wall pressure values grew. This was due to the diffusion of moisture in the form of water vapour which tended to migrate upwards. The vapour was absorbed by grains of lower moisture content and caused their swelling. The result of this phenomenon was an increase in the silo wall pressure. The wall pressure was the highest on the 10th day of the test cycle. A close correlation was observed between the values of the heaped density and mass of 1000 grains, and the wall load values. The wheat had the highest density and the highest mass of 1000 grains; it was for wheat that the highest wall pressure values were observed, while those for oats were the lowest. The highest values of wall pressure increase were observed at the line of contact between grain layers of different moisture content. They were greater than those measured at the bottom of the silo, which might cause wall deformation. On the 10th day of storage of wheat wall pressure recorded at the height of 575 mm from the bottom was 2100 Pa (pressure increase of 1160 Pa during 10 days). For barley the pressure recorded at the same height was 1720 Pa (an increase of 820 Pa), and for oats - 1580 Pa (an increase of 730 Pa). Below, at the level of 475 mm, the wall pressure dropped rapidly in all the cases, and then gradually increased downwards. Over the ten days of storage cycle, the wall pressure at the grain layer boundary grew 2.24-fold for wheat, 1.91-fold for barley, and 1.85-fold for oats. It is assumed that the increase in the wall pressure is mainly related to the content of starch in the grain, and the starch content is evidenced in the mass of 1000 grains. Starch is a component of considerable hygroscopicity.

In another experiment silo wall pressure was measured during the storage of cereal grain with less differentiated moisture content in the grain layers. In that case the increase in wall pressure was less pronounced.

Variance analysis of the results obtained in the study showed that the values of silo wall pressure were significantly affected (at the level of 0.05) by the type of cereal, the height above the silo bottom, the duration of storage, and the difference in moisture content between the grain layers.

Simultaneously with the increase in wall pressure, changes in grain temperature and moisture content were observed. The greatest changes in the values of those parameters also took place within the plane of contact between grain layers of different moisture. Moisture migration from one grain layer to the other caused an intensification in the process of grain respiration, the products of which were heat and water (plus carbon dioxide). The secretion of additional amounts of water caused an increase in the average moisture content of the cereal grain in the silo. The highest increase in the average moisture was observed in the case of wheat (1.62% during 10 days). In the case of barley and oats the values of the increase were

a
b
c

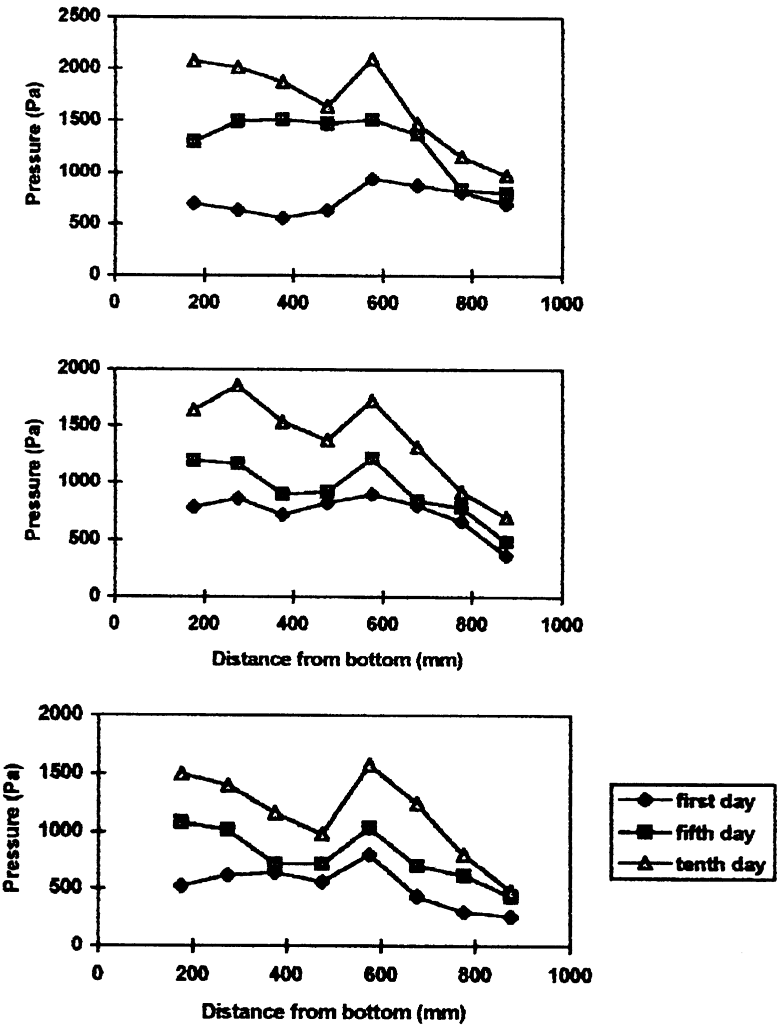

Fig. 2. Graph of silo wall pressure for Henika wheat (a), Ars barley (b) and Dragon oats (c) grains.

lower. The heat generated during the process of respiration caused an increase in the grain temperature. The temperature of wheat grain at some points in the silo increased to 36.5°C, that of barley - to 24°C, and that of oats - to 22°C.

The results of measurements were subjected to variance and regression analyses. Those resulted in the derivation of the regression equations which made it possible to calculate the values of the parameters studied with relation to other variable factors. The regression equations have the following forms:

- for Henika wheat:

  $p = 346.00 + 99.10t + 0.8023\ H$, (Pa),
  correlation coefficien t = 0.84065,
  determination coefficient = 72.19%;
- for Ars barley:

  $p = 292.10 + 69.24\ t + 0.69558\ H$, (Pa),
  correlation coefficient = 0.88667,
  determination coefficient = 78.62%;
- for Dragon oats:

  $p = 213.8 + 68.98\ t + 0.9388\ H$, (Pa),
  correlation coefficient = 0.83618,
  determination coefficient = 69.92%;

  where t - time (days) and H - height (mm).

CONCLUSIONS

1. Difference in grain moisture content in the silo causes grain swelling and an increase in the silo wall pressure.

2. Increase in the wall pressure depends on the type of cereal grain stored, the physical properties of the grain, the value of the gradient of moisture content difference, and the duration of storage.

3. Changes in the silo wall pressure are conderable and may result in silo wall deformation.

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