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ABSTRACT

In Portugal, brewer's spent grain (BSG) is produced in huge quantities as a by-product with moisture of 70–80%. Under environmental conditions, because of its high moisture and fermentable sugar content, BSG becomes an environmental problem after a short time (7–10 days). Thus, it must be transported to animal farms to be consumed within that period of time. In this paper, the application of a new technology of membrane filter press to achieve higher drying levels of BSG cake was studied. BSG, after being mixed with water, was filtered, water-washed, membrane-squeezed, and vacuum-dried reaching lower moisture levels (20–30%). The process cycle is approximately 115–180 min. Filtration was carried out at different feed pressure (3–5 bar) and different

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slurry concentrations (10–30 kg/m^3, dry weight) with and without diatomite filter aid precoat. Specific cake resistance, α, was found to increase with feed pressure increase and to decrease with slurry concentration increase with average values 1.86×10^{12} and 2.25×10^{13} m/kg for cakes produced with and without filter aid precoat, respectively. Cake dewatering via membrane squeezing was applied using hot water (65°C) and cake moisture was dropped from ~80% before squeezing to 51% after squeezing. Five minutes were found to be enough for that stage to be accomplished. With vacuum application over the hot cakes for 30 min, cake moisture decreased to ~20% for cakes with an average thickness, 0.7 cm. The produced cake loses more moisture by storing in open air (on the shelf), reaching an equilibrium value of 10.1% in less than 2 days. No bacterial activities were observed on the cake by storing for a 6-month period on the shelf. The drying levels achieved allow the cake to be stored in open air without bacterial activities facilitating its use as animal feed, at any time, and as a start material for other related BSG uses.

Key Words: Filtration; Membrane; Filter; Press; Dewatering; Spent grain; Cake.

INTRODUCTION

Brewer's spent grain (BSG) is a yellowish-brown granular residue left after the separation of the wort during the brewing process. Based on dry weight, BSG is composed of protein (31%), pentosans (19%), lignin (16%), starch and β-glucans (12%), cellulose (9%), lipids (9%), and ash (4%).[1] Due to its relative low cost and potential in nutritional value, BSG has been considered as an attractive adjunct for human food. Dietary fiber-rich and protein-rich flours, of potential use as ingredients in baking and formulated foods, are obtained by grinding and sifting the dry BSG.[2] Autohydrolysis of BSG was carried out to obtain xylo-oligosaccharides,[3] which were found to improve the diabetic symptoms in rats by its addition to the diet.[4] Moreover, high-fiber bread containing BSG has been shown to reduce plasma total lipids and cholesterol in rats.[5] In addition, BSG has been enzymatically treated for releasing added value-compounds, such as hydroxycinnamic acid (ferulic acid) with potential use in food industry.[6] BSG has also proved to be a suitable cultivation medium for species such as *Pleurotus ostreatus*,[7] and if mixed with the soil it improves its fertility for cultivation as observed for sugar beet.[8] BSG is also used for energy recovery, either by generation for biogas or direct combustion.[9]

Despite the various uses for the BSG mentioned here, it is still mainly consumed as cattle feed worldwide because of its high-protein content.

In Japan, for example, about 95% of BSG is used as cattle feed while disposal of the remaining 5% results in environmental problems.[10] Wet BSG is a perishable product (difficult to preserve under environmental conditions) due to its high moisture content (75–80%). Thus, marketing of wet BSG is getting more difficult and instead of being a by-product, some beer companies consider it as a waste to be dumped.[8,11] Due to its high moisture and fermentable sugar content, BSG is considered as an excellent medium for microbial growth. After some hours of air exposure, a fermentative process starts within BSG that causes dry matter loss and modifications in the product that could be dangerous for its use as animal food.[11] The fermentation caused by butyric acid bacteria *Clostridium Butyricum*, that is active in the temperature range 16–40°C with optimal growth at 30–40°C, transforms carbohydrates, starch, sugars, and lactic acid to butyric acid in the presence of air. The fermentation produces an increase in pH which favors molds formation and amino acids decomposition. Moreover, a prolonged air exposure of the BSG causes high nutrient loss, protein decomposition, and formation of toxic products.[11] Deterioration of the wet BSG takes place after an average period of 7 to 10 days from production, and under hot and humid conditions it may not be possible to store the wet BSG for a week. Thus, care must be taken to ensure that it does not deteriorate prior to being fed. A possible solution for storing BSG to be used as animal food is silage, where lactic acid is added, in order to obtain a fast decrease in slurry pH preventing the butyric fermentation, followed by storing in absence of air. However, silage is a costive process and difficult to insulate. In addition, if the silage is open or broken, preservation stops giving limitations to the process.[11]

BSG use and marketability would be significantly improved if the material is dried to be used as feedstuff and for the other purposes mentioned above.[2–9] Drying is also interesting in terms of reducing the product volume and, therefore, decreasing transport and storage costs. Nowadays, there are plants for drying BSG through a two-step process: pressing (to get a material with $<65\%$ moisture) and drying (to get a material with $<10\%$ moisture).[11] In another study, oven-drying and freeze-drying were used to obtain dried BSG. BSG composition was found to be similar after applying the two drying methods, with more advantages for the oven-drying by their being cheaper in addition to being more suitable for preservation to use in different purposes.[12]

In Portugal, the beer companies produce ~95,000 tons of BSG (70–80% moisture) per year that is being used as animal food with occasional silage to preserve extra BSG produced.

Obtaining lower levels of BSG moisture cake is an important matter. The aim of this paper is to produce dry, shelf-storable, BSG cakes using a new technology of membrane filter press. The dry cakes obtained can be used not only as animal food, at anytime, but also as a start material for other BSG uses.[2–9]

EXPERIMENTAL

Equipment Description

The membrane filter press (US Filter J-VAP, model no. 470V30-7-1MYLW, serial number JV0044, manufactured in 2000) is seven-chamber, plate and frame style filter press. Total volume of the seven chambers is 28 L with a total filtration area of 1.9 m^2. The membrane plate material is polypropylene with the size for each plate 470 mm. The membrane plates are three-part plates consisting of a flexible polypropylene membrane welded to each face of a rigid polypropylene body. A sketch of the membrane is shown in Fig. 1. Each membrane has a drainage surface made up from pips that strengthen the membranes and support the filter cloth, and the gaps between the pips provide a drain port path for the filtrate to exit to the filtrate discharge ports. In this study, the filter plates were rearranged to use three chambers only with 0.8143 m^2 filtration area and 12 L chambers' volume, using four plates producing three cakes in each filtration cycle.

The filter is center-fed from the central eye (eye 1) that also serves as the wash water inlet and the core-blow outlet. The upper-left-hand eye (eye 2) is a filtrate port that also serves as the port for blowing air in and discharging wash water. The eyes on the upper-right-hand, bottom-right-hand, and bottom-left-hand (eyes 3, 4, 5, respectively) are filtrate ports that also serve as discharge of wash water. The eyelets series on the top and bottom of each membrane connect filtrate to the discharge filtrate ports. The eyes 2, 3, 4, and 5 serve also as outlet ports for water vapor to depart the cake through the vacuum application step. A piping connection with a filter disc (from the same material of filter cloth) was also established, allowing vacuum to be applied through the central eye (eye 1) accelerating the drying stage.

The filter is opened, closed, and held at pressure with a single-acting cylinder (OTC P55-S 470 mm), manually powered hydraulic system with a hydraulic pressure of 700 bar at operating conditions.

The filter cloth used is a polypropylene multifilament fiber (9 oz/sq yd or 0.305 kg/m^2), satin weave, 140 × 42 thread count. The cloth air flow rating is 3–5 cfm (cubic feet per minute) or 4–6 L/sec. The cloth consists of a single sheet that drapes over both sides of each plate. The cloths are hung over the plates, extending from top to bottom and held in place by eyelets that fit over the cloth pins on top of the plates. The filter cloth from top and bottom from both sides were threaded together using plastic ties.

The filter operation steps are manually controlled through valves and switches for each motor in a control panel. The slurry feed pump is a pressure-regulated, air-operated, double diaphragm pump (All-Flo pump company, model: BK-15, serial no. 105647). The pumping cycle was continued

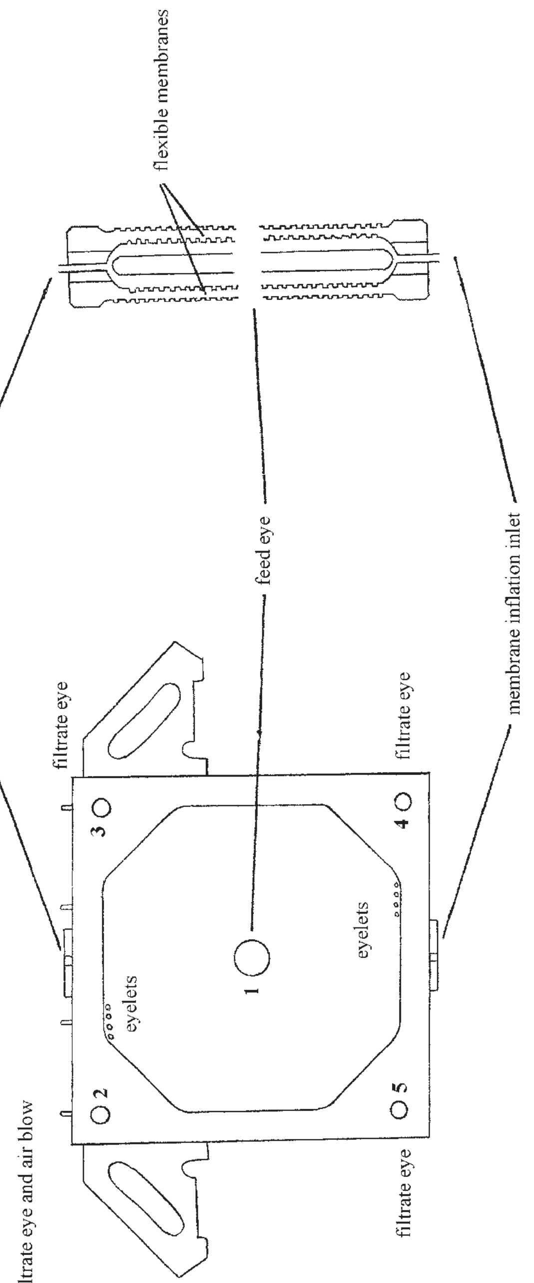

Figure 1. Membrane plate detail.

to operate until the filter chambers were filled with solid and the pump almost stalled. The feed pump was used at a pressure range of 3–5 bar. Cake washing was operated using pressurized water at 5 bar through the central core (eye 1, Fig. 1).

In the squeezing stage, the membrane plates are inflated with water. A centrifugal pump (MTH pump, model T51G BF) and a heater (Ogden, model: KS-0591-M7) were used to fill the membranes at squeezing pressure 6–7 bar and the water was returned to the squeeze water supply tank at 65°C.

Vacuum drying was applied over the hot cakes at 0.0481 bar, via a liquid ring vacuum pump (Squire Cogswell Company, number C00-2240/1, Type: PM124-M30A) through the filtrate outlet ports (eyes 2, 3, 4, 5) and the central core (eye 1), Fig. 1. Water vapor departs the hot cakes through the eyelets series on the top and bottom of each membrane plate and also through the central core and condensing in a tank, knock-out tank,[14] before reaching the vacuum pump.

The 13-step dewatering cycle is listed in Table 1. Three dewatering cycles are processed per day producing 1.35 kg and 2.46 kg of BSG (on dry basis) per batch (three cakes) for filtration without and with filter aid precoat, respectively.

System Limitations

The feed pressure was measured through a manometer installed between the feed pump and the press, however, cycling of the feed pump (double diaphragm pump) caused the pressure to fluctuate through the feed stroke of about the pressure value ± 0.2 bar and an average pressure value between the maximum and minimum for the manometer for each stroke was recorded;

Table 1. BSG dewatering steps.

Step	Time required, min.	Step	Time required, min.
1. Press close	2	8. Squeeze	15
2. Membrane drain	1	9. Air–drying	5
3. Diatomite precoat	10	10. Hot squeezing with vacuum drying	15–60
4. Fill press	1–2	11. Vent press	1
5. Filtration	40–60	12. Open press	1
6. Core blow	2	13. Retract plates and discharge cakes	3
7. Wash	10		

the viscosity of the slurry was assumed to be the same as the water; analysis of collected washing water was not carried out; effect of drying vacuum time was studied for cakes with similar thickness (a narrow range of thickness variation).

Slurry Preparation

BSG with particle size 0.5–5 mm and moisture content 80% was delivered from Sociedade Central de Cervejas Beer Company (Vialonga, Portugal) directly after its production and was stored in suitable sealed plastic containers at 2–4°C to stop fermentation.

It is difficult to transfer the slurry as delivered into the membrane filter press using the air-operated, double diaphragm feed pump. With a screw cavity pump, it may be possible. Thus, slurry was prepared by mixing a suitable weight of wet BSG with tap water in a concentration range of 40–120 kg/m^3 (10–30 kg/m^3 on dry basis). From preliminary experiments, the use of higher concentrations of BSG slurry blocked the tube between the feed tank and the feed pump discontinuing the feeding process. The water use is not only to carry the wet BSG into the filter press chambers, but also to wash away the residual wort, which is a fermentable medium, from the wet BSG. Mechanical and air agitators were used to keep the slurry homogeneously suspended in the feed tank during the filtration process.

A slurry of diatomite filter aid with an average particle size 30.1 μm was prepared by mixing 125 g diatomite with 75 L of tap water (1.667 g/L) in a 100 L tank. Pre-coating of filter aid was carried out by feeding the well-agitated diatomite slurry into the filter press at a rate of 35 L/min and the filtrate was returned to the precoat tank for recirculation. Precoating process was continued for 10 min. The precoat serves to protect the filter cloth from blinding caused by unfiltered particles and to facilitate cake removal at the end of the filter cycle.

Filtration and Drying Operations

Prior to diatomite precoating and dewatering cycle starting, the membranes should be drained. This is accomplished by deflating the membranes by closing the eyes 1, 3, 4 and 5 and applying air at pressure of 2 bar through eye 2 (Fig. 1). The water in the membrane plates from a previous squeezing step (in a previous dewatering cycle) is forced back to the squeeze water tank. This step ensures that there is no water in the membranes before the filtration cycle is started. The filtrate progress was monitored by the volume of filtrate produced. Volume was recorded to the nearest cubic centimeter using a calibrated 20 L filtrate vessel. Time was also recorded to the nearest seconds. The filtration process was continued until the feed pump almost stalled.

Core blow was carried out by applying air at low pressure (1–2 bar) through eye 2 (Fig. 1) for 2 min after closing the filtrate valves (eyes 3, 4, 5) and opening the central core (eye 1). This stage is important to empty the central core prior to washing and drying steps.

Washing was applied, after core blow, using water at pressure 5 bar through the central eye (eye 1, Fig. 1) and 90 L of wash water was collected. Cake drying was accomplished via membrane squeezing followed by vacuum drying. Membrane squeezing was carried out by circulating 65°C water through J-VAP membrane filter plates at pressures (6–7 bar) following the squeeze filtrate volume with time until the squeeze filtrate was far-dropping. This stage was continued for 15 min.

Air drying was applied after squeezing through eye 2 (Fig. 1) using compressed air at 5 bar for about 5 min. Hot squeezing was applied again at the same pressure for about 10 min to restore the cake temperature prior to vacuum application.

Vacuum was then applied at pressure of 0.0481 bar on the cake chamber simultaneously with continued cake squeezing. The vacuum in the cake chamber causes the boiling point of the water to drop to 45°C.[14] Different levels of cake dryness were achieved by varying the vacuum drying time. Straight after the dewatering cycle was accomplished and cakes were separated, moisture % was measured by drying ~50 g of a representative sample of each cake at 120°C until constant weight in a moisture analyzer oven (Mettler LJ16). The dried sample was allowed to cool in a desiccator and then weighed. The final moisture content was calculated from the difference in the weight of the cake sample before and after drying.

Experiments including filtration, squeezing, and vacuum drying were carried out at least three times and maximum analytical error was found to be less than 5% conditioned that the filter cloth is clean before use. Filter cloth was cleaned first by passing pressurized water over the cloth surface to remove big particles and then by impregnation in 10% alkaline hypochlorite solution overnight to remove the fine unfiltered particles followed by successive water rinsing to remove any residuals of the alkaline hypochlorite solution.

Cake Characterization

Using Poresizer 9320, the porosity of the dry cake was measured via mercury intrusion by IPNLABGRAN (Laboratory of Characterization and Certification of Granular Materials, Pedro Nunes Institute, Coimbra, Portugal). BSG cake was chemically analyzed in Section of Animal Production, Instituto Superior de Agronomia (Lisboa, Portugal).

RESULTS AND DISCUSSION

The classical filtration theory described in Svarovsky[13] was used to model the filtration behavior. Cake growth occurs as solids in the feed collect and accumulate on a growing layer of filter cake. For incompressible cakes, the cake resistance remains constant as the cake grows and the pressure drop is linear across the cake. The specific cake resistance, α, and medium resistance R_m are determined using the following equation:[13]

$$\frac{t - t_s}{V - V_s} = \frac{\alpha \mu c}{2A^2 \Delta P} \cdot (V + V_s) + \frac{\mu R_m}{A \cdot \Delta P} \tag{1}$$

Filtration at Different Feed Pressure

Using a slurry concentration of $20\,\mathrm{kg/m^3}$ (on dry basis), the filtration kinetics were carried out with and without diatomite filter aid precoat under different feed pressure in the range of 3–5 bar. Figure 2 represents the filtrate volume-time behavior, and Fig. 3 shows the variation of filtration rate against the accumulated filtrate volume. The filtration rate, which is high at the start of filtration, varies as the pressure builds and then shows a decrease as a result of the increased filtration resistance with the cake starting to form. The rate of filtration depends on the feed pressure. The higher the feed pressure, the higher the filtration rate for both filtration cases (with and without precoat) with higher rate values for the filtration with diatomite precoat.

Plotting the adjusted inverse rate, $(t - t_s)/(V - V_s)$ vs. the adjusted filtrate volume, $(V + V_s)$, gives a straight line with a slope from which the specific cake resistance is determined, Figs. 4(a and b). For the filtration system under study, careful data collection produced standard errors for the slope below 5% with r^2 values not less than 0.98. The specific cake resistance, α, was found to increase with feed pressure in both filtration studies (with and without precoat). This is because the cake becomes denser under high-feed pressure providing fewer and smaller passages for the filtrate flow. However, the specific cake resistance decreases as a result of diatomite precoating, Table 2. The diatomite precoat makes a bed over the filter cloth and the fine particles of BSG infiltrate into the void space of the diatomite bed offering less resistance to flow. Similarly, as shown by Kalafatoglu et al.,[15] the use of perlite filter aid precoat, in the separation of tincal insolubilities

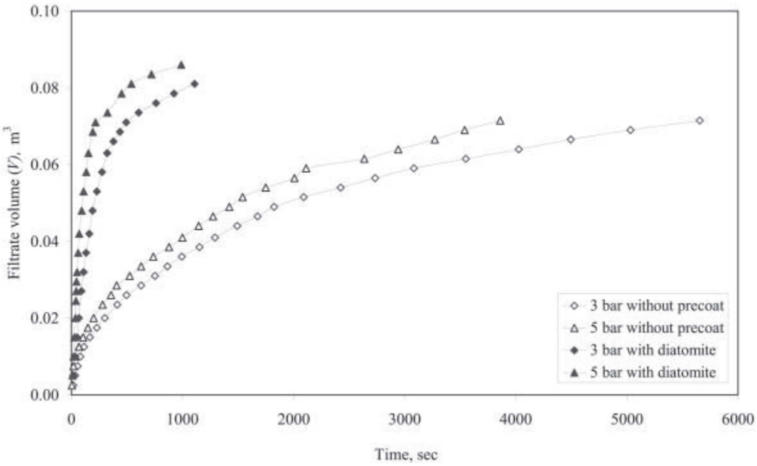

Figure 2. Filtration pattern at different feed pressure (slurry concentration $20\,\mathrm{kg/m^3}$).

from borax solutions during the dissolution of tincal concentrate, led to a considerable decrease in the specific cake resistance and as the amount of precoat increased, the specific cake resistance decreased.

According to the classical filtration theory, the medium resistance, R_m, should normally be constant. However, the theory has been under criticism[13]

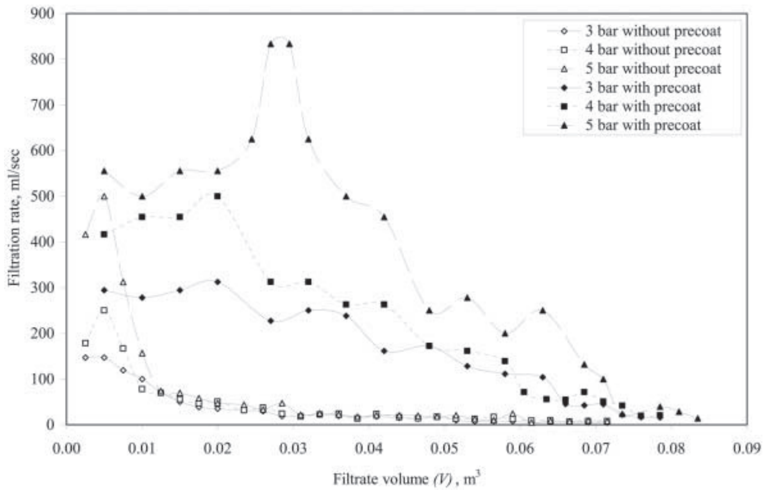

Figure 3. Filtration rate at different feed pressure with and without diatomite precoat (slurry concentration $20\,\mathrm{kg/m^3}$).

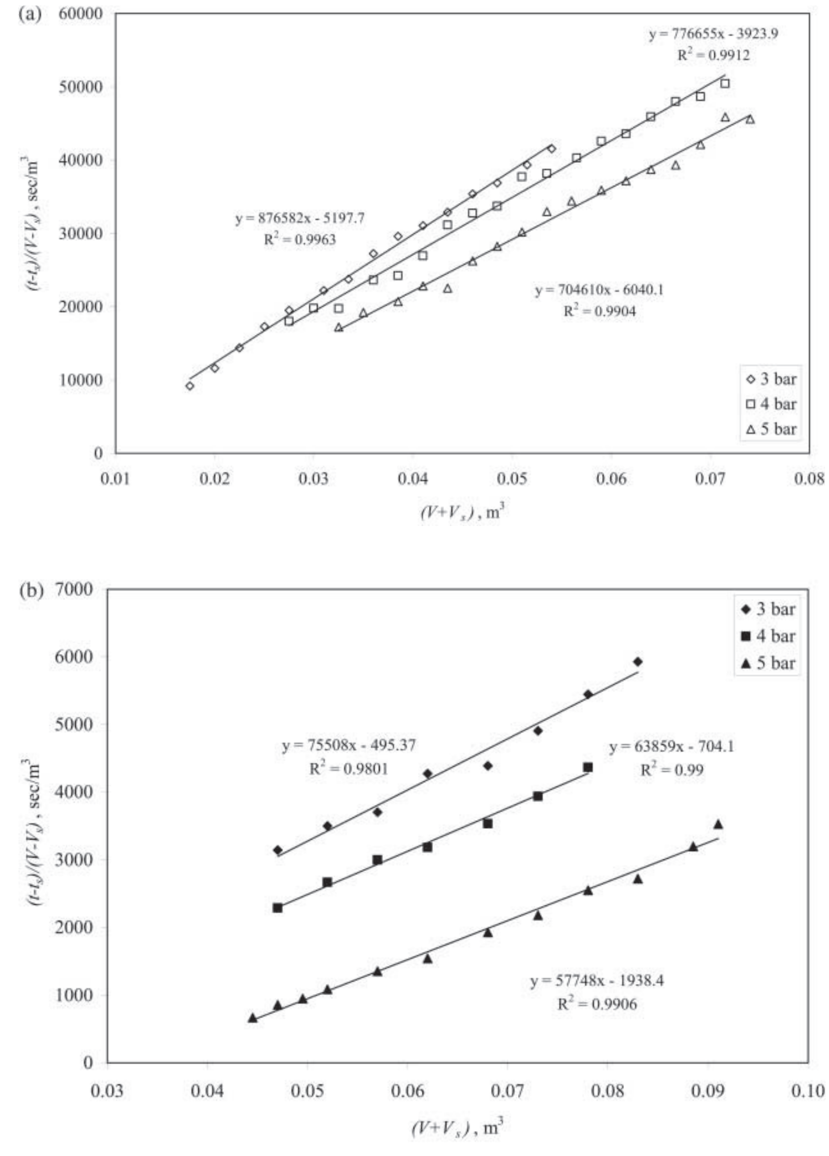

Figure 4. A plot of $(t - t_s)/(V - V_s)$ against $(V + V_s)$ at different feed pressure (slurry concentration $20\,kg/m^3$). a. without filter aid precoat; b. with filter aid precoat.

Table 2. Specific cake resistance (α) at different filtration conditions.

Feed pressure (bar)	Slurry conc. (kg/m^3)	α, without filter aid precoat (m/kg)	α, with filter aid precoat (m/kg)
3	20	1.74×10^{13}	1.50×10^{12}
4	20	2.06×10^{13}	1.69×10^{12}
5	20	2.34×10^{13}	1.91×10^{12}
5	10	2.81×10^{13}	2.42×10^{12}
5	20	2.34×10^{13}	1.91×10^{12}
5	30	2.17×10^{13}	1.70×10^{12}

since medium resistance, in practice, often appears as unrealistically small or even negative. In the current study, R_m is known with far less certainty than the specific cake resistance, and in most studied filtration cases, R_m values appeared unrealistically negative. The uncertainty of the intercept is too large to be used for medium-resistance determination. The larger error in R_m results from the extrapolation necessary for the intercept determination. The unrealistic R_m values could be because of the increased medium resistance, as a result of the penetration of some solids into the filter medium, and the variation of the cake resistance along the filtration process. Similar results with large errors in medium resistance were also obtained by Voit et al.[16] in their study of hafnium hydroxide filtration using a membrane filter press. Leu and Tiller[17] considered that some of the basic assumptions involved in flow through compressible porous media have shown to be incompatible with experimental data. The development of an adequate theory of filtration gets complicated because of the following two factors:[17]

a. The increase in the resistance in the septum (filtration medium) not only during the first few seconds, but also throughout the entire process in many cases[17,18]
b. Variation in cake resistance, continuing throughout the process as a result of subsequent closure of passages as small particles migrate downstream in the cake[17]

The fact that a pore could be blocked by particles much smaller than the pore itself was recognized early in filtration literature.[17]

Most cakes formed from biological materials are compressible. As liquid flows through a compressible bed of particles, viscous drag on the particles produces compressive pressure which causes α to increase and porosity to decrease toward the filter medium.[19]

The following empirical equation has been proposed to consider cake compressibility:[20]

$$\alpha = \alpha_0(\Delta P)^s \quad (2)$$

α_0 is a constant that represents the specific cake resistance at zero compressive pressure and s is the compressibility coefficient of the cake. s values vary between 0 for incompressible cakes and 1 for highly compressible ones.[15] Plotting the specific cake resistance values against the filtration pressures on a log-log scale shows a straight line whose slope gives the cake compressibility coefficient, s (Fig. 5). The values of α_0 and s are 3.87×10^9 m/kg and 0.472 ($r^2 = 0.994$), and 1.27×10^{10} m/kg and 0.573 ($r^2 = 0.999$), for filtration with and without precoat, respectively. The values of the compressibility factor, s, shown here, indicate the compressible character of the cakes.

Filtration under Different Slurry Concentration

Using a slurry concentration in the range of 10–30 kg/m^3 (on slurry dry basis), the filtration kinetics were carried out with and without a diatomite precoat under feed pressure 5 bar [Figs. 6 (a & b)]. Figure 7 shows the

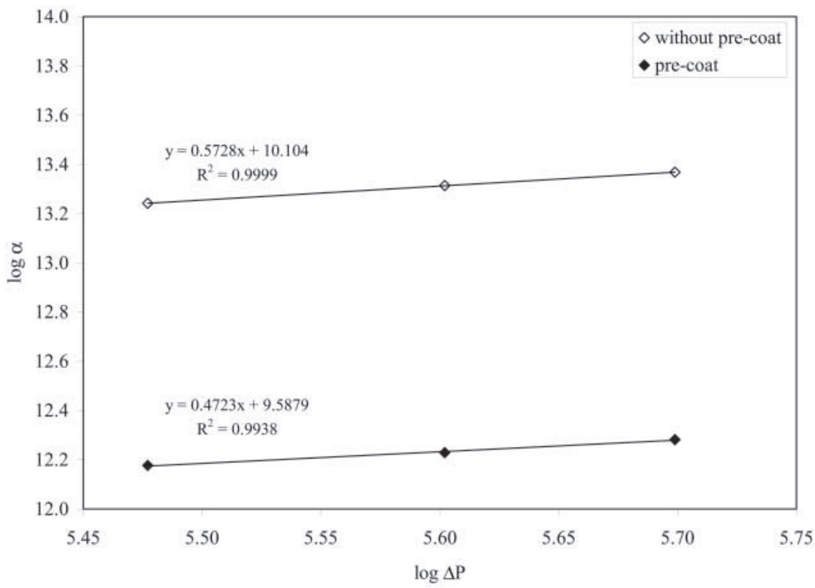

Figure 5. A plot of log α vs. log ΔP.

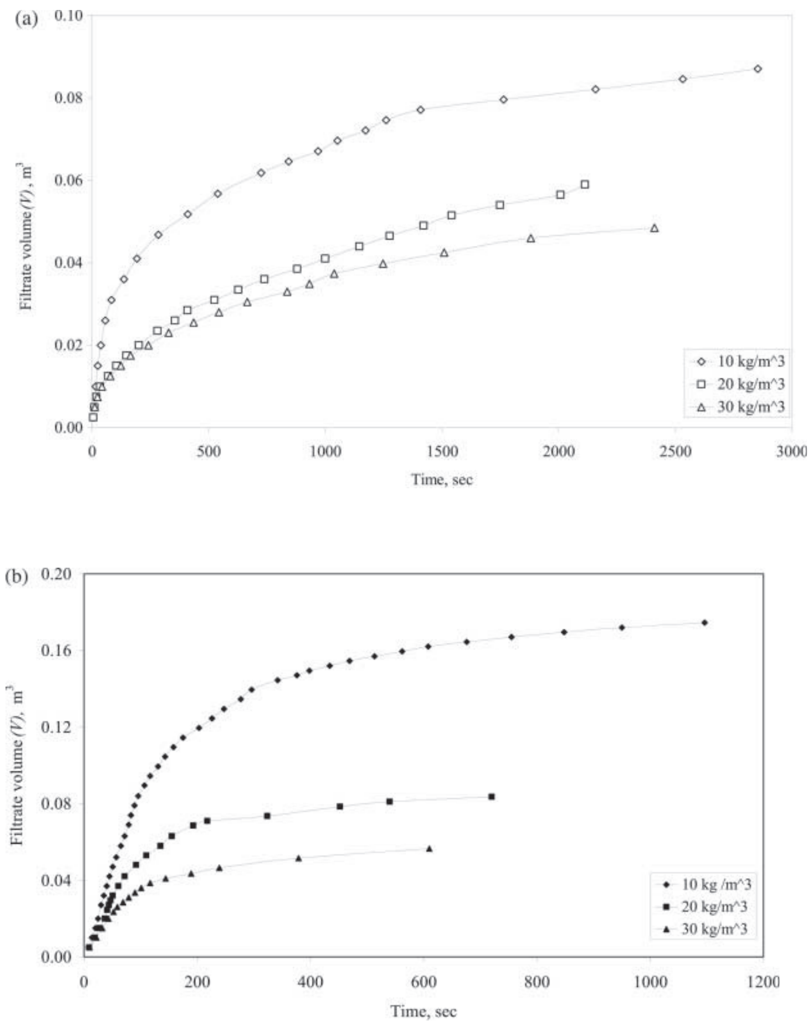

Figure 6. Filtration pattern at different slurry concentration (feed pressure 5 bar): a. without filter aid precoat; b. with filter aid precoat.

variation of the filtration rate with filtrate volume. The rate of filtration depends on the slurry concentration. Higher rate values were obtained with lower slurry concentration for both filtration studies (with and without precoat).

The specific cake resistance, α, calculated from the slopes of the straight lines of $(t - t_s)/(V - V_s)$ vs. $(V + V_s)$, Figs. 8 (a and b), shows a decrease with

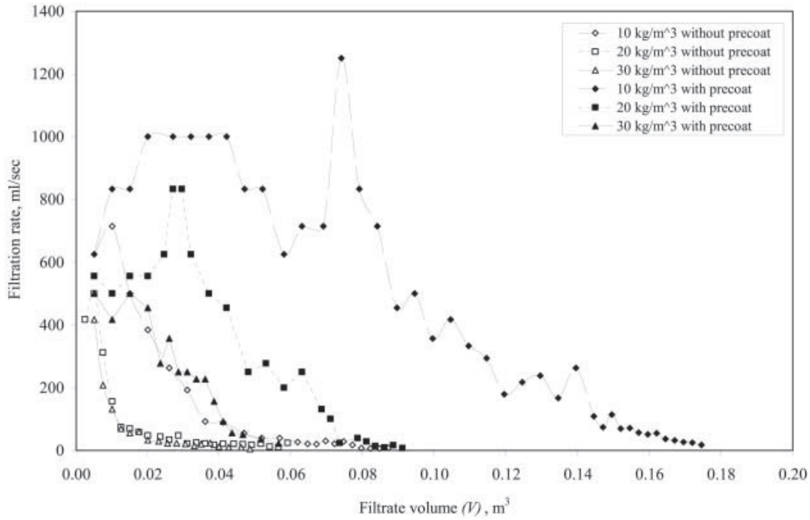

Figure 7. Filtration rate at different slurry concentrations with and without diatomite precoat (feed pressure 5 bar).

the increase in slurry concentration for both filtration studies (with and without precoat).

It is noticed that α changes not only with feed pressure but also with cake depth. As the cake thickness depends on the concentration of the particles in a slurry, α is correlated to slurry concentration as shown in the following equation:[19]

$$\alpha = \alpha_0 c^{-m} \tag{3}$$

It is observed that α decreases not only with the diatomite precoat but also with the increase in slurry concentration, In Table 2, the log-log plot of α and slurry concentration gives a straight line with a negative slope with m values 0.322 ($r^2 = 0.998$) and 0.238 ($r^2 = 0.992$) for the filtrations with and without diatomite precoat, respectively. Lower slurry concentration produces less solid content into the press, giving more chances for the particles to be arranged under pressure, leaving fewer voids producing denser and thinner cakes with higher α value. However, if the slurry concentration increases, more solid is produced into the filter chambers in a shorter time, giving less chances for particles to arrange and producing more voids and thicker cakes with lower α value.

The average values of α are 1.86×10^{12} and 2.25×10^{13} m/kg for filter cakes produced with and without filter aid precoat, respectively.

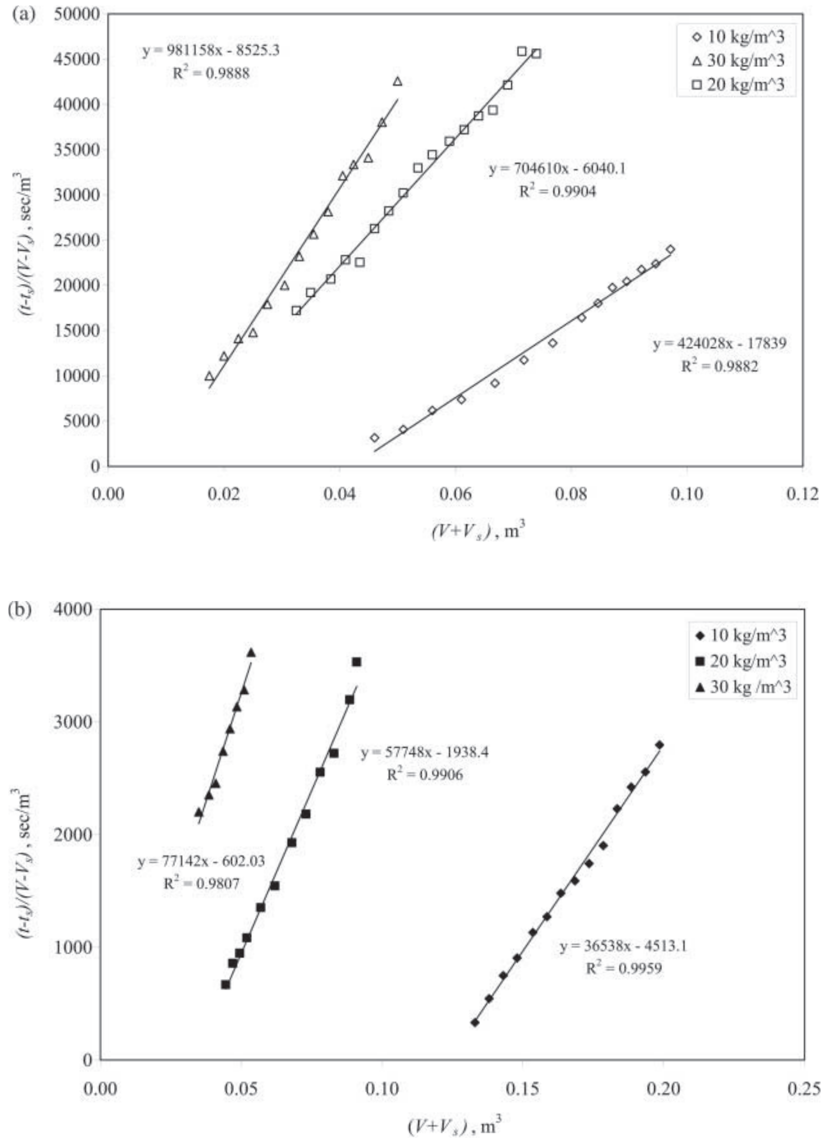

Figure 8. A plot of $(t - t_s)/(V - V_s)$ against $(V + V_s)$ at different slurry concentration (feed pressure 5 bar). a. without filter aid precoat; b. with filter aid precoat.

Cake Washing

Cake washing was applied after core blow and carried out by using pressurized water through the central eye (eye 1, Fig. 1). A pressure of 5 bar was required to make sure that the water crossed the cakes in all sides, displacing the residual wort that might be still available within the BSG cake. A volume of 90 L washing filtrate, which is more than seven times the cake volumes, was collected from the four outlet filtrate ports (eyes 2, 3, 4, 5), Fig. 1. The wash flow rate was in the range of 6–14 mL/sec for cakes with and without precoat, which was similar to the filtration rate at the end of the filtration step. However, no analytical tests were carried out on the washings after being collected. Washing was preferred to take place prior to the squeezing step as found from preliminary experiments for other slurries such as tannery waste (as will be published later) that squeezing decreases cake volume and porosity, producing denser cake. Thus applying wash water under pressure would cause the membranes to deflate, having larger size than the squeezed cake, and new passages for wash water can develop between the filter medium and the cake, resulting in less-efficient washing.

Cake Dewatering via Membrane Squeezing

The squeezing step is considered as a crucial step to the success of the dewatering process.[16] BSG cake produced by conventional pressure filtration at 5 bar contains about 80% moisture. For cakes with 1 cm thickness (after complete drying), squeezing, by passing water (at room temperature) at pressure 6.5 bar for 15 min through the membranes, decreases the moisture content to about 71%. Squeezing using hot water (65°C) at the same conditions uniformly dewaters the cake to 51%. A squeezing pattern with time using hot water at squeezing pressure (6–7 bar) is shown in Fig. 9. Most of the squeezable water was flown out of the cake in the first 3–5 min with flow rate higher at higher squeezing pressure (Fig. 10). Squeezing causes the particles in the filter cake to rearrange so they are more densely packed. The fluid in the voids between the particles must flow out and leave the cake through the filter cloth. The pressure gradient between the cake and the filter cloth provides the driving force for the fluid flow. As the cake become drier, it bears an increasing fraction of the imposed pressure, causing the pressure on the fluid to decrease. The decreasing pressure gradient causes the dewatering rate to decrease as the dewatering proceeds. Thicker cakes possess more solids than thinner ones, bearing higher fraction of the squeezing pressure. Thus, less pressure is applied on the fluid in thicker cakes than in thinner ones, resulting in more moisture content within thicker cakes after squeezing. The increased squeezing pressure results in increased dewatering and the maximum squeezing pressure, 7 bar, showed the best squeezing performance.

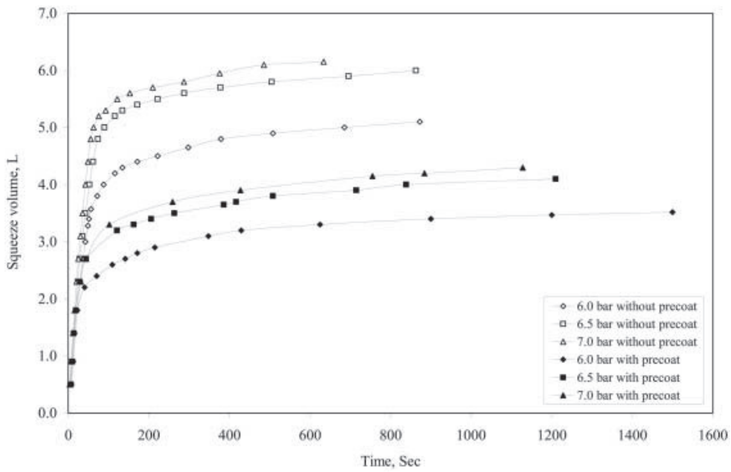

Figure 9. Squeezing pattern for the cake at different squeezing pressure.

Cake Air Blow

Air blowing is an important dewatering step and is used to displace water from the microscopic channels between the particles in the filter cake. Blowing also removes water from piping and channels inside the press prior

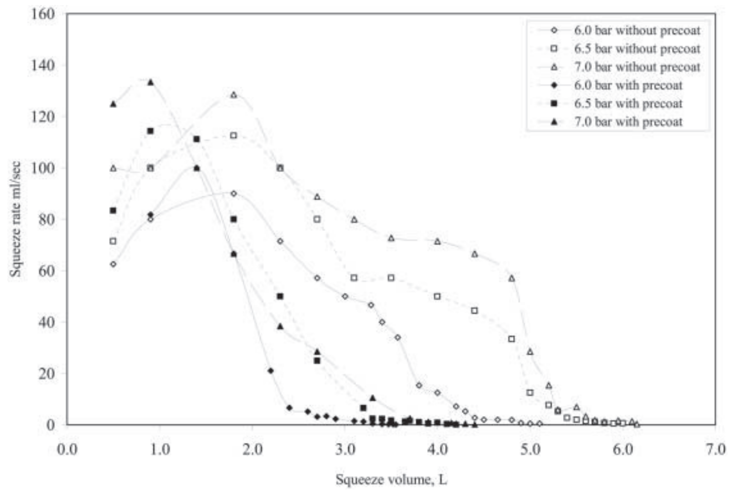

Figure 10. Squeeze rate vs. squeeze volume.

to vacuum application. Approximately, 850 mL of water are removed during the cake blow in each dewatering cycle. About 250 mL are from the central core and the rest are believed to be from the cakes as well as piping and channels in the press.

Filter Cake Drying

After the air blow step was accomplished, squeezing was applied again using hot water (65°C) for 10 min to restore the cake temperature after a loss caused by air blow. Vacuum drying over the hot cake was then applied simultaneously with continued squeezing. The key success of this step is based on the fact that water boiling point decreases under low pressure developed by vacuum. Vacuum application at 0.0481 bar would lower the water boiling point down to 32°C in an ideally sealed system. However, the actual boiling point referred in the U.S. Filter manual,[14] in the cake chambers under vacuum, was 45°C, which is still lower than the squeeze water temperature. Cake drying was studied varying the vacuum period applied. As the vacuum application period increases, cake moisture decreases. Cakes with similar thickness at different vacuum time were selected to investigate the effect of the vacuum application period (Fig. 11).

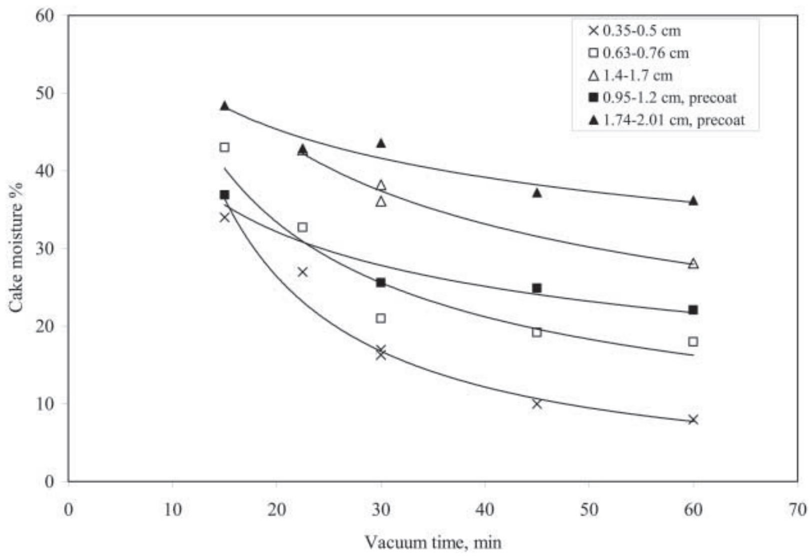

Figure 11. A plot of cake moisture vs. vacuum time at different cake thickness.

Higher slurry concentration produces thicker cakes as well as diatomite precoating. A plot of cake moisture vs. cake thickness under the same vacuum period, 30 min, is shown in Fig. 12. Cake thickness is an important factor for the efficiency of filter cake drying under vacuum. As the cake thickness exceeds 1 cm, it becomes difficult to achieve high levels of cake dryness with economic periods of vacuum application. This could be because of the fact that as the cake gets thicker, the heat transfer from the warm squeeze water through the membranes to the cake bulk becomes inefficient, resulting in less water evaporation and consequently a less dry cake.

Cake Discharge

The cake release behavior of squeezed, air-blown, vacuum-dried cake is dependent on the cake thickness and the availability of filter aid precoat. Diatomite precoated cakes, after releasing the press, separate very easily from the filter cloth regardless the cake thickness. Non-precoated cakes with thickness up to 1 cm separate easily whereas those with larger thickness show a difficulty in separation from the filter cloth with cake breaking. Such cakes possess high moisture content and heat transfer from squeeze hot water through the membrane into the cake bulk is not efficient. By the end of the vacuum application, the cake surface in both sides is drier than the cake bulk and is sticking to the filter cloth. Thus with plates opening, the cake breaks from the cake bulk.

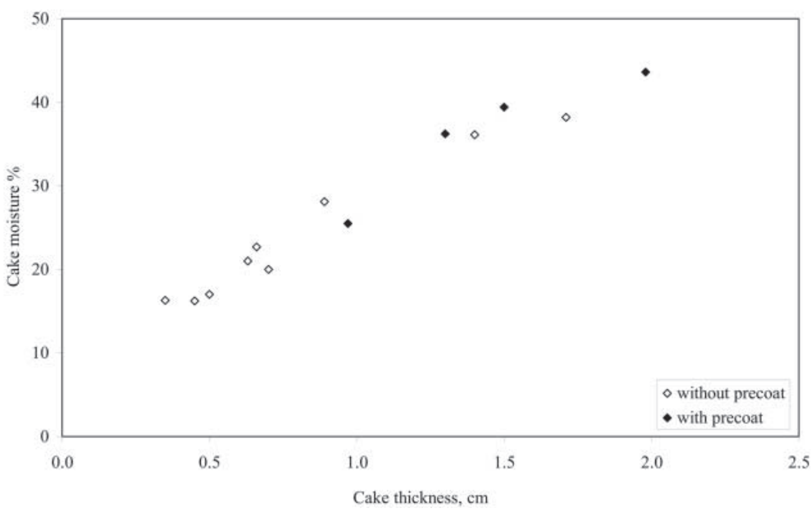

Figure 12. A plot of cake moisture against cake thickness using 30 min vacuum time.

System Capacity

On dry basis, each cake weighs, in average, about 980 and 540 g from those produced with and without precoat, respectively. About 1.88 and 1.04 kg of dry BSG cake are produced per 1 m^2 of the filter cloth in 1 h of operation for the filtration with and without a filter aid precoat, respectively. A summary of the whole dewatering process representing the moisture content at the end of each stage of the operation is shown in Fig. 13.

Cake Characterization

Using mercury porosimetry, some parameters were measured for a cake sample from those obtained without filter aid precoat, (Table 3). At the end of the dewatering process, an average moisture value of 20% was obtained for cakes with a thickness of 0.7 cm. The BSG cakes produced with the dewatering system, in the current study, are highly porous and experience more water evaporation by storing in open air (on the shelf), reaching an equilibrium moisture value of 10.1% in less than 2 days. At such low moisture

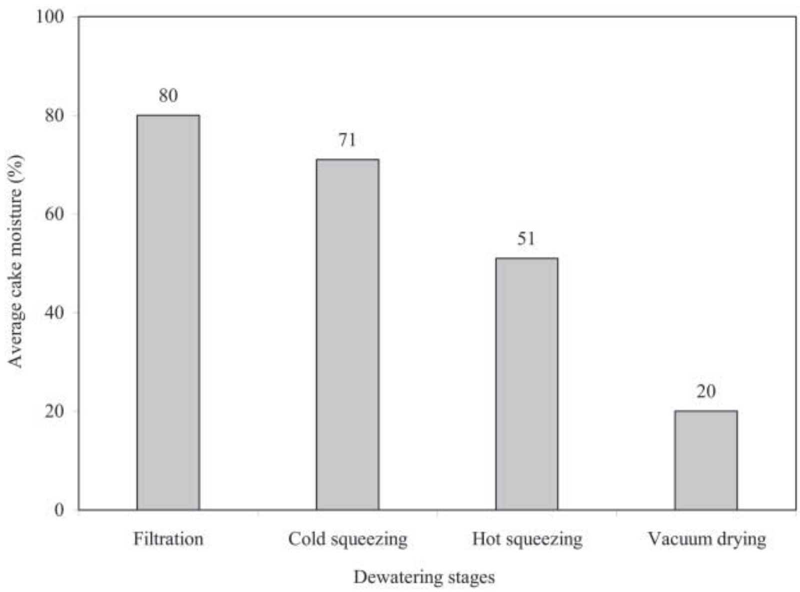

Figure 13. A plot of the BSG cake moisture with the end of every stage of the dewatering process (thickness of dry cake = 0.7 cm).

Table 3. Cake parameters.

Cake parameters	Values
Total intrusion volume, mL/g	0.1181
Total pore area, m^2/g	7.834
Median pore diameter, (volume) μm	4.689
Bulk density, g/mL	0.9949
Apparent density, g/mL	1.1274
Porosity, %	11.75

levels, no bacterial activities were observed on the shelf-stored cakes for a 6-month period.

Cake chemical analysis was also carried out and shown in Table 4. The analysis of the dry BSG strongly suggests its use not only as animal food, with the advantage of being shelf storable, but also as a starting material for other BSG uses.[2–9]

Diatomite (diatomaceous earth) is commonly used in feed mix by cattle and poultry owners to control internal parasites.[21] Diatomite precoated cakes produced in this study contain 2–3% of diatomite, which is considered as a valuable addition to BSG as animal food not only to control internal parasites but also due to the presence of minor elements.

CONCLUSION

BSG dewatering process using the membrane filter press consists of three main consecutive stages: filtration, membrane squeezing, and vacuum drying over hot cakes. The fresh water being mixed with the wet BSG helps to carry the BSG sludge into the press using a double diaphragm pump and

Table 4. Cake chemical analysis.

Cake analysis	Values, %
Dry matter under shelf-storing conditions	89.9
Ash in dry matter	3.9
Protein in dry matter	26.7
Fat in dry matter	8.9
Lignin	5.3
Fiber in acid surfactant, in dry matter	16.0
Fiber in neutral surfactant, in dry matter	56.9

also to displace the residual wort with the filtrate. For cakes with thickness in the range of 0.7–1 cm, moisture decreases from 80% by the end of the filtration stage to 51% with the hot-water squeezing and finally to 20–30% with the application of vacuum over hot squeezed cakes. Cake thickness can be considered as a key success for the whole dewatering process with economic application. From this study, cakes with 0.7-centimeter thickness appear the best suited for best drying with economic cost in addition to their easy separation.

Diatomite precoating helps to protect filter cloth from blinding that is caused by unfiltered particles. It also facilitates cakes removal at the end of the dewatering cycle. From this study, the use of diatomite precoat decreases the specific cake resistance showing higher filtration rate and consequently less filtration time. However, caution must be considered regarding the cake thickness. With diatomite precoating, when filtration continues until pump stalls, thicker cakes with cake thickness larger than 1.5 cm are produced, causing more difficulty in the following dewatering stages (squeezing and vacuum drying). Consequently, more operational time in the vacuum drying stage is necessary to achieve a satisfying level of cake drying. Thus, the filtration stage should be optimized by controlling the amount of solids that fed into the press to achieve precoated cakes with a thickness in the range of 0.7–1 cm.

Diatomite precoated cakes contain 2–3% diatomite, which is considered as a valuable addition to cake composition as animal food since it contains minor elements and helps to control internal parasites.

The use of membrane filter press has provided an efficient alternative method to dry the brewery spent grain in one continued cycle. This helps to decrease the sludge volume to a great extent and to achieve a drying level high enough to prevent bacterial activities under environmental conditions. Such achievements enable BSG to be shelf-stored and, thus, to be used for animal as a dry food at any time and for other uses related to BSG.

NOMENCLATURE

t	Time of filtration, sec
t_s	Time elapsed when the feed pressure becomes constant
V	Volume of filtrate produced in time t, m^3
V_s	Filtrate volume produced when the feed pressure becomes constant, m^3
α	Specific cake resistance (m/kg)
μ	Viscosity of filtrate, 0.001 Ns/m^2
c	Feed slurry concentration, kg/m^3

A	Area of filtration, 0.8143 m^2 for 3 cakes
ΔP	Total filter pressure drop, Pa
R_m	Filter medium resistance
α_0, m	Constants
s	Compressibility coefficient

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