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Project Title: **A NOVEL FINE COAL DEWATERING PROCESS WITH INTEGRATED BIOMASS UTILIZATION**

ICCI Project Number: 02-1/4.1A-2
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ABSTRACT

Illinois produces about 40 million tons of coal each year. Of that, fine coal accounts for more than 10% of the total throughput of coal preparation plants. The major economic and technical barrier to the recovery of coal fines is dewatering. Because the cost to treat fine coal is three to four times higher than that to treat coarse coal, it is often more practical to discard the coal fines than to recover them. It is estimated that U.S. coal producers currently discard between 27 and 36 million metric tons of fresh fine coal to refuse ponds each year. Over time, about 1.8 billion metric tons of fine coal have been discarded in abandoned ponds and 450 to 725 million tons are in currently active ponds. This material represents a waste of valuable natural resources and a loss of profit for coal producers. It can also create significant environmental problems.

On the other hand, agricultural production is one of the largest industries in Illinois. It was estimated in a recent research report that Illinois produces more than 26 million tons of dry corn residues annually, ranking first in the nation. If a novel, integrated process to utilize both coal fines and biomass can be developed, it may help not only the Illinois coal and agricultural industries, but the Illinois utility industry as well.

The overall objective of this project is to use biomass as a filter aid in the ISGS Intelligent Filter Press to improve the fine coal dewatering process and the handling of fine coal. The product, a biomass/fine coal mixture, can be used in co-combustion for power production.

In this project, both vacuum and filter press filtration behaviors of biomass/fine coal mixtures were investigated in lab scale facilities. Results indicated that addition of biomass helps filtration rates when biomass percentages are high. However, final moisture content also increases with an increased percentage of biomass in the mixture. Handling of the biomass/fine coal filter cake seems improved compared to the pure fine coal filter cake, especially when the cakes are dried. Further study is needed to determine pelletizing behavior and suitability for co-combustion.

EXECUTIVE SUMMARY

Coal preparation is used to upgrade as-mined coal to reduce the amount of mineral impurities, sulfur-bearing minerals, and hazardous trace elements. Fine coal generated in the preparation and mining processes accounts for more than 10% of the total throughput of coal preparation plants. Most conventional and advanced coal cleaning processes use water, creating dewatering problems for coal producers. End users are concerned not only with the lower heating value of the resulting wet, cleaned coal, but more importantly, with handling problems, such as stickiness and freezing. Both moisture and handling problems are exacerbated in coal fines. As a result, many utility coal contracts have limits on the amount of moisture and the quantity of fines allowed in the final coal shipments, making it difficult for coal preparation plants using currently available technology to process the fines and include them in the final product.

Fine coal dewatering is the least efficient and most costly step in coal preparation. Because the cost to treat fine coal is three to four times higher than that to clean coarse coal it is often more practical to discard the fines provided that the fine coal is only a small fraction of the total coal. U.S. coal producers currently discard between 27 and 36 million metric tons of fresh fine coal to refuse ponds each year. To date, approximately 1.8 billion metric tons of fine coal have been discarded in abandoned tailings ponds and around 450 to 725 million tons are being held in active ponds. Obviously there is a need for an innovative, low cost fine coal dewatering process that will reduce environmental problems related to fine coal ponding and at the same time increase the revenue stream for coal producers.

Global warming is a mounting concern in the world. Bio-energy is considered as one potentially viable option for reducing net CO_2 addition to the atmosphere. Furthermore, agricultural production is one of the largest industries in Illinois. One research report has estimated that Illinois produces more than 26 million tons of dry corn residues annually; the state ranks number one in the nation. One attractive technology is co-combustion of biomass with coal. In this scenario, biomass is mixed with coal and combusted in conventional boilers. Co-firing biomass and fine coal has the potential to help Illinois' agricultural, coal mining, and utility industries.

The objective of this project is to use biomass, which is readily available in Illinois, as a filter aid (and possibly a binding agent) to improve the fine coal dewatering and handling process. The biomass/fine coal mixture can be used as a co-combustion fuel to help the utility industry reduce CO_2 emission. The work performed in this project consisted of five major tasks with the emphasis on Tasks 3 and 4.

In Task 1, two biomass samples, sawdust and corn stover were selected and prepared. Corn stover is the most abundant biomass in Illinois. Sawdust is another biomass suitable for the purposes of this project. To be an effective filtration aid, biomass has to be ground to a suitable size. This study showed grinding biomass is a difficult task and the cost can be high. A suitable grinding method to get biomass in fine powder form needs to be identified. Because of this dilemma, the biomass used in the remaining tasks was not as fine as the coal.

In Task 2, the mixing of dry biomass samples and fine coal slurry was studied. The bulk density of dried biomass is low compared with fine coal. The difference in densities between biomass and fine coal make it difficult to mix biomass and fine coal slurry, especially when the solid content of the slurry is low. In this study, a HOBART mixing device at the ISGS was used. Experiments showed that when the fine coal slurry had a solid content of 40% or higher, mixing biomass and fine coal was not a difficult task and the mixture was uniform and would not settle. A fine coal slurry with solid content of 40% to 50% was used for mixing with the biomass in the remaining tasks.

In Task 3, the dewatering behavior of biomass/fine coal mixtures was tested in a bench-scale vacuum filtration device. Two types of biomass, sawdust and corn stover, were used. The effects of particle size of biomass and biomass/fine coal ratio were investigated. Results showed that when sawdust content was as high as 20%, vacuum filtration rates increased significantly. But that was not the case for corn stover. Even when corn stover content increased to 20%, the vacuum filtration rate was still lower than a filter cake consisting only of coal. The conclusion is that sawdust is more suitable as a filter aid than corn stover. This is most likely due to the fact that corn stover expands more when it is wet. It would be soft and leave less space between particles, and as a result, reduce the permeability of the cake. The final moisture content of filter cakes after vacuum filtration was high, ranging from 33% to 42%. Obviously, vacuum filtration alone will not achieve satisfactory moisture levels in a biomass/fine coal mixture.

In Task 4, a bench-scale ISGS Intelligent Filter Press was used to study the dewatering behavior of biomass/fine coal mixtures. The variables investigated in this task include the characteristics of the feed material, such as biomass particle size and biomass to fine coal weight ratio, and the operating parameters of the filter press, including number of tapping cycles, hydraulic pressure, and thickness of the filter cake. Results showed that the number of tapping cycles and the biomass particle size have insignificant impacts on the final moisture content of the filter cake. Biomass/fine-coal weight ratio (biomass percentage) showed significant influence on the final moisture content. As biomass usage increased from 5% to 20%, moisture content increased from 21% to 30%. The hydraulic pressure of the filter press also showed significant impact on the moisture content, especially when biomass usage was high. Biomass and fine coal may have different mechanisms in retaining moisture. For fine coal, the residual moisture content may be determined by the void between fine coal particles. However, the water absorbed into the biomass material might determine the moisture in biomass. Obviously, absorbed water is more difficult to remove by pressure, especially when the moisture content is relatively low. Overall, results obtained in the study show that biomass/fine coal mixtures can be dewatered to less than 30% moisture. This moisture content is acceptable if the filter cakes can be readily transported.

In Task 5, filter cakes were examined by X-ray microtomography. The porosity, pore size and pore size distribution of several filter cake samples were studied. No definite trend could be identified in the results. Lack of experience in preparing the samples for X-ray microtomography may have contributed to inconclusive results.

OBJECTIVES

The overall project objective is to use biomass as a filter aid to improve the dewatering process and the handling of fine coals and at the same time to produce a suitable biomass/fine coal mixture for co-combustion in utility power plants.

The basic principles of coal dewatering processes are similar. The performance of a dewatering process depends not only on operating conditions such as pressure drop across the bed (filter cake) but also on the physical properties, such as the permeability, of the filter cake formed. Permeability is the most important physical property of a filter cake that affects dewatering speed. The most effective way to improve the dewatering process is to improve the permeability of the filter cake.

In this project, biomass with a suitable mean particle size and particle size distribution will be added to the fine coal slurry to alter the matrix of the filter cake. It is expected that when biomass material is mixed with fine coal, the porosity, connectivity of capillaries, pore size and pore size distribution of the filter cake will be changed. The mean particle size and the size distribution of biomass is the key to the success of the proposed process. The weight ratio of biomass/fine coal also is an important variable. The optimum percentage of filter aid added will be determined experimentally.

It is also necessary to reduce the residual moisture content of the filter cake. An effective way to reduce the residual moisture content of the final product is to reduce the porosity. Since biomass can be considered as a compressible material, a filter press or mechanical device can be used to reduce the porosity of the filter cake.

After dewatering, biomass fibers are part of the matrix of the filter cake. It is expected that such a mixture will have an advantage over a pure fine coal filter cake during subsequent pelletizing. The fibers in the matrix may serve as a binder for the pellets. If the moisture content of the filter cake is within an appropriate range, the material may be pelletized directly without adding any binding material. The pelletized material can be easily handled and transported to end users. Due to the time limitation, however, pelletizing tests were not be carried out during this project. Further research in this area should consider conducting palletizing tests.

The work performed in this project consists of five tasks. The activities of each task are summarized below.

Task 1. Biomass selection and sample preparation

Two biomass samples were selected, pretreated, and ground to different mean sizes. Corn and corn by-products are probably the most abundant biomass in Illinois. Corn fibers from ethanol producing plants and corn stalks are both suitable candidates for this application. Corn stalk is currently recycled to farmland for soil quality amendment. Corn fibers from ethanol plants are sold at around $35/ton, and the price is expected to decrease as more and more ethanol plants are built. The other biomass to be investigated in this project was sawdust. According to a recent survey, Illinois produces about 282,000 tons of wood mill residues, which can be obtained at a cost of <$50/ton. If all of the residues can be used to treat fine coal, more than a million tons of fine coal could be treated annually.

Task 2. Mixing of biomass and fine coals

Dry biomass has a low bulk density compared with fine coal material. This large difference in density makes it difficult to mix biomass and fine coals uniformly. Several mixing mechanisms were tested to determine a suitable mixing device for biomass and fine coal. A HOBART mixing device at the ISGS was used and several impeller designs were tested. Other variables investigated included the particle size and the initial moisture content of the biomass.

Task 3. Dewatering behavior of biomass/fine coal mixture in a vacuum filter

Several biomass samples prepared in Task 1 were mixed with wet fine coal sludge (for the purposes of Task 3, wet biomass was used for more homogeneous mixing) and tested in a bench-scale vacuum filtration device. The particle size of the biomass material was expected to affect the filter cake matrix. It was not desired to grind biomass to a size smaller than fine coal for cost reasons. On the other hand, overly coarse biomass material has little effect on the performance of the dewatering process since biomass just separates from the fine coal and forms a segregated filter cake. The objective was to determine the optimum biomass particle size at which the overall performance of dewatering process is maximized. The biomass/fine coal ratio is another important variable that was investigated. As previously stated, there should be an optimum biomass/fine coal ratio at which the permeability of the biomass/fine coal mixture is greatest. Determining that ratio was also part of the objectives.

Task 4. Dewatering behavior of biomass/fine coal mixture in an ISGS filter press

Experiments were conducted with an existing prototype automated tapping filter press to determine important operational parameters and their impacts on the moisture content of the filter cake. The effects of feed characteristics such as solids content in the feed, thickness of the cake, biomass particle size, particle size distribution of the feed, and biomass/fine coal weight ratio, were tested under a fixed set of operating conditions. Then the impact of operating conditions on the dewatering characteristics for a given biomass/fine coal mixture were tested. The operating parameters investigated included hydraulic pressure, filtration time, and the number of tapping cycles. After identifying the important operating parameters and their ranges, tests were carried out by changing these parameters simultaneously to determine their interactions and to find optimum operating conditions.

Task 5. Filter cake microstructure analysis by X-ray microtomography

The performance of the dewatering process is closely related to the microstructure of the filter cake formed by the fine coal and biomass particles. Fundamental understanding of the microstructure of the filtration cake is important for further improving the dewatering process. Filter cakes formed during the filtration process were investigated through a technique called X-ray microtomography. The variables to be investigated include biomass/fine coal weight ratios and biomass particle size. X-ray microtomography is a powerful technique for studying three-dimensional microstructure of the filter cake. It can reveal the pore structure (connectivity), porosity, pore size, pore size distribution and heterogeneity of filter cakes. It is especially useful for this project because fine coal and biomass were blended together, probably incurring severe heterogeneity at a micro scale. Results obtained through the X-ray microtomography may help with understanding how the biomass is distributed among the fine coal and with improving the mixing process and providing other clues about appropriate treatment of biomass.

INTRODUCTION AND BACKGROUND

Illinois companies produce about 40 million tons of coal, generating billions of dollars of revenue[(1)]. Coal preparation is used to upgrade as-mined coal reducing the amount of non-combustible mineral impurities, sulfur-bearing minerals and hazardous trace elements, and generally producing a more uniform fuel with higher energy content. Fine coal produced during the coal mining and preparation process accounts for more than 10% of the total throughput of a coal preparation plant. Most conventional and advanced coal cleaning processes involve the use of water and the cleaned fine coal contains high moisture. End users are concerned not only with lower heating value of the resulting wet, cleaned coal, but more importantly, with handling problems, such as stickiness and freezing [(2)]. Both moisture and handling problems are exacerbated in fine coal. As a result, most utility coal contracts have limits on the amount of moisture and the quantity of fines allowed in coal shipments, making it difficult for coal preparation plants to process the fines and include them in the final product.

Fine coal dewatering is the least efficient and most costly step in coal preparation. Costs to treat fine coal are three to four times higher than cleaning coarse coal [(3,4)]. Cleaning cost is the primary economic and technical barrier to the utilization of coal fines [(3)]. Often, the capital and operating costs for water removal after cleaning are substantial enough to make the entire project uneconomical. It is often more practical to discard the fines than to recover them. A recent survey conducted by the U.S. Department of Energy indicates that U.S. coal producers currently discard between 27 and 36 million metric tons of fresh fine coal to refuse ponds each year. To date, approximately 1.8 billion metric tons of fine coal have been discarded in abandoned ponds, and 450 to 725 million tons are in active ponds [(3,4)]. The discarded fines represent a waste of valuable natural resources and a loss of potential profit for coal producers, as well as the potential for significant environmental problems. Obviously there is an urgent need for an innovative, low-cost fine coal dewatering process that will reduce environmental problems related with fine coal ponding and at the same time increase the revenue stream for coal producers.

On another note, global climate change is a mounting issue in the world. Using bio-energy is considered a viable option for reducing net CO_2 addition to the atmosphere. Agricultural production is one of the largest industries in Illinois. A recent research report [5] estimated that Illinois produces more than 26 million tons of dry corn residues annually, more than any other state in the nation. One attractive option is co-combustion of biomass with coal. In this scenario, biomass is mixed with coal and combusted in conventional boilers to produce electricity. Co-combustion of biomass and fine coal has the potential to help Illinois' agricultural, coal and utility industries.

The objective of this project is to use biomass, which is readily available in Illinois, as a filter aid to improve the performance of the fine coal dewatering process, reduce the residual moisture content of the final product, and at the same time improve the handling of fine coals. In addition, it is hoped that research will show that co-combustion of biomass/fine coal mixtures will help Illinois' coal and agricultural industries increase their revenues and help Illinois' utilities reduce their CO_2 emission.

EXPERIMENTAL PROCEDURES

The experimental procedures of each task are briefly presented here with emphasis on Tasks 3 and 4.

Task 1. Biomass selection and sample preparation

Two kinds of biomass, corn stover and sawdust, were selected mainly because of their availability and potential for use in Illinois. Illinois produces more than 26 million tons of dry corn residues and about 282,000 tons of wood mill residues annually.

Corn stover was obtained from a local farm in Bloomington, IL. It was chopped into one-inch pieces and had less than 10% of moisture. Several methods for pulverizing the corn stover were tried without much success. In the end, a grinder at the ISGS laboratory was used to pulverize the corn stover and then the material was sieved to four different sizes: – 70 mesh, 70 to 40 mesh, 40 to 16 mesh, and 16 to 8 mesh.

Sawdust was obtained from a physical plant on the campus of the University of Illinois at Urbana-Champaign. Biomass (sawdust and corn stover) was screened into three particle size categories: ≥16 mesh, 30 to 40 mesh, and 50 to 70 mesh. All three sizes together with an unsorted batch were used in the experiments. For one experiment, sawdust was ground to –200 mesh in a rod mill.

Task 2. Mixing of biomass and fine coals

A HOBART mixing device was used to prepare several mixtures with differing biomass/fine coal ratios and fine coal slurries with varying solid content. Due to the density difference between biomass and fine coal, different biomass/fine coal weight ratios (or biomass percentage) will result in cakes of different thickness if the total amount of the material (dry based) is kept the same. Filter cakes of differing thickness will lead to different filtration rates. In order to avoid this, different amounts of total dry materials were used. The various mixtures were visually compared with each other and general procedures developed for preparing a biomass/fine coal mixture that was compatible with the filtration devices used in the major tasks.

It was also found that, due to the density difference between biomass and fine coal, biomass and fine coal segregate when the solid content of mixed slurry is too low resulting in a filter cake that is not uniform. In order to avoid this segregation, the biomass/fine coal slurry was kept at a solid content exceeding 40%.

Task 3. Dewatering behavior of biomass/fine coal mixture in a vacuum filter

Fine coal slurries with known water content (ranging from 45% to 55% on a wet basis) were prepared for the experiments. Particle size distribution of the dried fine coal is listed in Table 1. The table shows that the particle size distribution of the fine coal used in the tests is very broad with 40% of the particles finer than 200 mesh. Tables 2 and 3 list the total material usage in the vacuum filtration experiments for sawdust and corn stover respectively.

Table 1. Particle size distribution of dried coal fine

Size (mesh)	≤200	200~140	140~70	70~50	50~40	≥40
Percent (%)	40.45	7.78	15.21	12.50	10.23	13.83

Table 2. Amount of material used in vacuum filtration experiments for sawdust

Sawdust (%)	Total Dry Material (g)	Dry Fine Coal (g)	Sawdust (g)	Fine Coal Slurry (g)
0	200	200	0	391
5	200	190	10	372
10	190	171	19	335
20	150	120	30	235

Water Content of Fine Coal Slurry: 48.88%

Table 3. Amount of material used in vacuum filtration experiments for corn stover

Corn stover (%)	Total Dry Material (g)	Dry Fine Coal (g)	Corn stover (g)	Fine Coal Slurry (g)
0	200	200	0	429
5	200	190	10	408
10	190	171	19	367
20	170	136	34	292

Water Content of Fine Coal Slurry: 53.40%

In order to keep the same vacuum conditions for each test, a vacuum oven was used as the vacuum source. Before each test, the vacuum oven is allowed to reach 24 inches Hg with a water pump. Then, the biomass/fine coal mixture with certain particle size and fine coal/biomass ratio was placed into a funnel. 350ml of water was added to the mixture and the filtration started. Time for the water level to lower to the cake surface was recorded. Filtration continued until the vacuum reduced to 15 inches Hg. The thickness of the filter cakes was between 0.9 and 1.1 inches for all of the tests. Moisture content was measured by using a vacuum oven at 110°C. For sawdust, each sample was repeated three times to obtain the average filtration time and moisture content. For corn stover, only the filtration time was repeated twice. The final cake was used to measure moisture content.

Task 4. Dewatering behavior of biomass/fine coal mixture in an ISGS filter press

The fine coal used in the filter press tests was the same as that used in the vacuum filtration tests (see Table 1). Fine coal slurries with known water content (ranging from 40% to 48% on a wet basis) were prepared for the experiments. Certain percentages of biomass from each size, including the unsorted group (passing an 8 mesh screen), were used in the experiments. Due to the difference in density between biomass and fine coal, a different biomass/fine coal ratio will result in a different cake thickness if the total amount of material in each experiment is kept same. Pre-tests were carried out in the ISGS Intelligent Filter Press to determine the usage of total dry material for different percentages of biomass. Table 4 listed the amount of biomass/fine coal slurry and biomass usage. The thickness of the cakes was between 1.1 and 1.2 inches.

Table 4. Amount of material used in filter press filtration experiments

Biomass (%)	Total Dry Material (g)	Dry Fine Coal (g)	Biomass (g)	Fine Coal Slurry (g)
0	861	861	0	1472
5	840	798	42	1364
10	770	693	77	1185
20	700	560	140	957

Water Content of Fine Coal Slurry: 41.50%

Since the slurry had a high solids content, it would not flow through the automated feeder, which was designed for pure fine coal slurry only. The mixture was thus placed into the filter press cylinder manually.

The operation procedures of the filter press are as follows: First, set the machine to a desired pressure (800psi, 1200psi or 1600psi) and number of tapping cycles (3, 6 or 9). Biomass/fine coal mixture is then manually placed into the filter press cylinder from the open end. Then, the automatic operating program runs. After the filtration process is finished, the filter cake is removed from the machine manually to avoid breaking it.

Filter cakes averaged 8 inches in diameter and 1.1 to 1.2 inches in thickness. A small amount of sample was punched out from the center of each filter cake to measure moisture. Moisture content was measured using a vacuum oven at 110°C. The sample was kept in the oven for 3 hours, after which it no longer lost weight.

During experiments, damage to the filter media by the larger corn stover particles was observed. The process failed every time damage was observed. Using finer size corn stover particles might prevent this problem, but grinding this material into fine particles was cost prohibitive. Owing to this observation, most tests were done using sawdust.

Task 5. Filter cake microstructure analysis by X-ray microtomography

Filter cakes from Task 4 were cut into small pieces using a sharp knife. The samples were then wrapped with paraffin film and shipped to Micro Photonics in Allentown, PA. Only sawdust/fine coal filter cake samples were used for this task since it was found that mold grew rapidly on the corn stover/fine coal mixture making them unsuitable for analysis.

RESULTS AND DISCUSSIONS

Task 1. Biomass selection and sample preparation

Two kinds of biomass were selected after potential materials were surveyed for available quantity, cost of acquisition and project suitability. Corn stover and sawdust were the two selected biomasses. During biomass preparation, pulverization of corn stover was found to be more difficult than sawdust, especially when fine particle sizes (– 200 mesh) were needed. Another undesirable feature of the corn stover was that mold grew in corn stover/fine coal filter cakes very easily. This phenomenon was observed after Task 3.

Task 2. Mixing of biomass and fine coals

Three factors including biomass particle size, biomass/fine coal ratio and the solid content of biomass/fine coal slurry were investigated. A HOBART mixing device was used. It was found that biomass and fine coal could be easily mixed as long as the solid content of the mixed slurry was high (greater than 40%). Low solid content caused the slurry to settle. A quantitative study of the mixing process was not conducted.

Task 3. Dewatering behavior of biomass/fine coal mixture in a vacuum filter

Tables 5 and 6 list results of the vacuum filtration experiments for biomass/fine coal mixtures. Figures 1 through 4 are graphic displays of the data. Figures 1 and 2 show the impact of the particle size and biomass content (in terms of percentage) on filtration time and Figures 3 and 4 show their impact on the residual moisture content of the filter cakes.

The results indicate that particle size of biomass has less impact on filtration time than biomass content. The filter cake with 20% sawdust content had the shortest filtering times for all four sawdust particle sizes as well as when no sawdust was used. Filter cakes with 10% sawdust had the longest filtration times. Pure fine coal filter cakes had shorter filtration times than filter cakes with 5% and 10% sawdust. It appears that in order to improve filtration rates using biomass, a high biomass content (greater than 20%) is needed.

The filtration performance of corn stover/fine coal filter cakes was very different from that of sawdust/fine coal filter cakes. The overall filtration rate of corn stover/fine coal mixtures is much lower than that of sawdust/fine coal mixtures. Pure fine coal had shorter filtration times than all of the corn stover/fine coal samples tested. This behavior may be explained by the fact that gluten exists in corn stover. Gluten is a tenacious elastic protein substance that would inhibit filtration. It may be released from corn grain during pulverization. Existence of gluten could significantly reduce the filtration rate.

Residual moisture content of biomass/fine coal after vacuum filtration ranged from 32% to 43%. Generally, sawdust/fine coal showed lower residual moisture content than corn stover/fine coal. The impacts of biomass particle size and content in filter cakes were not strong. No trends were clear. The residual moisture content of biomass/fine coal mixtures is rather high implying that biomass may be used as a filter aid in vacuum filtration to improve the filtration rate, but further dewatering will be needed.

Table 5. Results of vacuum filtration of corn stover/fine coal mixture

Sample Number	Corn Stover Particle Size (mesh)	% Corn Stover	Filtration Time (min)	Moisture Content (%)
83	≥ 16	5	48.50	36.90
85		10	87.95	36.37
86		20	85.78	38.86
87	40 ~ 30	5	53.00	39.33
88		10	95.37	41.54
89		20	59.20	41.31
90	70 ~ 50	5	39.13	39.16
91		10	44.80	40.92
92		20	33.47	41.73
93	unsorted	5	64.03	35.76
94		10	112.63	38.61
95		20	58.88	42.74
96	N/A	0	11.30	38.97

Table 6. Results of vacuum filtration of sawdust/fine coal mixture

Sample Number	% Sawdust	Sawdust Size (mesh)	Time to Filter Water to Coal Cake Surface (min)	Average Time (min)	Moisture Content (%)	Average Moisture Content (%)
34	5	≥ 16	12.63	14.71	35.44	34.09
47			14.78		33.80	
49			16.72		33.02	
35		30 ~ 40	21.02	21.27	37.20	36.75
48			20.25		35.68	
50			22.53		37.38	
36		50 ~ 70	18.92	20.49	37.37	37.40
51			20.07		36.53	
52			22.50		38.31	
37		unsorted	17.22	20.04	37.41	36.70
53			21.15		35.39	
54			21.77		37.30	
38	10	≥ 16	14.10	16.21	36.62	36.70
55			14.90		35.90	
56			19.63		37.59	
57		30 ~ 40	31.38	26.99	38.90	38.92
39			26.42		38.48	
58			23.17		39.37	
40		50 ~ 70	27.17	27.78	38.54	38.79
59			26.07		39.54	
60			30.10		38.28	
41		unsorted	26.18	26.64	39.35	37.36
61			24.57		36.01	
62			29.17		36.73	
68	20	≥ 16	2.35	2.93	33.96	34.12
69			2.98		34.31	
70			3.47		34.09	
71		30 ~ 40	2.40	4.81	36.40	34.38
72			3.73		32.59	
73			8.30		34.16	
74		50 ~ 70	2.45	2.95	36.20	35.14
75			2.53		36.51	
76			3.87		32.70	
77		unsorted	2.72	2.76	35.22	36.17
78			2.83		36.77	
79			2.72		36.53	
46	0	N/A	11.13	12.31	31.33	33.98
80			13.57		35.39	
81			12.22		35.23	

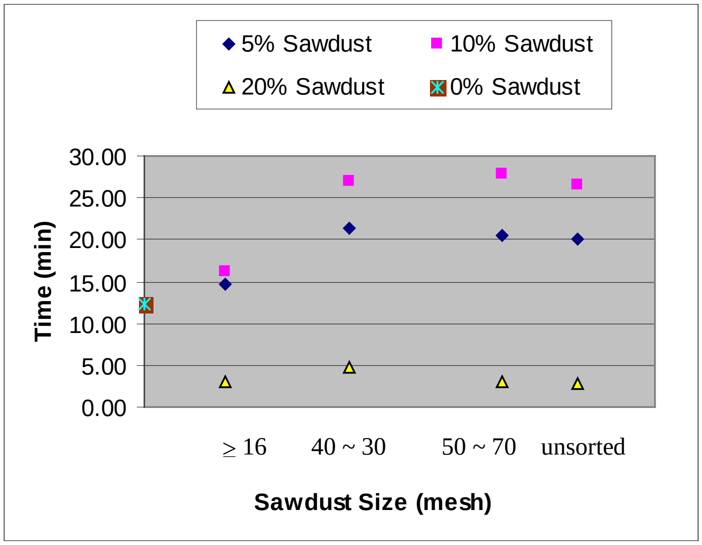

Figure 1. Effect of sawdust particle size and percentage on filtration time

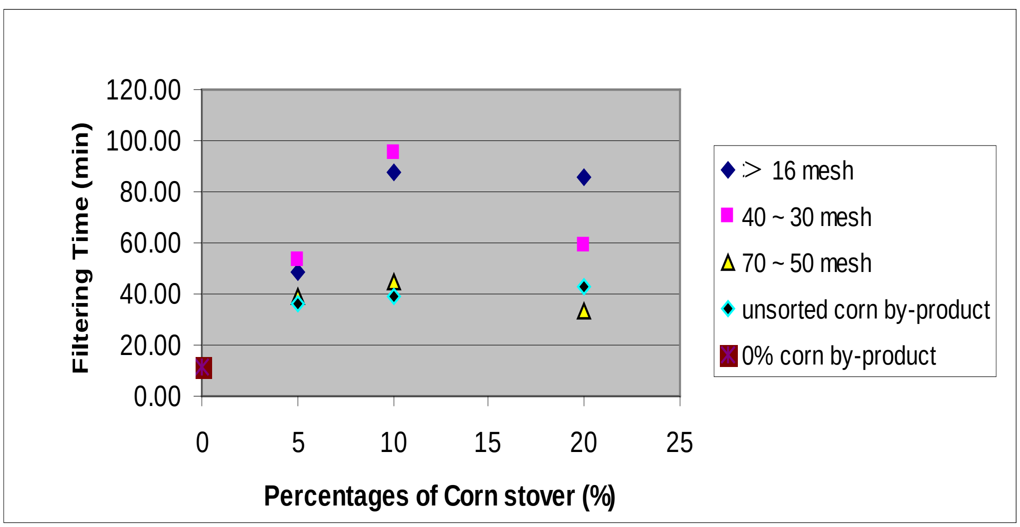

Figure 2. Effect of corn stover particle size and percentage on filtration times

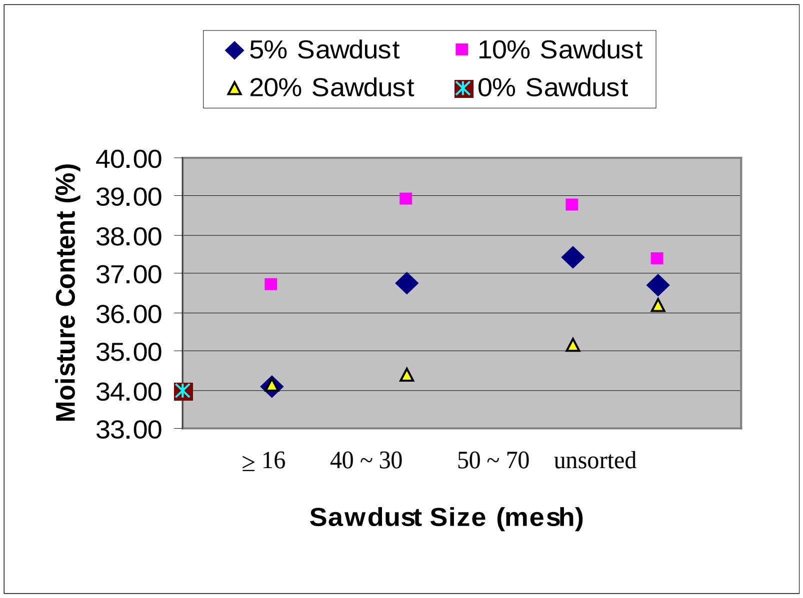

Figure 3. Effect of sawdust particle size and percentage on moisture content

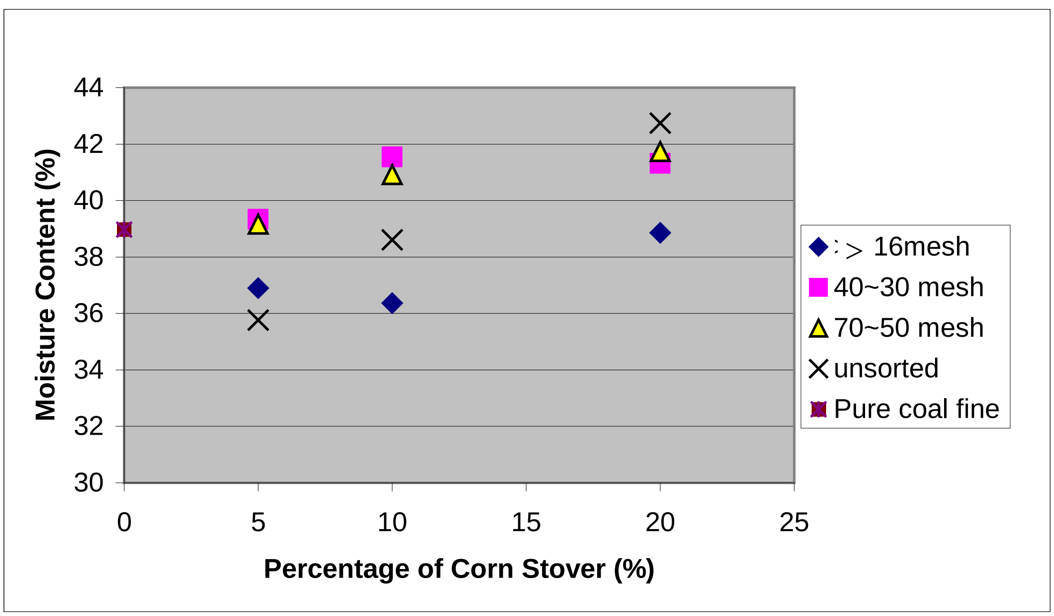

Figure 4. Effect of corn stover particle size and percentage on moisture content

Task 4. Dewatering behavior of biomass/fine coal mixture in an ISGS filter press

Hydraulic pressure, tapping cycles, biomass percentage, biomass particle size and thickness of the cake (total solids content) were investigated to determine their effect on residual moisture content. The experiments on the effect of tapping cycle (3, 6 and 9 cycles) were conducted with hydraulic pressure fixed at 1600psi. The experiments on the effects of hydraulic pressure (800psi, 1200psi and 1600psi) and the thickness of the filter cake (single, double, triple and quadruple) were carried out at 9 tapping cycles. In investigating the operating parameters of the filter press, all of the mixtures had 10% biomass.

Tables 7 and 8 list the results of the filter press experiments varying biomass percentage and particle size as well as the number of tapping cycles. Table 7 is for corn stover and Table 8 is for sawdust. These results were obtained at 1600psi of hydraulic pressure and a filter cake thickness between 1.1 and 1.2 inches. The impact of each parameter on the residual moisture content of the filter cakes is discussed below.

a. Influence of tapping cycle on the moisture content

The numbers of tapping cycles chosen in this study were 3, 6, and 9. Figures 5 and 6 are the results for 10% sawdust/fine coal mixture and 10% corn stover/fine coal mixture respectively. Other biomass contents exhibited the same trend. From these figures it can be seen that tapping cycle had little impact on the residual moisture contents of the filter cakes especially for corn stover/fine coal mixture. The sawdust/fine coal mixture showed influence of tapping cycle only when the sawdust particle size is small.

b. Influence of Particle Size and Percentage of Biomass on final moisture

Figures 7 and 8 show the impact of biomass particle size and biomass percentage on the residual moisture content of the filter cakes. Results showed that the particle sizes of the sawdust had little effect on the moisture contents when the sawdust usage is 5% and 10%. However, when the sawdust content reaches 20%, the filter cake with –70 mesh particle size showed the lowest moisture content.

It should be pointed out that particle size may impact the residual moisture content if the biomass is fine enough. The reason that experiments were not conducted with very fine biomass material is that the cost to grind biomass will be high. One test with – 200 mesh biomass was performed. Results showed that finer biomass material could reduce the moisture of the filter cake.

It is clear from Figures 7 and 8 that biomass content has a significant effect on the residual moisture content of the filter cakes. The residual moisture content of the filter cake increased with the increase of the biomass content. The 5% biomass/fine coal mixture had the lowest moisture contents for all particle sizes, whereas the filter cakes with 20% biomass had the highest moisture contents.

Table 7. Results of filter press filtration of sawdust/fine coal mixture

Sample Number	Sawdust (%)	Sawdust Particle Size (mesh)	Tapping Cycles	Res. Moisture (%)	Average Moisture (%)	S.D
4	5	≤ 70	3	21.16	21.93	0.69
5			6	22.49		
6			9	22.15		
7		70 ~ 40	3	21.83	21.86	0.04
8			6	21.83		
9			9	21.91		
10		40 ~ 16	3	21.31	21.72	0.41
11			6	21.72		
12			9	22.13		
13		16 ~ 8	3	22.26	22.54	0.71
14			6	23.34		
15			9	22.01		
16		unsorted	3	21.54	21.15	0.46
17			6	20.64		
18			9	21.27		
19	10	≤ 70	3	22.82	22.65	0.16
20			6	22.61		
21			9	22.52		
22		70 ~ 40	3	23.34	23.00	0.40
23			6	23.11		
24			9	22.57		
25		40 ~ 16	3	23.77	23.39	0.52
26			6	22.80		
27			9	23.61		
28		16 ~ 8	3	23.89	23.72	0.15
29			6	23.58		
30			9	23.71		
31		unsorted	3	23.69	23.39	0.32
32			6	23.06		
33			9	23.41		
34	20	≤ 70	3	26.67	26.42	0.33
35			6	26.04		
36			9	26.56		
37		70 ~ 40	3	28.35	28.23	0.71
38			6	27.47		
39			9	28.87		
40		40 ~ 16	3	29.91	30.58	0.67
41			6	30.58		
42			9	31.26		
43		16 ~ 8	3	28.67	29.55	0.82
44			6	29.69		
45			9	30.28		
46		unsorted	3	27.91	28.54	0.70
47			6	29.30		
48			9	28.43		

Table 8. Results of filter press filtration of corn stover/fine coal mixture

Sample Number	Corn Stover (%)	Corn Stover Particle Size (mesh)	Tapping Cycles	Moisture (%)	Average Moisture (%)	S.D
49	5	≤ 70	3	21.05	20.50	0.51
50			6	20.43		
51			9	20.03		
52		70 ~ 40	3	22.54	22.48	0.54
53			6	21.92		
54			9	22.99		
55		40 ~ 16	3	23.93	23.39	0.86
56			6	23.84		
57			9	22.40		
58		16 ~ 8	3	22.19	21.50	0.90
59			6	20.48		
60			9	21.82		
61		unsorted	3	21.38	21.15	0.21
62			6	21.10		
63			9	20.98		
64	10	≤ 70	3	22.68	22.76	0.12
65			6	22.90		
66			9	22.69		
67		70 ~ 40	3	23.48	24.10	1.02
68			6	23.54		
69			9	25.27		
70		40 ~ 16	3	24.95	25.80	1.27
71			6	25.18		
72			9	27.26		
73		16 ~ 8	3	24.81	24.94	0.14
74			6	24.92		
75			9	25.08		
76		unsorted	3	25.69	25.21	0.44
77			6	24.82		
78			9	25.11		
79	20	≤ 70	3	29.12	31.25	3.19
80			6	29.72		
81			9	34.92		
82		70 ~ 40	3	36.64	34.29	2.04
83			6	32.97		
84			9	33.25		
85		40 ~ 16	3	27.47	26.77	0.93
86			6	25.71		
87			9	27.12		
88		16 ~ 8	3	32.50	33.11	2.46
89			6	31.02		
90			9	35.82		
91		unsorted	3	27.56	29.51	1.82
92			6	29.80		
93			9	31.18		

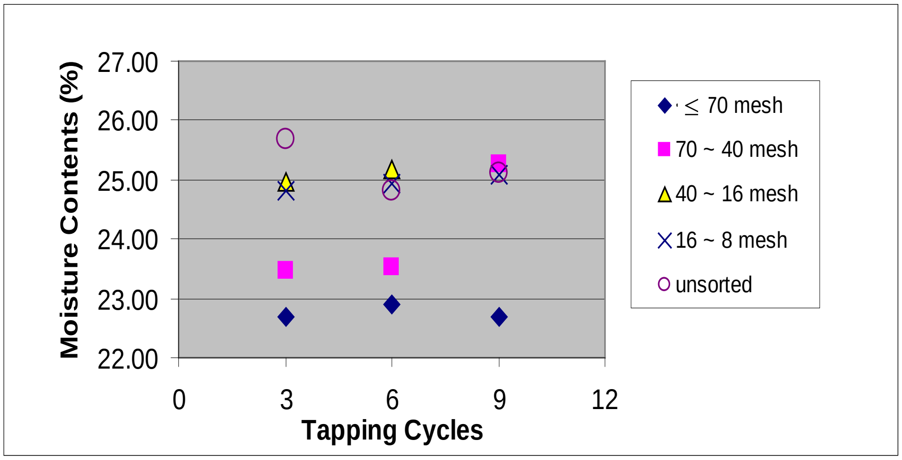

Figure 5. Influence of tapping cycle on the moisture content of 10% sawdust/fine coal mixture.

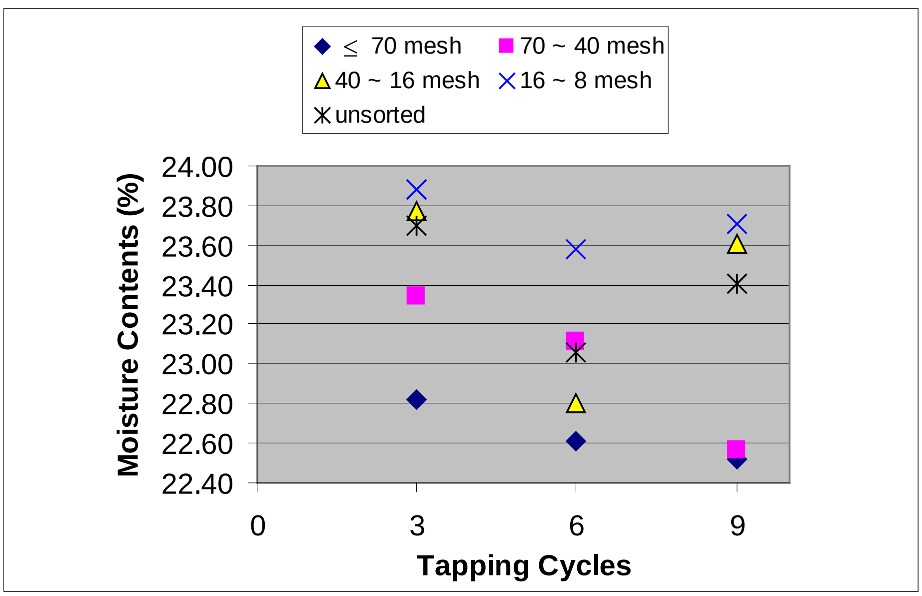

Figure 6. Influence of tapping cycle on the moisture content of 10% corn stover/fine coal mixture

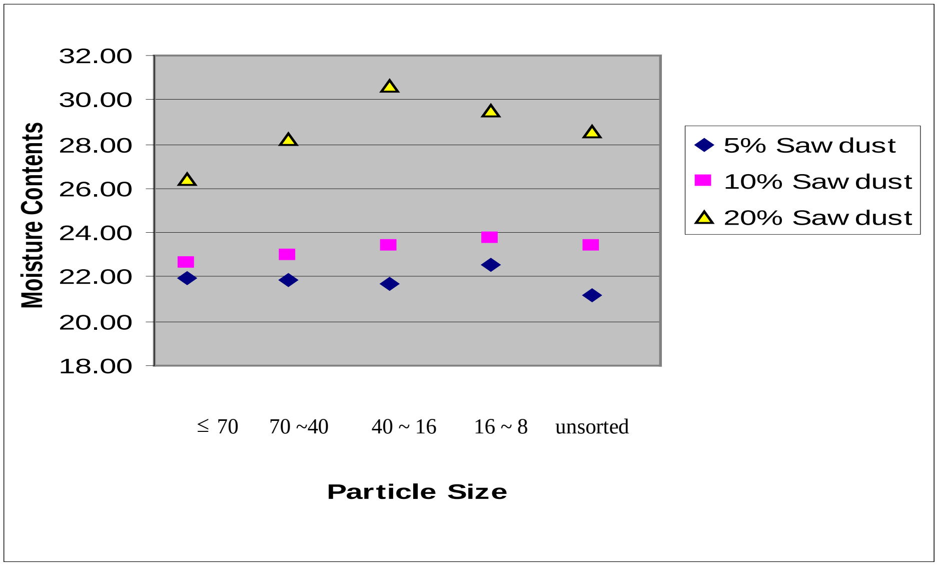

Figure 7. Influence of particle size and sawdust percentage on the moisture content

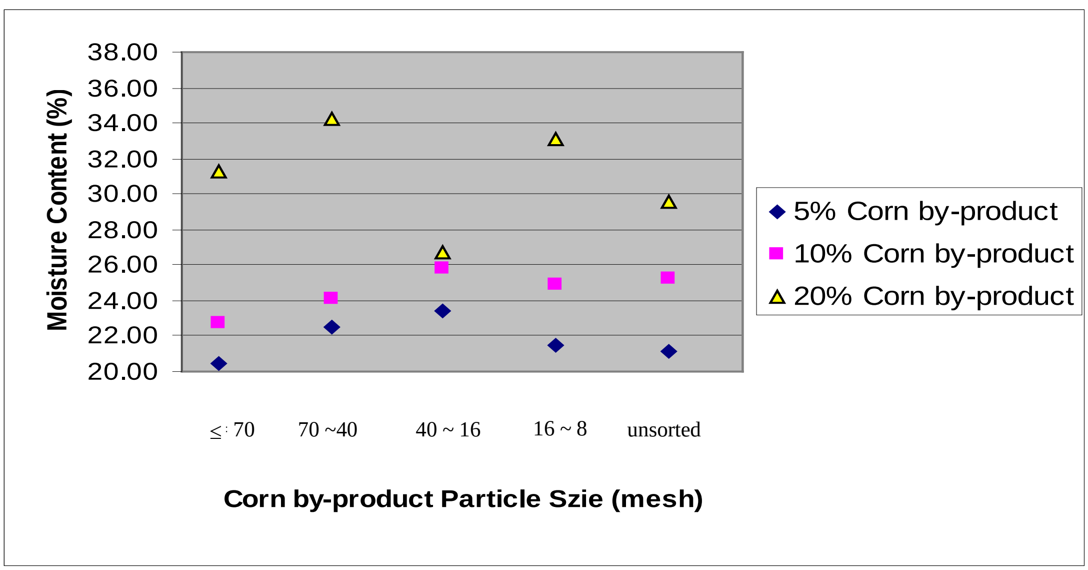

Figure 8. Influence of particle size and corn stover percentage on the moisture content

Table 9 lists the average moisture content for different biomass concentrations regardless of the particle sizes. It can be seen that the residual moisture content of the two biomass/fine coal mixtures is very close. Cakes with 5% sawdust and 5% corn stover had the same average moisture content (21.84% and 21.81%). Pure fine coal filter cakes showed the lowest residual moisture content. At higher biomass content, the residual moisture content of sawdust/fine coal is lower than that of corn stover/fine coal.

Table 9. Comparison of moisture content with different biomass concentrations

Biomass Concentration (%)	Average Moisture Content (%)		
	Sawdust	Corn Stover	Pure Fine Coal (0% biomass)
5	21.84	21.81	20.53
10	23.23	24.56	
20	28.67	30.99	

c. Pressure influence on the final moisture content

Tables 10 and 11 give the results from investigating the influence of pressure on moisture content. The hydraulic pressure was increased incrementally from 800psi to 1600psi. Results in Table 11 show that particle size has little effect on the residual moisture, which is similar to the results obtained in the previous section. Figure 9 is the relationship between average moisture content of sawdust/fine coal and filtration pressure. It can be seen that pressure had no effect on the moisture content of the pure fine coal. It does, however, influence the moisture content of the sample containing sawdust. This is expected since sawdust is a compressible material and higher pressure will increase the packing density of the biomass and reduce the moisture content. As for pure fine coal, it is incompressible and pressure will have little influence on its packing density.

Table 10. Moisture content for pure coal fine at different tapping cycles and pressures

Sample Number	Filter Pressure (psi)	Tapping Cycles	Moisture Content (%)	Average Moisture Content (%)
1	1600	9	20.66	20.53
109	800	9	20.92	
110	1200	9	20.18	
111	1600	3	20.62	
112	1600	6	19.94	
113	1600	9	20.86	

Table 11. Moisture content of sawdust/fine coal mixtures at different filtration pressures

Sample Number	Sawdust Conc. (%)	Filter Pressure (psi)	Sawdust Size (mesh)	Moisture (%)	Average Moisture (%)	S.D
94	10	800	≤ 70	24.97	24.89	0.11
95			70 ~ 40	25.05		
96			40 ~ 16	24.85		
97			16 ~ 8	24.80		
98			unsorted	24.78		
99		1200	≤ 70	22.85	24.27	0.82
100			70 ~ 40	24.62		
101			40 ~ 16	24.44		
102			16 ~ 8	24.95		
103			unsorted	24.49		
104		1600	≤ 70	24.16	23.98	0.21
105			70 ~ 40	24.17		
106			40 ~ 16	24.06		
107			16 ~ 8	23.69		
108			unsorted	23.84		
114	20	800	≤ 70	27.18	29.33	1.90
115			70 ~ 40	29.15		
116			40 ~ 16	30.82		
117			16 ~ 8	31.65		
118			unsorted	27.86		
119		1200	≤ 70	27.42	28.57	0.98
120			70 ~ 40	28.53		
121			40 ~ 16	30.13		
122			16 ~ 8	28.54		
123			unsorted	28.26		
124		1600	≤ 70	26.45	28.27	1.10
125			70 ~ 40	28.82		
126			40 ~ 16	28.66		
127			16 ~ 8	29.28		
128			unsorted	28.12		
129	5	800	≤ 70	25.16	24.65	0.91
130			70 ~ 40	25.95		
131			40 ~ 16	24.44		
132			16 ~ 8	24.00		
133			unsorted	23.71		
134		1200	≤ 70	22.96	22.70	1.83
135			70 ~ 40	23.12		
136			40 ~ 16	19.96		
137			16 ~ 8	25.07		
138			unsorted	22.39		
139		1600	≤ 70	22.54	22.80	0.20
140			70 ~ 40	22.87		
141			40 ~ 16	22.98		
142			16 ~ 8	22.97		
143			unsorted	22.64		

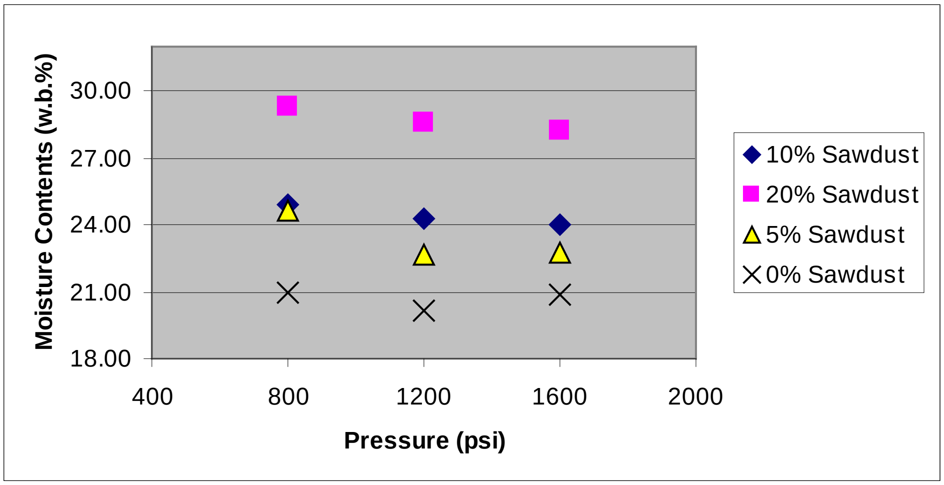

Figure 9. Effect of pressure on moisture content with different sawdust concentrations

d. Influence of thickness of the cake on the moisture content

The impact of cake thickness was studied at 1600 psi hydraulic pressure. Only sawdust samples were tested. The results, presented in Table 12 and Figure 10, showed that thickness of the filtered cake had a significant effect on moisture content. Moisture content increased as cake thickness increased for all samples regardless of the presences or size of biomass. The thicker the filter cake is, the higher the resistance from the filter press cylinder wall will be. This resistance reduces the effective hydraulic pressure. Using a larger scale filter press can significantly reduce such resistance.

Table 12. Moisture content of filtered cakes of various thickness

Sample Number	Filter Pressure (psi)	Tapping Cycles	Sawdust Conc. (%)	Sawdust Size (mesh)	Cake Thickness (inches)	Moisture (%)
104	1600	9	10	≤ 70	1.15	24.16
144					2.30	28.54
145					3.45	28.96
146					4.60	30.81
105				70 ~ 40	1.15	24.17
147					2.30	24.45
148					3.45	25.51
149					4.60	27.11
106				40 ~ 16	1.15	24.06
150					2.30	25.92
151					3.45	27.11
152					4.60	28.22
1			0	N/A	1.15	20.66
153					2.30	21.05
154					3.45	21.74
155					4.60	24.02

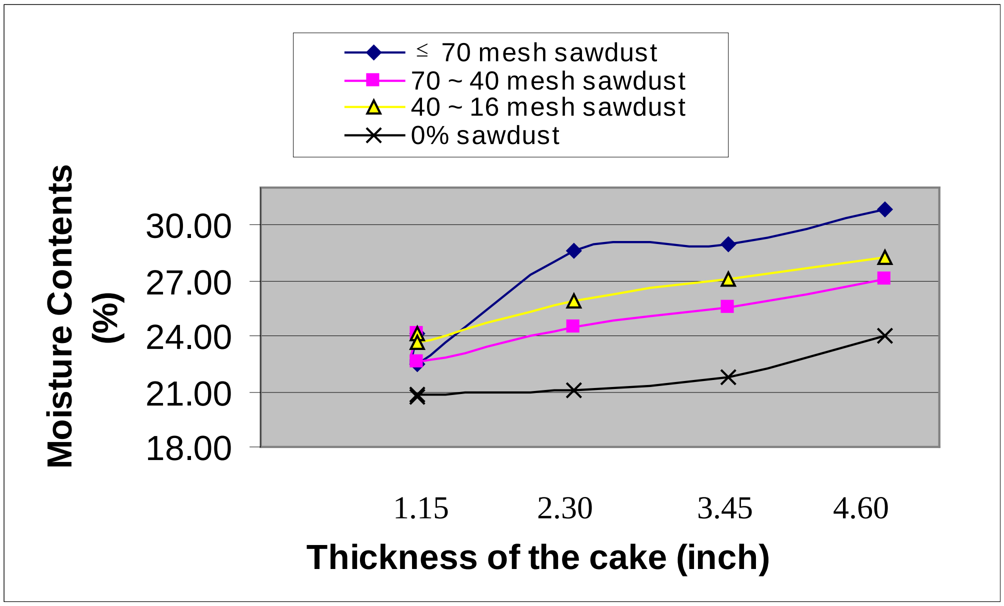

Figure 10. Moisture content of filtered cakes of various thickness

e. Filtration Rate

The filtration rate of pure fine coal and sawdust/fine coal mixtures was compared at two different pressures, 1600psi and 800psi. In these tests, – 40 mesh sawdust was used. In order to prolong the filtration time, the total amount of sawdust/fine coal mixture used was increased to six times the amount of the material used in regular tests. The thickness of these filter cakes was around 7 inches.

Figures 11 and 12 depict the results. At 1600psi hydraulic pressure, the material with higher sawdust content exhibits a higher filtration rate (slope of curves increases). This would indicate that sawdust or biomass can improve filtration rates. However, when the hydraulic pressure is reduced to 800psi, the same effect is not observed. At the lower pressure, all the four samples showed similar filtration rates (slope of curves is uniform).

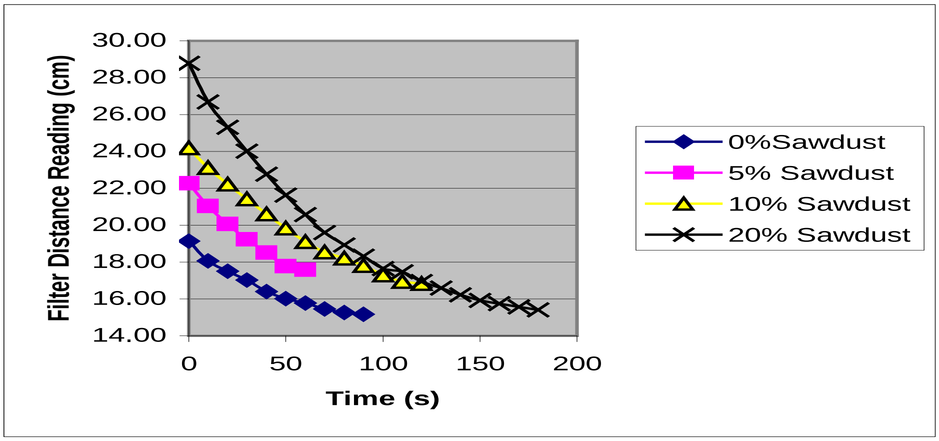

Figure 11. Change of the filter cake thickness with time at 1600 psi (– 40 mesh sawdust used)

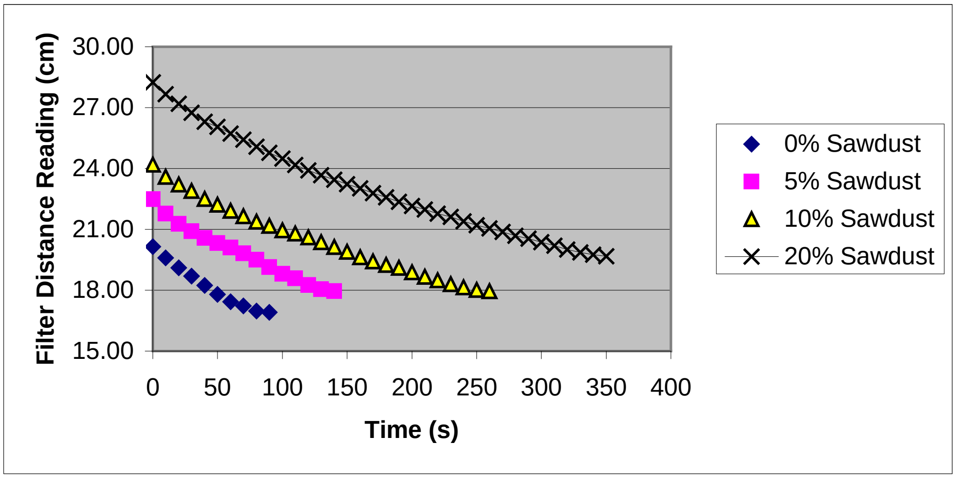

Figure 12. Change of the filter cake thickness with time at 800 psi (– 40 mesh sawdust used)

Task 5. Studies of the microstructure of filter cake by X-ray microtomography

Samples of fifteen sawdust/fine coal filter cakes were sent to Micro Photonics Inc. in Allentown, PA for analysis. Figure 13 is a typical picture from the X-ray microtomography scan. Porosity, mean pore size and pore size distribution of the fifteen samples are listed in Table 13.

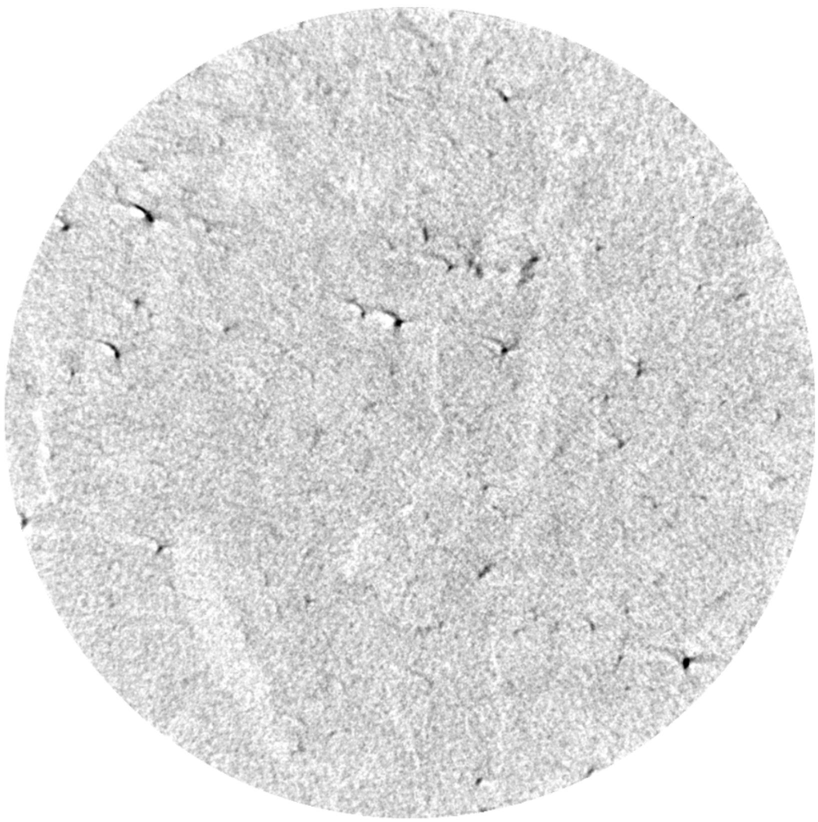

Figure 13. Typical picture of sawdust/fine coal mixture scanned by X-ray microtomography

The numbers listed in Table 13 show no trends for porosity, mean pore sizes or pore size distribution. This was a surprise to the PI. There are some possible explanations for this. One is that the sawdust/fine coal filter cake was loosely packed after it dried. Another reason suggested by Micro Photonics technicians was that the sample might have broken during the analysis, especially since the sample was cut into smaller pieces. Resolution of the X-ray Microtomography is still another possibility. Since most of fine coal particles used were less than 200 mesh, the capillary pores between the fine coal particles could be as small as a few microns. The X-ray microtomography machine used may not recognize these pores. Further improvements will be needed to prepare high quality samples for X-ray Microtomography analysis.

Table 13. Mean pore size, porosity and pore size distribution of filter cakes

Sample	Fraction of pore numbers in different pore size ranges								Porosity (%)	Mean Pore Size (%)
	0.000 - 0.079 mm	0.079 - 0.159 mm	0.159 - 0.238 mm	0.238 - 0.317 mm	0.317 - 0.396 mm	0.396 - 0.476 mm	0.476 - 0.555 mm	0.555 - 0.634 mm		
10%_16-8	91.88	7.81	0.3	0.02					3.785	0.046
10%_40-16	85.96	13.77	0.27						4.197	0.051
10%_40-70	88.92	10.23	0.76	0.09					3.173	0.049
10%_70	50.43	13.11	12.28	11.81	10.75	1.63			4.557	0.138
10%_lt70	92.74	6.83	0.33	0.1					2.284	0.046
10%_mixed	92.84	7.06	0.1						2.609	0.045
10%_mixed _wet	94.3	5.52	0.18						1.713	0.044
20%_mix	73.75	12.82	11.35	2.08					1.261	0.073
20%_40-16	63.46	7.35	8.98	12.64	6.34	1.23			6.978	0.115
20%_70	93.3	6.43	0.27						3.143	0.045
20%_70-40	64.55	20	4.89	3.83	3.26	2.76	0.44	0.28	11.369	0.097
20%_8-16	83.34	14.21	1.57	0.5	0.32	0.06			5.878	0.056
5%_16-8	95.47	4.49	0.04						1.936	0.043
5%_mixed	98.05	1.94	0.01						1.401	0.041

CONCLUSIONS AND RECOMMENDATIONS

The suitability of biomass as a filter aid and the dewatering behavior of biomass/fine coal mixtures were studied in this project. Vacuum filtration results indicate that adding biomass at 5% and 10% does not improve vacuum filtration performance, especially for corn stover. Vacuum filtration rates did improve at 20% biomass concentrations for sawdust/fine coal mixtures but not for corn stover/fine coal mixtures. Residual moisture content for the vacuum filtered cakes was high, suggesting that vacuum filtration alone will not be able to dewater biomass/fine coal mixtures to a satisfactory level.

In the ISGS filter press tests, adding sawdust improved the filtration rates at the higher hydraulic pressure of 1600 psi. The residual moisture content of biomass/coal fine filter cakes were between 20~30% when biomass content was below 20%. This suggests that it is possible to use the ISGS filter press to dewater biomass/fine coal mixtures to satisfactory levels of residual moisture. However, the moisture levels achieved with the biomass used in this study are no better than moisture levels attainable without biomass making it difficult to justify further analysis.

Several difficulties were encountered in grinding and otherwise preparing suitable biomass material for mixing with fine coal. Because these problems hampered the dewatering tests, the PI recommends that biomass grinding characteristics and other preparation issues be investigated before further dewatering studies are conducted.

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