Development and Analysis of Dry Forming System for Innovation of Papermaking Technology

JONG-MIN KIM*, HAK LAE LEE†, HYE JUNG YOUN, and MIN-GU HWANG

Department of Forest Sciences, College of Agriculture & Life Sciences
Seoul National University, San 56-1, Sillim-Dong, Kwanak-Gu, Seoul, 151-742, Korea
† lhakl@snu.ac.kr
* Now with Yuhan-Kimberly Co., 27-4, DangJung-Dong, Cunpo-City, Gyeonggi-Do, 435-831, Korea, (e-mail : JongMin.Kim@y-k.co.kr)

ABSTRACT

This study was conducted to develop dry forming technology and evaluate the properties of dry formed paper made from Hw-BKP. A dry forming mold (DFM) was developed to observe the phenomena of dry forming and evaluate the properties of formed papers. To upgrade the DFM a dry forming system (DFS) was developed. This DFS was designed to improve the formation of dry formed papers and enhance the productivity of dry forming.

Dry forming gave papers with greater bulk and opacity than wet forming. Tensile strength of dry formed paper was greater than that of conventional wet formed handsheet when they were made from the same dry disintegrated fibers. But tensile strength of conventional wet formed handsheet made from beaten fiber was much greater than that of dry formed paper made from dry disintegrated fibers. When solvent dried beaten fibers were used in dry forming, the tensile strength of dry formed papers reached 73.5% of the wet formed handsheets made from beaten fiber. It showed that dry forming has a significant potential in improving strength properties when proper preparation of fibers and appropriate humidification, pressing, and drying processes are employed.

INTRODUCTION

Paper industry has many problems in public relation these days. Public cares more and more about the conservation of our environment and energy saving. But paper industry has been criticized for using too much water and electrical and fossil fuel energies. Thus it is urgently required to develop a new vision for the continuing growth and development of paper industry. Technological renovation should be one of the most highly searched endeavors by today ' s paper technologists to break through the problems and limitations associated with conventional stack industries. And this type of technological renovation may be found by eliminating the basic and essential requirement for papermaking, i.e. water.

Water plays the roles of dispersing and transporting of fibers, forming web on the wire and making the fiber to bond for strength development in drying. In general, the consistency of fiber stock in papermaking headbox is less than 1%. In other words, 99 parts of water is used to disperse and transport 1 part of fibers in the papermaking headbox. Most of the water in headboxes and papermaking processes is recycled. It requires, however, huge amounts of energy and complicated equipments for recycling the process water. The process to control the water circuits has become bigger, larger and more complicated with the increases in production capacity and quality requirement.

Extensive research efforts and technological developments on the treatment of wastewater and recycling of process water have been made to keep the environmental regulation and to reduce the water consumption in the papermaking process. Despite these endeavors the paper industry is still one of the largest consumers of water, and this seems to be the same in the future if technological renovation is not developed and implemented. Many researches have been made to increase the papermaking consistency as an approach to reduce the water consumption. For instance, the relationship between consistency of stock and hydrodynamic properties of turbulent fiber suspension, the effect of increasing consistency on energy saving in papermaking, and the development of new high consistency former have been investigated[1,2,3]. The concept of high consistency forming has been a widely searched approach to reduce water use rate in papermaking. If we extend the idea of high consistency forming to extreme, a new method of forming papers without water, i.e. dry forming technology will emerge. It is possible to remove not to reduce all of the water required in wet forming process.

There are many fundamental problems to be solved for implementing dry forming technology, and these include to find fiber types most suitable for dry forming, to develop forming method for improving formation and paper properties, to optimize pressing and drying conditions for controlling paper properties, etc. This study was carried out to find answers to these key questions associated with dry forming. Two dry forming systems were designed and fibers prepared by simple dry disintegration and solvent exchange and drying of beaten fibers were used as raw materials. Different conditions of sheet moisture, pressing pressure and temperature have been examined for the optimization of pressing and drying processes.

EXPERIMENTAL

Materials

Hardwood bleached kraft pulp (Hw-BKP) was used to prepare four types of fibers including two types of dry fibers and two types of wet fibers. One type of dry fibers was prepared by employing simple disintegration in dry state while the other type of dry fiber was obtained by solvent exchange and drying of beaten fibers. One type of wet fiber was prepared using conventional disintegration in a laboratory disintegrator. The other type of wet fiber was prepared after beating in a laboratory Valley beater.

To make a solvent exchanged dried beaten fiber, ethyl alcohol and hexane were used as solvents to substitute water and ethanol in the fiber, respectively. The purity of ethyl alcohol and hexane were higher than 99% and 96%, respectively.

Dry and wet disintegration

To make dry disintegrated fiber, about 300 g of Hw-BKP was torn in small pieces and put into a dry disintegrator. After closing the lid of the dry disintegrator, the rotor consisted of 2 parts was rotated at 700 rpm for 30 min. Hw-BKP was disintegrated into separated fibers by the mechanical force by the rotor and frictional force by fibers[17]. The disintegrated fibers were screened with a vibration screen which had a 40 mesh wire to eliminate unslushed fibers. To make wet disintegrated fiber, 2000 mL (1.2% consistency) of Hw-BKP slurry was placed in a low consistency disintegrator, and disintegrated for 3000 revolutions.

Development of DFM (dry forming mold)

Dry disintegrated fibers were flocky and looked like lumps of fluffed fibers. To make the lumps well dispersed several types of stirrers providing various shear conditions were designed and tested. When the dispersed fibers passed through a narrow gap, for instance the holes in the screen plate, under positive or negative pressure, the deposit and plugging of fibers in the gap were observed[18,19]. To avoid the deposition and plugging of fibers, intensity of the pressure was controlled and the positive and negative pressure pulse was applied through the gap. The movements of fibers were evaluated as forcible air flow was applied in pipes and cylinders. The effect of humidification time on the moisture contents of dry formed fiber pads was measured. Flow in the DFM was analyzed by measuring the flow velocity in the dry forming mold with a hot wire anemometer (AM-4214, Sechang Instrument. co.).

Papermaking process with DFM

Fig. 1 shows the process diagram to make handsheets with the use of DFM. Hw-BKP was disintegrated and screened. And then the dry disintegrated fibers were passed through the disperser and screen plate. After that they flowed through the forming zone of DFM and deposited on the forming wire until the basis weight reached 80 gsm. When forming of a pad with dry fibers was completed, the formed fiber pad was humidified. The fiber pad taken out from DFM was pressed between two blotting papers at 28~113 kgf/cm^2 for 1~5 minutes. In conventional papermaking wet sheet of paper with dryness less than 25% is delivered to press. It is impossible to press the wet fiber pad at such a high pressure as several tens kgf/cm^2 because it causes destruction of fiber pad structure[20]. However, in the case of dry formed fiber pad, very high pressing pressure can be applied because the fiber pad contains small amount of water. Furthermore its high permeability and bulky structure allow high pressing pressure.

The temperature and pressing time of hot pressing were 120 °C and 10 seconds, respectively. When hot pressing was applied, a 100 mesh stainless steel wire was inserted between the upper heating plate and fiber pad, and two blotting papers were placed between the lower plate and fiber pad. After pressing, the paper was weighed to measure its dryness, and then dried with a cylinder dryer.

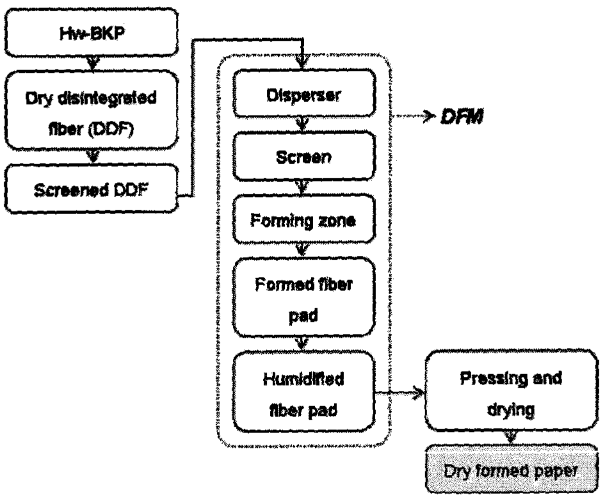

Fig. 1. Papermaking process with DFM.

Preparation of dried beaten fiber

Disintegrated Hw-BKP slurry at a consistency of 1.53% was beaten to 450±5 mL CSF in a Valley beater. The beaten slurry was drained on the 200 mesh stainless wire, and divided into four portions and then placed in 5 L beakers. It was soaked in ethyl alcohol for 2 days to substitute water with ethanol. After two days of soaking the solvent was drained, and fresh ethyl alcohol was filled again for another solvent exchange. Solvent exchange procedure was repeated twice for each solvent. When the water was substituted with ethyl alcohol, it was substituted again with hexane. Same method of substituting ethyl alcohol with hexane was followed, and repeated twice. And then the hexane was evaporated by heating the fiber for 10 hours at 70°C to get dry beaten fibers with fibrils.

Development of DFS (dry forming system)

DFS was developed to obtain papers with better formation and to impart more feasibility as a practical forming system. Fig. 2 shows the schematic drawing of DFS. The straight line arrows display the flow direction of dry fibers and the dotted arrows show the flow direction of air, water aerosol, and steam. Lumps of dry fibers were fed into the dispersers, where they were dispersed into dry fibers. Three slots were placed in the disperser, and these allowed only the well dispersed fibers proceeded to the forming zone. In other words, the slots between the dispersers restricted the forward movement of fiber lumps and helped complete dispersion of the lumps. The selected fibers dropped on the movable forming table with a fine wire as a forming medium. And then the accumulated fiber pad moved into the humidifier where it was humidified. Suction was applied below the forming table to enhance downward movement of fibers. Suction was also installed to improve the flow of water aerosol or steam in the humidifier.

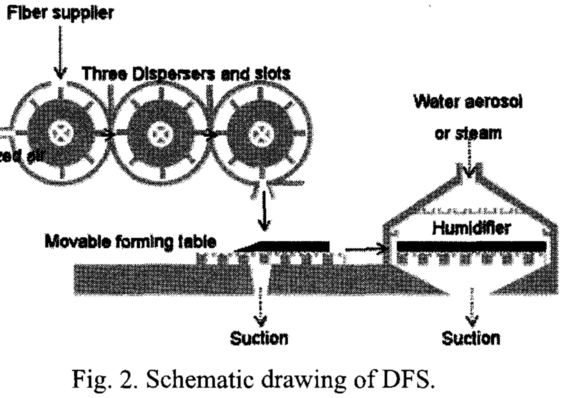

Fig. 2. Schematic drawing of DFS.

Papermaking process with DFS

Fig. 3 shows the papermaking process with DFS. The processes of fiber preparation, pressing, and drying were the same as those of DFM. Dry fibers was fed into the disperser 1 and passed through the slot, and this process was repeated in the disperser 2 and 3. And then well dispersed fibers were deposited on the forming table. Uniform distribution of the fibers in the cross direction was important for improving formation because the table moved constantly back and forth in the machine direction until the required amount of fiber deposited on the table. The formed fiber pad was humidified by water aerosol or hot steam. The principle of humidification process was the same as in DFM. In some cases, hot steam was applied rather than room temperature water vapor. Same pressing and drying processes were used as in DFM. However, when hot pressing was applied, the temperature of hot pressing, pressing time, and pressing pressure were 90°C, 1 minute, 28 and 56 kgf/cm^2, respectively. All papers were made to have a basis weight of 80 gsm.

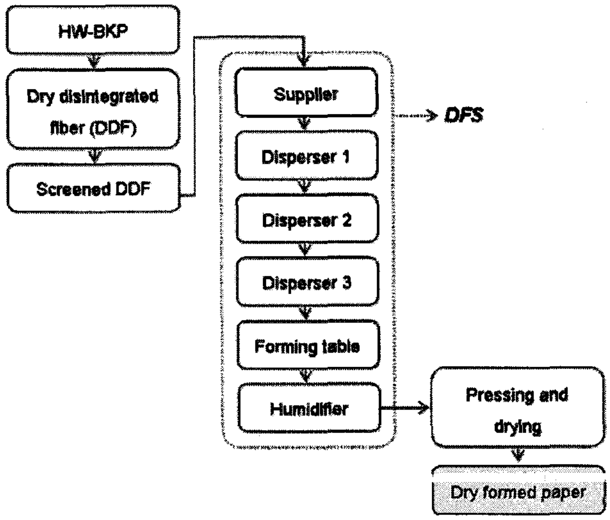

Fig. 3. Papermaking process with DFS.

RESULTS AND DISCUSSION

Comparison of dry and wet disintegration

The dry disintegrated fibers showed highly bent and folded appearance. It seemed that the fiber shape was influenced by the stress which occurred during dry disintegration. On the other hand, the wet disintegrated fibers showed straight shape with no significant kinks and twists. Fig. 4 shows the fiber length distribution curves of dry and wet disintegrated fibers. The average fiber lengths of dry and wet disintegrated fibers were 0.73 mm and 0.74 mm (length-weight), respectively. It should be noted that even though the fiber length distributions of the dry and wet disintegrated fibers were similar the appearance of individual fibers were quite different when they observed with a microscope. This indicates that the physical damages of fibers caused by dry and wet disintegration were quite different for these two fibers.

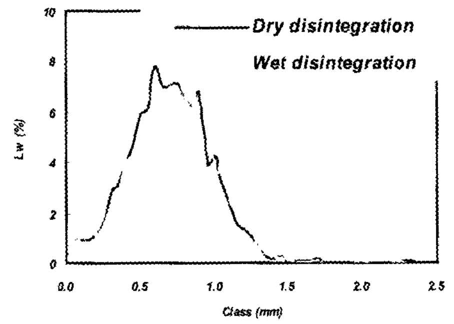

Fig. 4. Fiber lengths of dry and wet disintegrated fibers.

External shapes of the fiber pads made with DFM

Fig. 5 shows the photographs of the cross section and surface of the fiber pad on the forming board before humidification. Fibers were piled up on the board and it looked like snow. The basis weight of the fiber pad was 80 g/m^2. Figs. 6 and 7 show the pictures of the humidified fiber pads, whose moisture contents were 39% and 73%, respectively. The more humidification was made, the more water was condensed on fibers. The permeable structure of the fiber pad was maintained although fiber pad had high moisture content of 73%.

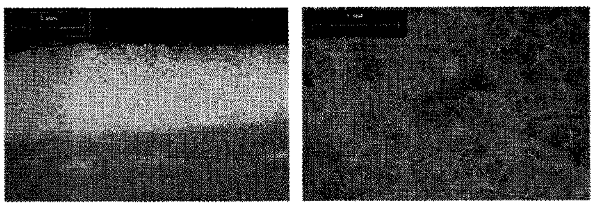

Fig. 5. Microscopic pictures of fiber pad on the forming board before humidification.

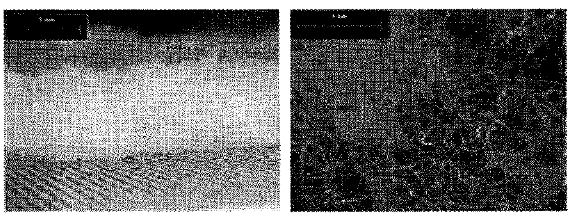

Fig. 6. Microscopic pictures of the humidified fiber pad with 39% moisture content.

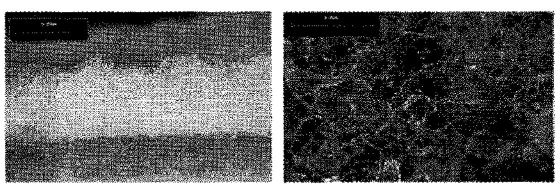

Fig. 7. Microscopic pictures of the humidified fiber pad with 73% moisture content.

Properties of the dry formed papers with DFM

Effect of initial moisture contents

Figs. 8 and 9 show the bulks and opacities of the dry formed papers as a function of initial moisture contents and pressing pressures. The bulk decreased as the initial moisture content increased. The bulk decreased more when the pressure was high. The opacity also decreased as the initial moisture content and pressure increased. In Fig. 10, the tensile strengths increased as the initial moisture content increased. Especially, the increase of tensile strength was prominent when the initial moisture content was increased from 39% to 53%.

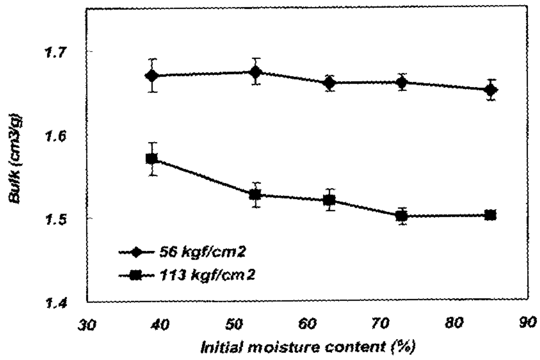

Fig. 8. Bulks of the dry formed papers as a function of initial moisture contents and pressing pressures.

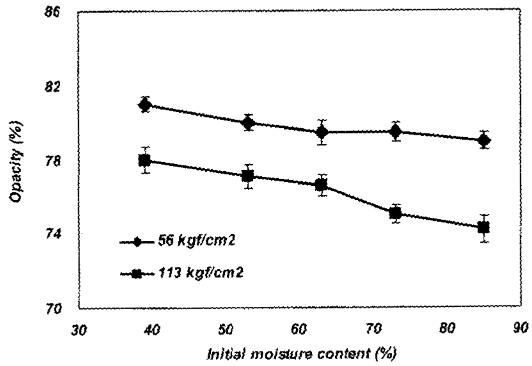

Fig. 9. Opacities of the dry formed papers as a function of initial moisture contents and pressing pressures.

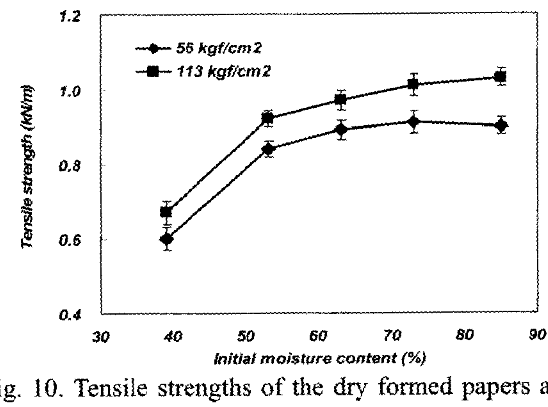

Fig. 10. Tensile strengths of the dry formed papers as a function of initial moisture contents and pressing pressures.

Effect of pressing conditions

Figs. 11 and 12 show the bulk of the dry formed papers as a function of pressing pressures and times when the initial moisture contents were 39 and 73%, respectively. The bulk decreased in both cases as the pressing pressure and time increased. Even though the lowest pressing pressure conditions was excessively greater than the pressure applied in conventional pressing process, the bulk was substantially greater than conventional wet formed papers. Figs. 13 and 14 show the tensile strength. The tensile strength increased as the pressing pressure and the pressing time increased. Especially when the initial moisture content was 73%, the tensile strength increased greatly with the increase of the pressing pressure. This indicates that the pressing pressure and initial moisture content are more important factors than the pressing time for improving tensile strength.

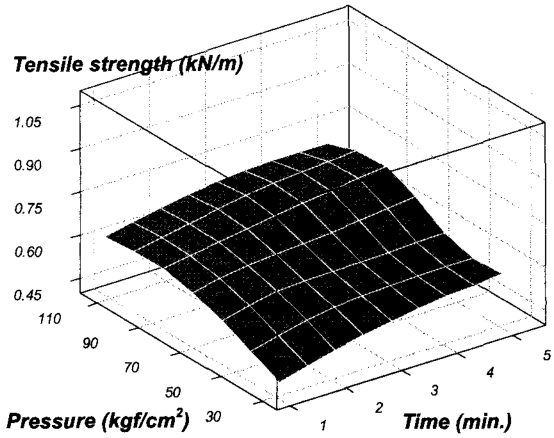

Fig. 13. Tensile strength of the dry formed papers as a function of pressing pressures and times when the initial moisture content was 39%.

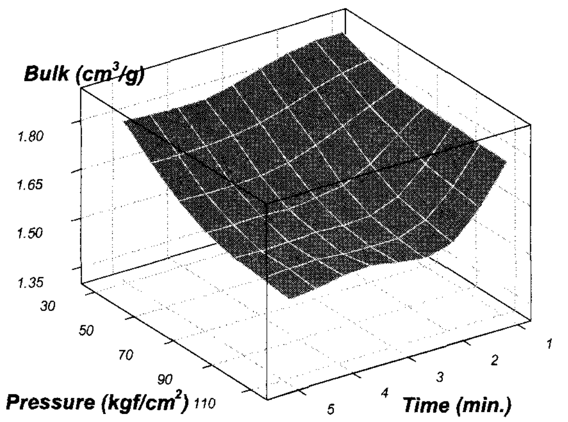

Fig. 11. Bulk of the dry formed papers as a function of pressing pressures and times when the initial moisture content was 39%.

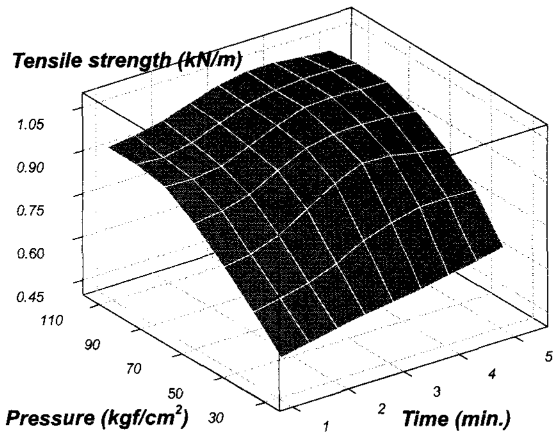

Fig. 14. Tensile strength of the dry formed papers as a function of pressing pressures and times when the initial moisture content was 73%.

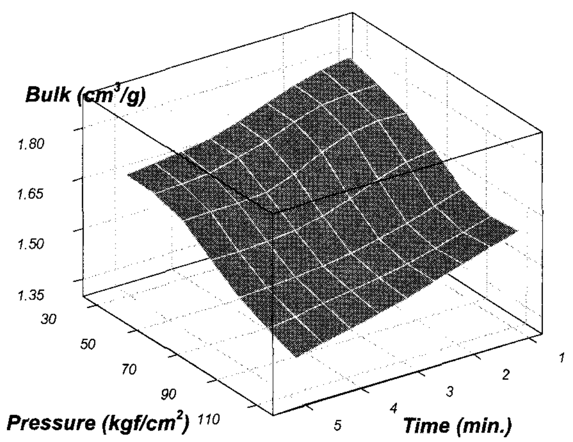

Fig. 12. Bulk of the dry formed papers as a function of pressing pressures and times when the initial moisture content was 73%.

Dried beaten fiber

Specification

Fig. 15 shows the fluffy lumps of dried beaten fibers. Each fiber was separated chemically but entangled physically. As shown in Fig. 16, WRV of the dried beaten fiber was lower than that of the wet beaten fiber. But it was higher than that of the dry disintegrated fiber. Even though the WRV of dried beaten fiber was not as large as that of wet beaten fiber, it appeared that the dried beaten fiber would form papers with improved strength property compared with the dry disintegrated fiber[27]. Fig. 17 shows the fiber lengths of the dried and wet beaten fibers. The dried and wet beaten fibers had the same fiber length of 0.67 mm (length-weight). The size distributions of the dried and wet beaten fibers were similar each other. These results showed that the dried beaten fiber had properties similar to the wet beaten fiber both in morphology and fiber length.

Fig. 15. The fluffy lumps of dried beaten fibers.

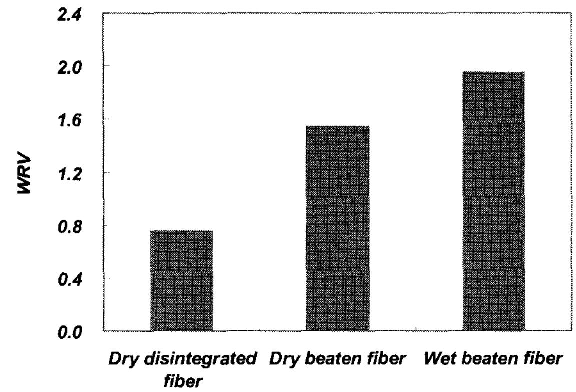

Fig. 16. WRV of the dry disintegrated, dried beaten, and wet beaten fibers.

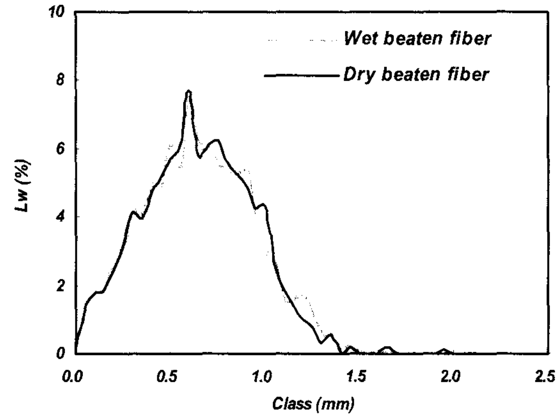

Fig. 17. Fiber length distribution of dried and wet beaten fibers

Application of dried beaten fiber with DFM

Fig. 18 compares tensile strengths of papers. 'Conv' stands for the handsheet made from beaten fiber using conventional wet forming method. and 'DF-28~113' and 'DFB-28~113' indicate dry formed papers with dry disintegrated and dried beaten fibers, respectively. The numbers means the pressing pressure in kg/cm^2. The results of the dry formed paper were displayed with lines because the tensile strength showed variations depending upon the experimental conditions such as initial moisture content, pressing time, and pressing pressure. When beaten fiber was used tensile strength increased greatly and it reached up to 72.7% of the tensile strength of wet formed handsheet. This shows that there is a possibility of improving tensile strength with the use of dried beaten fiber, and this would solve one of the most critical limitations of dry formed paper.

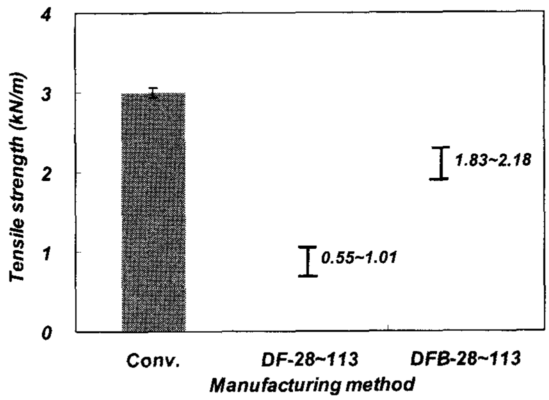

Fig. 18. Tensile strength as a function of manufacturing methods and fiber used.

Improving properties of dry formed paper with DFS

Comparison of the paper properties made with DFS and DFM

Fig. 19 shows the bulks of the papers made with DFM and DFS. The pressing pressures and the papermaking facilities are shown on the X-axis. The initial moisture content of papers made with DFM and DFS were 73% and 70%, respectively. All papers were pressed for three minutes. The results of DFM and DFS were also similar. But the standard deviation for the papers made on DFS was lower than that of DFM. This indicates that the paper made with DFS is superior in formation and repeatability. Fig. 20 shows the formation energies of the papers made with DFM and DFS. The dry disintegrated and dried beaten fibers were used as raw materials. 'DDF' and 'BF' shown on the X-axis indicate that the paper was made from dry disintegrated fiber and dried beaten fiber, respectively. The formation deteriorated when the dried beaten fiber was used probably due to increases in floc formation by fibrils. Paper made with DFS had superior formation when the same fiber was used. Fig. 21 shows that tensile strengths were similar when the pressing pressure was 28 kgf/cm^2. However, the paper made with DFS showed a little higher tensile strength when the pressing pressure was 56 kgf/cm^2. The results showed that DFS improved paper formation, and this resulted in increases of tensile strength[31].

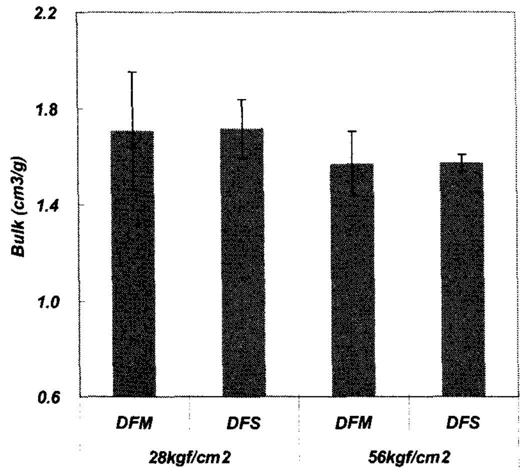

Fig. 19. Bulks of the papers made with DFM and DFS.

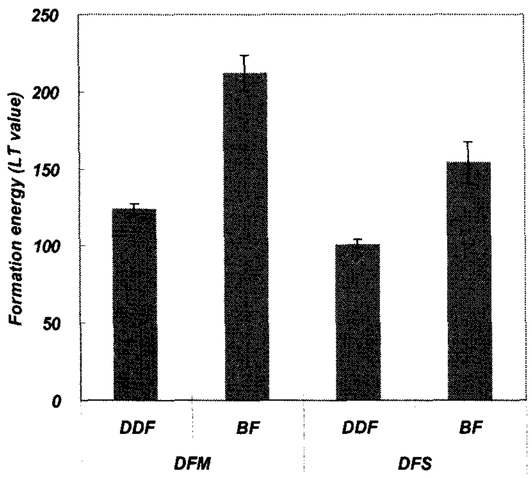

Fig. 20. Formation energies of the papers made with DFM and DFS.

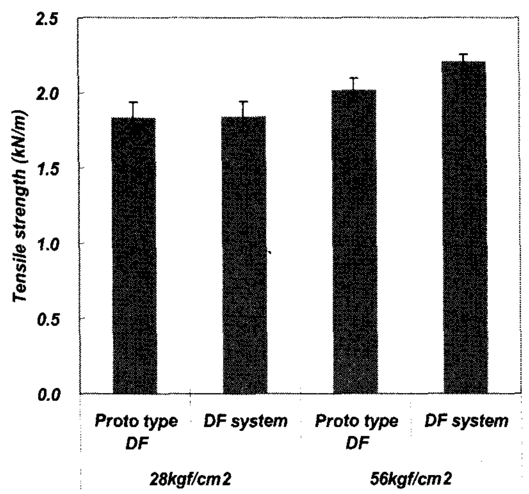

Fig. 21. Tensile strengths of the papers made with DFM and DFS.

Heat-applied paper

Figs. 22 and 23 show the bulks and opacities of the dry formed papers made from dried beaten fiber influenced by steaming and high temperature drying. The dry formed fiber pad was humidified with hot steam, and then pressed at 90°C, i.e. at a temperature below the water boiling point, for 1 minute. All papers in this experiment were made form dried beaten fiber. The heat-applied paper showed higher bulk and opacity because of quick evaporation of water and short pressing time. Drying papers at high drying rates would have huge advantages not only in decreasing the pressing time but also obtaining better quality in terms of bulk, opacity, and light scattering.

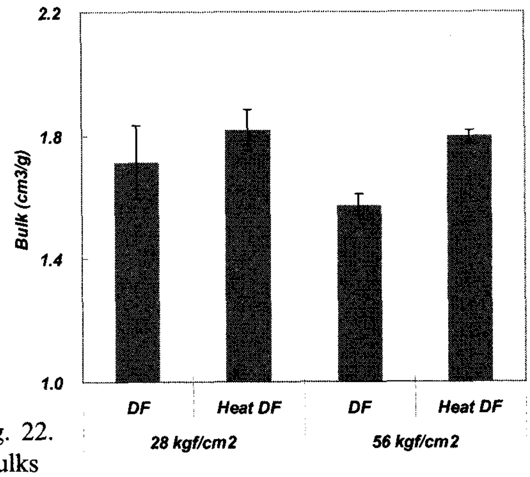

Fig. 22. Bulks of the papers with and without heat application.

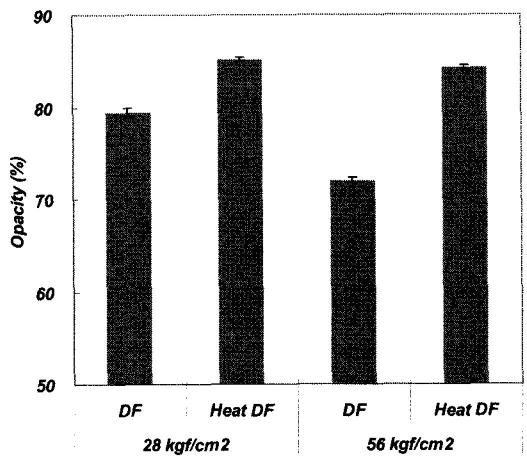

Fig. 23. Opacities of the papers with and without heat application.

Comparison of conventional handsheet with dry formed paper

SEM images

Fig. 24 shows the SEM images of a conventional handsheet made from beaten fiber. The cross section of the handsheet was quite compact. And it can be seen that many fibrils were entangled on the surface of the top side. Figs. 25 and 26 show the SEM images of the dry formed papers made from dry disintegrated fiber and dried beaten fiber, respectively. The papers were humidified to 53% moisture content and pressed to 56 kgf/cm^2 for 3 minutes without heating. The cross section of the paper shown in Fig. 25 had compact structure because of the high pressing pressure. There was no fibril on fiber surface. The dry formed paper and wet formed handsheet made from same dry disintegrated fiber showed similar surface feature. Dry formed paper, however, showed more compact structure because high pressing pressure was applied. In Fig. 26, it can be seen that the paper had compact Z-directional structure. And wrinkled fibers and many fibrils were on the surface. Two dry formed papers had similar compact structure but the surface appearance was quite different. The dry formed paper made from the dried beaten fiber had more wrinkles and fibrils on fiber surface than the paper made from dry disintegrated fiber. It would cause significant differences in tensile strength[28,29,30].

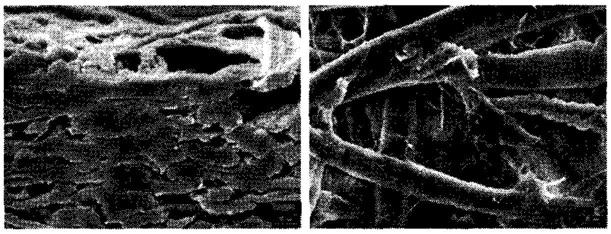

Fig. 24. SEM images of the conventional handsheet made from beaten fiber.

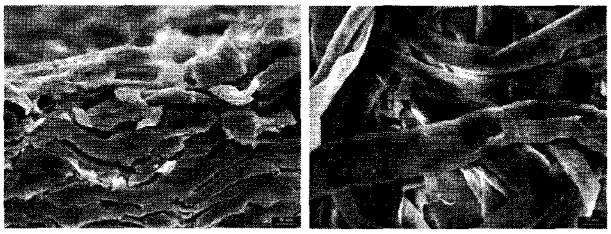

Fig. 25. SEM images of the dry formed paper made from dry disintegrated fiber.

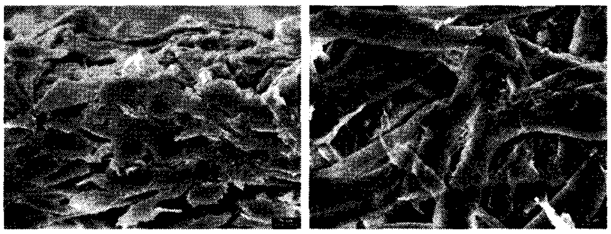

Fig. 26. SEM images of the dry formed paper made from dry beaten fiber.

Bulk and tensile strength

The bulk and tensile strength are two major properties representing the characteristics of the dry formed paper because these are opposite end properties and they can be changed easily by such process factors as humidification and pressing. Therefore comparing the bulk and tensile strength of the dry formed paper is the most effective ways to get an idea on the general characteristics of dry formed papers. Table 1 shows the fibers and process conditions employed to make dry formed papers shown in Figs. 27 and 28. The representative features of dry formed papers such as bulk and tensile strength were selected and compared with those of conventional handsheets.

Fig. 27 shows the bulks and tensile strengths of conventional handsheets made from dry disintegrated and beaten fibers ("Conv. Dry disintegrated fiber", "Conv. Beaten fiber"). The handsheet made from the beaten fiber had higher tensile strength and lower bulk than that made from the dry disintegrated fiber. The arrows indicate the change of the bulk and tensile strength when dry forming method was applied instead of the conventional handsheet-making method. The solid arrow shows the change when the increase of bulk was preferred to the increase of tensile strength. The dotted line arrow shows the change when the increase of tensile strength was preferred to the increase of bulk. When dry disintegrated fiber was used, the tensile strengths of dry formed papers were superior to that of the conventional handsheet in both bulk and tensile strength preference mode. However, when the tensile strength of the dry formed paper was improved, the bulk decreased greatly because of the application of high pressing pressure as DF-2 showed. When beaten fiber was used, the tensile strengths of dry formed papers were inferior to that of conventional handsheet in both bulk and tensile strength preference mode. However, the bulks of the dry formed papers were higher despite higher pressing pressure than that employed for conventional handsheet-making method. When the dried beaten fiber was used and the dry forming method of DF-3 was used, the tensile strength of dry formed paper increased to reach 73.5% of that of the conventional handsheet. Furthermore it also showed substantially higher bulk.

Fig. 28 shows the change of the bulk and tensile strength of dry formed papers when hot steaming and pressing was used along. It also shows that what happens when mixed fiber was used. In the case of the dry formed paper made from the dry disintegrated fiber (Heat DF-5), both tensile strength and bulk increased even though the tensile strength was lower than that of DF-2. The bulk reached 125.3% of that of conventional handsheet made from beaten fiber. In the case of the dry formed paper made from the dried beaten fiber (Heat DF-6), significant increase in bulk and little change in tensile strength compared with DF-4 were obtained. When mixed fiber was used, bulk and tensile strength located in between DF-5 and DF-6.

Table 1. Fibers and process conditions employed for dry formed papers depicted in Figs. 27 and 28.

Expression	Fiber used and heating	Initial moisture content (%)	Pressing pressure (kgf/cm2)	Pressing time (min)
DF-1	Dry disintegrated fiber	39	28	1
DF-2	Dry disintegrated fiber	85	113	3
DF-3	Dried beaten fiber	39	28	3
DF-4	Dried beaten fiber	70	58	3
Heat DF-5	Dry disintegrated fiber with heat	67	28	1
Heat DF-6	Dried beaten fiber with heat	67	56	1
Heat DF-7	Dry mixed fiber with heat	67	56	1

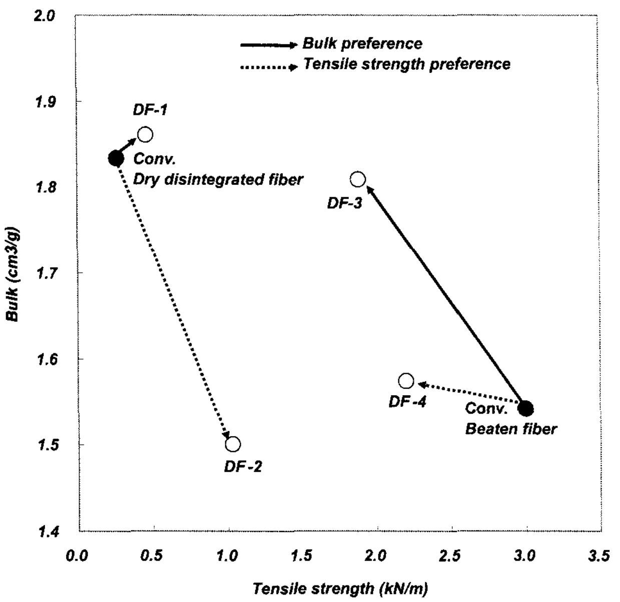

Fig. 27. Bulks and tensile strengths of the dry formed papers made from dry disintegrated and beaten fibers.

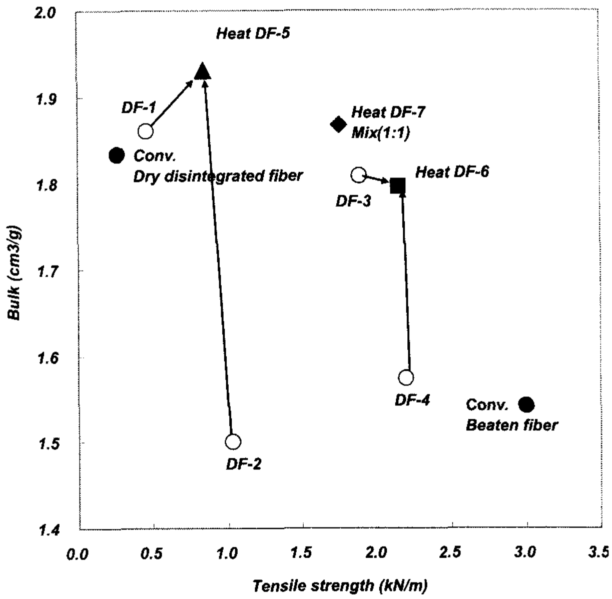

Fig. 28. Bulks and tensile strengths of the dry formed papers when the hot steam and pressing and mixed fiber were applied.

CONCLUSIONS

DFM to be developed first was good at making and evaluating dry formed paper. However, DFM had problems which were related to productivity and continuity, and there was much room for improving the paper formation. DFS was developed so that the process problems could be overcome and the formation be improved. The dry formed fiber pad had very bulky and porous structure before pressing, and that was pressed to high pressure in order to prevent paper structure like sponge or cotton battling. As initial moisture content increased, the moisture content after pressing and the tensile strength also increased. The bulk and the opacity however decreased. As pressing pressure and time increased, the tensile strength increased, and the moisture content after pressing, the bulk, and the opacity decreased. When the beaten fiber was used, the tensile strength of the dry formed paper was lower than that of the wet formed handsheet. However, the bulk of the dry formed paper was higher despite of higher pressing pressure. The dry formed paper could reach 73.5% of the tensile strength and 125.3% of the bulk as compared with those of the conventional wet formed handsheet. It dared to be judged that the tensile strength of dry formed paper increased impressively with this study even though the tensile strength was lower than that of conventional handsheet.

ACKNOWLEDGEMENT

Financial support from KIEST (Korea Institute of Environmental Science and Technology) is gratefully acknowledged. And it was partially supported by BK 21, Korea Research Foundation.

REFERENCE

1. Gullichsen, J., Harkonen, E., Medium consistency technology, TAPPI J. 64(6):69-72, (1981).
2. Paulapuro, H., Komppa, A., RAINA, Energy-efficient paper production, Final report on energy research programme 1988-1992. Ministry of Trade and Industry, Energy Department, Reviews B:165, Helsinki (1994).
3. Cichoracki, T., Gullichsen, J., Paulapuro, H., High consistency forming: a new concept, TAPPI J. 84(3):1-8, (2001); text available at www.tappi.org.
4. Kim, C.H., Song, D.B., Lee, Y.M., Kim, J.O., Jung, H.S., Park, J.Y., Utilization of pulp fibers for developing expanded shock-absorbing materials, 2005 KTAPPI spring proceeding, KTAPPI press, pp. 68-75.
5. White, F.M., fluid mechanics fourth edition, pp. 59-89, 215-252, McGraw-Hill (1999).
6. Cussler, E.L., diffusion : mass transfer in fluid system, pp. 226-227, 331-349, Cambridge university press (1997).
7. Peel, J.D., paper science and paper manufacture, pp. 164-169, Angus Wilde publications inc. (1999).
8. Seo, Y. B., Choi, C. H., Seo, S. W., Lee, H. L., Shin, J. H., fiber property modification by mechanical pretreatment, TAPPI J. 1(3):8-13, (2002).
9. Nazhad, M. M., Harris, E. J., Dodson, C. T. J.,Kerekes, R. J., the influence of formation on tensile strength of paper made from mechanical pulps, TAPPI J. 83(12):63 (2000) ; full text available at www.tappi.org.
10. Retulainen, E., Niskanen, K., Nilsen, N., papermaking science and technology : paper physics, Finnish paper engineers' association and TAPPI, pp.62-66, 74 (1998).
11. Heikkurinen, A., Hattula, T., mechanical pulp fines-characterization and implications for defibration mechanism, 18th lnt. Mech. pulping conference, EUCEPA, Oslo, p.294 (1993).
12. Lumiainen, J., refining- a key to upgrading the papermaking potential of recycled fibre, Paper technology, September 1994, pp.41-43.