Improvement of plybond strength of two-ply sheets by spraying of starch blends

JEONG YONG RYU AND HAK LAE LEE

ABSTRACT: Mills have sprayed natural starch slurry onto the formed wet web as a way to improve plybond strength of multiply boards. This technique, however, becomes less effective with recent technological changes that include increases in machine speed, increased use of recycled fibers, and closure of the papermaking system. In this study the effects of wet web dryness, amount of starch slurry sprayed, and drying temperature on the development of plybond strength were investigated using handsheets made from recycled softwood kraft pulp. Spraying of starch resulted in substantial increase in plybond strength. Maximum strength was obtained when the dryness of the wet web was around 10%–11%. Rapid drying at high temperature also decreased plybond strength, which we attributed to the deficiency of moisture for the gelatinization of starch. Using starch blends was suggested as an alternative for improving plybond strength at high drying rate. Stepwise gelatinization of starches substantially improved plybond strength. Optimization of the three-component starch mixture was carried out based on a three-component mixture design technique.

Application: The results of this study may help mills optimize the practice of spraying starch onto the formed wet web to improve plybond strength of multiply boards.

Multiply forming technology plays an important part in the manufacture of a wide range of paper and paperboard products. It is being used to produce medium- to high-basis-weight grades because of fiber cost economy, and to improve their properties [1, 2]. These benefits are made possible by producing structured multiply webs. For example, the outer layers may be made with a furnish that best meets the requirements of the sheet surface, while the inner part of the sheet would be made from a furnish that meets other needs [1].

Multiply sheets, however, exhibit the potential for delamination, i.e., the breaking away of one ply from the other. The strength of the bond between individual layers, known as the plybond, is one of the important quality requirements of multiply products that must be controlled. Meeting this requirement has become more difficult these days due to reduced plybond strength of multiply sheets. Increased use of recycled fibers as raw materials, changes in sheet forming processes that affect fines distribution of individual webs, and increases in papermaking speeds that increase the solids content of combining webs are the main factors that adversely affect plybond strength [1, 3].

Spraying of natural starch slurry onto the formed wet web has frequently been adopted to improve plybond strength of paperboards. It is highly effective in terms of retention of starch granules. By selecting the place where the starch is sprayed it is possible to control the z-directional distribution of starch in the web. Spraying starch before the dry line, for instance, causes the starch granules to be distributed more evenly in the z-direction, since the suction force acting over the vacuum boxes sucks the starch downward with draining water [4, 5].

Uncooked starch granules sprayed onto the wet web should be gelatinized during drying to improve plybond strength. Diverse factors, including the amount and distribution of sprayed starch in the web, gelatinization temperature of the starch, solids content of the web entering the dryer, and drying rate will affect the development of plybond strength from sprayed starch [5].

This conventional starch spraying technique, however, can be less effective on modern, higher speed machines. Substantial speed increases of multiply forming machines can cause significant changes in many factors that adversely affect plybond strength development by sprayed starch. In general, the higher the nip pressure applied by the couch roll and presses, the higher will be the plybond value within normal attainable limits [6].

Highly efficient pressing that increases the wet web dryness after the press often adversely affects plybond strength development of multiply board combined after starch spraying. Spraying more starch frequently aggravates the problem. This suggests that when an excessive amount of starch is sprayed the starch particles tend to act like filler particles and prevent interfiber bonding [7].

Our preliminary study showed that increasing the drying temperature also reduces plybond strength. These phenomena may occur because the deficiency of moisture in the web prevents the gelatinization of starch granules.

It is uneconomical and impractical to slow down the paper machine or to reduce the drying rate to the keep moisture level of the web high enough for extended period of time to improve plybond strength of multiply board sprayed with starch slurry. Obviously, a new approach is required for improving the effectiveness of starch spray in plybond strength improvement for today's high speed multiply board machines.

In this study, we investigated the effects of wet web dryness, amount of starch sprayed, and drying temperature on the development of plybond strength. We used handsheets formed with recycled softwood kraft pulp to determine why the plybond of multiply sheets decreases when they were formed on high speed paper machines. A new approach for improving the efficiency of starch spray has also been investigated and optimization of the starch blend was carried out based on a three component mixture design technique.

MATERIALS

Softwood bleached kraft pulp (SW-BKP) in dry form was beaten in a laboratory beater to 320 mL CSF. The beaten pulp was dewatered and bone-dried at 105°C to obtain hornified recycled fibers. Dried fibers were disintegrated again and beaten to the same level of freeness. The water retention value of the freshly beaten pulp was 2.44 g water/g fiber, while that of recycled fiber was 1.84 g water/g fiber. The average length and weight weighted fiber lengths of the recycled fiber were 1.35 mm and 1.83 mm, respectively.

To impart red color to a fraction of fiber, we added 0.1% of a direct red dye to the recycled SW-BKP before beating. Unadsorbed dye was thoroughly removed by washing the pulp and then drying it. A handsheet prepared with red colored fibers was joined with a handsheet formed with untreated white fibers after couching and then pressed. No migration of red dye occurred from the red sheet to the white sheet. Dyeing caused no difference in plybond strengths of two-ply handsheets; i.e., one made by combining a red and a white colored handsheets and the other made with two uncolored handsheets showed the same plybond strength. This indicates that dyeing did not influence the interfiber bonding property of fibers. Dyeing of one layer was carried out to determine the delamination layer for two-ply sheets. If two different colored layers were obtained after Scott internal bond testing, it indicates that separation was made between plies. When two patch-colored or same-colored surfaces were obtained after delamination, it indicates that plybond strength between the two layers was greater than the internal bond strength of the sheet.

Natural corn starch (NCS) and two oxidized corn starches (OCS) that differ in gelatinization temperature and viscosity have been used for spraying (**Table I**). NCS showed the highest Brookfield viscosity, while OCS-II with low gelatinization temperature was most fluid. The gelatinization temperature in Table I was measured as a temperature range from the moment when gelatinization started until 5% of the starch granules lost their crystallization characteristics.

Property	NCS[1]	OCS-I[2]	OCS-II[3]
Mean granule size (μm)	13.3	13.3	13.7
Gelatinization temperature (°C)	62~72	55~65	50~60
Brookfield viscosity (cps, measured with No. 3 spindle, 5%, 50°C, 60 rpm)	760	125	7.

[1] NCS: natural corn starch, [2] OCS-I: oxidized corn starch I, [3] OCS-II: oxidized corn starch II

I. Characteristics of starches.

METHODS

Handsheets with a basis weight of 100 g/m^2 were formed on a laboratory sheet mold modified to have a vacuum dewatering system. We used vacuum dewatering to control the dryness of wet sheets. Vacuum level, the duration of vacuum application, the number of vacuum dewatering steps, etc., were varied to obtain handsheets with dryness ranging from 8.3% to 15% by approximately 1% intervals.

Starch slurry at 2.0% solids was sprayed onto the wet web formed on the sheet mold. Starch spraying equipment designed to control the amount of sprayed starch slurry was installed on the handsheet mold frame. The amount of starch spray ranged from 0.5 g/m^2 to 2.0 g/m^2, and it was controlled within ±0.03 g/m^2.

Two handsheets were joined together with wire sides facing outward and pressed under the pressure of 6.3kg/cm^2 for 5 min. A press felt and absorptive paper pad were placed on both sides of the two-ply sheet before pressing. By doing so, the dryness of pressed two-ply sheets was kept constant at 42.5%. Pressed sheets were dried using a cylinder dryer. We used a drying temperature of 100°C in all cases except one set of experiments that examines the effect of drying temperature. Cylinder temperature was varied from 50°C to 100°C in 10°C intervals when the effect of drying rate was examined. Scott internal bond strength of the two- ply handsheets was determined according to TAPPI useful method UM 403.

RESULTS AND DISCUSSION

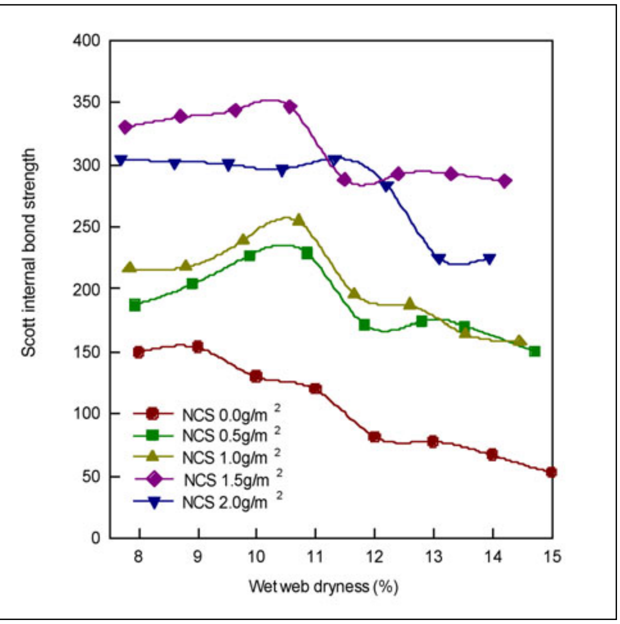
Effect of wet web dryness and amount of sprayed starch

Wet web dryness is one of the most critical factors affecting plybond strength of multiply boards [5]. In fact, three different types of wet web dryness should be considered for multiply board. They are the web dryness at which the starch is sprayed, the dryness of each ply at the combining point and the combined web dryness entering the press. These drynesses are often different on commercial paper machines since additional vacuum dewatering steps are involved after spraying starch and combining plies. We may speculate the effect of these drynesses of wet webs on plybond strength. It is not possible, however, to show solid verifications on the speculations due to practical difficulties associated with experimentations on this subject on a commercial machine.

It is well known that starch sprayed before the dry line tends to migrate into the web along with draining water during vacuum dewatering [5]. This indicates that it is more effective to spray starch after the dry line to prevent starch migration into the web. Migration of starch granules can also occur in pressing since it is a process that makes water contained in the web move in z-direction. This means that the improvement of plybond by the sprayed starch also depends upon the dryness of the wet web entering the press.

The effect of wet web dryness before starch spraying and amount of starch sprayed on plybond strength of two-ply sheets is depicted in **Fig. 1**. The amount of starch spray did not cause any variation in wet web dryness after pressing which remained constant at 42.5%. Plybond strength of webs containing no starch increased as the wet web dryness decreased, and the difference between maximum and minimum values was greater than 90 kJ/m^2. This indicates that stronger contact between the plies is possible when the web dryness is low. Free water that is present at the pickup nip gives fluidity at the interface for migration of fines and fibrils. Fines at the interface fill the voids and promote more intimate surface contact between plies (6). Decrease of fines content on the joining top sides of the handsheet due to high vacuum dewatering appeared to be another main cause of plybond reduction [5, 6].

Spraying 0.5–1.5 g/m^2 of starch resulted in substantial increase in plybond strength, and maximum strength was obtained when the dryness of the wet web was around 10%–11%. Plybond strength decreased as the wet web dryness decreased below 10% of dryness. We interpreted this was observed because the migration of starch with the water, press drained from the top side to wire side of the combined web, caused a reduction in plybond strength. Plybond reduction at low dryness range was less significant when 1.5 g/m^2 of starch was sprayed probably because the loss derived from starch migration is less significant at high spray levels of starch. It should be noted that a substantial reduction in plybond strength was observed when 2.0 g/m^2 of starch was sprayed. This suggested that spraying excessive amount of starch would be detrimental to plybond strength.

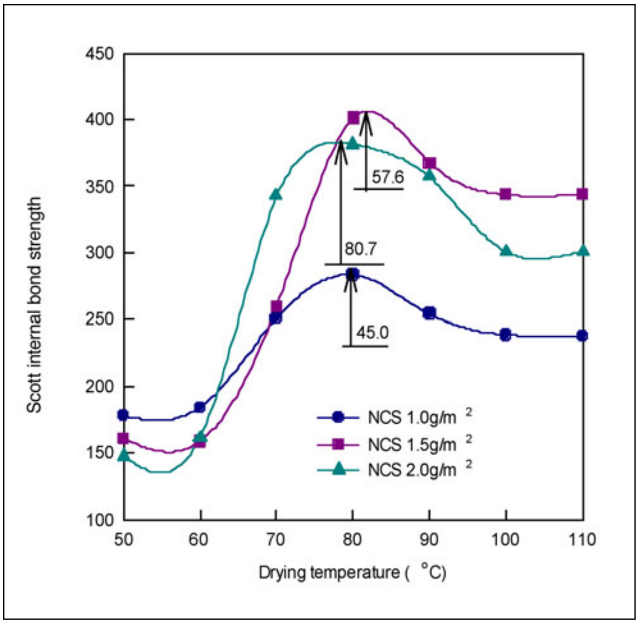


1. The effect of wet web dryness and spraying amount of unmodified corn starch on the Scott internal bond strength of two-ply handsheets.

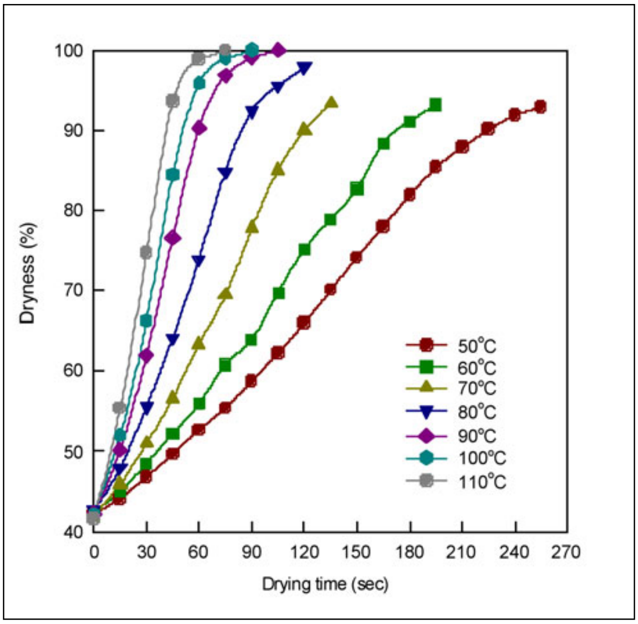
Effect of drying temperature

The effect of drying temperature on the Scott internal bond strength of the two-ply handsheets is depicted in **Fig. 2**. As the temperature of drying cylinder increased, the plybond strength increased, reached a maximum around 80°C and decreased again. When the dryer temperature was lower than 60°C, the plybond strength decreased as the amount of sprayed starch was increased. This indicates that the presence of ungelatinized starch granules adversely affects the plybond strength. It has been shown that uncooked starch acts like a filler particle and reduces sheet strength [7]. This also shows that enough heat and moisture should be present in the sheet for complete cookout of starch.

When the drying temperature ranged from 60°C to about 80°C, Scott internal bond strength increased abruptly. Especially, at the drying temperature of 70°C, substantial improvement was obtained with the handsheets containing 2.0 g/m^2 of natural corn starch. Even though the starch was not fully gelatinized at this temperature, swollen granules made a significant contribution to the improvement of plybond strength. At 80°C greater plybond strength was obtained



2. The effects of drying temperature on the Scott internal bond strength of two-ply handsheets.



3. The effect of drying temperature on the dryness of two-ply handsheets.

when the amount of sprayed starch was 1.5g/m^2, i.e., starch spray of 2.0 g/m^2 gave lower plybond strength. This is most probably because the web sprayed with 2.0 g/m^2 of starch was deficient in moisture for the starch granules to absorb for full gelatinization. Scott internal bond strength of the two-ply sheets with 2.0 g/m^2 of starch substantially decreased after the maximum as temperature increased above 80°C, which was attributed to the rapid evaporation of moisture from the web that restricted starch gelatinization. Reduction in plybond strength at high drying temperature was observed at all levels of starch spray. This shows that slow drying of the wet web at a temperature around 10°C higher than the gelatinization temperature provides maximum benefits of starch spray in improving plybond strength.

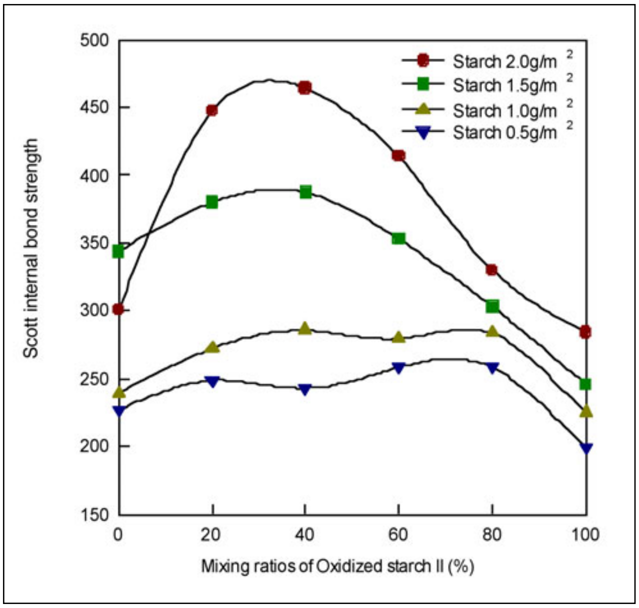
Figure 3 shows the change of sheet dryness with drying time at various temperatures. Obviously sheet dryness increased more rapidly at high drying temperature. Dryness increased almost linearly until it reached 90%.

In gelatinization of starch it is required for the web to have enough moisture for an extended period of time at a temperature above the gelatinization point. Drying the sheet at a high temperature will increase sheet temperature and the drying rate, but often results in incomplete gelatinization of starch. This is because the moisture in the web would evaporate too quickly for the starch to be gelatinized at high temperatures. As the amount of starch spray increases, the disadvantages of drying at high temperatures for plybond strength improvement will increase since there are many more starch granules competing for moisture. This explains why the difference in plybond strengths between maxima and dried at 100°C was substantially greater when the largest amount of starch was sprayed (Fig. 2). This clearly shows that it is necessary to either decrease the drying rate or the gelatinization temperature of starches to obtain the full benefits of starch spray in improving plybond strength.

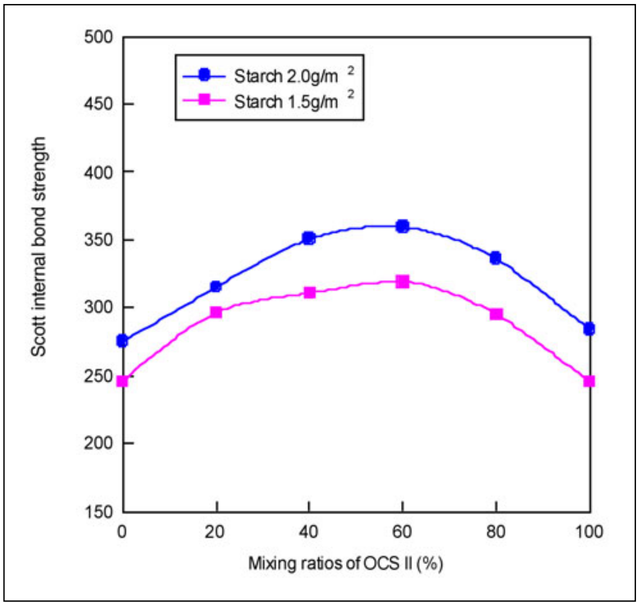
Effect of starch mixture

Low web dryness at the dryer inlet and a relatively slow drying rate are required for efficient gelatinization of natural starch, which is obviously impractical and uneconomical to employ. Mixing of oxidized starch that gelatinizes at a lower temperature than unmodified starch was examined as an alternative method to improve the plybond strength when high temperature drying was employed. It was expected that low gelatinization temperature starch will gelatinize when the sheet contains larger amount of water. And this will reduce the amount of water required to gelatinize the remaining starch with high gelatinization temperature.

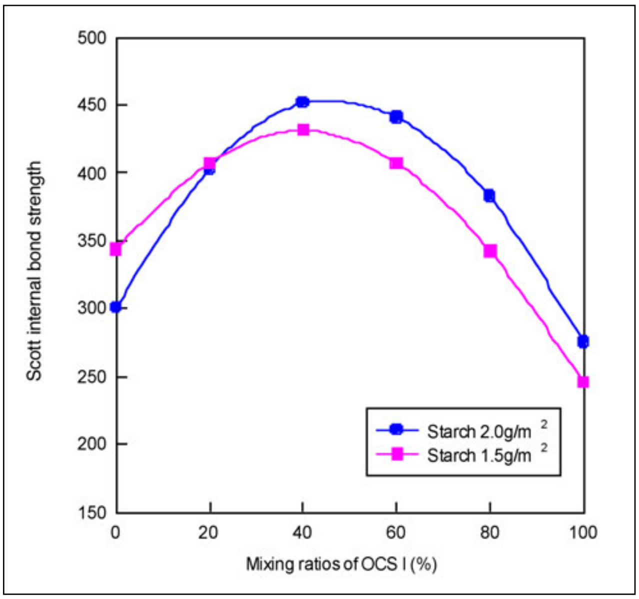
Figure 4 shows the effect of mixing ratios of OCS-II to NCS on Scott internal bond strength of two-ply sheets. Spraying oxidized starch only gave lower plybond strength than NCS since it has lower bonding potential than NCS. And this difference was most significant when 1.5 g/m^2 of starch was sprayed. Mixing of OCS-II provided no significant improvement in plybond strength when 0.5 and 1.0 g/m^2 of starch was sprayed. Spraying 1.5 g/m^2 of starch, however, gave substantial improvement in plybond strength. Most significant improvement was obtained when 2.0 g/m^2 of starch containing 40% of OCS was sprayed. This was unexpected since an increase of the sprayed starch from 1.5 g/m^2 to 2.0 g/m^2



4. The effects of mixing ratios of OCS-II to NCS on the Scott internal bond strength of two-ply handsheets.



6. Scott internal bond strength of two-ply handsheets versus mixing ratios of OCS-II to OCS-I.



5. The effects of mixing ratios of OCS-I to NCS on the Scott internal bond strength of two-ply handsheets.

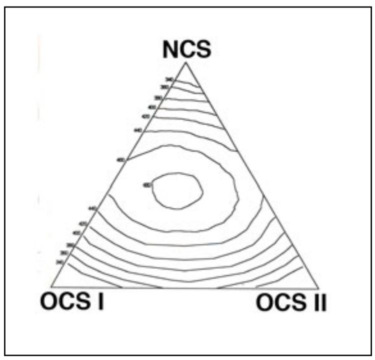
decreased bonding strength when NCS was used (Figs. 1 and 2). This shows that almost complete gelatinization of starch was obtained when a starch mixture was sprayed. This demonstrates that it is very effective to have two different starches with low and high gelatinization temperatures in improving plybond strength when large amounts of starch need to be sprayed. Mixing two different starches allows two stage gelatinization of starches, and this allows both starches to gelatinize more efficiently and contribute for the improvement of internal bond strength.

The same trend of plybond strength improvement was observed when OCS-I was used along with NCS (**Fig. 5**). Improvement of plybond strength was also obtained when mixture of two oxidized starches were sprayed (**Fig. 6**). The mixture of two oxidized starches only provided a marginal increase in plybond strength since oxidized starches have lower bonding potential than NCS.

Three-component mixture design

To extend our understanding of the influence of mixing three starches on plybond strength development, we used a three-component simplex centroid design technique [8, 9].

Figure 7 shows the contour plots of Scott internal bond strength. Maximum internal bond strength of 484.8 kJ/m^2 was obtained when the mixing ratio NCS:OCS-I:OCS-II was 6:5:4. In this case, delamination occurred not at the interface but inside the sheet indicating the plybond strength exceeds that of the internal bond strength.



7. Contour plot for the Scott internal bond strength of two-ply handsheets sprayed 2.0 g/m^2 of starch blends.

CONCLUSIONS

We used handsheets made from recycled softwood kraft pulp to investigate the effects of wet web dryness, the amount of starch slurry sprayed, and drying temperature on the development of plybond strength.

Plybond strength of the web containing no starch increased as the wet web dryness decreased. The difference between maximum and minimum values was greater than 90 kJ/m². This indicates that stronger contact between the layers is possible when the web dryness is low. Spraying 0.5 to 1.5 g/m² of starch resulted in a substantial increase in plybond strength. Maximum strength was obtained when the dryness of the wet web was around 10%–11%. Plybond strength of the two-ply sheets treated with starch spray decreased as the wet web dryness decreased below 10% of dryness. The migration of starch with the water press drained from the top side to wire side of the combined web may have caused this reduction. Substantial reduction in plybond strength was observed when 2.0 g/m² of starch was sprayed.

When the drying temperature ranged from 60°C to about 80°C, Scott internal bond strength increased abruptly. At a drying temperature of 80°C greater plybond strength was obtained when the amount of starch was 1.5g/m² rather than 2.0 g/m², which was attributed to the deficiency of moisture for starch gelatinization at higher spraying rate.

Mixing oxidized starch with a low gelatinization temperature with natural starch was very effective in improving plybond strength when a large amount of starch was applied. The influence on plybond strength development of mixing three starches was evaluated using a three-component simplex centroid design technique. Maximum internal bond strength was obtained when the mixing ratio of NCS:OCS-I:OCS-II was 6:5:4. **TJ**

Submitted: December 8, 2005
Accepted: December 9, 2005

LITERATURE CITED

1. Attwood, B. and Moore, G., *An Introduction to the Theory and Practice of Multiply Forming*, Pira International, 1995, pp. 1-10.
2. Müller, H., *The 21st International Conference on Pulping and Papermaking Technology Proceedings*, Korea TAPPI, Seoul, Korea, 1994, p. 41.
3. Unkila, K., *J. Korea TAPPI* 28(3): 74(1996).
4. Weiss, H., *Paper* 191(6): 340(1979).
5. Davies, B., *Paper Technol. Indust.* 18 (7): 186(1977).
6. Smook, G.A., *Handbook for Pulp and Paper Technologist*, Angus Wilde Publication, Vancouver, British Columbia, Canada, 1992, pp. 306-307.
7. Hofreiter, B.T., "Natural products for wet-end addition," in *Pulp and Paper, Chemistry and Chemical Technology*, Vol. 3, (J.P. Casey, Ed.), John Wiley & Sons, New York, New York, USA, 1981, pp. 1483-1485.
8. Scheffe, H., J. *Royal Statisti. Soc.*, B. 20: 344(1958).
9. Lee, H.L., Kang, H.C., and Bae, J.H., *Pan-Pacific Pulp and Paper Technology Conference Proceedings*, Part B, 1992, pp. 37-43.

INSIGHTS FROM THE AUTHORS

We chose this research topic to find a way to reduce the consumption of starch used for improving plybond strength of multiply boards. This is the first research on starch spraying from our laboratory. The effort was to find the best mixing ratio of different starches for maximum plybonding. We applied a three-component mixture design technique to address this issue. The most interesting thing for us was to see the role of moisture, temperature, and heating time in gelatinization of starch granules. It is especially noteworthy that increasing the amount of starch will have no effect in plybond when the multiply board machine runs fast. The starch granule requires moisture, temperature, and time for its gelatinization. The mill may benefit either by controlling the moisture level of the wet web or by using proper starch combinations for maximum plybond strength.

Lee

Ryu

Lee is professor at the Department of Forest Sciences CALS, Seoul National University, Seoul 151-921, South Korea; Ryu is a Ph.D. principal research scientist in the Chemical Biotechnology Research Center of the Advanced Chemical Technology Division, Korea Research Institute of Chemical Technology; email Lee at lhakl@snu.ac.kr.