

Amphoteric dry strength chemistry approach to deal with low-quality fiber and difficult wet-end chemistry conditions in the Asian and North American markets

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ABSTRACT: With Japan's high recycling rates and low access to fresh fiber sources, reaching strength targets in manufacturing packaging materials is a challenge. Declining quality of recycled fiber and minimal freshwater consumption results in difficult wet-end chemistry conditions in terms of high conductivity and elevated levels of dissolved and colloidal substances (DCS). These trends are somewhat typical of other Asian regions. Due to global trade, Asian packaging materials have become a part of the North American (NA) raw material pool. The gradual closing of mill water circuits for fresh water and energy savings results in more difficult wet-end chemistry conditions experienced in North America. China's ban on the import of mixed paper and the consequent ban on all waste-paper imports triggered a significant price drop in recycled raw material, resulting in plans for increased manufacturing capacity in North America. Between increased demand, decreasing fiber quality, and movement towards more closed white water systems associated with packaging grade paperboard (even a virgin fiber mill uses a fair amount of recycled fiber), new methods to overcome strength reduction in raw materials must be proactively considered for North America.

Reviewing the strategies currently used in the Asian industry regarding strength development is an excellent starting place for NA producers. A clear difference between Asian and NA wet-end chemistry is the dominant position of amphoteric dry strength agents. This paper reviews the fundamentals of dry strength development that explain the trend towards the increased application of amphoteric dry strength technology for poor-quality fiber and highly contaminated water circuits in Asian markets. This paper discusses the development and application performance of the novel 4th generation amphoteric polyacrylamide (AmPAM) dry strength technology, based on selected laboratory and mill case studies.

Application: As U.S. paper quality deteriorates as it has already done in Asia, this research paper will help papermakers develop a pathway to continue making quality products.

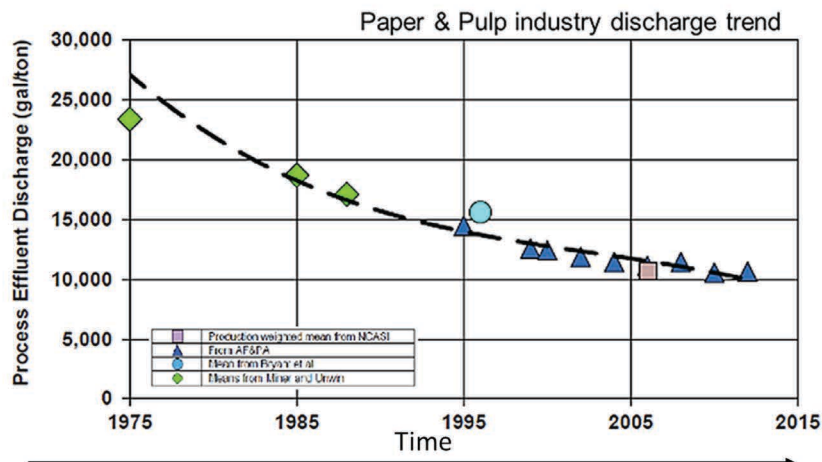
Over the years, recycled fiber quality has decreased, especially in the Southeast Asian markets. At the same time, Japanese, Korean, and other recycled mills in Southeast Asia have increasingly operated with lower and lower water consumption (increasing degree of closure), resulting in high conductivity levels and anionic trash in their wet ends. During this time, the application of dry strength polymers has evolved towards amphoteric technology, which proved to be more effective towards poor-quality fiber and less sensitive to increased conductivity levels and anionic trash. High white water conductivity has made applying cationic dry strength additives relatively ineffective. This fact, combined with the low-quality recycled fiber that requires a significant strength boost, resulted in an increased reliance of the Asian paperboard manufacturers on amphoteric technology for strength enhancement.

The performance gap between amphoteric and cationic polymer strength development opens with declining fiber

quality and increased mill water closure, precisely where the North American (NA) recycling mills are heading. Some NA machines are already operating under these deteriorating conditions. Recycled grades are very demanding due to their lower and variable strength raw materials. The NA old corrugated containers (OCC) raw material was traditionally considered to be of better quality in terms of strength than OCC from Europe and Asia. A higher influx of fresh chemical pulp and lower ash content contributed to the higher strength of the NA OCC. Demand for Asian and European commercial goods has resulted in an influx of inferior quality boxes into North America, resulting in decreased and variable OCC raw material quality. With the current trends observed in North America, the experiences and best practices of Asian paper producers and suppliers should be of interest to minimize the negative impacts of declining fiber quality and increased wet-end conductivity.

The NA OCC quality is declining due to the increased

DRY STRENGTH ADDITIVES



OCC



Mixed Waste

OCC



1. Illustration of the trends affecting the strength of North American packaging grades: increased closure of mill water circuits and lower quality of the raw material. Effluent discharge data from [1]. (OCC: old corrugated containers.)

number of recycling cycles, pressure for raw material cost reduction, China's 2018 decision to ban all mixed waste-paper imports, and the consequent decision to completely ban all recycled paper imports. This move resulted in a sudden drop in recycled paper prices and the announcement of new recycled (mainly packaging) machine projects in North America. The expected decline in China's output of packaging grades created a chance to fill the projected supply gap. Implementing mixed office waste containing lower-strength fiber (mechanical) and a higher level of mineral fillers in the furnish will further deteriorate the quality of recycled fiber. **Figure 1** represents the general trends in North America. These trends will make NA furnish gradually resemble that of the Japanese and Asian markets. **Figure 2** illustrates the differences in OCC quality between various regions in terms of fiber length (green line), fines content (blue bar), and ash content (red bar).

Another factor that will pressure the packaging strength requirements is the long overdue trend to lower basis weight in North America. This trend will create additional challenges in some strength properties, mainly compression strength, that greatly depends on the product's basis weight. Combining the lowering of basis weight trend with the deterioration of fiber quality and increasing contamination of the process water justifies reviewing all available ways of improving chemical strength.

FUNDAMENTALS OF DRY STRENGTH DEVELOPMENT

General dry strength considerations

Strength is the most critical quality specification for all packaging grades. Despite graphics paper declining over the last decade, the overall paper industry records growth due to significant production increases in packaging grades. Packaging grades encompass various products, all sharing the need for some strength parameter. The major strength requirements for packaging grades are burst, tensile, compression, and z-direction strength.

Hubbe [2] and Lindstrom et al. [3], in their excellent reviews, discussed the fundamentals of strength development in paper and board. The well-known fundamental Page equation (Eq. 1) consists of two parts describing the strength of individual fibers and the strength of the bond between the fibers.

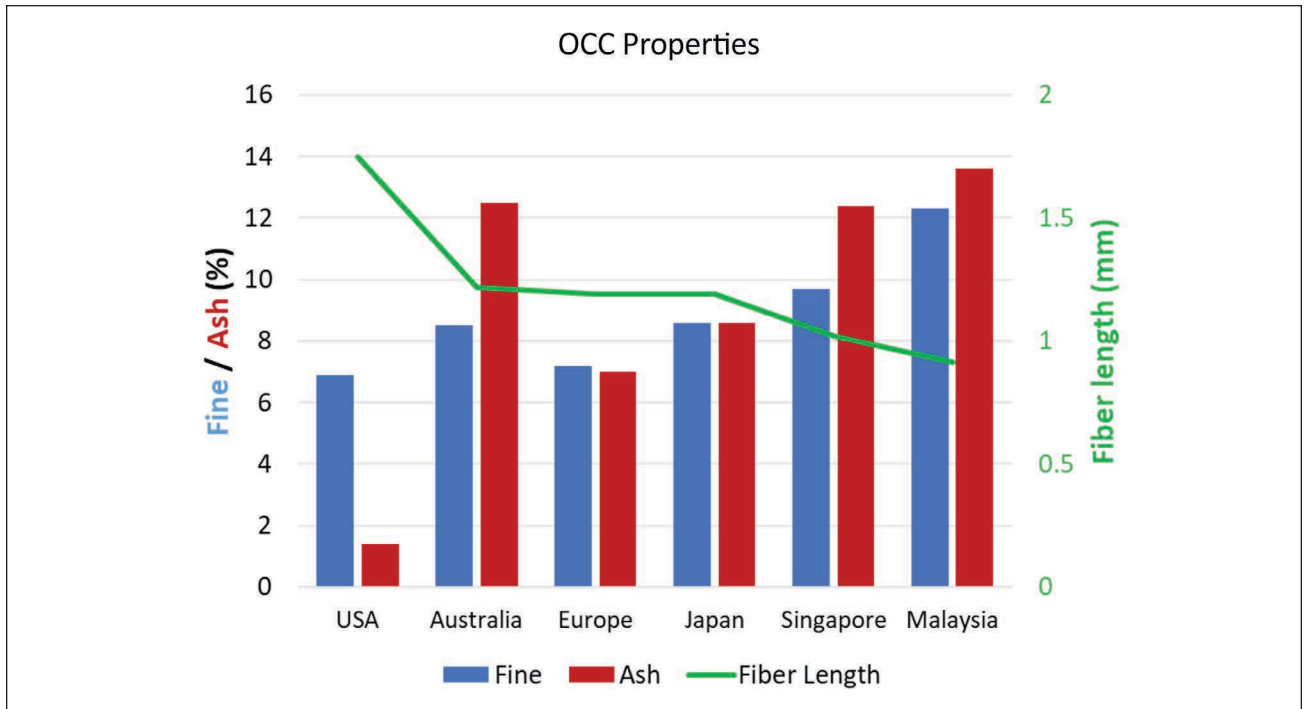
$$\frac{1}{T} = \frac{9}{8Z} + \frac{12A\rho g}{bPL(RBA)} \quad (1)$$

where:

T = tensile breaking length

Z = zero-span tensile

A = fiber average overlapping area

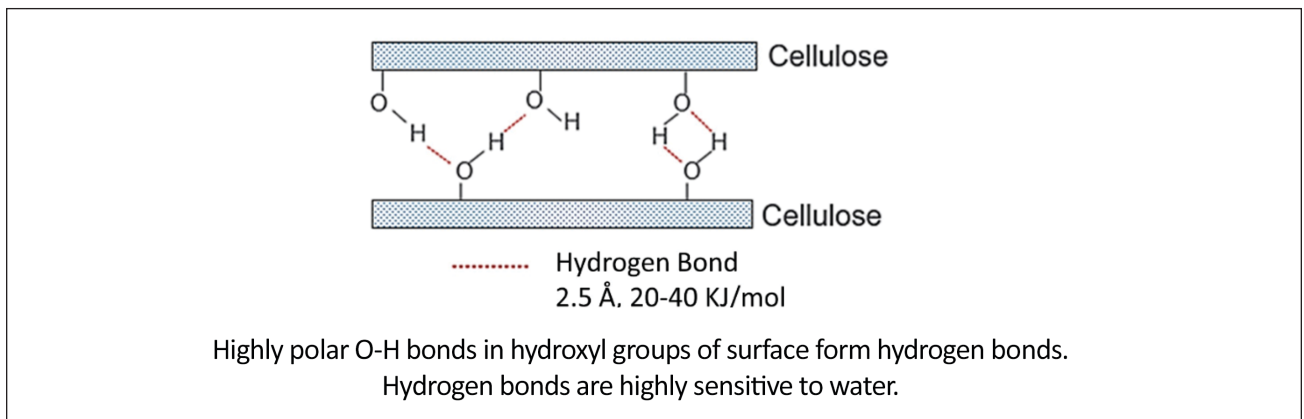


2. The OCC quality in fiber length, ash, and filler content based on 2018 data.

ρ = fiber density
 b = bond strength
 P = fiber perimeter
 L = fiber length
 RBA = relative bond area

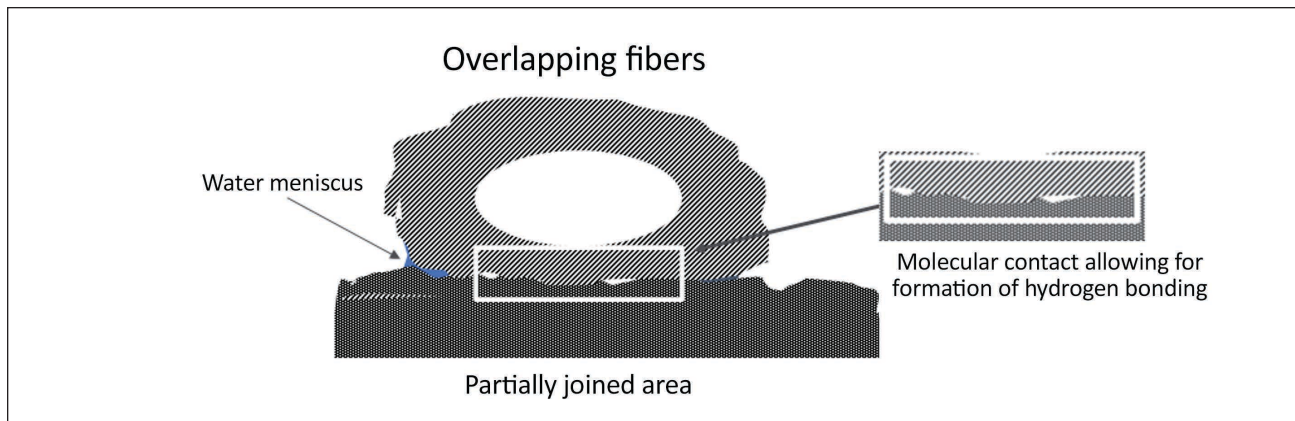
The individual fiber tensile strength is rarely a limiting factor in paper strength. The paper almost always fails in the fiber-fiber bonding area described by the second term of the Page equation. Fiber length (L) and relative bond area (RBA) are the most critical inter-fiber bond strength parameters. In many cases, fiber length is entirely fixed for individual mills, as it depends on the wood species used. It is well known that softwood kraft pulp is utilized by paper-makers when more strength is needed, which illustrates the impact of fiber length on the strength.

The RBA component of the Page equation deserves attention when attempting to develop strength. The higher the RBA, the higher the breaking length of the paper. The RBA depends on the number of fiber-fiber overlap areas and how the fiber collapses in the overlap areas. The strength developed in the fiber-fiber crossing results from hydrogen bonding between the hydroxyl groups of the fibers (**Fig. 3**). Hydrogen bonding is a short-distance phenomenon, not exceeding a few angstroms ($1\text{\AA}=10^{-10}\text{ m}$). Fibers must be in this range of molecular contact to allow the hydrogen bond to form. The consolidation process starts in the press section through physical press loading. After the presses, fibers are still too far apart for hydrogen bonding to form. The final force bringing fibers into molecular contact involves meniscus forces from the evaporation of the last parts of water from the fiber crossings area early in the dryer section (**Fig. 4**).

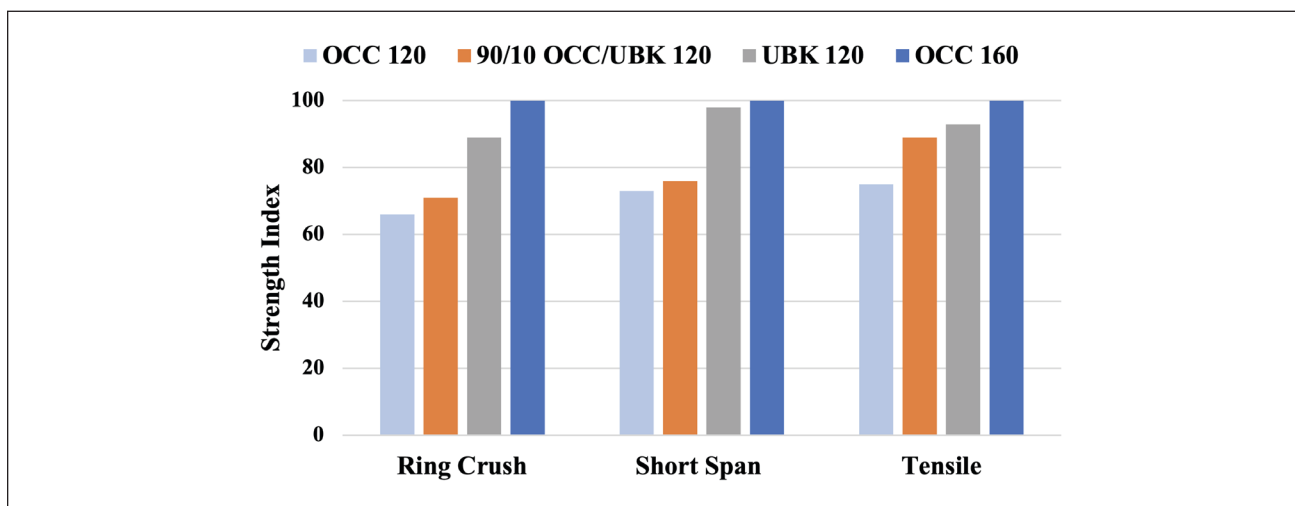


3. Hydrogen bonding responsible for dry strength of paper/board products.

DRY STRENGTH ADDITIVES



4. Meniscus forces from the water in the fiber-fiber overlap area that are responsible for fibers collapsing and bringing fibers to a distance, allowing for hydrogen bond formation.



5. Strength properties for unbleached kraft (UBK), OCC, and UBK/OCC (10/90) pulps at 120 g/m² (25 lb). The dark blue bar represents OCC pulp at 160 g/m² (33 lb). Data are relative to the strength of the 160 g/m² OCC handsheets (100%).

Fiber quality has the most critical impact on the paper's strength. One of the factors not always controllable by papermakers is the selection of the wood species, mainly affecting fiber length. The other fiber-related factors are the pulping process and the bleaching process. Low yield, fiber-length preservation, and chemical kraft or sulfite processes result in stronger pulps due to fiber length and fiber quality (longer and more collapsible fibers increasing RBA). On the other end of the spectrum are high-yield mechanical pulps, such as thermomechanical pulp (TMP), stone groundwood pulp (SGW), pressurized groundwood pulp (PGW), and refiner mechanical pulp (RMP), which generate shorter fiber and high fines levels and are much weaker. The impact of fines on the strength depends on the type of fines. Fresh fines contribute positively to strength, while low-quality recycled fines reduce strength.

Papermakers have some operational tools available to improve the strength of their products. These tools include:

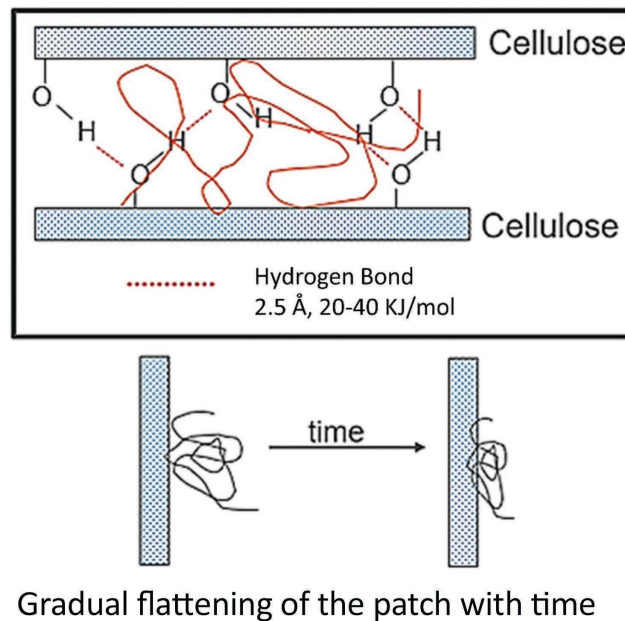
- Refining of pulps and reject refining for mechanical pulps. Refining for strength (in contrast to refining for

opacity or smoothness) focuses on improved fiber collapsibility, cell wall hydration, and fiber fibrillation. Different strength goals require different refining strategies regarding specific energy, intensity, consistency, plate design, and some chemical pretreatment.

- Sheet formation – avoiding over-flocculation. In most cases, over-flocculation weakens the sheet, since the failure of the sheet under strain follows the line of weakest strength.
- The jet/wire ratio controls fiber orientation.
- Press loading – increasing solids content after presses. Increasing pressing loads is limited by the requirement to avoid sheet crushing.
- The drying profile and dryer section defines how long the sheet remains under restraint.

Issues specific to recycled pulps

The strength narrative changes significantly in the case of recycled pulps. Bleached or unbleached, virgin pulps are typically strong enough that good operational practices



6. Role of dry strength agent in strengthening the hydrogen bonding responsible for dry strength of paper and board products. The more extended conformation of adsorbed patch allows for better results.

allow paper or board production with no or minimum dosage of dry strength additives. The most critical factors affecting the strength of recycled paper and board grades are:

- Lower anionic charge on the fiber surface compared to virgin fiber due to a gradual reduction of the hemicellulose content and previous treatment with cationic additives (starches, fixatives, wet strength, dry strength, other). Cationic additives penetrate the fiber pores wider than 20 nm, reducing the fiber charge.
- Lower fiber length due to refining.
- Fiber hornification makes previously dried fibers less flexible and collapsible, impacting their bonding properties.
- Less fiber swelling potential at higher pH compared to virgin fiber.

Fibers lose binding capability with every recycling cycle, although the most significant drop in quality occurs after the first recycling cycle. **Figure 5** illustrates the relative strength (ring crush, short span, and tensile) of the handsheets prepared from OCC pulp and unbleached kraft (UBK) pulp. For each strength parameter, 120 g/m² handsheets were made with OCC, OCC reinforced with 10% UBK, and 100% UBK pulp. These sheets were compared to 160 g/m² handsheets made of 100% OCC pulp. These data allowed us to estimate the strength loss due to recycling and the impact of added basis weight and reinforcing pulp on strength recovery. These data are critical to large organizations using virgin and recycled pulps and to offering a standard product performance regardless of the furnish.

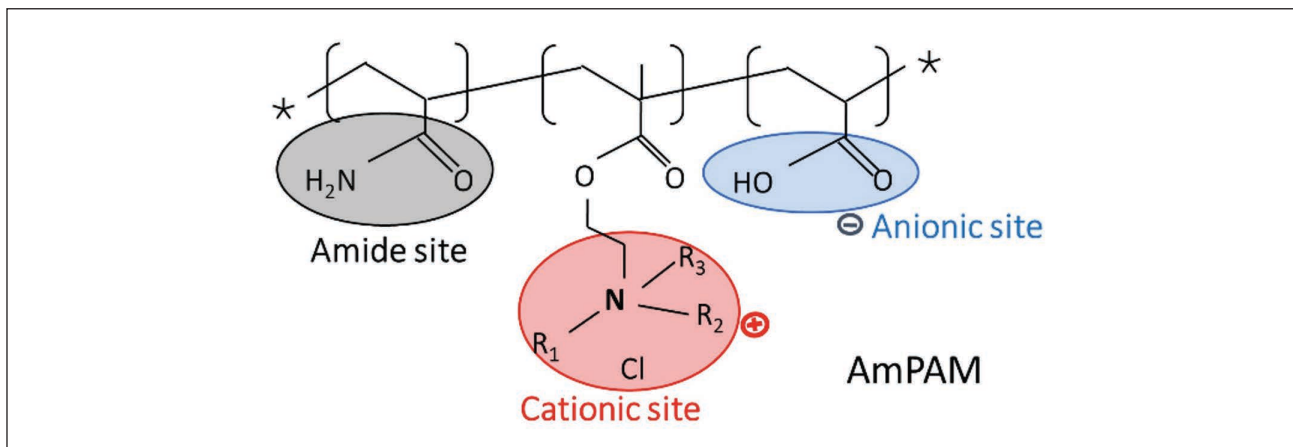
Dry strength additives

As a result of the previously noted factors, recycled fiber packaging grades rely more on dry strength additives than mechanical treatment for strength development. Originally starch, typically cationic, was a dry strength additive of choice. The dry strength additives create more ability for hydrogen bonding in the overlap area. In terms of the Page equation (Eq. 1), dry strength additives increase the strength of the fiber-fiber bonding area (**Fig. 6**). The initial patch of the adsorbed dry strength agent is essential in developing a strength benefit. The initial patch flattens with time, making a selection of addition point important.

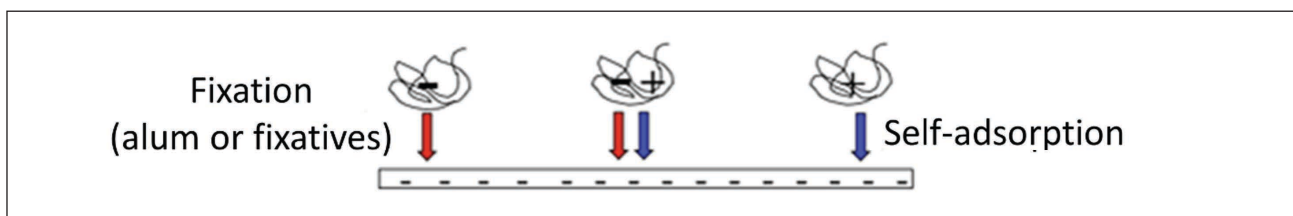
Cationic synthetic dry strength additives were introduced to the market in the 1990s. However, an abundant supply and good cost position made starch a practically unchallenged choice in dry strength applications at that time. The starch dosage-performance curve shows charge saturation at about 1% applied cationic starch on a dry basis. This saturation effect is related to the fiber surface's anionic charge. For any cationic functional chemistry, adsorption to the fiber is a primary requirement for performance. Once a cationic additive neutralizes the anionic charge on the surface, no more additive is adsorbed spontaneously.

Lower-quality recycled fiber offers less surface charge to adsorb cationic dry strength additives. Several strength enhancement applications were developed to overcome these adsorption challenges. These applications combine the addition of cationic and anionic dry strength agents, either sequentially or premixing them just before the addition point. Interaction between cationic and anionic prod-

DRY STRENGTH ADDITIVES



7. Example of amphoteric terpolymer based on the acrylamide polymer backbone. Quaternary amine function provides a cationic charge, and acrylic acid provides a negative charge. The anionic charge of acrylate may be reduced at very low pH. (AmPAM: amphoteric polyacrylamide.)



8. Adsorption mechanism of cationic, anionic, and amphoteric strength additives.

ucts forms polyelectrolyte complexes and improves adsorption to the fiber.

Amphoteric dry strength agents carry cationic and anionic substituents on the polyacrylamide chain. **Figure 7** shows an example of an amphoteric terpolymer with cationic and anionic charges.

Adsorption mechanisms

Due to the anionic and cationic charges in the amphoteric dry strength agents, their adsorption mechanism to the fiber is different from the cationic dry strength product (**Fig. 8**). Cationic strength additives rely on self-adsorption to the negatively charged fiber surface. The amount of the negative charge limits the amount of adsorbed strength agent. It is worth mentioning that other cationic additives, such as sizing, also rely on this mechanism. If strength and sizing are required, these two applications may compete for the negatively charged site on fibers. The anionic substances have to be fixed to the fiber. The amphoteric strength products utilize much less of the anionic charge since their net charge is, in most cases, only slightly cationic. In some cases, adding alum, polyaluminum chloride (PAC), or coagulant may add fixation to the self-adsorption pathway if additional retention is required.

Benefits of polyampholytes dry strength agents

According to Hubbe [2], amphoteric polymers (ampholytes) outperform other strength additives. Some characteristics

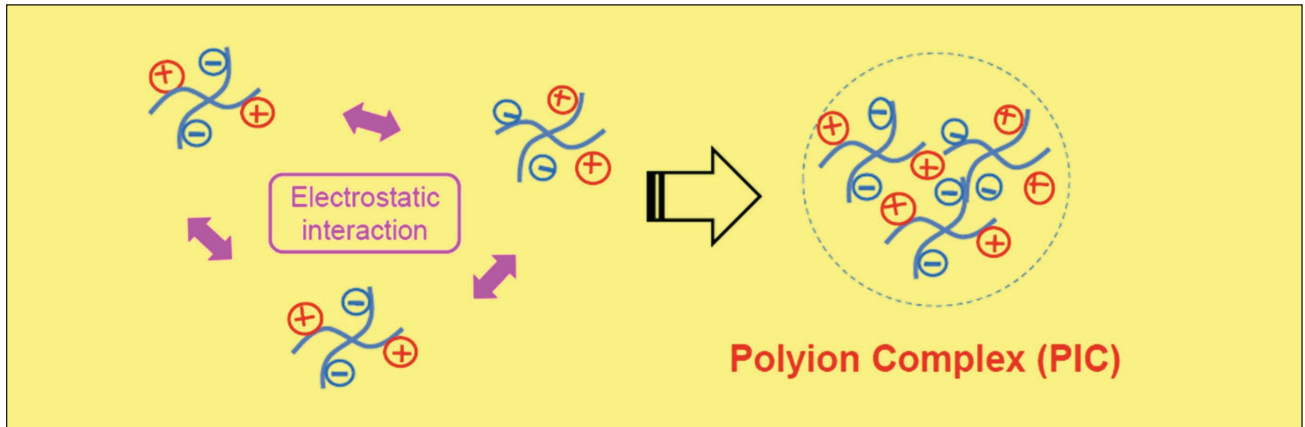
of these polymers that explain such observations include:

- Ampholytes do not cause a charge imbalance, allowing for better retention and higher polymer loading.
- Ampholytes show better adsorption to the fiber and lead to better strength response.
- Ampholytes show a lower potential for over-flocculation.
- Ampholytes create a more hydrogel-like layer when adsorbed on the fiber, forming a meniscus responsible for pulling fibers together and resulting in more areas where close fiber-fiber contact is developed to allow hydrogen bonding formation. These models were supported by water retention value (WRV) tests [4] and a quartz crystal microbalance study (Song [5]).
- Ampholytes can form intermolecular and intramolecular polyelectrolyte complexes that lower their solubility and drive their adsorption (**Fig. 9**). Formation and visualization of polyelectrolyte complexes were discussed by Kumagae et al. at TAPPICon 2019 [6].

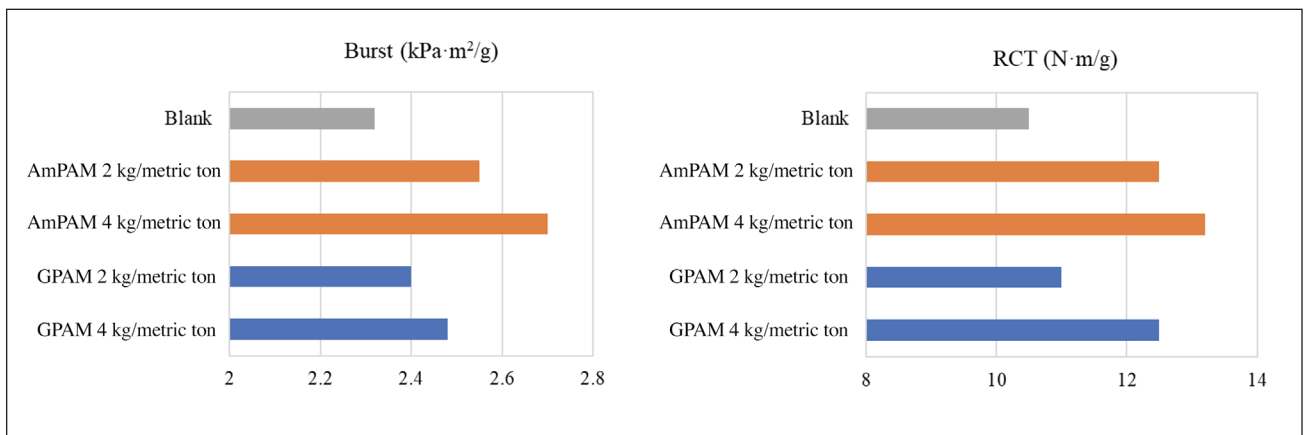
Water chemistry

Increased water circuit closure makes water chemistry more complex, affecting strength development and the performance of dry strength agents. Therefore, when dry strength agents are required, the water chemistry conditions reduce the activity of dry strength additive performance.

Xu, Pruszyński, and Hart [7] and Lindström [8] reviewed the impact of conductivity on papermaking. Increased conductivity reduces interaction between the exact charges



9. The blocky distribution of charges in AmPAM allows for forming of polyelectrolyte complexes that improve their adsorption to the fiber.



10. Strength development comparison of glyoxalated polyacrylamide (GPAM) and AmPAM.

(anionic in this case) and fiber swelling. Increased conductivity can cause cationic additives to coil, reducing their adsorption and making the adsorbed patch extend less from the surface, which results in weaker bonding.

Another trend related to mill water closure is increasing levels of anionic trash, also called dissolved and colloidal substances (DCS), measured by colloidal titration. Cationic additives are consumed by the anionic trash materials, rendering them inactive [9,10].

EXPERIMENTAL RESULTS

Technology

Several factors may be different between various amphoteric dry strength additives. In the most generic sense, the term “amphoteric” confirms the presence of cationic and anionic charges and tells little about the product. Developing the latest 4th generation amphoteric dry strength technology required several decades of research and field efforts. Several parameters were the focus of these optimization efforts:

- **Molecular weight and its distribution:** Too low molecular weight material is challenging to be retained on the fiber, while too high molecular weight fraction

may cause undesired stock over-flocculation.

- **Charge:** Both net charge (ratio of cationic and anionic monomers) and charge density are critical to performance; both ratio and density of charge impact product adsorption to the fiber.
- **Charge distribution – random vs. blocky distribution:** Blocks of cationic and anionic charges may form internal polyelectrolyte complexes, driving the adsorption to the fiber. Such a charge distribution makes the amphoteric technology an all-in-one dual polymer program.
- **Crosslinking:** Some degree of crosslinking makes a polymer more rigid and makes the patch on the fiber more extended and more persistent, with a lower tendency to lay flat on the surface. This behavior opens more flexibility with the application point of the additive.

Table I shows typical properties of the amphoteric product used in the performance examples discussed in this paper.

DRY STRENGTH ADDITIVES

Appearance	Solid, %	Viscosity, mPa·s/25°C	Specific Gravity, 25°C	pH (1% solution)	Ionicity	Solubility
Slightly white-turbid viscous	15% minimum	7,000~13,000	1.05	3.0–5.0	+/-	Soluble in water

I. Essential properties of the discussed 4th generation amphoteric dry strength (AmPAM) technology.

Performance examples

Figure 10 shows a laboratory comparison of the burst and compressive strengths of glyoxalated polyacrylamide (GPAM) and amphoteric polyacrylamide (AmPAM) for a typical OCC furnish. This data suggests that the addition rate of AmPAM required to meet comparable strength, as measured by burst strength test (BST) and ring crust test (RCT), with GPAM can be significantly lower than that of GPAM. The laboratory studies were done using mill furnish and samples of the GPAM products used in the mill. Due to the technical information's proprietary character, the details of these products were not available. However, it may be safe to assume that these GPAM products were optimized for the mill application and represent a good benchmark for performance comparisons.

Figure 11 shows lab data comparing GPAM and AmPAM with OCC at a pH close to 7.0. Conductivity was adjusted with sodium chloride (NaCl) to 1.5 mS/cm and 4.5m S/cm. As shown in Fig. 11, AmPAM is superior to GPAM in the case of burst strength for both conductivity levels, 1.5 mS/cm and 4.5 mS/cm. This improvement results from increased solubility and possibly better conformation of the adsorbed polymer layer of AmPAM. Some formation improvement observed in the case of AmPAM could also be a factor here. As mentioned earlier, the focus on molecular weight distribution aimed to remove higher molecular weight tailings responsible for formation problems.

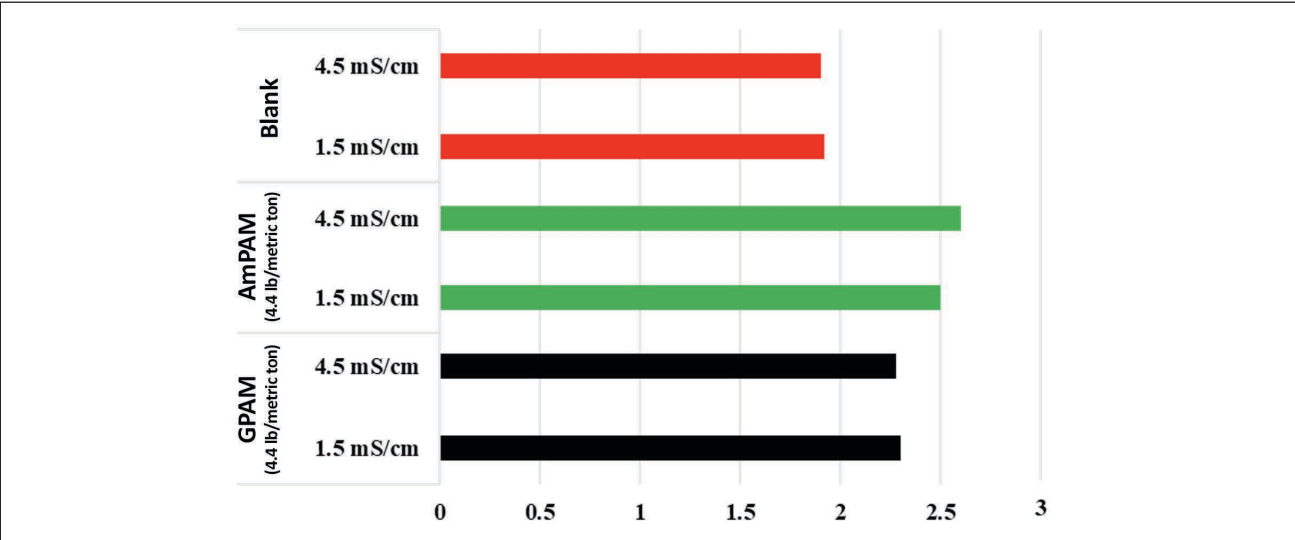
AmPAM as a booster for GPAM application

Although AmPAM offers more robust performance in “difficult” water chemistry conditions, GPAM typically offers extra drainage and productivity benefits besides strength development. Therefore, the combined GPAM and AmPAM, at a carefully tuned ratio, may be an ultimate dry strength/productivity solution. Studies performed using U.S. OCC mill furnish (**Fig. 12** and **Fig. 13**) demonstrate the benefits of such a combination in terms of strength benefit.

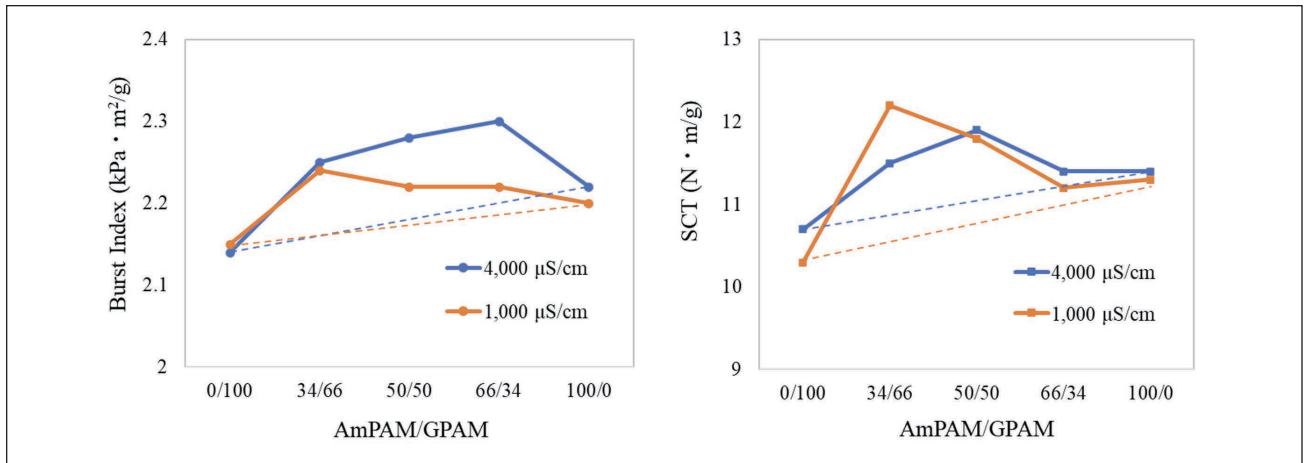
Figure 12 shows the impact of the varied GPAM and AmPAM addition ratio on BST and short-span compression test (SCT) at two conductivity levels: 1000 µS/cm and 4000 µS/cm. The total dosage for each program was maintained at 4.4 lb/metric ton (2 kg/metric ton). Based on the results, combined AmPAM and GPAM applications provided better results than both single GPAM or single AmPAM programs.

Figure 13 shows results for a similar study using U.S. OCC furnish for BST and STFI. In this study, the total dosage of the applied chemical program was kept at 5 lb/metric ton. The program mixing 2.5 lb/metric ton of each, AmPAM and GPAM, outperformed an application of 5 lb/metric ton GPAM or 5 lb/metric ton AmPAM, added separately.

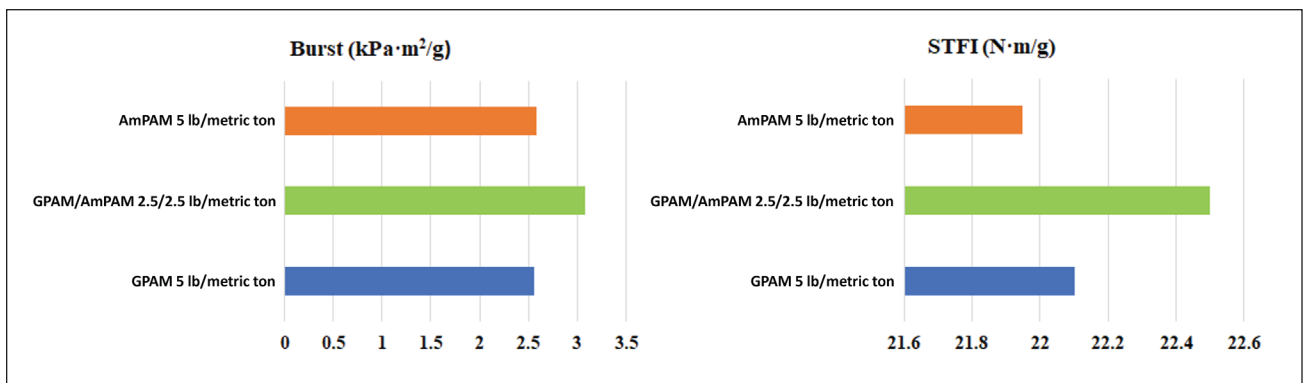
The blocky distribution of the 4th generation AmPAM presented in this paper offers discrete regions of anionic charge for interaction with cationic GPAM molecules. This synergy may result from the interaction between cationic



11. Burst strength comparison of glyoxalated polyacrylamide (GPAM) and AmPAM in different conductivity conditions.



12. Synergy between AmPAM and GPAM application in the U.S. OCC raw material strength development. The total combined dosage of strength additives was kept constant at 4.4 lb/metric ton. (SCT: short-span compression test.)



13. Synergy between AmPAM and GPAM application in the U.S. OCC raw material strength development. The total combined dosage of strength additives was kept constant.

GPAM and anionic fragments of AmPAM by forming intermolecular polyelectrolyte complexes that reduce the solubility of both products and increase their adsorption to the fiber. Such interaction would not be possible in the entirely random distribution of cationic and anionic charges.

The synergy of AmPAM technology presented in this paper allows for optimizing the dry strength program by simply augmenting existing GPAM applications by adding suitable AmPAM products. A detailed pre-trial mill survey will determine the starting configuration of such a combined application and provide papermakers with initial recommendations. For individual machine systems, the papermaker and supplier will then optimize the order of addition, the distance between GPAM and AmPAM addition points, and their dosage ratio.

AmPAM/GPAM synergy

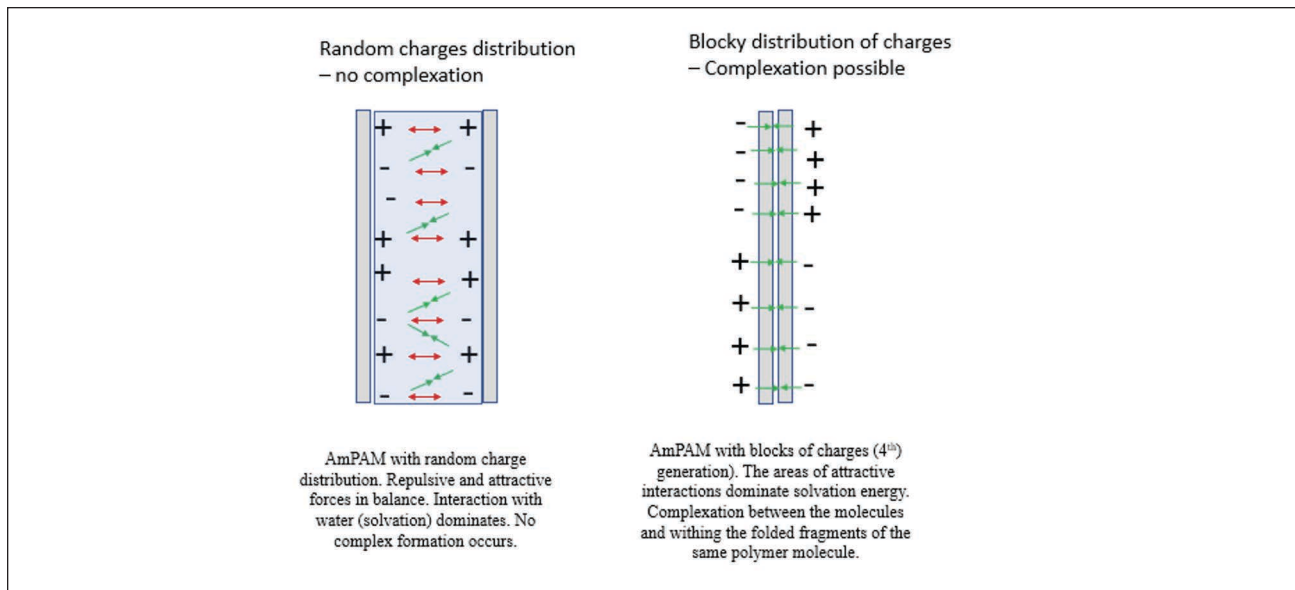
A possible explanation for the observed synergy between cationic GPAM and 4th generation APAM is the formation of the polyelectrolyte complexes driving adsorption to the fiber. The adsorption process remains in competition with solubility; the more soluble any substance is, the less adsorbable it is to the solids in the papermaking furnish.

Substances with cationic or anionic charges or highly polar bonds with partial anionic and cationic charges (dipoles) can form hydrogen or dipole-dipole bonds with polar water molecules. This ability to interact with water molecules makes such substances less disruptive to water structure and more soluble. The highly soluble substances follow the water phase and show less tendency to adsorb on the solids.

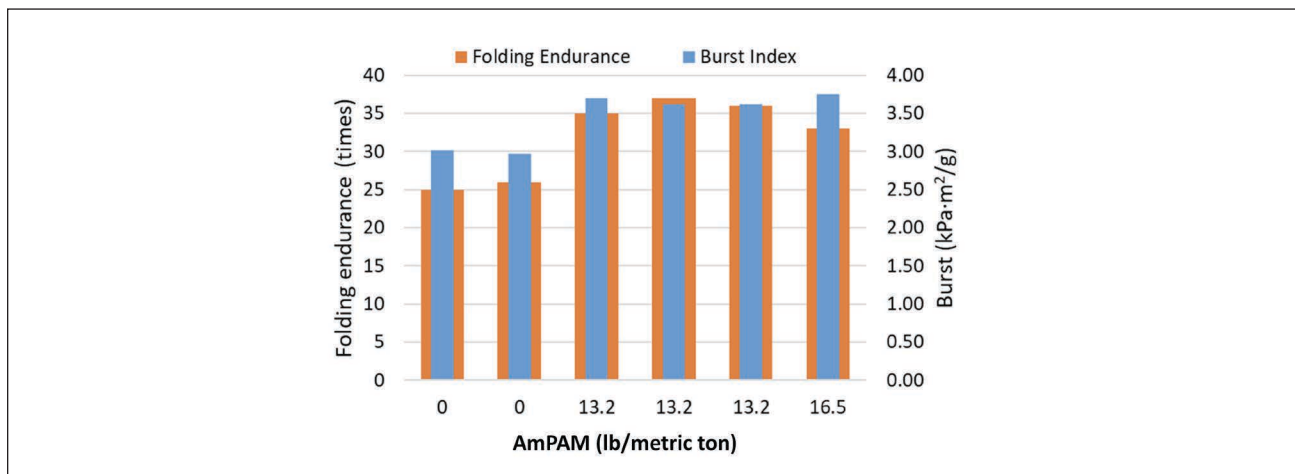
Formation of polyelectrolyte complexes (PEC) requires bringing opposite charges close together, which reduces their ability to interact with water and makes them less soluble, promoting better absorption to the fiber. Several authors provided a general overview of the polyelectrolyte complexes (simplexes); the impact of the chemistry of the individual components; their molecular weight, branching, and charge density; and the effect of pH and conductivity [11-13].

Due to their better adsorption, the sequential addition of cationic polymer with the anionic polymer, i.e., dual systems, improves the dry strength of the paper and other paper properties and boosts flocculation performance [14-16]. Hubbe [17-19] reviewed strength program strategies based on the application of cationic dry strength programs and anionic additives. Esser and Truppner [20] discussed

DRY STRENGTH ADDITIVES



14. The blocky distribution of charges on the 4th generation of AmPAM makes it uniquely able to form intermolecular and intramolecular polyelectrolyte complexes. The authors suggest that this explains the synergy between 4th generation AmPAM and cationic GPAM.



15. Mill A: Impact of AmPAM addition level on burst and folding endurance of 47 lb linerboard new product.

the example of the strength program based on the co-application of cationic and anionic polymers based on polyvinyl amine.

The potential for forming PEC is higher for the 4th generation amphoteric dry strength technology discussed in the paper. In the case of earlier generations of amphoteric dry strength agents, with cationic and anionic charges randomly distributed within the polymer chain, PEC formation is less favorable, since the repulsive forces between the exact charges counteract attractive forces between the opposite charges. To allow for intermolecular and intramolecular PEC formation, charges of the AmPAM must be distributed in distinct blocks (**Fig. 14**). A product with a blocky distribution of cationic and anionic charges was one of the concepts driving the development of the 4th generation of AmPAM presented in this paper. Kumagae

and co-authors presented the microscopic evidence of the PEC formation [6].

Mill Cases

Mill A

In this case, the mill was developing new grades and could not reach the required strength targets using starch.

Mill A produced 47 lb (230 g/m²) linerboard using low-quality Asian OCC as raw material. The mill was trying to reach the strength target required for new grade development. The mill operated at neutral pH and used cationic wet-end starch (4.4 lb/metric ton) and size press starch (132 lb/metric ton). This mill was not able to reach the strength target. The impact of AmPAM on the burst and folding endurance is presented in **Fig. 15**. Using 13.2 lb/metric ton of AmPAM, burst strength (BS: blue bars) was increased by

Condition No.	4G AmpAM, lb/metric ton	Incumbent AmpAM, lb/metric ton	Burst Index, kPa·m ² /g	Ring Crush Cross-Direction Index, N·m/g
1	0.0	9.7	3.27	153
2	9.5	0.0	3.43	157
3	8.1	0.0	3.42	156
4	6.8	0.0	3.34	154
5	6.2	0.0	3.25	155
6	0.0	8.1	3.20	152

II. Mill B: Linerboard: 175 g/m²; furnish: 100% old corrugated containers (OCC); pH: neutral; conductivity 3500–4000 µS/cm. Replacing incumbent AmpAM with the 4th generation (4G) AmpAM.

Condition No.	4G AmpAM, lb/metric ton	Incumbent AmpAM, lb/metric ton	Stockigt Size (s)	Stuff Box ZP, mV	Headbox ZP, mV
1	0.0	7.9	32	+ 1.3	+ 2.1
2	7.9	0.0	39	- 0.4	- 1.2

III. Mill C: Sizing improvement in kraft packaging paper with the addition of 4G AmpAM strength additive (ZP: zeta potential).

up to 20% from around 3.0 to 3.60–3.70 kPa·m²/g. The AmpAM dosage of 16.5 lb/metric ton burst strength of 3.7 kPa·m²/g was achieved. Folding endurance (red bars) was also improved from an initial value of around 25 to 37 at 13.2 lb/metric ton of AmpAM. A further dosage increase to 16.5 lb/metric ton resulted in the drop of folding endurance to 33, indicating increased sheet brittleness. The mill reached the necessary goals for new grade development at the dosage of 13.2 lb/metric ton of AmpAM.

Mill B

For Mill B, the goal was savings through the reduced dosage of applied strength additive. This mill produced 36 lb (175 g/m²) linerboard using low-quality Asian OCC as raw material. The mill operates at the neutral pH and elevated conductivity of tray water between 3500–4000 µS/cm. **Table II** shows the results of replacing the incumbent AmpAM with the new 4th generation AmpAM.

As incumbent AmpAM was replaced at the same dosage level with 4th generation AmpAM (condition 2), a significant increase in BS was observed. This response in BS allowed reducing the dosage of 4th generation AmpAM by about 30% from 9.5 lb/metric ton to 6.2 lb/metric ton (conditions 3,4,5), while maintaining the required BS target. The cross-machine direction (CD) ring crush index was stable through these trials, indicating a strong relationship between any compression tests based on weight. The application of the 4th generation AmpAM allowed the mill to achieve cost reduction goals. Mill case B illustrates differences between various AmpAM technologies resulting from optimized chemicals parameters such as molecular weight and distribution, charge density and charge localization,

and crosslinking level. Those differences could lead to different performance among various AmpAM dry strength products. The exact reason for improved performance was not identified due to the proprietary character of the competitive product's structural details. Based on the research leading to 4th generation technology, narrow molecular weight distribution and blocky charge localization could bring significant performance benefits and contribute to the results described in mill case B.

Mill C

Mill C's objective was to improve sizing efficiency with kraft paper through system charge optimization. The mill produced softwood kraft (SWK)-based packaging grades and operated at pH = 4.2. The mill used 4.4 lb/metric ton of cationic starch and incumbent dry strength AmpAM with significantly higher cationic charge density.

In this acidic system, the current AmpAM was highly cationic. Additionally, low pH suppresses the negative charge of the fiber. The combination of highly positively charged AmpAM and low negative charge on the fiber caused system over-cationization and resulted in issues with the retention and effectiveness of cationic sizing emulsion. Replacing the current AmpAM with 4th generation AmpAM at the same addition rate (**Table III**) resulted in recovering the negative charge in the stuff box sample. As a result, the retention of the sizing agent was increased, and sizing results improved.

Mill D

Mill D's objective was increasing the speed of the paper machine and reducing energy consumption by bypassing

DRY STRENGTH ADDITIVES

Condition No.	AmPAM, lb/metric ton	Surface Starch, lb/metric ton	Burst Index, kPa·m ² /g	Ash in Board, %	Starch in Paper, %
1	7.0	35.2	3.52	8.9	3.2
2	7.5	24.2	3.50	9.9	2.5
3	10.1	0.0	3.45	10.6	1.4
4	10.1	0.0	3.47	10.5	1.5
5	11.0	0.0	3.49	10.7	1.7

IV. Mill D: Linerboard: 175 g/m²; furnish: 100% OCC; pH: neutral; starch: 44 lb/metric ton on size press.

the size press in the case of a neutral pH liner grade.

Mill D produced 36 lb linerboard using 100% Asian typical low-quality OCC. The machine operated at neutral pH and used 44 lb/metric ton starch applied through the size press. The requirement of post-size press drying slowed down the machine, as the dryer section's capacity limited its speed. The mill used a size press to obtain the paper grade's specified burst strength target. **Table IV** presents the data from the trials. By increasing the addition rate of AmPAM from 7.0–7.5 lb/metric ton (conditions 1 and 2) to 10.0–11.0 lb/metric ton (conditions 3 and 4), the mill could bypass the size press while maintaining the BS at the required level. Ash content and starch level in the sheet are also listed in the table to allow better discussion of the observed strength results.

CONCLUSIONS

Several generations of amphoteric dry strength polyacrylamide-based products have been developed to help Asian papermakers deal with low-quality fiber and difficult wet-end conditions. This development included optimization of molecular weight, molecular weight distribution, ratio and distribution of cationic and anionic charges, and degree of crosslinking. This effort has resulted in a unique dry strength 4th generation amphoteric technology.

The examples of mill and laboratory cases presented here illustrate the potential of 4th generation amphoteric technology to increase strength, reduce cost, improve sizing or other cationic additives performance, or to reduce or eliminate size press starch application. This paper reviewed gradual trends in recycled fiber and process water quality in the NA market. Similar trends in Asia resulted in the dominance of amphoteric dry strength additives. This paper presented the opportunity of boosting the performance of the GPAM-based dry strength program with the addition of AmPAM technology. These blended programs offer papermakers opportunities to optimize chemical cost, product quality, basis weight reduction, or raw material cost. All these opportunities are more relevant to mills using recycled fiber and operating at higher conductivity and cationic demand levels than virgin kraft mills. **TJ**

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Papermakers in the United States are experiencing challenges in strength development for products due to decreased fiber quality and deteriorated wet-end conditions. It is worth learning from papermaking counterparts in other countries about their experiences in dealing with low fiber quality and challenging wet-end conditions. This knowledge can prepare U.S. paper mills for successful runs under these circumstances.

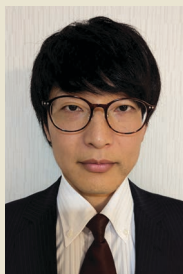
For this study, we used a molecular level approach for the papermaking additives to mitigate the negative impacts from challenging wet end conditions. The amphoteric molecular design was applied to starch (a natural polymer) modification for better additive performance. The same principle was applied to the synthesized polymer in this research, while the detailed molecular design was different.

The most difficult aspect of this study was finding the similarities and differences in papermaking be-

tween the different countries. We addressed this through better communications among the global team that participated. While papermakers from different countries face different fiber and water conditions, there is great value in learning from one another.

For mills dealing with deleterious fiber quality and water conditions, this research points out that there is an option for maintaining strength properties. Our next step is to test amphoteric strength polymers in U.S. mills via machine trials.

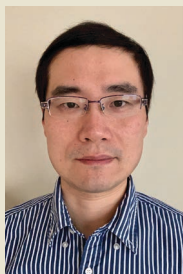
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