

## Research Article

# Nanosericite as an Innovative Microparticle in Dual-Chemical Paper Retention Systems

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Dual-chemical retention systems based on 2 cationic polyacrylamides, a colloidal silica, and a globular anionic polymer microparticles were investigated and an exfoliated nanoparticle indigenous mica mineral, sericite, was examined for its efficacy in substituting commercial microparticle preparations. The results indicated that nanosericite generated FPR between 76.9 and 80.9% for fines and chemicals. Its ash retention values, however, were higher and tended to increase with doses of polymer, nanosericite, or Sc to between 16 and 24%. As for paper physical properties, nanosericite was not amenable to substitute the c-PAMb/polymer with only handsheet stiffness superior to the combination. Nanosericite, however, showed good substitution capacity than the c-PAMa-colloidal silica combination. Regardless of the c-PAMa doses, all examined handsheet physical properties incorporating nanosericite were superior to colloidal silica. The optimal performance was observed with c-PAMa dose of 200 ppm. Optical properties of the handsheets indicated that with nanosericite substitution, brightness values were comparable to the polymer group, while its substitution capacity for colloidal silica decreased with increasing c-PAMb dose. Only at c-PAMa dose of 300 ppm, it appeared to have good substitution for colloidal silica. Substituting nanosericite for colloidal silica appeared to reduce the c-PAMa charge and increased the overall cost effectiveness.

## 1. Introduction

Dual-chemical retention system has been used in paper-making wet end for decades. The system uses short-chain branched cationic polymer to destabilize the well-dispersed state of pulp and which is conducive to the formation of small flocs with surface cationic charges. Subsequently, addition of high-molecular weight anionic polymers or particles allows the formation of large bridging flocs in pulp suspension. Many studies have proven that the system can improve drainage, uniformity, fine retention, and ash content and reduce energy consumption in drying and increasing machine speed [1–5]. Presently, the most frequently deployed dual-chemical system comprises low molecular weight cationic polyacrylamides as the cationic polymers, together with anionic charged microparticles with size range from 1 nm to 1  $\mu$ m which are insoluble in water and have large specific surface areas [6–9].

Commercially, major suppliers such as BASF, Eka, Nalco, and Ashland offer microparticle systems mostly of colloidal silica or globular high-molecular polymers. In the present study, we opted to use an indigenous mica mineral, sericite, to substitute the conventional microparticles in dual-chemical systems. Sericite is mined at Shiangyang, region of Taitung County, Taiwan. The mine has an estimated store of 15 million tonnes with sericite comprising about 50% of the ore. At present, the annual production is 3200 tonnes. Sericite is a platy silicate inorganic material with formula of  $KAl_2(AlSi_3)O_{10}(OH)_2$ . When treated with molten alkali and then acidic swelling process, exfoliated nanoscale sericite or nanosericite can be produced. NS is known to have chemical stability, large specific surface area, anti-UV, antistatic, heat resistant, and electrical insulating properties. In addition, NS can form hydrogen bonding with the hydroxyl groups on bacterial cellulose chains, enhancing the dimensional stability of cellulosic films, heat resistance, and mechanical strengths. The flat

platy structure of NS is a 2D nanomaterial. The plate surfaces are negatively charged, while the edges are positively charged; therefore, in water dispersion, NS tends to self-aggregate, forming 3D network and precipitate. Proper treatment is required to allow NS to maintain stable dispersive state in aqueous phase [10–12].

In order to verify the potential of substituting NS for the conventional microparticles in a dual-chemical system, the study used a  $2^2$  factorial design to examine the interactions between NS and 2 commercial cationic polymers (c-PAMa and c-PAMb) and its benefits in a microparticle system. The physical and optical properties of the resulting handsheets prepared from different wet end chemical regimes were compared and the optimal NS dosing conditions were established. The information may provide reference for further developing NS as a viable paper-making chemical.

## 2. Experimental

**2.1. Experimental Design.** The self-prepared NS was analyzed for size distribution and transmission electron microscopy observation. Two cationic polymers (c-PAMa and c-PAMb), and 3 anionic microparticles, colloidal silica (Sc), globular polymer (gp), and NS doses, were the independent variables in a  $2^2$  factorial analysis. The NS, like Sc and gp, was dosed according to comparable solids content. The first pass retention (FPR), ash retention, and the physical and optical properties of the handsheets were the dependent variables so as to arrive at an optimal dual chemical dosing condition that produces the best paper properties. Finally, the IBM SPSS statistics 20 software was used to conduct a two-way ANOVA to establish the efficacy of using NS as a microparticle component.

**2.2. Chemicals.** The following chemicals and fiber were used to make handsheets: flocculent cationic polyacrylamide (c-PAMa): Eka PL1510, ( $M_w = 5.5\text{--}5.7 \times 10^6$ , density =  $0.8 \text{ g/cm}^3$ , 88% solids content); flocculent cationic polyacrylamide (c-PAMb): BASF Percol 182, ( $M_w = 6.5\text{--}7 \times 10^6$ , density =  $0.8 \text{ g/cm}^3$ , 88% solids content); Sc: Eka NP882, (15% solids content, average size = 31.68 nm), branched network of 25 silicate spheres of 2.5 nm each, specific surface area is  $700 \text{ m}^2/\text{g}$ , with anionic surface charges; gp: BASF M305, (40% solids content, density =  $1.0 \text{ g/cm}^3$ , average size = 249.53 nm), a highly structural 3D anionic polyacrylamide having high anionic charges, and when reacting with fines and fillers, the main body of the polymer molecule tends to fracture and adsorbs to fiber forming flocs; NS was self-prepared in the laboratory. The preparation conditions entailed reacting sericite with NaOH at 1:1.5 ratio at  $240^\circ\text{C}$  for 4 h, then acid intercalated the mineral with 60% nitric acid, followed by pH adjustment with NaOH to neutrality. At this stage, the NS is exfoliated and appeared translucent gelatin-like. Repeated rinsing with deionized water allowed removal of salts. The suspension was pH adjusted to <6 using acetic acid, and then epoxy silane was suitably added to coat exfoliated sericite plates forming a uniform aqueous dispersion. At 10% solids content, the NS has CEM = 85.9 meq/100 g, and

average particle size = 120.67 nm. X-ray diffraction analysis of the NS preparation also showed that the original sericite diffraction peaks at 4.36 Å and 6.43 Å had shifted to 4.36 Å and 7.90 Å, indicating that the molten salt treatment has effectively expanded interlayer spaces, causing the original crystal lattice to disappear.

Other chemicals used in the handsheet preparation included cationic starch, ZMCAT-T305-1, (D.S. = 0.01%, Zhi-mao Starch, Taiwan); sizing agent AKD TD-15, (15% solids content, Ashland, Taiwan); and filler,  $\text{CaCO}_3$ , Hydrocarb 75F, 15% solids content, pH 9.23, ISO brightness 94.92%, particle diameter 0.4–2.0  $\mu\text{m}$  (Omya, Taiwan). The pulp stock, with brightness 81% ISO, was prepared using a bleached hardwood kraft pulp (BHKP) at 3% consistency and having 430 mL CSF.

### 2.3. Methods

**2.3.1. Characterization of Nanosericite.** The aqueous dispersion of NS was caught using a carbonized copper mesh and observed with transmission electron microscopy (JEM-1400, Jeol Co., Japan). A dynamic laser scattering device (DLS, Nano S 90, Malvern Co., UK) was used to determine the particle size distribution.

**2.3.2. Stock Preparation.** Pulp refining in the laboratory was based on simulations of the mill site furnishing 150 principles. A laboratory Valley beater (model 303, Liensheng, Taiwan) was used to refine the BHKP from their original freeness to 430 mL CSF. The pulp then diluted to 0.3% for further experiments.

Addition of wet end chemicals also simulated the on-site practice with the following chemicals addition sequence and the doses were based on the oven-dry weight of the pulp: pulp at 0.3% consistency; sizing agent (AKD TD15, 1%); cationic starch 1%; filler 25%; and c-PAMa/microparticles or c-PAMb/microparticles. For the fiber surface zeta potential determination, after adding the chemicals, 500 mL portion of the stirred pulp suspension was taken and measured with an SZP meter (Mütek SZP 06) to determine the zeta potential. Because in the different microparticle systems, the original concentrations differed; in order to allow for comparisons, the microparticle doses were recalculated as actual microparticle solids content in the experiments. Thus, in the cPAMa system, the doses of Sc and NS added were 300, 450, and 600 ppm with respect to dry pulp; and in the c-PAMb system, gp and NS doses were 40, 80, and 120 ppm with respect to dry pulp. The experimental results are shown in Figure 1. As a control group, a set with pulp of 0.3% consistency was added with sizing agent (AKD, 1.0%), cationic starch 1%, and 25% filler loading only.

In the study, 2 dual-chemical retention systems were compared; these, based on the optimal additions of commercial systems, were c-PAMa/Sc = 200 : 3000 ppm; and c-PAMb/gp = 200 : 200 ppm, respectively. The optimal substitution amounts of NS after converting to dry-weight basis were c-PAMa/NS = 200 : 4500 ppm; and c-PAMb/NS = 200 : 800 ppm, respectively. The aforementioned doses were set as the middle values. And Table 1 shows the parametric values of the  $2^2$  factorial design.

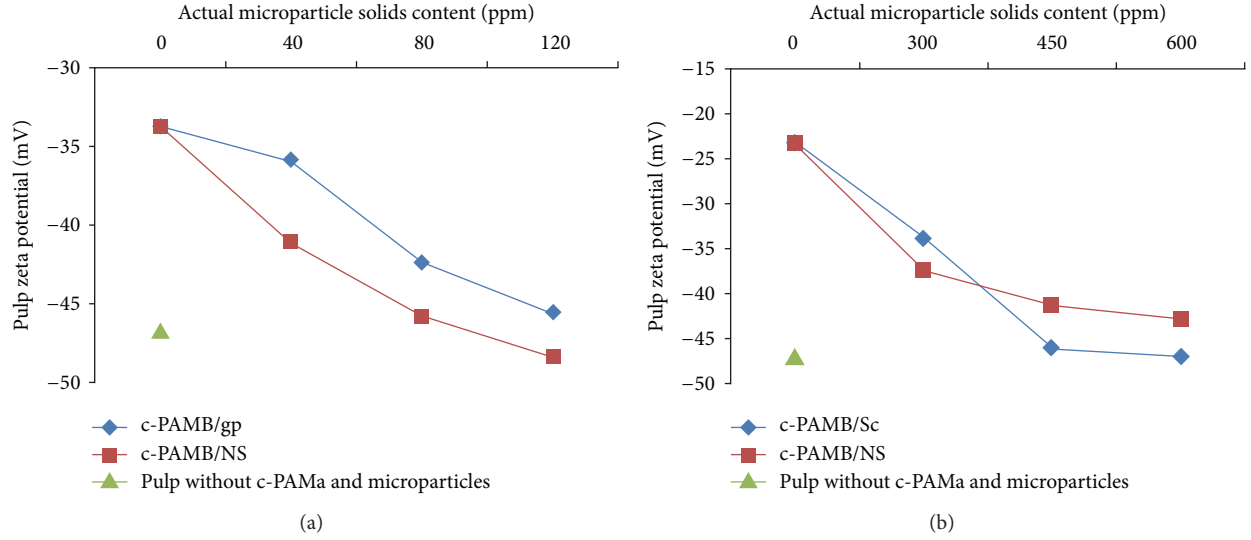


FIGURE 1: Effects of adding different doses of microparticles on the pulp zeta potentials in (a) c-PAMa and (b) c-PAMb systems.

In the determination of first pass retention rates, a dynamic drainage jar (DDJ, Electrocraft & QMC, USA) was used to obtain pulp filtrate. A pulp sample of 500 mL at consistency  $C_i$  was put in DDJ and stirred with an impeller at 1000 rpm for 20 s; the distance between impeller and wire was 3.175 mm. Then, the spigot was turned on to drain the suspension. Two hundred mL of filtrate was collected and oven-dried to obtain its solids content and to calculate filtrate consistency  $C_0$ . Then, FPR % was defined as  $(C_i - C_0)/C_i \times 100$ .

**2.4. Handsheet Preparation.** Handsheet formation was based on the method of TAPPI T205 sp-95. The actual procedure was as follows: (1) pulp was disintegrated at 0.3% consistency with a standard disintegrator; (2) sizing agent (AKD, 1%), cationic starch 1%, and filler 25% were added in sequence separately and maintained in stirring for 30 min; (3) polyacrylamide was added and stirred for 60 s; (4) microparticle was added and stirred for 60 s; (5) handsheets of 60 g/m<sup>2</sup> were formed using a standard sheet mold, air-dry overnight; (6) handsheets were conditioned in the standard atmosphere for >24 h; and (7) handsheet physical and optical properties were measured.

**2.5. Handsheet Standards.** The physical and optical properties of handsheets were tested according to various ISO standards, that is, ash content, ISO 2144: 2000; brightness, ISO 2470-1: 2008; grammage, ISO 536: 1995; opacity, ISO 8791-4: 1992; tear index, ISO 1974: 1990; tensile index, ISO 1924-2: 1994, and stiffness, ISO 5628: 2012.

### 3. Results and Discussion

**3.1. Effects of Different Microparticles on the Surface Charges of the Stocks.** According to prior studies, the surface charge of fibers is the main determinant of the first pass retention.

TABLE 1: Codes for the dual-chemical combinations and their respective dosing factors.

c-PAMa (100 ppm)			
	-1	0	1
Sc			
-1	A1Sc1: 1/20	A2Sc1: 2/20	A3Sc1: 3/20
0	A1Sc2: 1/30	A2Sc2: 2/30	A3Sc2: 3/30
1	A1Sc3: 1/40	A2Sc3: 2/40	A3Sc3: 3/40
NS			
-1	A1NS1: 1/30	A2NS1: 2/30	A3NS1: 3/30
0	A1NS2: 1/45	A2NS2: 2/45	A3NS2: 3/45
1	A1NS3: 1/60	A2NS3: 2/60	A3NS3: 3/60
c-PAMb (100 ppm)			
	-1	0	1
gp			
-1	B1gp1: 1/1	B2gp1: 2/1	B3gp1: 3/1
0	B1gp2: 1/2	B2gp2: 2/2	B3gp2: 3/2
1	B1gp3: 1/3	B2gp3: 2/3	B3gp3: 3/3
NS			
-1	B1NS1: 1/4	B2NS1: 2/4	B3NS1: 3/4
0	B1NS2: 1/8	B2NS2: 2/8	B3NS2: 3/8
1	B1NS3: 1/12	B2NS3: 2/12	B3NS3: 3/12

A = c-PAMa, B = c-PAMb; 1 = lower, 2 = middle, and 3 = higher level of 2<sup>2</sup> factorial design. Ex: A1Sc1: 1/20 means both c-PAMa and Sc under lower level and the concentrations are 100 ppm and 2,000 ppm, respectively.

When the fiber surface charge approaches the isoelectric point, repellency among the particles decreases. Fiber fines and long fibers or filler particles and fibers form microflocs. The microflocs generally will not affect paper formation, they can, however, help increase retention of chemicals, filler, and fines [9]. In order to investigate the effect of microparticles on the first pass retention in depth, we predetermined the doses of cationic polymers, c-PAMa and c-PAMb, to be 200 ppm,

TABLE 2: The first pass retention rates of pulp stock with NS substituting Sc and gp.

Nanoparticle concentration	c-PAMa FPR (%)		
	A1	A2	A3
Sc			
2000 ppm	74.90	81.23	82.71
3000 ppm	77.04	81.99	81.37
4000 ppm	77.39	82.36	81.86
NS			
3000 ppm	73.30	75.30	75.73
4500 ppm	73.53	76.73	76.00
6000 ppm	73.98	76.70	75.62
Nanoparticle concentration	c-PAMb FPR (%)		
	B1	B2	B3
gp			
100 ppm	73.56	80.89	79.35
200 ppm	76.28	81.98	78.20
300 ppm	80.84	81.79	78.19
NS			
400 ppm	77.70	76.91	80.71
800 ppm	77.40	79.01	80.88
1200 ppm	76.93	80.67	76.22

while examining the effects of adding varying Sc, gp, and NS doses on the fiber surface charges.

From Figures 1(a) and 1(b), the pulp suspension without addition of the retention aids had a surface charge of  $-46.8$  mV, and upon adding cationic polymers, the charge became  $-23.2$  and  $-33.7$  mV, respectively, for the c-PAMa and c-PAMb. Along with addition of increasing amounts of anionic microparticles, however, the fiber surface charge gradually reverted to the original value or even more negatively charged. Compared to the first pass retention rates of Table 2, the A2/Sc, A2/NS, B2/gp, and B2/NS indicated that the more closely the charge approached the original value, the better the FPR became. Nevertheless, a clearer cut relationship between various retention aids doses and FPR still awaits further experimental clarification.

### 3.2. TEM Observation and Size Distribution of Nanosericite.

Figure 2 shows the TEM micrograph of our lab-prepared nanosericite. The figure clearly shows that NS is a 2-D nanomaterial with platy appearance of ca. 250 nm in length and width and ca. 50 nm in thickness.

The particle size distribution by DLS of the NS preparation is shown in Figure 3.

The DLS measurement of the lab-prepared NS had particle diameters concentrated at the 100 to 200 nm range, and an average diameter of 120.67 nm. The DLS technique mainly detects the Brownian motion of the particles and infers spherical equivalent diameter of the particles. Because NS particles are platy, hence, the inferred sizes tend to be smaller than those observed in the TEM micrograph.

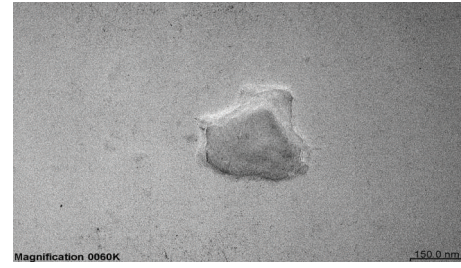


FIGURE 2: TEM micrograph of a nanosericite particle.

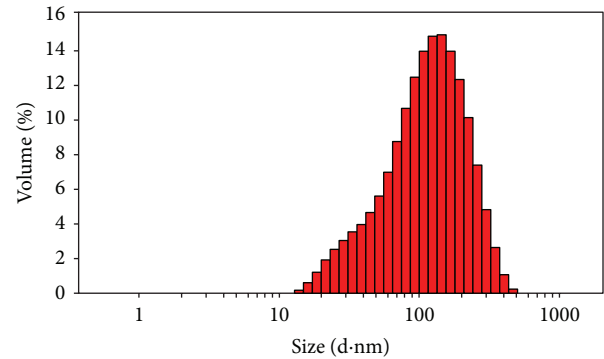


FIGURE 3: Size distribution of the NS preparation.

### 3.3. Effects of NS Substitutions of Microparticles on the Handsheets Physical Properties

**3.3.1. First Press Retention.** The first pass retention determines the percentage ratio of pulp stock versus the original amounts. The effects of substituting Sc and gp with NS on the first pass retention rates are shown in Table 2.

From Table 2, the first pass retention rates with NS substituting for Sc and gp had values ranging from 73.30% to 76.73% and from 76.91% to 80.88%, respectively. When NS was the microparticle, regardless of the cationic polymer, a 0.02% dose produced the best first pass retention results. In the case of c-PAMb versus NS, matching higher dose of c-PAMb with the lower dose NS allowed attainment of similar FPR as that of gp. In other words, at comparable solids content, the platy NS can effectively retain calcium carbonate and fines. Conversely at high NS dose with c-PAMb, the FPR performance decreased, possibly due to self-aggregation of NS at the concentration and altered the microflocs of the system. At comparable solids content, NS appeared to be less effective than Sc in working with c-PAMa with respect to FPR. Again, we suspect that the high concentration of NS may be to blame.

**3.3.2. Ash Content.** In this study, both Sc and NS are minerals that retain as ash after incineration of the pulp; hence at the higher doses, addition of microparticles can contribute to a slight increase in ash content. However, the negatively charged NS at sufficient high concentrations might interfere with the binding of fines with cationic polymer aid. In addition, different degrees of mineral self-aggregation affect



TABLE 3: Effects of substituting Sc and gp with NS on the ash content of handsheets.

Nanoparticle concentration	c-PAMa		
	Ash content (%)		
	A1	A2	A3
Sc			
2000 ppm	16.49	21.99	21.92
3000 ppm	18.06	21.39	21.62
4000 ppm	18.12	22.13	19.77
NS			
3000 ppm	17.04	19.96	23.39
4500 ppm	18.85	23.22	23.75
6000 ppm	19.91	21.15	24.01
Nanoparticle concentration	c-PAMb		
	Ash content (%)		
	B1	B2	B3
gp			
100 ppm	15.85	17.25	20.35
200 ppm	17.67	17.74	21.68
300 ppm	18.94	19.03	22.32
NS			
400 ppm	16.16	18.33	21.90
800 ppm	17.26	17.98	20.94
1200 ppm	18.09	19.35	23.10

the shapes of microflocs and the interstices among fibers and microflocs which in turn affects retention of calcium carbonate [10–12]. At similar grammages, increase in paper ash content leads to decreased demand of c-PAM and microparticles which can lower costs and mitigate the effect of fiber flocs on paper formation, leading to better opacity and uniformity [6]. The effects of substituting NS for Sc or gp on the ash retention are shown in Table 3.

The results indicated that substituting Sc or gp with NS increased ash retention which tended to increase with increasing c-PAM dose. At similar grammage, NS can better retain calcium carbonate, probably because of its platy shape and negatively charged surface and positively charge plate edges that allow formation of stacked network aggregates. These are envisaged to form flexible flocs that expand to bridge interfiber spaces and to embed minute calcium carbonate particles in the network. However, the deduction still requires further verifications.

**3.3.3. Physical Properties of Handsheets.** Handsheets prepared with different stocks were tested for their tensile indices, burst indices, and stiffness. The results are shown in Figures 4, 5, and 6.

Increased addition of microparticles in a dual-chemical system often leads a higher calcium carbonate, or ash retention (Table 3). As noted by Li et al. [13], Gaudreault et al. [14], and Petersson [12], the effects of filler loading on the physical properties of paper suggest that filler interferes with interfiber bonding and over charging the system would lead to reduced strengths. At optimal loading, however, filler

particles mainly reside in interstices of fibers and can even slightly increase paper strengths. In our study, the results of the c-PAMa/Sc system were in agreement with the above statements (Figures 4(a) and 6(a)). At the higher level of cationic polymer, the tensile, tear, and stiffness performance all tended to decrease. Although the A1Sc1 condition applied the least amounts of chemicals, the resulting handsheets had the highest strength properties, nevertheless. Comparing Tables 2 and 3, however, suggests that the good strength performance arose largely from good fiber-to-fiber bonding; the amount of fiber demand was rather high. In the case of A2NS3, the optimal commercial dose for cPAMa, the high NS charge could effectively substitute for Sc and result in enhanced tensile, tear, and stiffness. In this case, the FPR was low; however, the ash retention was high, indicating that paper contained less amount of fiber and maybe conducive to reduced raw material cost.

Figures 4(b) and 6(b) show the effects of substituting NS for the c-PAMb/gp systems. The results indicated that there was a lack of consistency among the paper physical properties of the c-PAMb/gp dual chemical. The probable cause of error might be that gp was unable to rapidly and uniformly disperse in water. The B1NS1 handsheets produced comparable tensile, tear and stiffness to the B1gp1 while having FPR and ash retention higher than the B1gp1 group. We deem that at lower dose, NS might disperse in the stock rapidly and is less likely to form self-aggregation, and the positively charged plate edges were allowed to attract fines and filler particles. This phenomenon was congruent with the observations of Perng et al. [10] and Wang et al. [8]. When the zeta potential of cationic polymer retention is comparable to that of microparticles in the system, generally FPR of the paper and its mechanical properties are optimized [8, 9]. In this study the consideration was focused on comparable solids content in the microparticle parts, and charge balance of the system was neglected. If conversely, zeta potential was the dose dictating factor, then more superb paper physical properties might ensue instead.

**3.3.4. Optical Properties of Handsheets.** One important factor affecting paper opacity and brightness is the brightness of filler used to load the paper. The intrinsic ISO brightness of calcium carbonate used in the study was 94.2%. As Antunes et al. [15] and Petersson [12] noted, fiber-to-fiber bonding tends to be interfered by filler particles, especially when fillers trap in interstices of fibers leading to decreased paper mechanical strengths and the overall light scattering of the paper, causing the paper to appear brighter. Paper transparency shows the opposite trend as paper brightness, with higher brightness reflecting higher calcium carbonate loading and greater lighter scattering, thus lower transparency or higher opacity. The effects of different retention aid conditions on the brightness and opacity of the resulting handsheets are shown in Figures 7 and 8.

Figure 8 shows that regardless of whether NS was deployed in a dual-chemical system, increasing cationic polymer and microparticle charge increases generally caused increase in ash content and brightness gain. In particular, substituting NS for Sc produced better results; for instance,

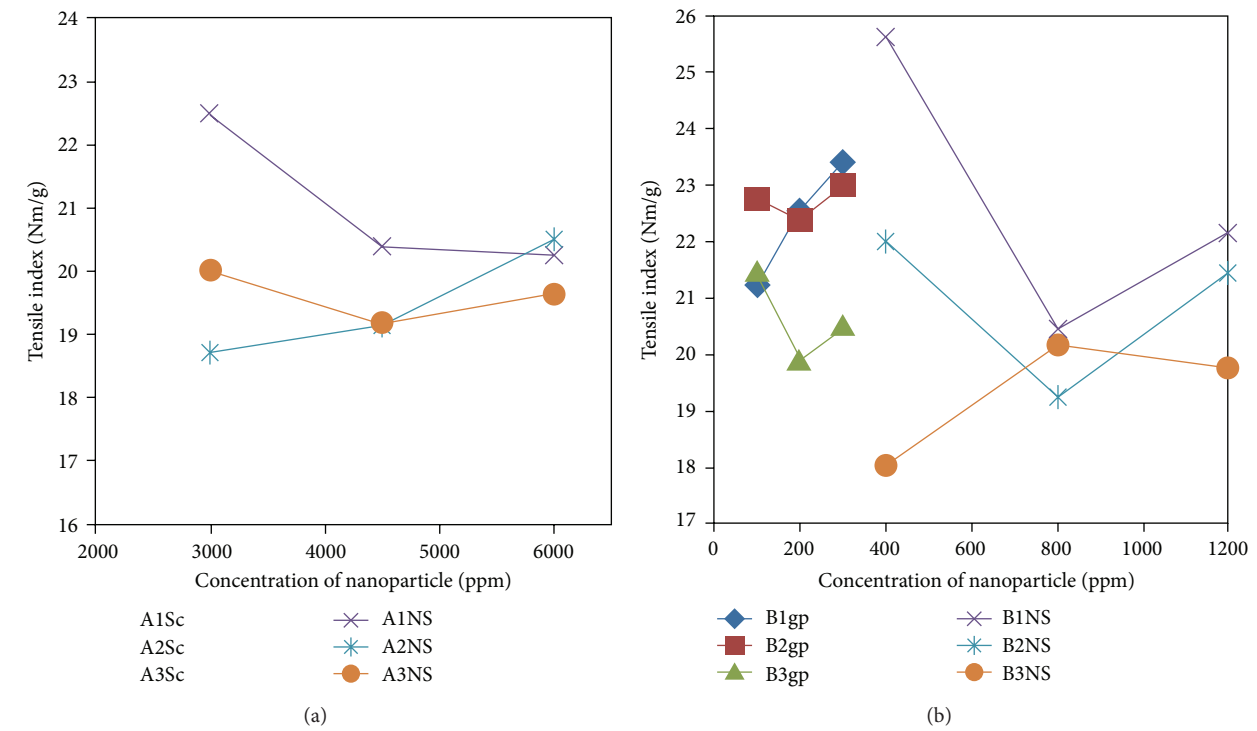


FIGURE 4: Effects of NS substituting for (a) Sc or (b) gp on the tensile strength of the resulting handsheets.

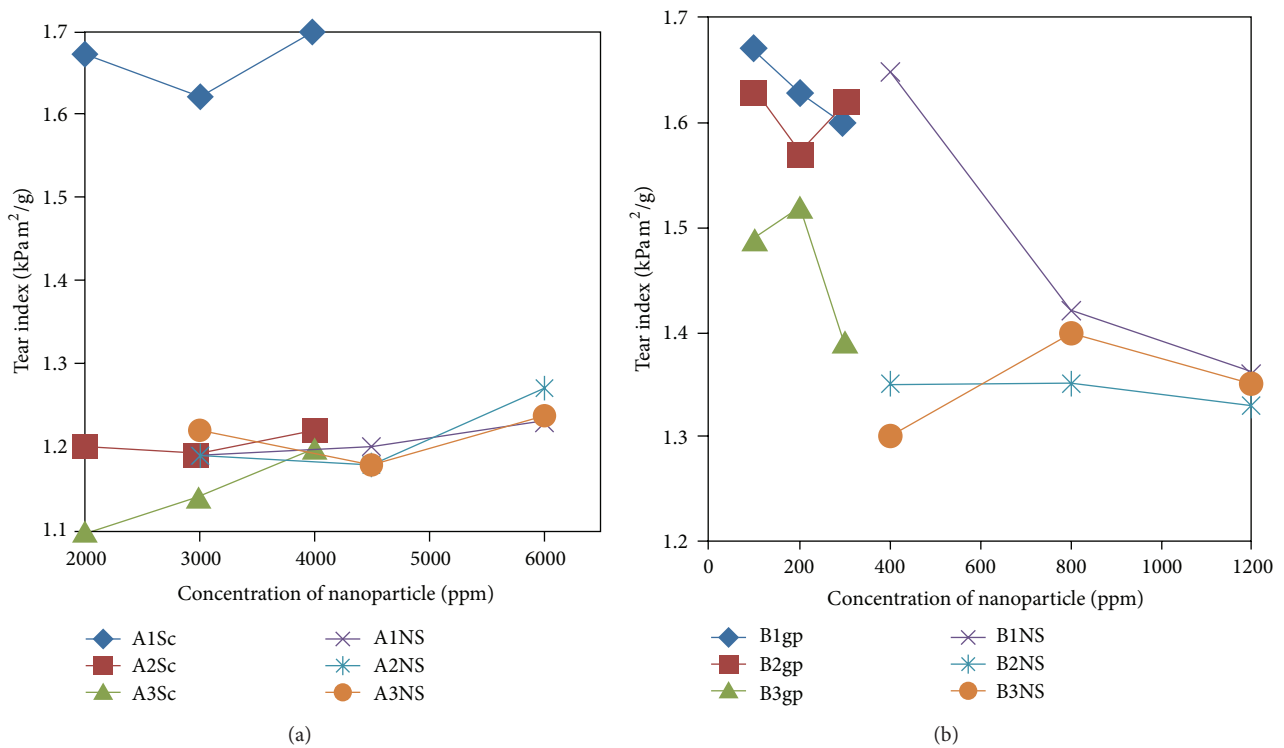


FIGURE 5: Effect of NS substituting for (a) Sc or (b) gp on the tear indices of the resulting handsheets.

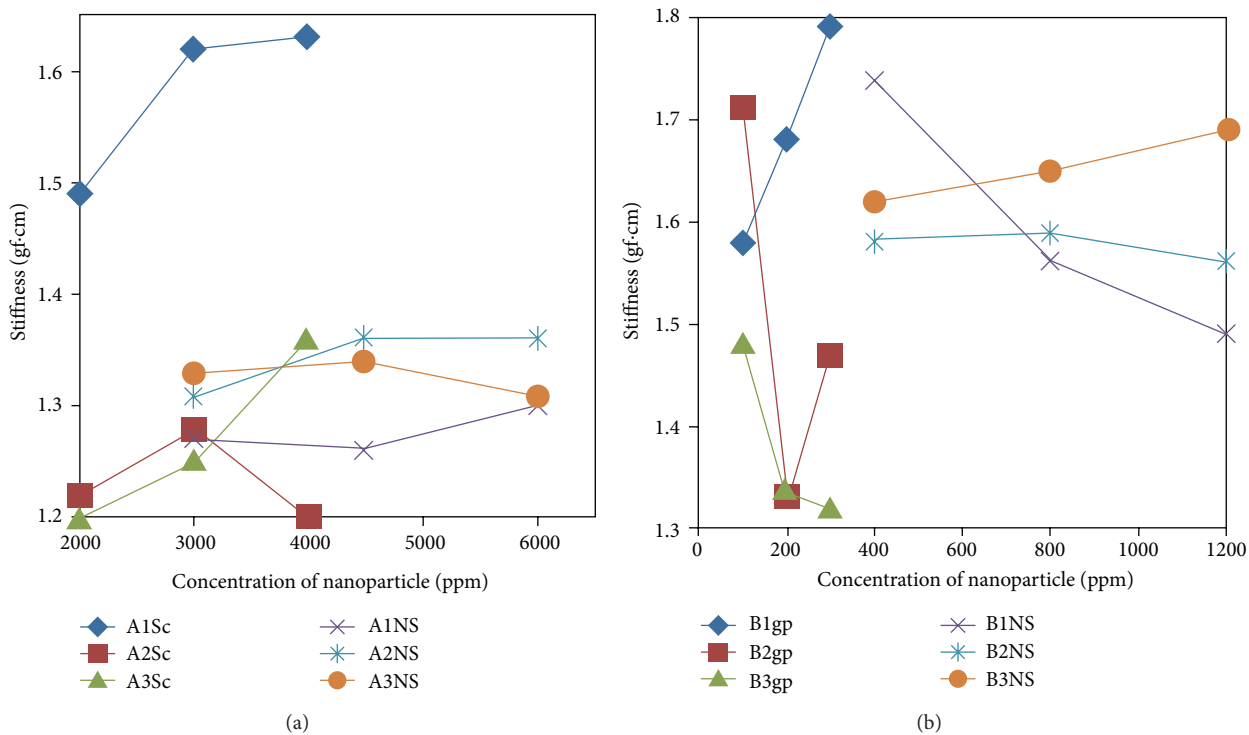


FIGURE 6: Effect of NS substituting for (a) Sc or (b) gp on the stiffness of the resulting handsheets.

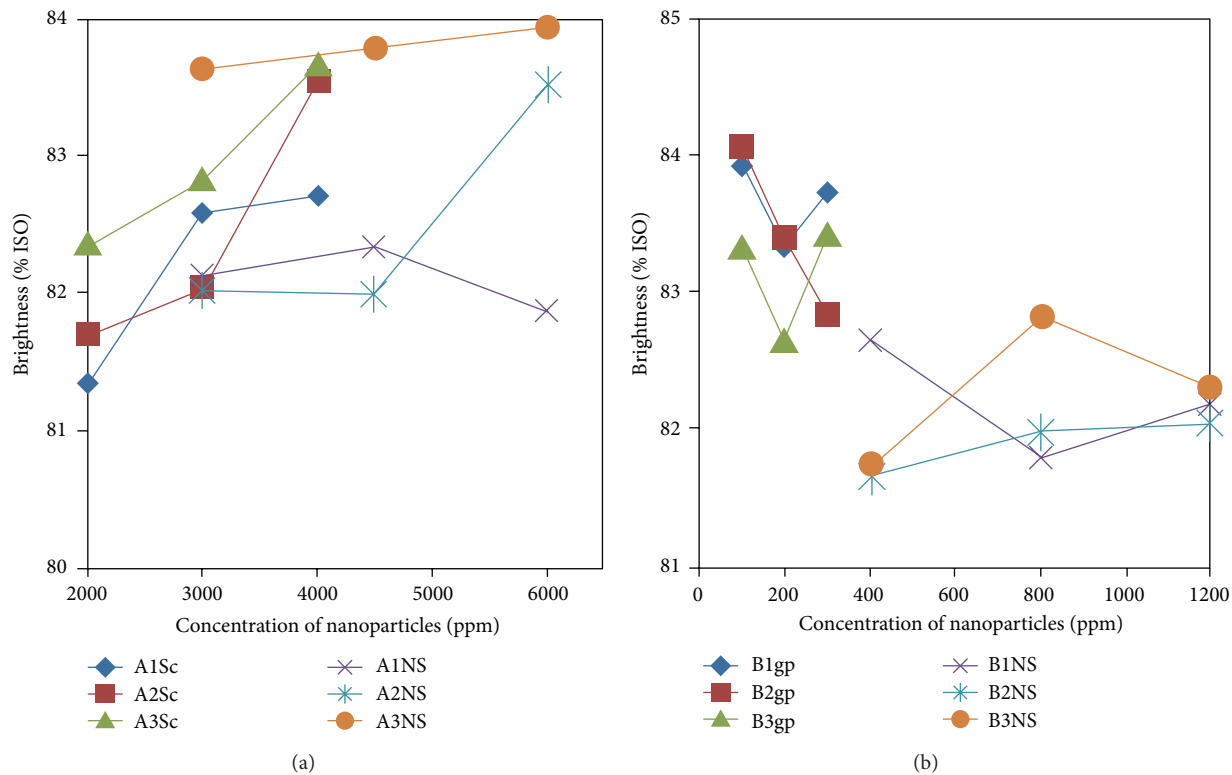


FIGURE 7: Effects of substituting NS for (a) Sc and (b) gp on the handsheet brightness.

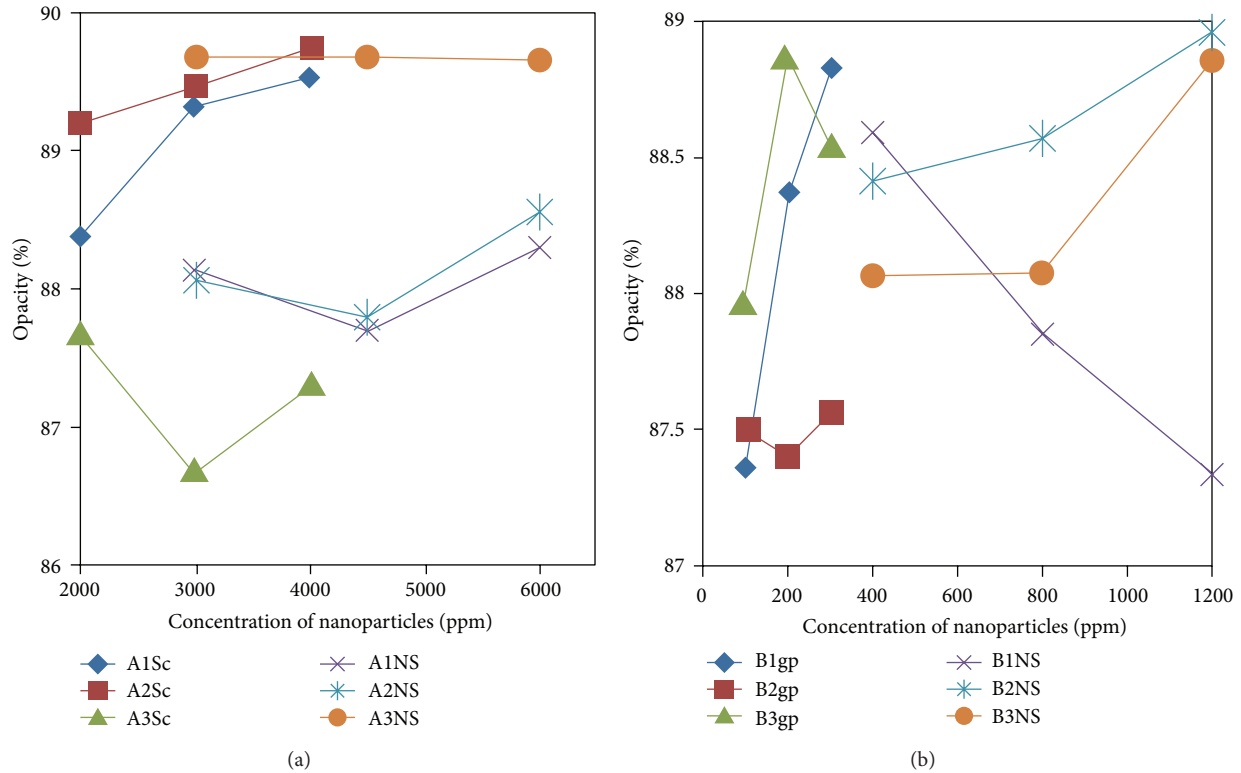


FIGURE 8: Effects of substituting NS for (a) Sc and (b) gp on the handsheet opacity.

the A3NS curve in Figure 7(a) demonstrated that at higher doses, c-PAMa and NS produced paper with brightness superior to all c-PAMa and Sc combinations. In the case of c-PAMb/gp groups, however, substituting NS for gp tended to decrease paper brightness albeit only slightly.

Figure 8 shows the effects of 2 dual-chemical systems with/without NS substitution on the paper opacity. Opacity tended to decrease slightly with increasing ash content which was in agreement with the results of Perng et al. [10]. Overall, there were no consistent patterns in cationic polymer or microparticle doses versus opacity of the paper.

**3.4. SPSS Statistics.** A two-way ANOVA was carried out for the  $2^2$  factorial experimental design examining the effects of the independent variables, cationic polymer, and microparticle doses on the main effects and interactions of FPR, ash content, tensile index, burst index, stiffness, brightness, and opacity of the resulting paper. At the premises of 95% confidence interval, 12 experimental sets, and 4 degree of freedom, the ANOVA results indicated, for instance, that for the c-PAMa/Sc system, substituting NS for Sc had no significant effect on the FPR. Only the main effect of c-PAMa dose affected the overall FPR (F-factor: 1.631; c-PAMa: 2.038), and the NS dose as well as interaction of the dual-chemicals showed no significant effect. As for ash retention, in c-PAMa/Sc system, only c-PAMa showed significant effect (F-factor: 2.020; c-PAMa: 3.536); however, in c-PAMa/NS system, both c-PAMa and NS doses and their interaction

showed significant effects (F-factor: 0.412; c-PAMa: 5.227; NS: 1.747; interaction: 1.130). There was no significant main effect or interaction of the dual-chemical doses on the mechanical strengths and optical properties of tensile, burst, stiffness, brightness, and opacity when NS was substituted for Sc.

In the c-PAMb/gp system, NS substitution of gp exerted no significant effect on the FPR; the main effects of microparticle doses, however, were more pronounced than those of the cationic polymer main effect (F-factor: 0.923; c-PAMa: 1.520; gp: 3.107). NS substitution of gp showed no significant effects on the ash retention. Except for burst index (F-factor: 0.155; NS: 0.195) and stiffness (F-factor: 0.052; NS: 0.088; interaction: 0.158), in which NS showed significant main effects, but the interaction of NS and cationic polymers showed only significant effect on stiffness but not the burst index; both NS and cationic polymer main effects were not significant for tensile index, paper brightness, and opacity.

## 4. Conclusions

Based on the experimental results, substituting c-PAM/Sc with NS at comparable solids content concentrations showed no significant strength change while significantly increasing ash content of the paper. This could be conducive to reduced fiber consumption and production cost. At c-PAMa dose of 200 ppm, NS substitution of Sc resulted in FPR >81% and ash retention >21%, regardless of the NS doses, while there was no major impact on the strength properties. As for the c-PAMb/gp retention system, only at c-PAMb dose



of 300 ppm, substituting NS for gp achieved FPR >80%. In such cases, regardless of the NS doses and ash content of paper was all >20%. Handsheet tensile and bursting strengths of c-PAMb/gp system were superior to the c-PAMb/NS results, only stiffness of the latter was better than the gp group. Optically, gp group had slight advantages; however, the differences were minor and there was no significant drawback by substituting NS for gp.

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