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ENGINEERING AND GINNING

Effect of Machine-Fiber Interaction on Cotton Fiber Quality and Foreign-Matter Particle Attachment to Fiber

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ABSTRACT

Changes in cotton fiber quality and attachment forces between foreign-matter particles and fibers were studied at different stages from the time of harvest through lint cleaning to develop new and less damaging methods for removing foreign-matter particles from cotton fiber. The study involved 75 samples collected from five field locations near College Station, Texas, including three replications and five harvesting and processing treatments: (1) hand picked and hand ginned, (2) machine picked and hand ginned, (3) machine picked, seed-cotton cleaned, and hand ginned, (4) machine picked, seed-cotton cleaned, and machine ginned, and (5) machine picked, seed-cotton cleaned, machine ginned, and one-stage lint-cleaned. A microscope was used to identify foreign-matter particles in each sample. Physical characteristics of the particles and their attachment to fibers were investigated and classified. Results indicated that each machine-fiber interaction during the harvesting through ginning process had the net effect of decreasing the size of foreign-matter particles. The particles had no obvious difference in shape across the processing stages. The tightness of particle-fiber attachment, the number of neps, and the short-fiber content differed significantly as a function of mechanical interactions: they increased as the number of mechanical interactions increased. Processing through the gin stand was a major contributor to the increase in short fiber content. The majority of the foreign-matter particles were leaves, but proportions of the particle categories changed with stages of processing. With an increased number of mechanical interactions the proportion of leaf particles decreased and the proportion of seed-coat fragments and stems increased.

Cotton goes through a series of mechanical processes from being harvested in the field to being pressed into a bale at the gin. At each step of the process cotton fiber quality is affected by interactions between fiber and mechanical actions (Mangialardi, 1985). U.S. cotton is mechanically harvested by either a cotton picker or a cotton stripper. A cotton picker uses high-speed rotating spindles to remove seed cotton from plant bolls. Then counter-rotating doffers unwind the cotton from the spindles, and the loose cotton is blown up through a duct into a basket and subsequently formed into a module. A cotton stripper removes the seed cotton by stripping the entire boll off the plant. The cotton is then separated from other plant material in the field or at a gin with mechanical cleaning devices. In comparison with hand harvesting, machine harvesting of cotton dramatically speeds up and reduces the cost of harvest in U.S. However, in general, machine harvesting decreases cotton fiber quality, particularly in terms of increased nep content and lint foreign-matter level (Baker and Brashears, 2000; Baker and Hughs, 2008; Calhoun et al., 1996; Faulkner et al., 2008; Hughs et al., 2000; Willcutt et al., 2002).

Machine-harvested cotton contains about 13% to 35% foreign matter including plant leaves, sticks, stems, seed-coat fragments, funiculi, shale, grass, etc. (Funk et al., 2005). It is desirable to remove as much foreign matter as possible from cotton fiber with minimal damage to the fiber. Removal of foreign matter at the gin involves cylinder cleaners and stick machines before fiber-seed separation to remove large particles from seed cotton, and lint cleaners after fiber-seed separation to remove smaller particles that remain in the lint cotton. Two general types of lint cleaners are currently on the market, the air-type and the saw-type. Saw-type lint cleaners are more common because of their higher cleaning efficiency. In the saw-type lint cleaner, lint from the gin stand or prior lint cleaner is formed into a batt on a condenser drum and fed onto a rapidly rotating saw cylinder

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through a set of feed rollers. While the fiber batt is on the saw cylinder, it is cleaned by a combination of centrifugal force, scrubbing action between saw cylinder and grid bars, and gravity assisted by an air current (Anthony and Mayfield, 1994).

Seed cotton and lint cleaning are necessary steps in the ginning process. However, these steps, particularly saw-type lint cleaning, create fiber damage. For example, Mangialardi (1985) found that the seed-cotton drying and cleaning system and the gin stand produce neps. Furthermore, the saw-type lint cleaner damaged fiber by creating neps and reducing staple length (Mangialardi and Anthony, 1998). According to Gordon and Bagshaw (2007), a fixed-batt saw lint cleaner caused 10% to 20% increase in the nep level, 0.3- to 0.4-mm reduction in the upper-quartile length by weight, and significant increase in short-fiber content (SFC), depending on varieties ginned. The longer and finer a cotton fiber is, the greater the damage caused by the lint cleaner.

As cotton fiber quality has become more important on the world market, researchers have worked to find the causes of fiber damage and to develop new methodologies and mechanical systems to reduce damage and loss of fiber while retaining the high efficiency of the saw-type lint cleaner (Anthony and Griffin, 2001; Baker, 1987; Columbus, 1985; Gordon and Bagshaw, 2007; Hughs et al., 1992; Rutherford et al., 1999). Many improvements have been made in saw-type lint cleaner manufacturing over the years, but today the same cleaning principles that were developed in the 1940s are still used (Baker et al., 1992).

To explore the possibility of inventing a new fiber cleaning device that is significantly different from "saw and bar" processing, it is critical to develop a fundamental understanding of the nature of cotton lint and foreign matter and their physical, chemical, and possibly even electrical interactions before and during the cleaning process. Imaging sensors and software analysis have been used in High Volume Instrument (HVI) machines to provide an estimate of lint trash content. More recently, Whitelock et al. (2009) have examined the variation in particle size distribution of trash particles before and after lint cleaning using image analysis. As other studies have shown (e.g., Morey et al., 1976b), foreign-matter content was found to decrease with lint cleaning; however, the rate of trash removal was not consistent across particle sizes. Although maximum particle size decreased with increased levels of lint cleaning, average particle size increased.

Another method to understand the interaction between processing stages and the impact on foreign matter is through microscopic examination of foreign matter and its interactions with cotton fiber. Morey et al. (1976a) used stereomicroscopy and bright-field microscopy to examine the botanical composition of Shirley Analyzer waste from machine-picked and machine-stripped seed cotton. Bract content ranged from 32% to 52% of the total waste amount, and cotton leaves and weed particles were major components. They observed that seed cotton contained a larger proportion of bract and leaf materials than lint did before lint cleaning. Using the same method, Morey et al. (1976b) determined the type of trash materials present in lint before and after saw-type cleaning, and whether lint cleaning selectively removed any of the botanical components. As the size of particles decreased, the proportion by weight of bract and leaf increased, and the content of seed-coat fragments decreased. They found lint cleaning to be ineffective at reducing the proportion by weight of leaf particles, but heavier materials such as stem particles were reduced in proportion. Although the work of Morey et al. (1976a, b) was aimed at illuminating the botanical composition of trash particles in cotton and not at the way those particles are attached to the fiber, it indicated that much can be learned through microscopy on foreign-matter particles in cotton fiber.

The objectives of this study were 1) to determine changes in the type and size of foreign-matter particles, on particle-fiber attachment, and on cotton fiber damage at each stage of machine processing from harvesting through ginning; 2) to determine the particle-fiber attachment force differences among various particle types.

MATERIALS AND METHODS

Sample Collection and Analysis. The methods used in this work for sample collection and preparation were basically the same as those reported by Thomasson et al. (2009), because this work was the continuation of that research project. Cotton samples were collected from five field locations at Texas A&M University's IMPACT Center near College Station, TX, in 2007. The five locations were identified and selected with a soil-EC map and with consideration of cotton quality variability within the field. At each location, one cotton sample was hand harvested and another one was collected from the harvester's basket as the cotton was harvested by a John Deere cotton picker (model 9996). Each sample weighed approximately 2 kg. When the sample was hand harvested, all the cotton on a plant was picked except that from immature and partially open bolls that a cotton picker might not be able to pick up. Those hand-picked and machine-harvested samples were sub sampled to make three replicates and hand ginned at the laboratory. Cotton modules that contain cotton from the sampling location were identified, and samples were collected from the identified modules after the modules were ginned with a Lummus system (Lummus 158 gin stand) at Scarmardo Gin Co. (Caldwell, Texas). The cotton went through a drying process to remove moisture before seed-cotton cleaning.

Five treatments representing various processing stages of the cotton were used in the study:

Treatment 1: Hand harvested and hand ginned (HH). Samples of seed cotton were hand harvested at the five locations and were hand ginned, representing fiber prior to mechanical interaction.

Treatment 2: Machine harvested and hand ginned (MH). Samples were collected from cotton harvested by a cotton picker at the five locations. These samples were also hand ginned, and they represent fiber that has only undergone mechanical interaction with the harvester.

Treatment 3: Machine harvested, seed-cotton cleaned, and hand ginned (MSH). The modules made from the cotton harvested in the same field locations were ginned at a commercial gin. Samples that were collected at the feeder apron were hand ginned, and they represent fiber that has undergone mechanical interactions with the harvester and seed-cotton cleaning equipment in the gin.

Treatment 4: Machine harvested, seed-cotton cleaned, and machine ginned (MSM). As the modules described in treatment 3 were ginned, samples were collected immediately after fiber-seed separation, and they represent fiber that has undergone mechanical interactions with the harvester, the seed-cotton-cleaning equipment in the gin, and the gin stand.

Treatment 5: Machine harvested, seed-cotton cleaned, machine ginned, and one-stage lint-cleaned (MSML). Samples from the modules were collected after one stage of lint cleaning, and they represent fiber that has undergone mechanical interactions with the harvester, the seed-cotton-cleaning equipment in the gin, the gin stand, and one saw-type lint cleaner.

Each treatment was replicated three times. In total there were 75 samples (5 field locations, 5 treatments, and 3 replicates). For each sample, the subsampling procedure involved removing a randomly selected portion of lint weighing 2.0 to 2.3 g. The subsamples were placed under a Caltex Scientific LX100 digital video microscope (Irvine, CA). Fifty randomly selected foreign-matter particles were manually removed with delicate tweezers from most of the lint subsamples, and particular attention was paid to minimizing the number of fibers removed with the particles. There were nine subsamples that contained a total number of visible particles of fewer than 50. All the particles in those nine subsamples were removed for particle classification. Each particle was identified as belonging to one of seven categories: leaf, stem, funiculi, seed-coat fragment, shale (lining of the bur), stick, and grass (Fig. 1). Each particle was assigned a two-dimensional shape that best described it: rectangular, square, triangular, or round. Each particle was also measured for length in two dimensions. While being removed, each particle was subjectively assigned to a category regarding strength of attachment to the fiber (low to high was represented by the numbers 1 through 5, respectively) and the level regarding number of fibers attached (low, medium, high, respectively). It should be pointed out that all fibers on the seed-coat fragment, including the fibers that are physically attached to and biologically growing out of the seed-coat fragment were counted as attached fibers. After the 50 particles (except for the aforementioned nine subsamples) had been removed and categorized, all remaining visible particles were carefully removed, and the mass of all foreign-matter particles measured.

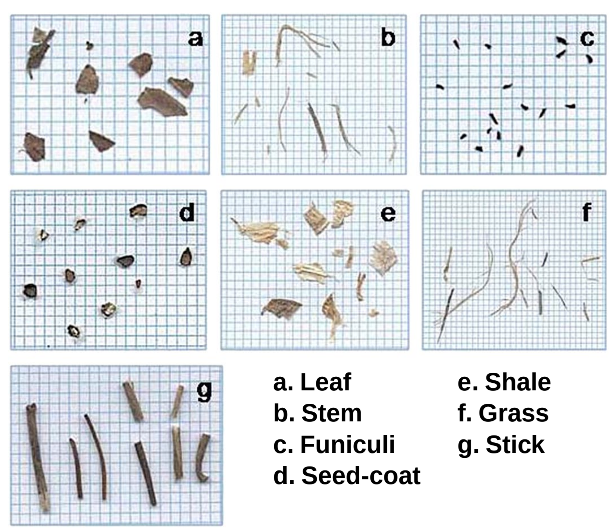

Figure 1. Seven categories of foreign-matter particles including leaf, stem, funiculi, seed-coat, shale, stick, and grass. The grid scale is 2 mm.

All 75 samples were analyzed at Cotton Incorporated to determine the effect of mechanical interactions, from harvesting through ginning, on fiber quality. Fiber quality parameters including neps and SFC were measured with Advance Fiber Information System (AFIS) and HVI tests.

Data Analysis. Averages of particle measurements for each sample and treatment were calculated, including the ratio of trash to fiber mass, proportion of foreign-matter types, dimensions of the particles, tightness of particle-fiber attachment, and level of number of fibers attached to the particle. One-way ANOVA and a Tukey post-hoc test were conducted with SAS to compare the effects of mechanical interactions on particle-fiber attachment, nep content, SFC, and micronaire. The effect of the sampling location on those parameters was also analyzed using the ANOVA test.

RESULTS

Objective 1 (Changes During Processing). The percentage of particles of the various types of foreign matter and the mass ratio of foreign-matter particle to fiber varied among the processing stages (Table 1). The majority of foreign-matter particles were leaf in all the processing stages, with high percentages in the MH (93%) and MSH (88%) samples. In the MSM and MSML samples, the proportion of leaf particles decreased while the proportion of the stem and seed-coat fragment particles increased. This occurrence could be attributable to stem breakage and creation of seed-coat fragments by the gin stand during fiber-seed separation. After lint cleaning, the majority of particles remaining in the lint were leaf and seed-coat fragment particles, a fact consistent with the results of Boykin et al. (2009). It is also apparent that hand ginning led to a substantial amount of seed-coat fragments, as they were 19% of the total amount of particles in the HH samples (Table 1). The MH samples had the highest foreign-matter-to-fiber-mass ratio (10.93%), and the ratio decreased with additional processing. It was obvious that hand-harvested cotton was much cleaner than machine-harvested.

The foreign-matter particles had no obvious difference in distribution of shapes among the processing stages (Table 2). However, particle size decreased as cotton went through more and more machine-processing stages. The relative importance of fracturing of particles versus selective removal of larger particles is unknown. In samples from MH through MSML, the additional stages of mechanical interaction reduced the number of low-level number of attached fibers from 93% to 52% and increased the number of medium and high levels from 6% to 41% and 1% to 7%, respectively. This suggests that the number of fibers attached to a particle increases with increasing mechanical interaction, but it is still unclear what roles are played by removal of easy-to-remove particles versus increasing the difficulty to remove each particle. Furthermore, more mechanical processing stages were associated with more tightness of attachment between particles and fibers (Fig. 2). A one-way ANOVA test revealed that tightness of particle-fiber attachment differed significantly among processing stages ($F(4, 70) = 75.71$, $p < 0.0001$). Tukey post-hoc comparison of the five processing stages (Table 3) indicated that MSML samples had significantly higher particle-fiber tightness (M = 2.13, SD = 0.20) than the other sample types. The tightness of MSM samples (M = 1.87, SD = 0.26) was significantly higher than that of the HH, MH, and MSH samples. The tightness of MSH samples (M = 1.27, SD = 0.10) did not significantly differ from that of MH and HH samples. The tightness of HH samples (M = 1.43, SD = 0.22) was significantly higher than that of MH samples (M = 1.16, SD = 0.07). This could be due to the larger proportion of seed-coat fragments in the HH samples (Table 1). Tighter particle-fiber attachment was generally associated with seed-coat fragments.

Table 1. Types of foreign-matter particle and the ratio of foreign matter to fiber mass across treatments.

Treatment	Foreign Particle Type (n) (%)							Foreign matter by Mass (%)
	Leaf	Stem	Funiculi	Seed-coat	Shale	Grass	Stick	
HH	72	1	3	19	3	1	1	2.93
MH	93	1	2	1	1	0	2	10.93
MSH	88	4	2	1	1	1	3	5.24
MSM	59	12	7	16	4	1	1	6.12
MSML	59	10	5	22	3	0	1	2.14

Table 2. Distribution of level of number of fibers attached to particle, particle shape, and particle dimension across treatments.

Treatment	Level of Attached Fibers (%)			Particle Shape (%)				Dimension (mm)	
	Low	Med	High	Square	Rectangular	Triangular	Round	X	Y
HH	80	7	13	11	58	21	10	3.32	1.62
MH	93	6	1	12	57	21	10	3.70	1.86
MSH	88	11	1	10	62	20	8	3.37	1.39
MSM	63	32	5	14	59	17	10	2.96	1.24
MSML	52	41	7	11	64	17	8	2.58	1.07

Table 3. Effect of the mechanical interactions on the tightness of particle-fiber attachment, nep content, and SFC (AFIS test). Means with the same letter are not significantly different.

Treatment	No of Obs	Mean of Tightness	Std Dev	Mean of Neps (cnt/g)	Std Dev	Mean of SFC (w) (%)	Std Dev
HH	15	1.43[a]	0.22	54.26[a]	16.00	3.89[a]	1.64
MH	15	1.16[b]	0.07	72.80[a]	17.87	7.83[a,b]	2.20
MSH	15	1.27[a, b]	0.10	150.73[b]	26.86	10.62[b]	3.34
MSM	15	1.87[c]	0.26	264.93[c]	25.40	21.02[c]	6.81
MSML	15	2.13[d]	0.20	338.60[d]	21.22	20.92[c]	4.84

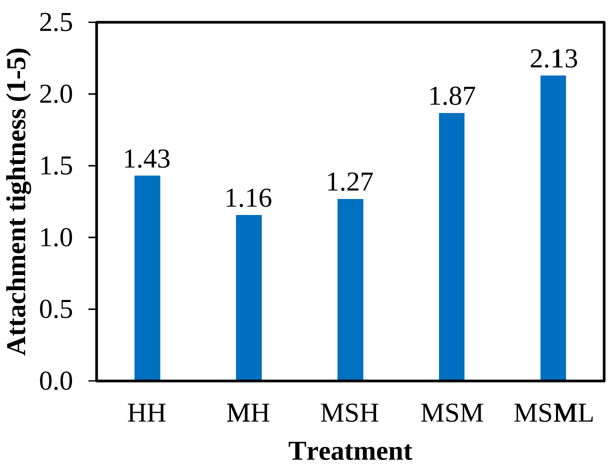

Figure 2. Mean of tightness of attachment between foreign-matter particles and fiber among various processing stages.

Results in this study suggest that each cotton processing stage created neps (Fig. 3). The ANOVA test showed that the nep content differed significantly as a function of increasing mechanical interactions (F (4, 70) = 473.82, $p < 0.0001$). Tukey post-hoc comparison across the processing stages indicated that the mean number of neps of MSH samples (M = 150.73, SD = 26.86) was significantly higher than that of HH (M = 54.26, SD = 16) and MH samples (M = 72.8, SD = 17.87). The number of neps of MSM samples (M = 264.93, SD = 25.40) was significantly higher than that of MSH samples, and the number of neps of MSML samples (M = 338.60, SD = 21.22) was significantly higher than that of MSM samples (Table 3). Comparing nep content among nearby processing stages, it was found that the dryer and seed-cotton cleaners increased the nep content from 72.80 to 150.73 cnt/g, the nep level increased to 264.93 cnt/g after gin stand, and became as great as 338.6 cnt/g after the first saw-type lint cleaner.

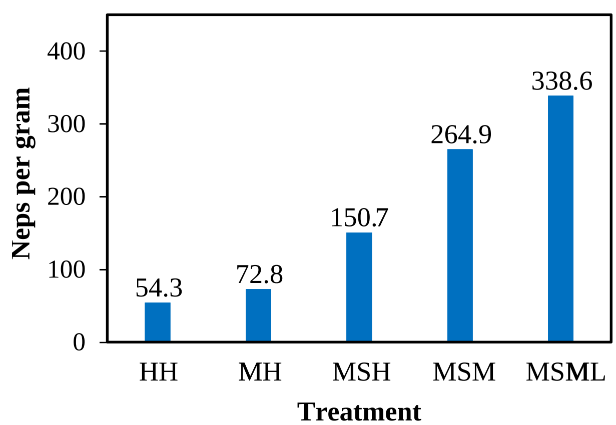

Figure 3. Nep content across the treatments.

The one-way ANOVA test indicated that the effect of mechanical interactions on SFC (AFIS test) was also significant (F (4, 70) = 51.40, $p < 0.0001$). The SFC of MSH samples (M = 10.62, SD = 3.34) was significantly higher than that of HH samples (M = 3.89, SD = 1.64) (Table 3). The SFC of MSM samples (M = 21.02, SD = 6.81) was significantly higher than that of MSH samples as well (Fig. 4). It was observed that the gin stand was a major contributor to SFC, producing increase of SFC from 10.62% to 21.02% during fiber-seed separation. Though seed-cotton cleaning was associated with an increase in SFC, the effect was not statistically significant. The SFC of MSM samples was about the same as that of MSML samples. This fact could possibly be attributed to similar levels of creation and removal of short fiber by the lint cleaner.

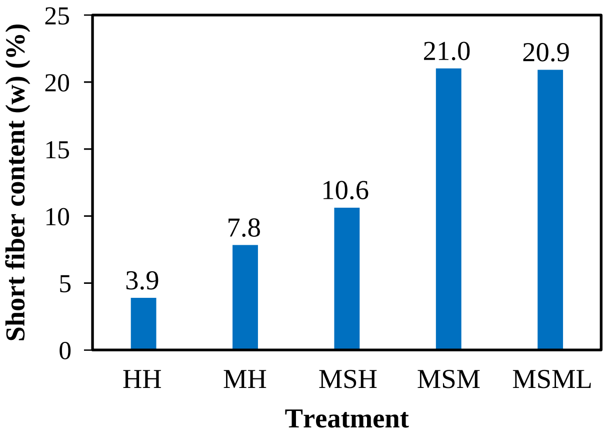

Figure 4. SFC (AFIS test) of the lint at each processing stage.

Effect of the mechanical interactions on micronaire and SFC (HVI test) is given in Table 4. As shown in the AFIS data, the ANOVA test indicated again that the SFC differed significantly as a function of increasing mechanical interactions ($F (4, 70) = 93.14$, $p < 0.0001$). The ANOVA test showed that the effect of mechanical interactions on micronaire was significant ($F (4, 70) = 23.92$, $p < 0001$). The micronaire of MSH samples ($M = 4.44$, $SD = 0.21$) was significantly lower than that of MH samples ($M = 4.78$, $SD = 0.19$).

Table 4. Effect of the mechanical interactions on micronaire and SFC (HVI test). Means with the same letter are not significantly different.

Treatment	No of Obs	Mean of Micronaire	Std Dev	Mean of SFC (%)	Std Dev
HH	**15**	**4.87^{a}**	**0.21**	**5.99^{a}**	**0.50**
MH	**15**	**4.78^{a}**	**0.19**	**6.83^{b}**	**0.28**
MSH	**15**	**4.44^{b}**	**0.21**	**7.57^{c}**	**0.72**
MSM	**15**	**4.49^{b}**	**0.13**	**8.53^{d}**	**0.49**
MSML	**15**	**4.35^{b}**	**0.14**	**9.19^{e}**	**0.50**

One way ANOVA tests revealed that sampling location had no significant effect on the tightness of particle-fiber attachment ($F (4, 70) = 0.38$, $p = 0.8200$), nep content ($F (4, 70) = 0.04$, $p = 0.9964$), and SFC ((AFIS test, $F (4, 70) = 0.17$, $p = 0.9533$); (HVI test, $F (4, 70) = 0.85$, $p = 0.4993$)). However, the effect of sampling location on micronaire of the cotton samples was significant ($F (4, 70) = 4.08$, $p = 0.0050$). Spatial variability in micronaire existed within the field. Similar results were found in studies by Elms et al. (2001) and Guo et al. (2004).

Objective 2 (Particle Types and Attachment Force). Upon considering the effect of particle type on tightness of particle-fiber attachment and number of fibers attached to a particle (Table 5), seed-coat fragments had the highest tightness index of 2.81 (Fig. 5). Sticks were second highest (2.44), followed by funiculi, shale, and stem particles, which had similar tightness (1.71-1.77). Leaf and grass particles were attached to the fiber most loosely, with a tightness index of 1.3.

Table 5. Type of foreign-matter particle versus the tightness of particle-fiber attachment and level of number of fibers attached to particle.

Particle Type	Particle Amount (n)	Average Tightness (1-5)	Average Attached Fiber Level (%)		
			Low	Medium	High
Funiculi	**130**	**1.71**	**73**	**25**	**2**
Grass	**21**	**1.33**	**86**	**14**	**0**
Leaf	**2683**	**1.34**	**85**	**14**	**1**
Seed-coat	**402**	**2.81**	**14**	**50**	**36**
Shale	**87**	**1.76**	**71**	**27**	**2**
Stem	**218**	**1.77**	**73**	**26**	**1**
Stick	**43**	**2.44**	**40**	**58**	**2**

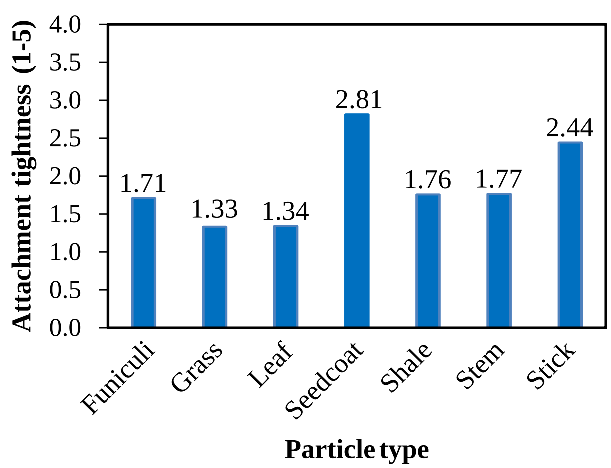

Figure 5. Tightness of particle-fiber attachment of various particle types.

In terms of the effect of particle type on the number of fibers attached to a particle, seed-coat fragments and sticks had greater numbers of fibers attached than the rest of the particle types (Table 5,

Fig. 6). In general, the least number of fibers were attached to leaf and grass particles. The number of fibers attached to funiculi, shale, and stem particles was at a medium level compared to seed-coat and stick group and the leaf and grass group.

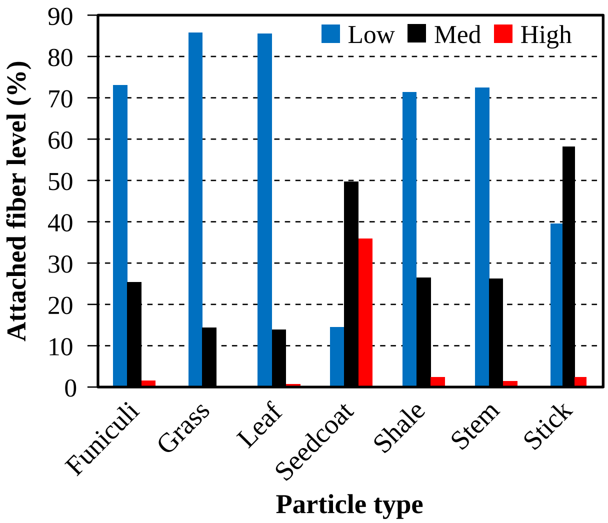

Figure 6. Effect of foreign-matter particle type on the level of number of fibers attached.

DISCUSSION AND CONCLUSION

The distribution of foreign-matter particle shape showed no obvious difference among various processing stages. Particle size decreased as the number of mechanical interactions increased. Leaf was the major component of foreign matter in cotton across all processing stages. With an increasing number of mechanical interactions the proportion of leaf in total foreign-matter particles decreased and the proportions of seed-coat fragments and stems increased. This could be due to an increase in tightness of particle-fiber attachment caused by the mechanical interactions, or it could be due to the possibility that each processing stage removes easy-to-remove particles and leaves the more difficult-to-remove particles. Mechanical interactions had a statistically significant effect on particle-fiber tightness of attachment. Tightness increased with an increasing number of the mechanical interactions. The number of fibers attached to the particle also tended to increase as the cotton went through more processing stages. The effect of mechanical interactions on nep content and SFC was also statistically significant. In comparing nep content between nearby processing stages, the mechanical interactions of seed-cotton cleaning, fiber-seed separation, and lint cleaning were associated with 107% (72.80 to 150.73 cnt/g), 76% (150.73 to 264.93 cnt/g), and 28% (264.93 to 338.60 cnt/g) increases in nep content, respectively. Increased mechanical harvesting and processing of seed-cotton resulted in reduced micronaire values because of more immature fiber being removed from the plant relative to hand harvesting and changes in trash size and content that affect the reading. Comparing SFC before and after fiber-seed separation, the gin stand was associated with a 98% increase in SFC. No significant effect of sampling location on the tightness of particle-fiber attachment, nep content, and SFC was found in this study. Spatial variability of the micronaire within the field was observed.

Seed-coat fragment and stick particles were more tightly attached to the fiber than the other foreign-matter particles such as the funiculi, shale, and stem. Relatively speaking, the leaf and grass particles were more loosely attached to the fiber and easier to remove. Along the same lines, more fibers were attached to seed-coat fragments and stick particles than to the other types of foreign-matter particles. Smaller numbers of fibers were found to be attached to leaf and grass than to funiculi, shale, and stem.

In measuring tightness of particle-fiber attachment and number of fibers attached to particles, the fibers that are physically attached to the seed-coat fragment were not considered separately from fibers biologically growing out of the seed-coat fragment; i.e., all fibers attached to a seed-coat fragment particle were counted as attached fibers. Considering this, it is possible that stick particles would have the highest tightness index of particle-fiber attachment and the greatest number of the fibers attached. This might be determined if the fibers growing out of seed-coat fragments were not counted as attached fibers in classifications.

This study has helped develop a fundamental understanding of the effect of mechanical interactions with cotton on physical characteristics of foreign-matter particles, particle-fiber attachment, and fiber quality. However, due to the great difficulty of accurate quantitative measurements, critical factors such as tightness of particle-fiber attachment and number of fibers attached to a particle were determined subjectively (1 to 5 for the tightness index; low, medium, high for the number of fibers attached). With a view to developing new methods for cleaning cotton that reduce fiber damage, quantitative measurements of these factors might be more illuminating. More research is also needed to determine how foreign-matter particles are physically, chemically, and even electrically attached to fiber at various processing stages.

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DISCLAIMER

Mention of a commercial product is solely for the purpose of providing specific information and should not be construed as a product endorsement by the authors or the institutions with which the authors are affiliated.

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