

Dry particle coating for improving the flowability of cohesive powders

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Abstract

Several dry processing techniques are used to coat cohesive cornstarch powder with different size silica particles. For nanosized silica guest particles, FESEM images show that both the magnetic assisted impaction coater (MAIC) and the hybridizer (HB) produce particles that are significantly more uniformly coated than using either a V-shape blender or simple hand mixing. Image analysis confirms that MAIC and HB provide higher surface coverage for the amount of guest material (flow aid) used. The improvement in flowability of coated cornstarch is determined from angle of repose measurements using a Hosokawa powder tester. These measurements show that nanosized silica provides the best flowability enhancement, whereas mono-dispersed 500-nm silica does not improve the flow properties of cornstarch at all. This observation agrees with a simple theoretical derivation based on the original Rumpf model, which shows that the flowability improvement is inversely proportional to the guest particle size for a given host particle size or size of surface asperities. Experimental results also indicate that surface-treated hydrophobic silica is more effective in improving the flowability of cornstarch particles than untreated hydrophilic silica. An increase in processing time using MAIC and the V-blender also improves the flowability of the cornstarch since the guest particles are more deagglomerated and better dispersed, the longer the processing time.

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1. Introduction

Handling and processing of fine particles (smaller than $\sim 30 \mu\text{m}$) is a generic industrial problem. These powders have poor flowability due to the cohesion force arising mainly from Van der Waals attraction. Besides utilizing aeration and vibration, addition of a flow agent is also an effective way to improve the flowability of cohesive particles, as discussed in the pioneering work of Molerus [1] and other researchers [2–5]. For example, a small amount of fumed silica “guest” particles discretely coated onto the surface of cohesive “host” particles can improve the flowability. However, most flow agents like fumed silica consist of very fine particles that have a strong tendency to form agglomerates. Thus, proper dispersion of the flow agent is a very important issue for obtaining discrete coating and flowability improvement.

Previous research by our group [6–9] indicates that dry coating techniques such as magnetic assisted impaction

coating (MAIC) and the Hybridizer (HB) can be used to improve the dispersion and adhesion of the flow agent onto the cohesive primary particles. The potential advantages of these processes are their high coating efficiency, low cost and environmentally benign operation. However, a systematic investigation of their performance has not been done as compared to, for example, a commercial V-shaped blender or even simple hand mixing. Therefore, a series of coating experiments using a model cohesive powder (cornstarch) was conducted with various dry coating devices to examine their coating efficiency. We were particularly interested to see how changing the properties of the flow agent (guest particles) would affect the flowability of the coated cohesive particles. For example, what is the effect of the size of the flow agent on flowability? Does it matter whether it is hydrophilic or hydrophobic?

To examine the effect of particle size, different silicas with size range from 20 nm to 2 μm were chosen. This effect was addressed theoretically by Mei et al. [10] by using the JKR theory to analyze the cohesion force before and after coating. The effect of the different surface properties of the

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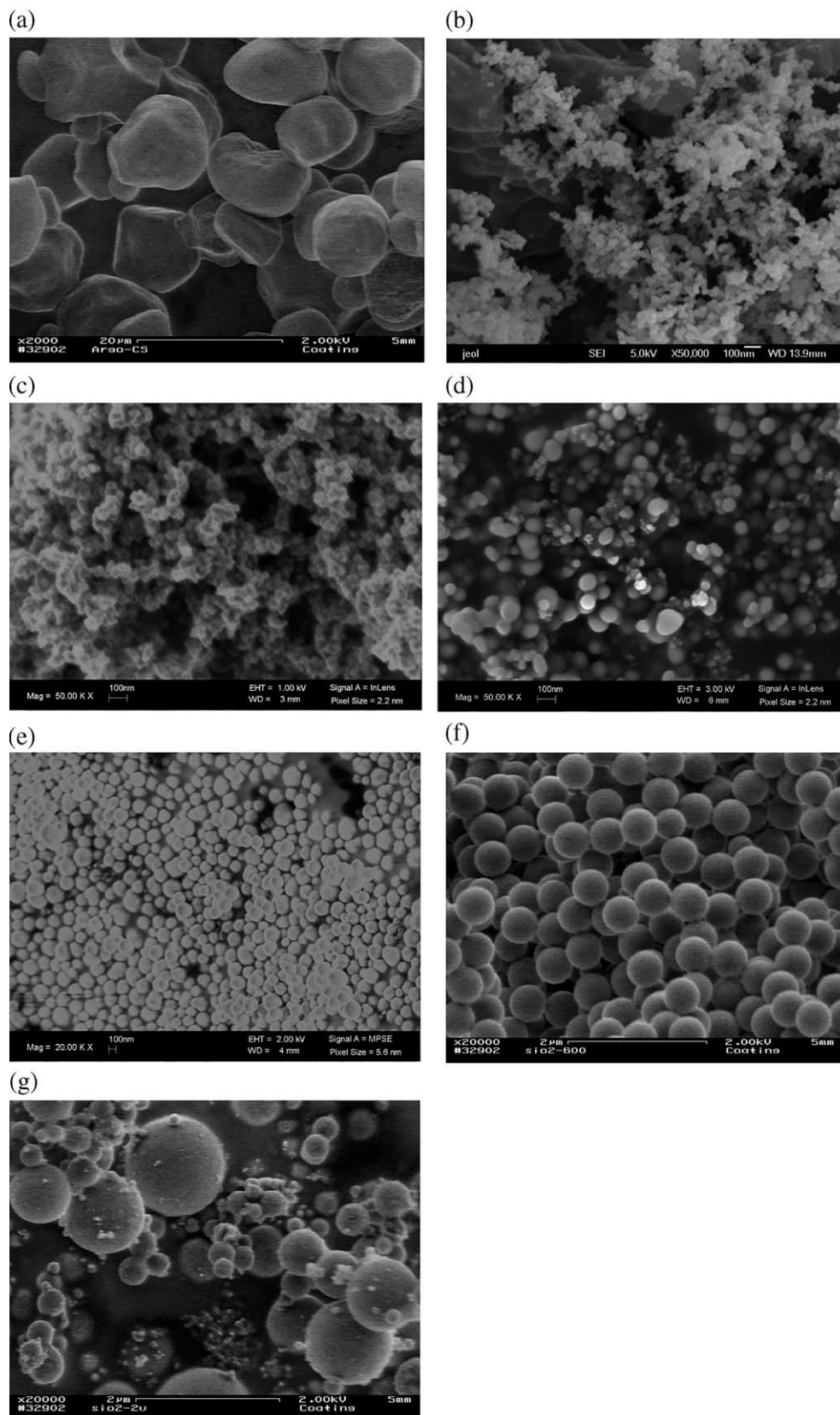


Fig. 1. FESEM images of host and guest particles. (a) Cornstarch; (b) R972; (c) EH-5; (d) OX-50; (e); Lab synthesized 100-nm silica; (f) COSMO55; (g) P-500.

coating material on flowability is examined by coating with the same size of both hydrophobic and hydrophilic silica.

2. Experimental

2.1. Powders

Cornstarch (Argo) is used as host particles for dry coating. As shown in Fig. 1(a), the field emission scanning electron microscope (FESEM) image indicates that the cornstarch particles are rounded individual particles with a mean size of around 15 μm , which was also verified using a Coulter particle size analyzer. The density of cornstarch is around 1550 kg/m^3 .

Six different silica particles were used as guest particles: (1) Aerosil R972 silica supplied by Degussa with a specific surface area of 114 m^2/g . A FESEM image (Fig. 1(b)) shows highly agglomerated particles with a primary particle size around 20 nm in a chainlike structure. Its surface has been modified by dimethyldichlorosilane to make it hydrophobic. (2) CAB-O-SIL EH-5 silica supplied by Cabot, also around 20 nm (Fig. 1(c)), is similar in structure to R972 except that its surface is hydrophilic. (3) OX-50 silica supplied by Degussa has an average size of about 40 nm (Fig. 1(d)) and is hydrophilic. (4) 100-nm silica, synthesized in our laboratory using the Stöber process and is hydrophilic (Fig. 1(e)). (5) COSMO55 supplied by Catalyst and Chemical Ind. Co. Ltd (Japan) is 500 nm mono-dispersed hydrophilic spherical silica particles (Fig. 1(f)), but tends to form large agglomerates, which need to be dispersed during the coating process. (6) P-500 hydrophilic silica, also supplied by Catalyst and Chemical Ind. Co. Ltd (Japan), has an average size of around 2.25 μm (Fig. 1(g)) with a wide size distribution. The particle density of all of these silicas is 2650 kg/m^3 . The properties, size, etc., of all the particles (host and guests) used in the experiments are summarized in Table 1.

2.2. Coating processes

The percentage by mass of guest particles used in the coating experiment is calculated based on the assumption of

Table 1
Properties of host and guest particles

	Size	Density (kg/m^3)	Hydrophilic/Hydrophobic
<i>Host particle</i>			
Cornstarch	15 μm	1550	Hydrophilic
<i>Guest particles</i>			
R972	~20 nm	2650	Hydrophobic
EH-5	~20 nm	2650	Hydrophilic
OX-50	~40 nm	2650	Hydrophilic
Lab	~100 nm	2650	Hydrophilic
COSMO55	~500 nm	2650	Hydrophilic
P-500	2.25 μm	2650	Hydrophilic

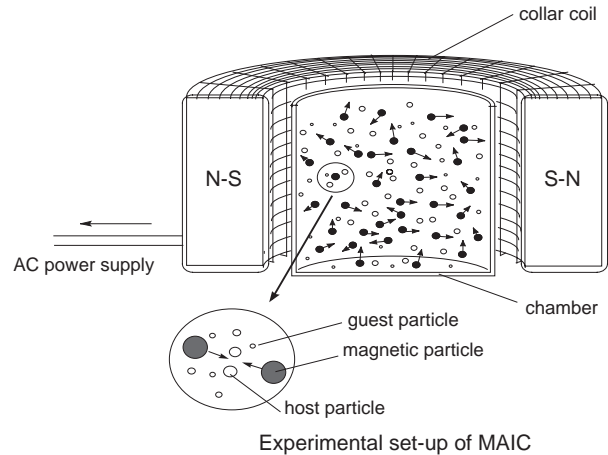


Fig. 2. Experimental setup of MAIC.

100% surface coverage of the host particles with a monolayer of guest particles. We assume that all guest particles are of same size, both host and guest particles are spherical, and that the host and guest particles do not deform during the coating process. Based on these assumptions, the weight percentage of guest particles (Gwt.%) for 100% surface coverage is:

$$\text{Gwt}\% = \frac{(Nd^3\rho_d)}{(D^3\rho_D) + (Nd^3\rho_d)} \times 100 \quad (1)$$

Here:

$$N = \frac{4(D+d)^2}{d^2} \quad (2)$$

From Eq. (1), the weight percentages of guest particles needed to coat 15- μm cornstarch particles are 0.91%, 19.6% and 57.6%, respectively for 20-nm, 500-nm and 2.25- μm silica. Accordingly, in our experiments, 1.0 wt.% of nanosized silica and 20 wt.% 500-nm silica were used. In addition, we also performed coating experiments with 0.1 wt.% and 0.01 wt.% of the nano-silica and 2.0 wt.% of the 500-nm silica. For the large 2.25- μm silica guest particles, we only conducted experiments using 2.0 wt.% even though this is much less than theoretically needed to produce a monolayer of guest particles on the surface of the cornstarch.

Two different dry coating devices and a dry mixer were studied to determine the coating performance as described below:

- (1) *Magnetic Assisted Impaction Coating (MAIC)*: Fig. 2 is a schematic diagram of the MAIC apparatus. The oscillating magnetic field generated by the coil is used to accelerate and spin the large magnetic particles mixed with the host and guest particles promoting collisions between the particles and with the walls of the vessel. Since the magnetic particles “fluidize” the host and guest powders, “soft” coating occurs by powder impaction. The magnetic particles used here

are barium ferrite particles coated with polyurethane and have a size range from 1.4 to 1.7 mm. The weight ratio of magnets to host and guest particles is 3 to 1. The size and weight ratio of the magnetic particles were chosen on the basis of previous research using MAIC performed by our group. Unless stated otherwise, the processing time using MAIC was 10 min.

- (2) *Hybridizer (HB) coating*: Fig. 3 is a schematic diagram of the Hybridizer. It consists of a very high-speed rotating rotor with six blades, a stator and a powder re-circulation circuit. The rotor diameter is 118 mm, and the outer edge of each blade is 35 mm from the rotational axis. The powder mixture (host and guest particles) is subjected to high impaction and dispersion due to collisions with the blades and the walls of the device and continuously re-circulates in the machine through the cycle tube. Particle coating is achieved due to the embedding or filming of the guest particles onto the host particles by high impaction forces and friction heat. Since the HB operates at very high rotating speed, a very short processing time is required to achieve coating. The operating conditions used in our experiments are 6000 rpm for 2 min.
- (3) *V-shaped blender (VB) mixing/coating*: Fig. 4 is a schematic diagram of a V-shaped Blender (Patterson–Kelly, BlendMaster). The blender achieves good powder mixing as the vessel is rotated slowly, and during each rotation, the powder flows into the two arms followed by powder pouring back towards the apex of the system. In our apparatus, the vessel was operated at 25 rpm and an internal stirring bar (also called an agitator bar) that rotates at very high speed (3600 rpm) is used to enhance the mixing behavior inside the chamber. The tips of the intensifier bar

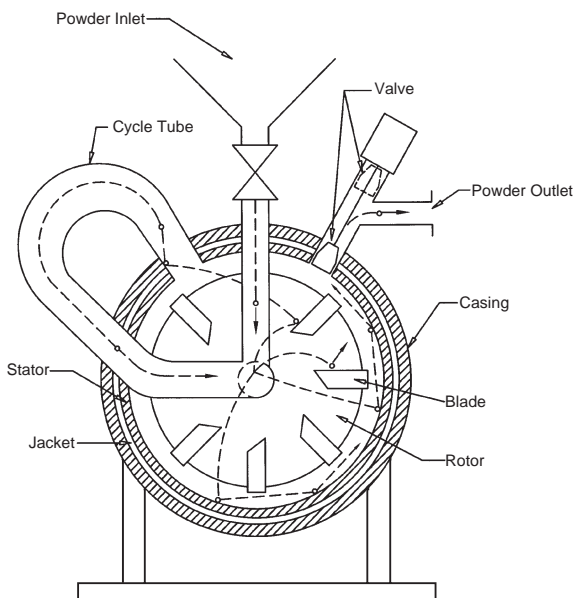


Fig. 3. Experimental setup of Hybridizer.



Fig. 4. Snapshot of V-blender.

extend 55 mm from the rotational axis. For each batch, 150 g of particles is charged into a 4-quart vessel and processed for 2 to 40 min. A small amount of primary (host) powder is first mixed with the guest material (flow aid) in a plastic zip-lock bag, and then this mixture is added to the rest of the primary powder into the vessel of the V-blender. Unless stated otherwise, the processing time in V-blender was 10 min.

- (4) *Hand mixing*: Experiments using simple hand mixing were also conducted as a control. In this procedure, the primary material was placed in a bottle along with the flow aid, and then the sealed bottle was shaken by hand for approximately 10 min.

3. Characterization

A Coulter LS 230 particle size analyzer, LEO 922 and a LEO 1530 VP field emission scanning electron microscope (FESEM) are used to measure the particle size distribution of the host and guest particles. A Hosokawa powder tester (PT-N) is used to measure the angle of repose (AOR) of the coated cornstarch particles to characterize their flowability. The procedure used to measure AOR was as per ASTM standard; ASTM D6393-99, “Bulk Solids Characterization by CARR Indices”, and each reading is an average of at least three observations. FESEM images are also used to observe the distribution of the guest particles on the surface of the host particles; MATLAB is used for image analysis.

4. Results and discussion

4.1. Evaluation of dry coating processes

Coating experiments were performed using the same amount of silica guest particles with cornstarch as the host

particles in the three different devices, with hand mixing done as a control. The AOR of the coated products (which is a measure of their flowability) [9,11–13] was plotted in Fig. 5 to compare the coating efficiency of different coating devices. For a 1.0 wt.% coating of EH-5, which corresponds to a 100% monolayer surface coverage, the figure shows that MAIC, HB and VB are all capable of significantly improving the flowability of cornstarch and reducing its AOR from 52° to 27°, 30° and 33°, respectively. Even hand mixing reduces the AOR to 38°.

The corresponding SEM images are shown in Fig. 6. For MAIC and HB coated products (Fig. 6(a and b)), the fumed silica particles, EH-5, are dispersed evenly onto the cornstarch particles and there are no observed large silica agglomerates. The V-blender is also capable of coating fumed silica onto cornstarch, but the distribution of the fumed silica on the surface of cornstarch is not uniform. As shown in Fig. 6(c, left), agglomerates of fumed silica look like “patches” on the cornstarch surface and some small silica agglomerates, as well as uncoated cornstarch surfaces are also observed (Fig. 6(c, right)). The results indicate that the deagglomeration efficiency of the V-blender is not as good as MAIC and HB.

A reasonable explanation for this behavior is that in MAIC, the small magnets spin and rotate very fast, leading to many repeated collisions of the cornstarch particles with each other, magnets, and the vessel walls, helping deagglomeration of the EH-5 particles so as to obtain a “smooth” coating surface. For the Hybridizer, due to its very high-speed rotation, the impaction and dispersion forces between particles are very strong resulting in a uniform coating. Compared to these devices, the V-blender, even with an internal stirring bar is not capable to fully

disperse the guest particles, and hence agglomerated particles are found on the surface in form of “patches”. Hand mixing is only capable of coating part of cornstarch surface, as shown in Fig. 6(d, left), and large individual agglomerates of EH-5 are observed on the coated product, as shown in Fig. 6(d, right) (see circled area). The results shown here confirm that nanosized fumed silica is a good flow agent for cohesive cornstarch particles, and the flowability of the three machine processed samples is much better than the hand mixed sample.

For a 0.1 wt.% coating of EH-5, which corresponds to a theoretical 10.9% surface coverage, Fig. 5 shows that MAIC, HB and the V-blender all improve the flowability of cornstarch and reduce the AOR to 30°, 33° and 34°, respectively. However, for this small amount of silica addition, hand mixing has no effect in improving the flowability of cornstarch. Corresponding SEM images (Fig. 7) clearly show that the nanosized guest particles are uniformly coated on the surface of the cornstarch for both the MAIC and HB processed samples, as shown in Fig. 7(a and b). As stated before, the V-blender is less effective in deagglomeration of EH-5 agglomerates, thus less guest particles are observed on the surface of the cornstarch (Fig. 7(c)), and some small agglomerates are also observed as seen in Fig. 7(d). For hand mixing, only a few guest particles are attached onto the cornstarch surface as seen in Fig. 7(e) and large agglomerates are detected (Fig. 7(f)). These results indicate that both MAIC and HB are capable of deagglomerating and dispersing the nanosized guest particles and coating them evenly on the surface of cornstarch. Compared to those devices, the V-blender is less effective in breaking down the small agglomerates of fumed silica; thus its coating efficiency is relatively lower

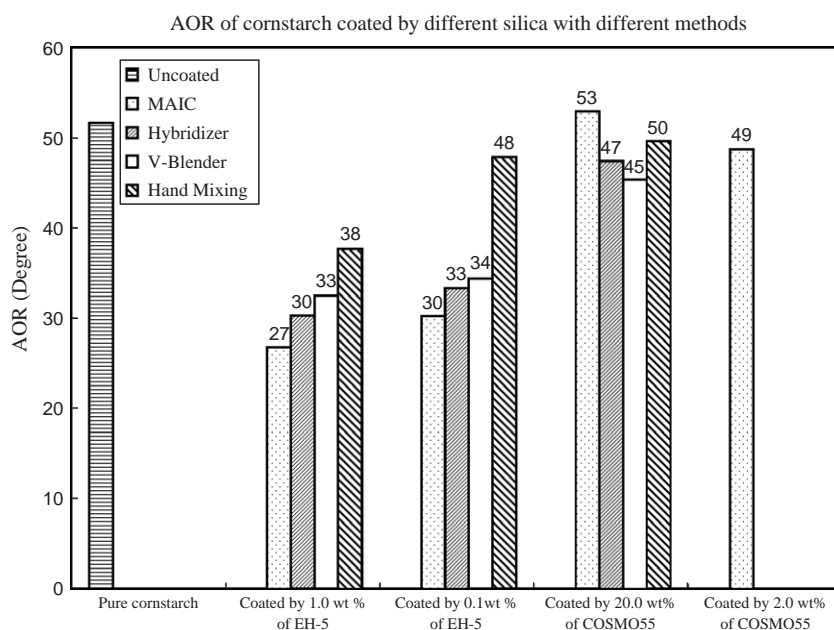


Fig. 5. Angle of repose of coated cornstarch samples.

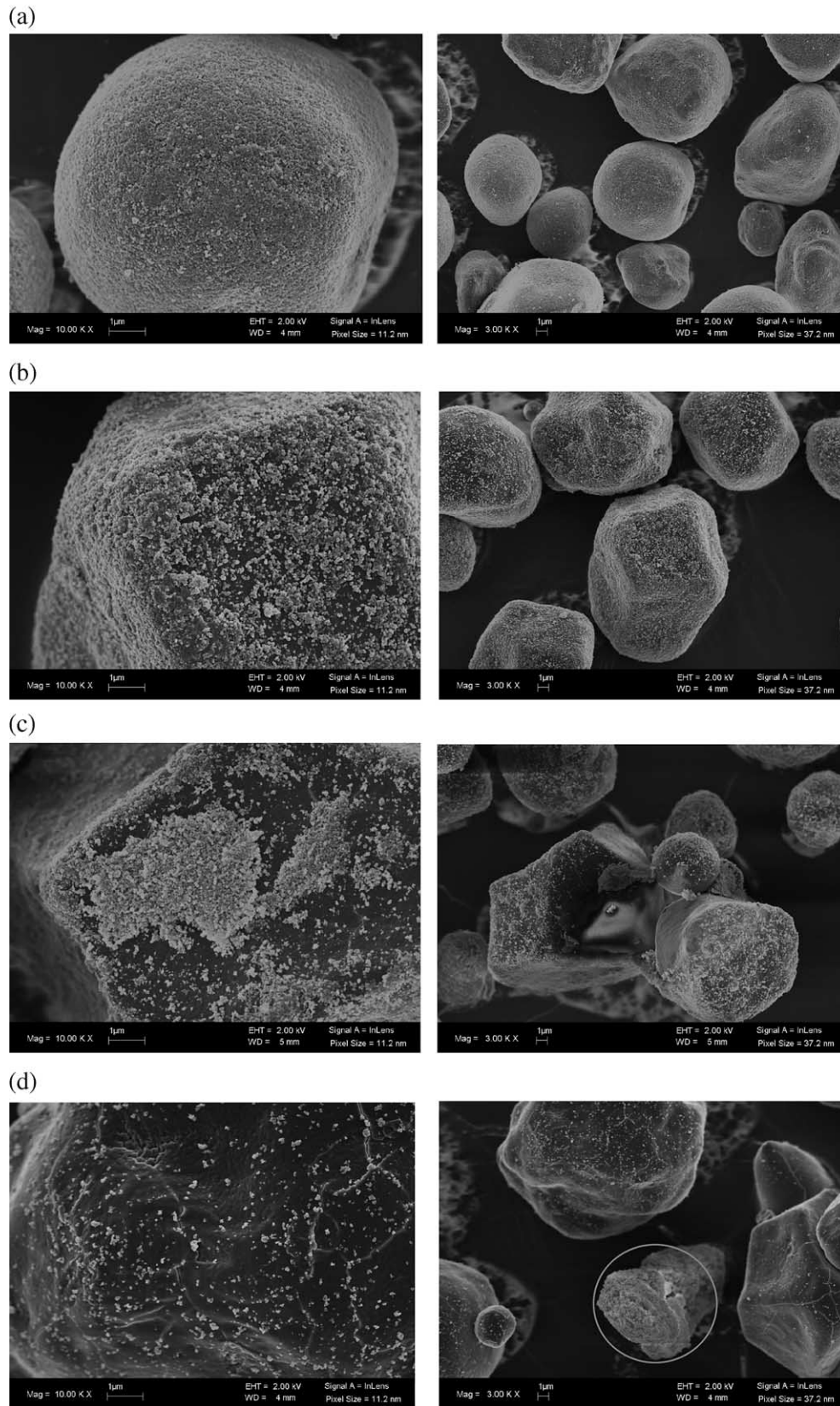


Fig. 6. SEM images of coated cornstarch with 1.0% EH-5. (a) Left: MAIC coated cornstarch with magnification of 10,000 \times ; right: MAIC coated cornstarch with magnification of 3000 \times ; (b) left: Hybridizer coated cornstarch with magnification of 10,000 \times ; right: Hybridizer coated cornstarch with magnification of 3000 \times ; (c) left: V-shaped blender coated cornstarch with magnification of 10,000 \times ; right: V-shaped blender coated cornstarch with magnification of 3000 \times ; (d) left: Hand mixing coated cornstarch with magnification of 10,000 \times ; right: Hand mixing coated cornstarch with magnification of 3000 \times .

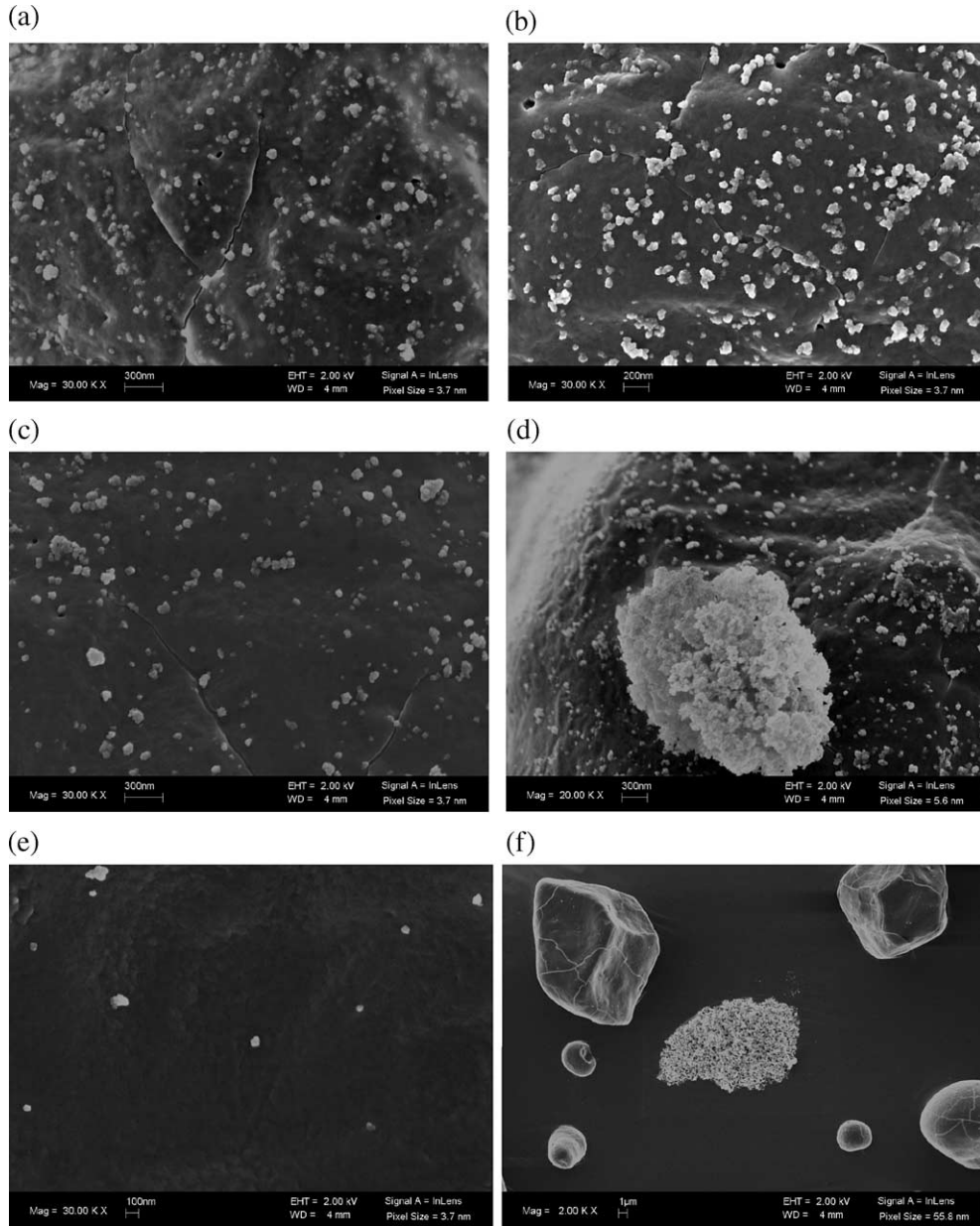


Fig. 7. SEM images of coated cornstarch with 0.1% EH-5. (a) MAIC; (b) Hybridizer; (c) V-blender; (d) V-blender; (e) Hand mixing; (f) Hand mixing.

than MAIC and HB. For hand mixing, the impaction forces between the particles are not sufficient to breakdown the silica agglomerates, hence very little coating occurs.

A quantitative evaluation of the deagglomeration/dispersion capability of the different dry coating devices has also been conducted by image analysis of the SEM images of Fig. 7(a,b,c,e) using MATLAB to calculate the surface coverage of the guest particles. The results, shown in Table 2, indicate that a surface coverage of 1.72%, 6.74%, 13.27%

and 10.72% is obtained for cornstarch processed by hand mixing, VB, HB and MAIC, respectively. As stated before, the theoretical surface coverage for 0.1 wt.% coating of fumed silica is 10.9, which is very close to what is achieved by the HB and MAIC processed samples. While the coverage by the V-blender is a reasonable 6.74%, it includes small agglomerates, and hence the dispersion of the guest particles is not even. These results imply that both the HB and MAIC can deagglomerate 0.1 wt.% of silica particles and coat them evenly onto the cornstarch surface evenly. The V-blender is not nearly as effective, and coating cannot be achieved by hand mixing.

Similar experiments were also conducted with 500-nm silica particles as shown in Fig. 5. The AOR results of using 20.0 wt.% of COSMO55 for coating, corresponding to

Table 2
Surface coverage of cornstarch coated with 0.1 wt.% EH-5

	MAIC	Hybridizer	V-blender	Hand mixing
Surface coverage (%)	10.72	13.27	6.74	1.72

approximately 100% surface coverage, are 53°, 47°, 45° and 50° for MAIC, HB VB and hand mixing, respectively. Although the AOR results indicate that the 500-nm guest particles have no obvious effect in improving the flowability of cornstarch, the SEM images (Fig. 8) indicate that a reasonable coating of guest particles occurred using MAIC, HB and VB as shown in Fig. 8(a–c), but for hand mixing as shown in Fig. 8(d), only a few particles are seen on the surface of the cornstarch. These results indicate that all three devices are capable of deagglomerating the larger 500-nm silica particles and coat them onto the surface of cornstarch; however, coating could not be achieved by hand mixing.

Coating experiments with 2.0 wt.% of COSMO55 silica particles were also conducted using MAIC. The AOR of the coated sample is 49°, which indicates that the amount of these guest particles added has no significant effect in improving the flowability of cornstarch.

4.2. The effect of guest particle size

We have shown above that a large improvement in the flowability of cornstarch particles is obtained by coating them with nanosized silica, but coating with 500-nm guest particles does nothing to improve the flowability (see Fig. 5). These results indicate that the size of the guest particle size plays an important role. An order of magnitude effect of

the guest particle size in reducing the cohesion between two host particles can be estimated based on van der Waal' forces. Two coated particles can have either a single or multiple mutual contacts assuming they are sparsely but sufficiently coated by the guest particles, but for the sake of doing an order of magnitude analysis, a contact between a guest particle of one host to another host (shown in Fig. 9(a)) is considered. There are also contacts between two guest particles on two different hosts (shown in Fig. 9(b)) that can occur. For the case shown in Fig. 9(a), it is assumed that the guest particle, C, is attached to the host A, on the left, and is in contact with the host particle, B, on the right. In dry coating, there is some minor deformation of the host or guest or both, hence the van der Waals attraction between A and C is higher than the attraction between C and B, which are simply in contact without significant deformation [8]. Therefore, the amount of force required to pull them apart, i.e., the coated particle on left (assembly of A and C) and the host particle on the right, B, is given by the following equation

$$P_{\text{coated}} \cong \frac{A}{12} \frac{dD}{d+D} \frac{1}{h_0^2} \quad (3)$$

Here A is the Hamaker constant for these materials (assumed to be approximately the same), and h_0 is the atomic scale separation between the two, for which a value

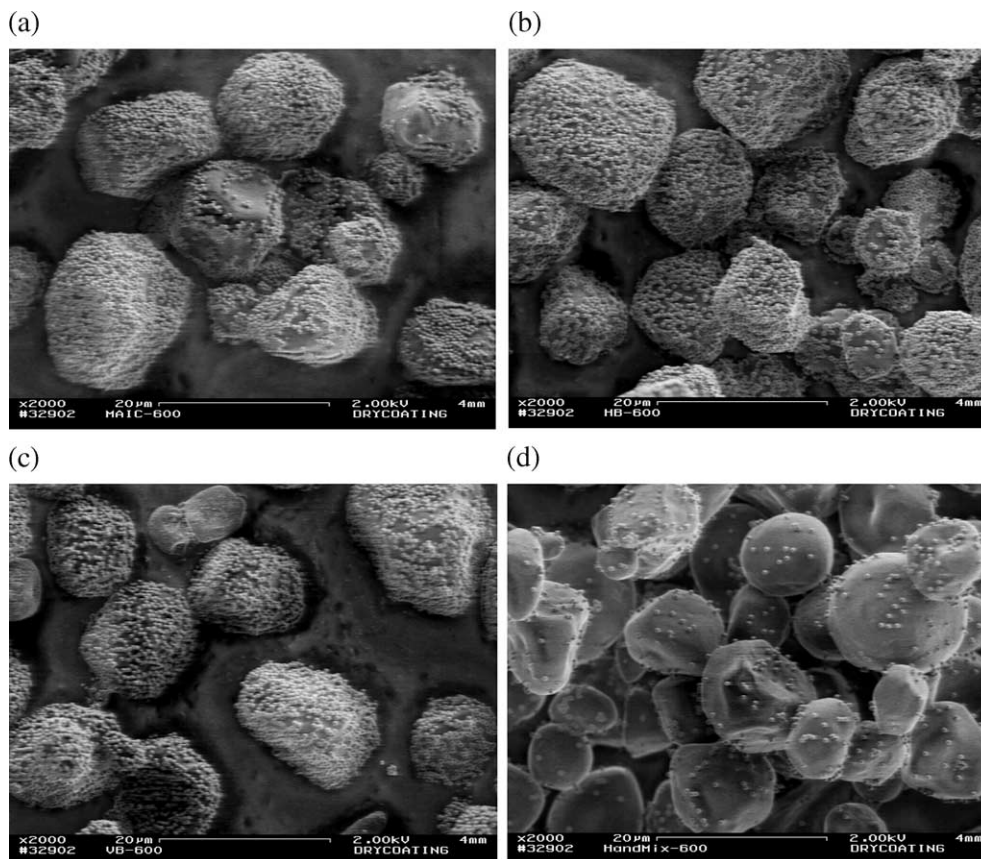


Fig. 8. SEM images of coated cornstarch with 20% COSMO55. (a) MAIC; (b) Hybridizer; (c) V-blender; (d) Hand mixing.

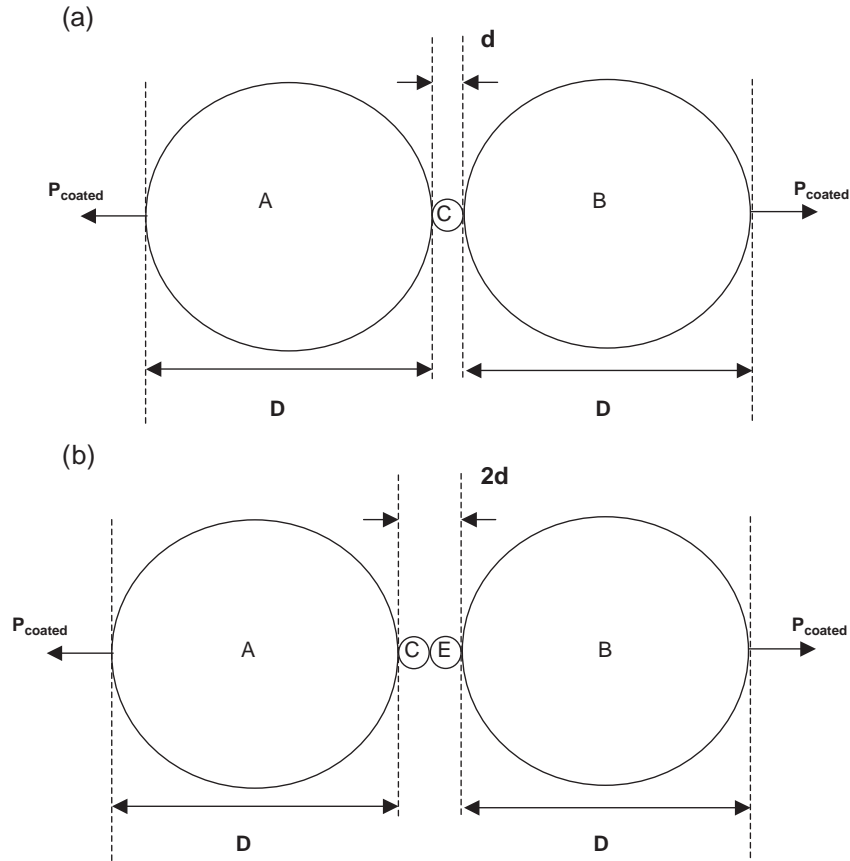


Fig. 9. Schematic diagram of cohesion force between coated particles. (a) A single contact between the guest particle attached on the left host particle and the host particle on right. (b) A single contact between the guest particle attached to the left host particle and the guest particle attached to the right host particle.

of 0.165 or 0.4 nm is usually used. The total van der Waals attraction force between B and the assembly of A and C involves a second term, because there is also a van der Waals attraction between particle A and particle B having a spacer C between them. That term is given by

$$P \approx \frac{A}{12} \left[\frac{D}{2(2h_0 + d)^2} \right] \quad (4)$$

but is several orders of magnitude smaller than the first term, hence it can be neglected.

Eq. (3) is a simplification of the exact equation, given by Rumpf [14], which includes two terms. The first is the right hand side of Eq. (3), and the second is the right hand side of Eq. (4). Rumpf's equation has also been used by Huber and Wirth [15]. Since d is much smaller than D , Eq. (3) can be further simplified as

$$P_{\text{coated}} \cong \frac{A}{12} d \frac{1}{h_0^2} \quad (5)$$

If the two particles are not coated, then the van der Waal's attraction force between the two is simply given by,

$$P_{\text{uncoated}} \cong \frac{A}{12} \frac{D}{2} \frac{1}{h_0^2} \quad (6)$$

For particles of size of the order of microns, Molerus [16] and Massimalla and Donsi [17] point out that Eq. (6) gives an unrealistically high value of the attraction force and they suggest that rather than using the size of the particles in contact, D should represent the asperities of the particles and that a typical value of this parameter is 0.2 μm .

Then the ratio between the force required to detach the coated particle compared to the force to detach an uncoated particle is

$$\frac{P_{\text{coated}}}{P_{\text{uncoated}}} = 2 \frac{d}{D} \quad (7)$$

where D is either the diameter of the host particle or the size of the asperities $\sim 0.2 \mu\text{m}$ depending on the size of the host particles (assuming that the Hamaker constants are approximately the same). However, one can also select the guest material in such a manner as to have reduced values for the Hamaker constant in Eq. (3).

It is noted that this result is the same as that obtained by Mei et al. [10], who analyzed the cohesion force with and without the presence of a guest particle (as illustrated in Fig. 9(a)) by extending the JKR theory. They provide the following equation for the ratio of "adhesion" force

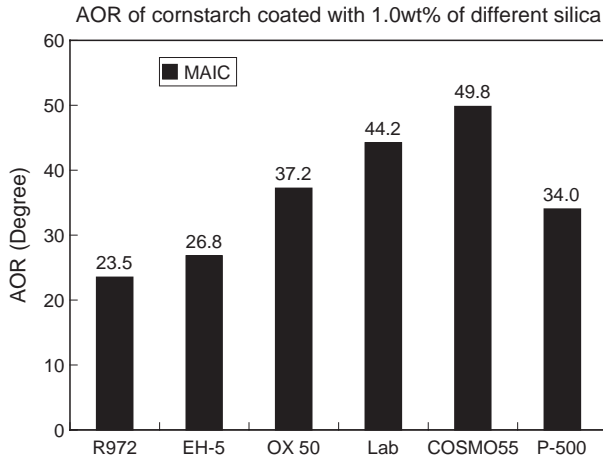


Fig. 10. Angle of repose of 10-min MAIC coated samples with different silica.

between coated and uncoated particles, i.e., the force needed to pull them apart:

$$\frac{P_{\text{coated}}}{P_{\text{uncoated}}} = 2 \frac{d}{D} \frac{\Delta\gamma}{\Gamma} \cong 2 \frac{d}{D}. \quad (8)$$

When the contact case of Fig. 9(b) is analyzed, it is clear that the weakest contact is that between the two guests, C and E, which should give the magnitude of the force required to break them apart. Again, the total force between the particles A and B includes several terms, i.e., direct attraction between C and E, A and B, A and E, as well as B and C. However, the last three terms are several orders of magnitude smaller than the first term (attraction between C and E), which can then be used to estimate the breaking force.

$$P_{\text{coated}} \cong \frac{A}{12} \frac{d}{2} \frac{1}{h_0^2}. \quad (9)$$

Dividing Eq. (9) by Eq. (6)

$$\frac{P_{\text{coated}}}{P_{\text{uncoated}}} = \frac{d}{D} \quad (10)$$

which differs from Eq. (7) only by a factor of 2.

An analysis of multiple contacts yields essentially the same results, i.e., the reduction in the contact force due to the presence of small guest particles is proportional to the size ratio between the guest and host particles (or asperities of the host particles), and for a fixed host size, would only depend on the size of the guest particle. In other words, the reduction in the cohesion force is inversely proportional to guest particle size. Thus, the cohesion force between cornstarch particles in the presence of a 20-nm guest silica particle is much less (about 4%) than the cohesion force in the presence of a 500-nm guest silica particle.

To obtain a better understanding of this phenomenon, 1.0 wt.% of R972, OX-50, lab synthesized 100-nm silica and 2.25- μm silica particles were used as guest particles (in addition to the EH-5 and COSMO55 particles that were

previously used) for coating cornstarch with MAIC. The results (Fig. 10) indicate that the AOR for the different sized silica particles monotonically decreases as the guest particle size is reduced, except for the 2.25- μm silica. The AOR of the 2.25- μm silica coated cornstarch decreases from 52° to 34°, which contradicts our previous conclusion. However, FESEM images (Fig. 11(a and b)) of the coated cornstarch particles indicate that the 500-nm and 20-nm guest particles appear to be almost mono-dispersed and evenly coated onto the cornstarch particle surface. However, for the 2.25- μm

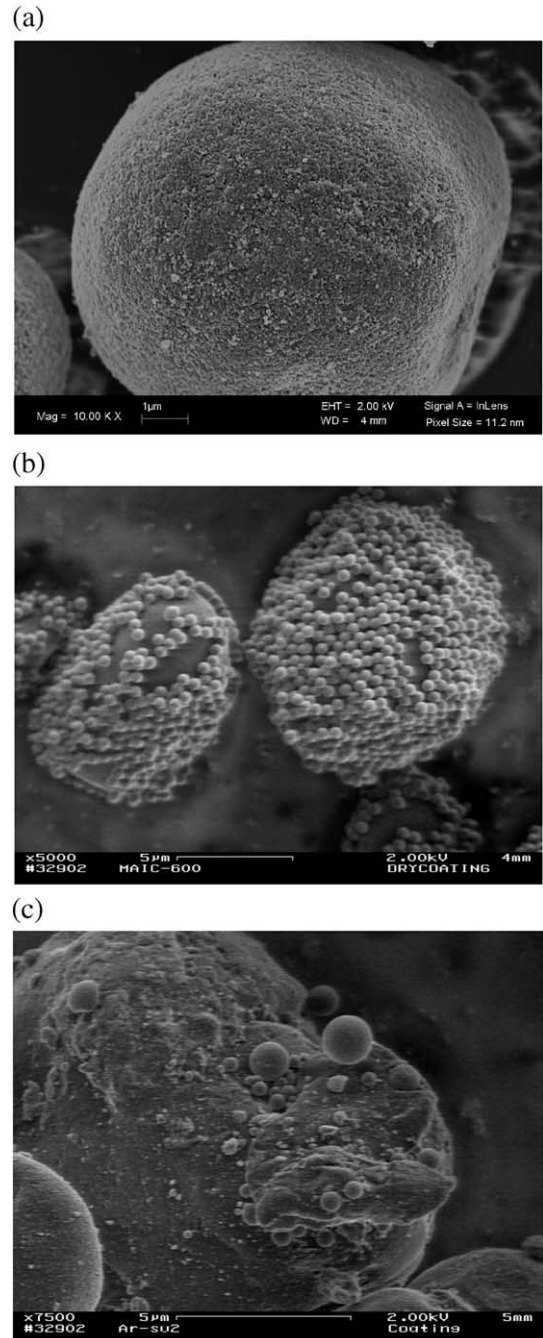


Fig. 11. FESEM images of 10-min MAIC coated samples with different silica. (a) EH-5; (b) COSMO55; (c) P-500.

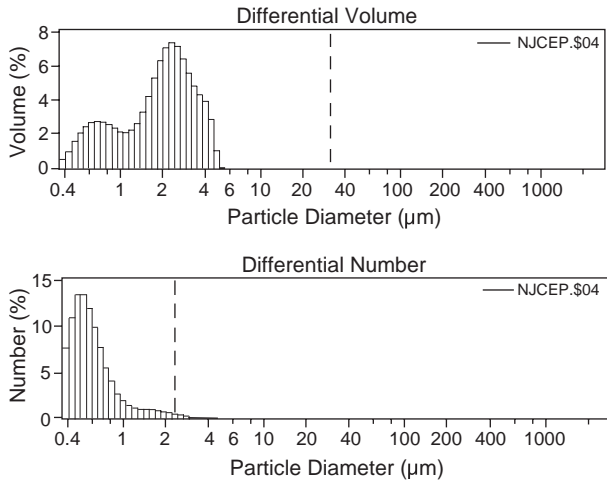


Fig. 12. Particle size distribution of P-500 silica.

silica guest particles, the particle size analyzer results (as shown in Fig. 12) indicate that it has a wide size distribution. The corresponding SEM image of the coated product also confirms that there is a lot of nanosized silica on the cornstarch surface (Fig. 10(c)), even though the average guest particle size is 2.25 μm. It is believed that these small nanosized particles are responsible for the improvement in the flowability of the coated cornstarch.

4.3. The effect of guest particle amount

As shown in Fig. 13, the AOR results of the MAIC coated samples indicate that the flowability of cornstarch is improved by increasing the amount of nanosized particles. By increasing the amount of guest particles (EH-5) from 0 to 0.01, 0.1 and 1.0% by weight, the corresponding AOR is reduced from 52 to 47, 30 and 27, respectively. FESEM images (Fig. 14) also clearly indicate that the surface

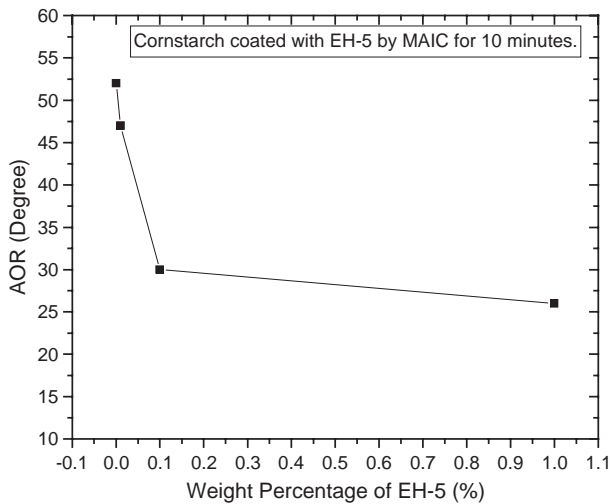


Fig. 13. Angle of repose of 10-min MAIC coated samples with different loading of EH-5.

coverage of the guest particles increases as the percentage of nanoparticles is increased. This is due to a decrease in direct contact of cornstarch particles with one another, which results in a reduction of Van der Waals force between the particles as discussed above. When the coating is very low, such as 0.01%, there is a high probability that no guest particles are present between the contact of two cornstarch particles, but as this amount is increased, the contacts always have the guest particle(s) present, reducing the cohesion.

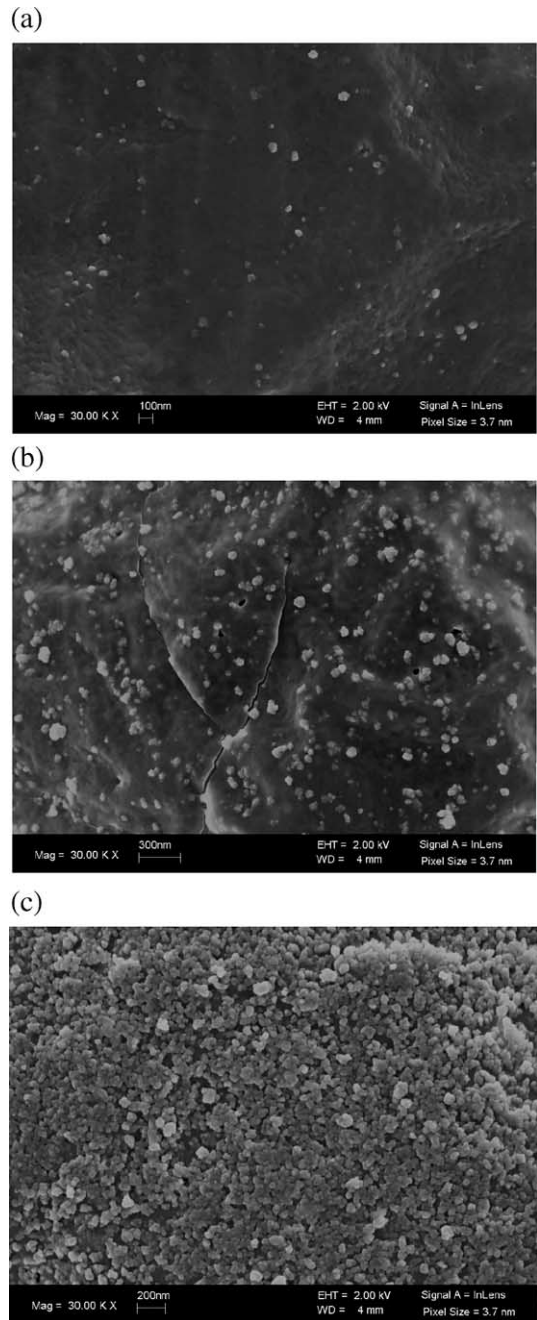


Fig. 14. FESEM images of 10-min MAIC coated samples with different loading of EH-5. (a) 0.01%; (b) 0.1%; (c) 1.0%.

Table 3

Surface coverage of cornstarch coated with EH-5 at different guest loadings using MAIC, processed for 10 min

EH-5 (wt.%)	0	0.01	0.1	1
Measured surface coverage (%)	0	1.96	10.72	90.23
Theoretical surface coverage (%)	0	1.10	10.97	100.00

Image analysis using MATLAB was also performed for the images shown in Fig. 14, the results shown in Table 3 indicate a surface coverage of 1.96%, 10.72% and 90.23% are obtained for 0.01, 0.1 and 1.0 wt.% silica loading, respectively. It is noted that the experimental surface coverage for the different silica loading is very close to the theoretical calculations which are 1.1, 10.9 and 100, respectively. The results indicate that MAIC appears to deagglomerate the guest particles more effectively and disperse them evenly onto cornstarch particles. These results and the corresponding AOR results also suggest that it is not advisable to add any more silica beyond 1.0 wt.%.

4.4. The effect of processing time

Experiments were also conducted to determine the effect of processing time using MAIC and VB. Since HB processing time is already quite small, i.e., 2 min, the effect of processing time was not studied in the HB. Fig. 15 shows the results for MAIC, indicating that when using 1.0% of EH-5 as the coating material, the AOR decreases from 33.9 to 23.6 as the processing time is increased from 5 to 40 min. When R972 is used as guest particles, the AOR decreases from 30.9 to 19.8. As shown in Fig. 1, both of these nanosized silica particles are highly agglomerated materials. Since MAIC is a relatively “soft” coating device, a longer processing time favors deagglomeration of the guest particles and a more uniform and larger surface coverage resulting in better flowability. Similarly, as shown in Fig. 16, a longer processing time improves the AOR results for

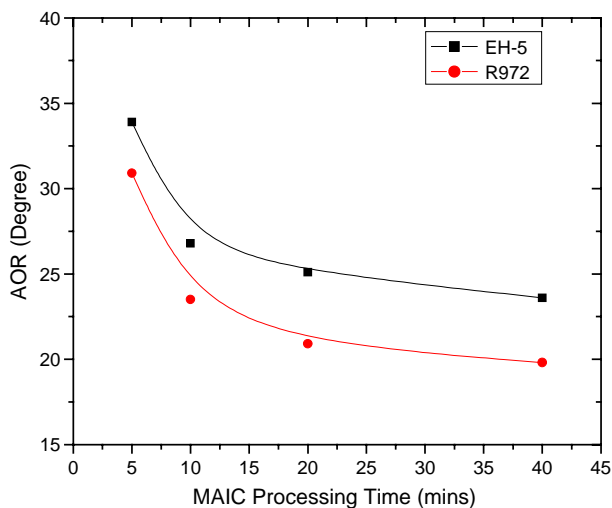


Fig. 15. Angle of repose of EH-5 (1.0 wt.%) and R972 (1.0 wt.%) coated samples using MAIC for 5, 10, 20 and 40 min.

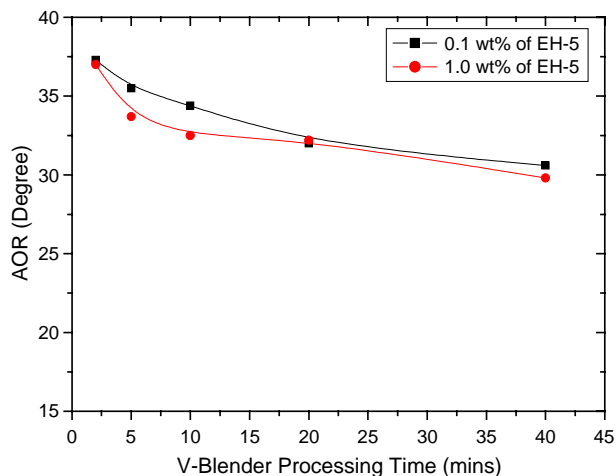


Fig. 16. Angle of repose of EH-5 coated samples using V-blender for 2, 5, 10, 20 and 40 min: (a) EH-5 0.1 wt.% and (b) EH-5, 1.0 wt.%.

the VB for both 0.1 and 1.0 wt.% of EH-5 loading. This was expected as longer processing time in a VB can improve the deagglomeration and subsequent dispersion of nano-silica agglomerates.

4.5. The effect of hydrophilic/hydrophobic surface properties

The results shown in Fig. 15 also indicate that hydrophobic nanosized silica is more effective in improving the flowability of cornstarch than hydrophilic silica. A hydrophobic silica surface is obtained by treating the hydrophilic silica surface with dimethyldichlorosilane which results in an alkyl ended surface molecule, which is water repellent. The water repellent surface reduces moisture adsorption and the formation of liquid bridges, rendering the cornstarch particles less cohesive and improving their flowability.

Furthermore, it is well known that the surface of cornstarch is rich in hydroxyl groups. Hydrophilic silica also has a surface that contain hydroxyl groups, but hydrophobic silica has a surface that contain alkyl groups. van der Vegate and Hadziioannou [18] have shown that the mean adhesion force (measured by AFM) between hydroxyl groups is 0.9 nN, but is only 0.3 nN between an alkyl group and hydroxyl group. This implies that the adhesion force for the hydrophobic silica coated cornstarch is smaller than the adhesion force for the hydrophilic silica coated cornstarch as per the AFM measurements. Thus the hydrophobic silica is more effective in improving the flowability of cornstarch compared to hydrophilic silica.

5. Conclusions

The comprehensive study reported here indicates that it is possible to improve the flowability of cornstarch by coating with nanosized silica, using dry coating devices such as MAIC and HB. A V-blender can also be used, but is less effective, especially for very small amounts of

guest particles. Although it is possible to obtain a uniform coating of 500-nm silica particles on cornstarch by processing in MAIC and HB, the coating does not improve the flowability; the large guest particles do not sufficiently reduce the van der Waals forces between the host particles. Based on the original Rumpf model for estimating the adhesion force between coated particles, a simple equation is presented that predicts that the amount of reduction in the cohesion force for the coated particles is inversely proportional to the size ratio of the guest and the host particles (or for large host particles the size ratio of the guest particles and the asperities of the host particles), indicating that smaller guest particles provide a larger reduction in the cohesive force. The experimental results agree with this theoretical prediction with the exception of 2.25 μm P-500, for which, the improvement in flowability observed is attributed to the large amount of fines present.

It is also found that increasing the amount of 20-nm silica (within a certain limit) as well as increasing the processing time, when using MAIC as the coating device, improves the flowability of cornstarch. An increase in the processing time makes the coating more even, and reduces the size of very small agglomerates of guest particles adhered on the surface of the host particles, and hence the “effective” guest particle size is reduced as a function of the processing time. Hydrophobic silica is more effective in improving the flowability of cornstarch than hydrophilic nanosized silica due to the elimination of liquid bridges if any moisture is present and the reduction of the adhesion force between the treated guest and host particles.

Nomenclature

A	Hamaker constant
d	diameter of guest particles
D	diameter of host particles
h_0	minimum separation between two contacting particles
P_{coated}	cohesion force in the presence of coated particles
P_{uncoated}	cohesion force without coated particles
ρ_d	density of guest particles
ρ_D	density of host particles
$\Delta\gamma$	surface energy
Γ	cohesion energy

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