NRRI Evaluation of Starch-Based Binders for Agglomerating Red Oak

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1.0 Objective

To identify the moisture uptake and durability performance of a variety of starch-based binders and additives when they are mixed with ground torrefied red oak wood and briquetted on a Komarek B220 roll press.

2.0 Project Summary

Cargill Industrial Starch (CIS) focuses on adding value to various starch fractionations through new market development. The purpose of this project is to identify the effect of different starch fractions on torrefied wood briquettes when blended at nominal 1% to 3% inclusion rates into torrefied red oak using the performance metrics of Kansas State Tumbling can durability and 24-hour moisture uptake. It was originally envisioned that conventional ring and die pelletizing could create testable 6.35 mm (¼ inch) pellets. However, after repeated failures and a multitude of die plugging issues, the decision was made to trial rotary briquetting as an alternative densification technique using a Komarek B220B briquetter.

Previous batching trials conducted by the NRRI with the Komarek B220B using torrefied red oak as feedstock have yielded viable briquettes across a variety of binder types. Recent upgrades to the densification circuit have been made and include new grinding, larger batching and conveyance devices that enhance the safety and operational aspects of the system while allowing a variety of individual and unique densification equipment to be set in place and operated consistent with client needs across a variety of industries.

3.0 Raw Materials

The batches and binder amounts (dry basis) used in this briquetting trial are shown in Table 1. The torrefied red oak used in the trial had an average torrefaction level ~23,721 J/kg (~10,220 Btu/lb) and was previously ground through a hammermill equipped with an 0.125 inch (3.175 mm) mesh screen.

Table 1. Batches trialed.

Batch Label	Binder Percentage
CS-0 (control)	0.0%
CS-1 (control)	0.0%
CS-2	1.0%
CS-3	3.0%
CS-4	1.0%
CS-5	3.0%
CS-6	3.0%
CS-7	3.0%
CS-8	3.0%
CS-9	2.2%
CS-10 (control)	0.0%

Note: CS-0 and CS-10 used a different oak t-wood (lower BTU and different particle distribution) compared to the t-wood the CS-1 through CS-9 batches used.

4.0 Equipment

- Balance
- Moisture Balance
- Oven
- Ro-Tap sieve shaker (Model: RX-29)
- Kansas Tumbling Can
- Komarek B220B Briquetter equipped with one smooth roll and one pocketed roll and die size of 1.0 inch x 1.5 inch (25.4 mm x 38.1 mm)
- 50 ft^3 (1.42 m^3) triple pass ribbon blender equipped with live steam injection and heated jacket

5.0 Production and Testing Methods

5.1 Moisture Content

The moisture content of the raw received material was taken at both the Coleraine and Duluth laboratories using a moisture balance. The moisture content of the raw material during briquette production was taken at key times in the process. The moisture of the collected briquettes was taken after the samples had undergone the appropriate curing time (at least 18 hours). The briquette moisture was taken by placing trays with three briquettes (taken from the steady-state sample bucket) into the oven for 24 hours and recording final moisture content on wet weight basis.

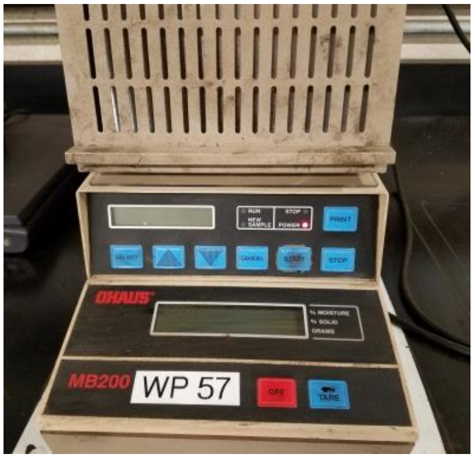

Figure 1. Moisture balance.

5.2 Particle Distribution

Particle distribution was determined using no. 8 (2.38 mm), 16 (1.19 mm), 20 (0.841 mm), 30 (0.595 mm), 40 (.420 mm), and 50 (0.297 mm) mesh sieves shaken for five minutes using a Ro-Tap sieve shaker (Model: RX-29). After five minutes, the mass retained on each sieve was determined.

Figure 2. Ro-Tap sieve shaker and sieve set.

5.3 Briquette Production

The pretreatment technique used in the briquetting trials was hot compaction. With hot compaction, the material is fed into a 50 ft^3 (1.42 m^3) triple pass ribbon blender equipped with live 15 lb. (67 N) steam injection and insulated heating blankets. The material is mixed and exposed to the heated environment for as long as necessary until the appropriate moisture content and material temperature is reached. The material is then transported through another screw, bucket elevator, and screw configuration before being fed into the B220 briquette machine where it is densified.

The B220 operation conditions were kept consistent by setting the screw feed rate at whatever speed invoked an 18–20 amp draw from the B220 briquette rolls; 18–20 amps was chosen as the standard during operation, as this implied that the briquette rolls were receiving consistent throughput from the feed screw to produce high density briquettes. The B220 hopper was also pre-filled to a certain level before starting the briquetting process to ensure that there was enough material to put a uniform load on the briquette rolls.

The following production parameters were pursued during the Cargill trials:

- Mixer exit temp = 150˚F–175˚F (66^{o}C–79^{o}C).
- Approximate tuned moisture = 6.0%–8.0%. Measured from sample port.
- Steam time = 15–30 minutes.
- Bottom roll is pocketed, and top roll is smooth.
- Roll speed = 11–13 RPM.
- Feed = adjusted to keep amps steady on briquetter rolls.
- Roll pressure = 2,500–2,700 psi (17,237–18,616 kPa).
- Roller gap = between 35 and 40 thousandths of an inch (0.89–1.02 mm).

Steady-state operating condition was defined as the point where the B220 briquetter roll amperage draw had stabilized around 18–20 amps and briquettes were ejected in a consistent and steady manner with a stable exit temperature. Once a steady-state condition was achieved, buckets of briquettes were collected and allowed to cure at ambient conditions before being analyzed.

Note: Sample buckets were marked for further testing if they were collecting briquettes at **steady state** and at the **mid-point of the production run.** Example: if five buckets were generated, the third or fourth bucket would be deemed the best candidate for further testing, as it was certain that there was no contamination from the previous mixture and the briquetter was not creating the low-density briquettes that usually form during the beginning and end of production.

Figure 3. Komarek B220 briquette press.

5.4 Bulk Density

The bulk density was measured by weighing a one-cubic-foot wooden box with briquettes. The briquettes were selected from buckets containing briquettes collected during steady-state production. The briquettes were poured into the box, and it was hand vibrated and shaken 15–25 times to consolidate the briquettes before weighing.

Figure 4. Equipment used for bulk density testing.

5.5 Fines and Flashing

To help demonstrate a material handling circuit of the briquettes, they were cast across a vibratory screen (Midwestern Screen, Model No. S-1578) with and any fines or flashing smaller than ½ inch measured. The steady-state five-gallon sample collected during a particular run were poured onto the screen (set at a 15˚angle) slowly to allow for uniform screening. The pounds of material that passed and survived on top of the screen was recorded and weighed. The migration of the briquettes across the screen and the corresponding fines and flashing smaller than 12.7 mm (½ inch) is depicted in Figures 5 and 6 below. It should be mentioned that in an actual circuit, these fines and flashing would represent the recirculation load that is conveyed back to the briquetter.

Figure 5. Vibratory screener and picture of briquettes during process.

Figure 6. Pictorial of the briquettes retained on the screen and the fines passing.

5.6 Kansas State Durability

Those briquettes that survived the screening were then subjected to a tumbling durability test. Tumbling durability was performed using a Kansas State Tumbling Can method (Seedburro Durability Tester, Fig. 7) with a modified approach to accommodate briquettes versus pellets. The 500 g of the briquettes were placed into the tumbling can and tumbled for 10 minutes at the standard 50 rotations per minute. After 10 minutes, the sample was removed, placed on a 7/16 inch mesh (11 mm) sieve, sieved for 2 minutes, and the +7/16 inch mesh (+ 11 mm) sample was weighed. Percent durability was determined using the following formula: $(\frac{Final\ Mass}{Initial\ Mass})$*100. This test was done in replicates of five.

Figure 7. Kansas Tumbling Can apparatus.

5.7 Moisture Uptake

Water uptake was determined by completely submerging a group of briquettes in water (Fig. 8). The percentage uptake of water was determined 24 hours after the briquettes were removed and allowed to free drain on a paper towel for 1–3 minutes. The mass was then determined. This is done at two different time points: before immersion and after 24 hours. A decrease in mass after 24 hours corresponds to substantial disintegration of the briquettes. Percent-moisture uptake was determined using the following calculation:

$$\left(\frac{(Final\ Mass - Initial\ Mass)}{Initial}\right) * 100$$

Figure 8. Visualization of water immersion and uptake procedure.

5.8 High Heating Value

The high heating value of samples was measured at the Biomass Conversion Lab by using an IKA C 200 Calorimeter (Fig. 9).

Figure 9. IKA C 200 Calorimeter.

5.9 Proximate Fuel Analysis

Samples were also sent to a certified lab (Twin Ports Testing, Superior, WI) for proximate fuel analysis. Proximate fuel analysis was used to determine the ratio of moisture, ash, and volatile matter, fixed carbon by difference, sulfur, and SO_2 within samples. The high heating value was also determined.

6.0 Results

Figure 10. Visualization of the briquette product. CS-0 and CS-10 briquettes (left) consisted of t-wood that had a lower heating value and different particle distribution than the t-wood CS-1 through CS-9 (right) had.

Table 2. Twin Ports Testing proximate test results. All samples analyzed were in their raw, ground form as received.

Sample	As-Received Moisture (%)	Proximate Dry Basis Percent Composition					
		Ash Content (%)	Volatile Matter (%)	Fixed Carbon by Difference (%)	Sulfur (%)	Dry Basis BTU/lb	Dry Basis J/g
CS-0	N/A	N/A	N/A	N/A	N/A	N/A	N/A
CS-1	6.02	1.68	60.63	37.68	0.015	7608*	17,696
CS-2	9.16*	1.85	61.44	36.71	0.015	10,351	24,076
CS-3	5.03	1.50	60.21	38.29	0.012	10,380	24,142
CS-4	4.92	1.82	62.34	35.85	0.042	10,257	23,856
CS-5	5.53	1.61	59.00	39.38	0.015	10,460	24,328
CS-6	5.19	1.55	61.35	37.10	0.013	10,386	24,156
CS-7	4.52	1.43	65.37	33.20	0.012	9,934	23,105
CS-8	5.18	1.60	64.61	33.79	0.015	10,111	23,517
CS-9	5.21	1.56	59.78	38.66	0.023	10,555	24,550
CS-10	8.56	1.62	68.30	30.08	0.014	9,548	22,208

Note: Errors occurred during the CS-1 and CS-2 testing. The calorific value of CS-1 T-wood were tested separately and shown to contain a higher energy value (see Table 3). The moisture of CS-2 was also tested separately (Tables 3 and 4) and shown to be lower.

Table 3. Samples analyzed by the Biomass Conversion Lab.

Sample	Final Moisture Content at Mixer Before Briquetting	Moisture After Briquetting	Dry Basis BTU/lb	Dry Basis J/g
CS-0*	N/A	4.59%	9,006	20,948
CS-1*	N/A	5.06%	9,960	23,167
CS-1	12.98%	5.86%	9,740	22,655
CS-2	14.17%	6.42%	9,742	22,660
CS-3	11.77%	5.44%	9,739	22,653
CS-4	14.72%	5.88%	9,606	22,344
CS-5	11.73%	6.18%	9,728	22,627
CS-6	17.39%	5.38%	9,867	22,951
CS-7	9.49%	6.60%	9,433	21,941
CS-8	11.91%	6.17%	9,486	22,064
CS-9	13.45%	6.33%	9,840	22,888
CS-10*	14.28%	5.21%	8,649	20,118

*Raw feed

Table 4. Moisture content of raw feed (taken at NRRI-Duluth). Samples CS-0 and CS-10 were not available.

Batch Label	As-Received Moisture Content (Wet Basis)
CS-0	N/A
CS-1	7.40%
CS-2	5.70%
CS-3	6.30%
CS-4	6.30%
CS-5	7.40%
CS-6	7.60%
CS-7	6.70%
CS-8	6.50%
CS-9	6.20%
CS-10	N/A

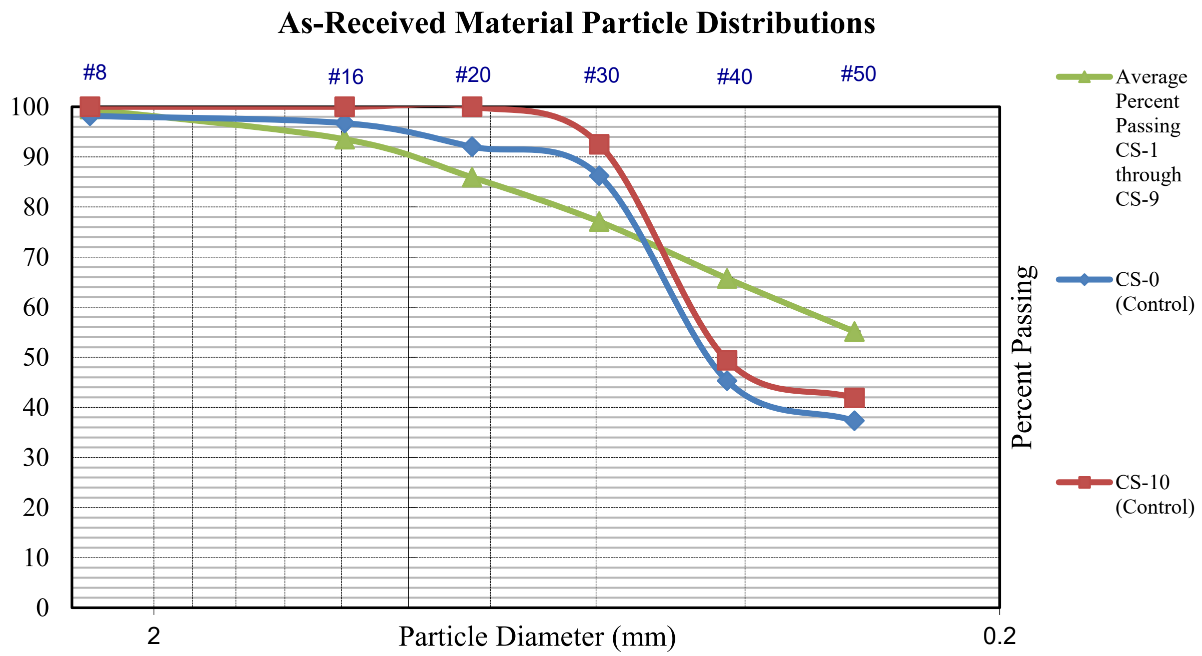

Figure 11. Particle distributions of ground material.

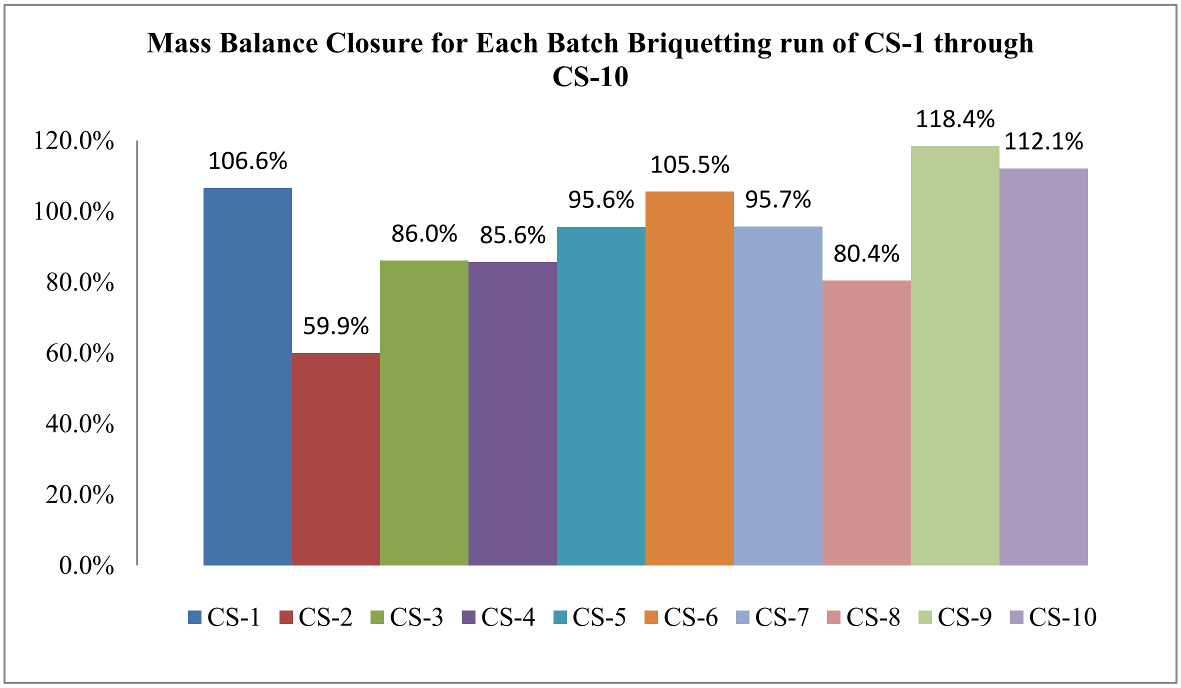

Figure 12. Mass balance closure expressed as a percentage of material recovered/ material fed.

Table 5. Process operating conditions of sample buckets taken at steady-state and used for screening, durability, and moisture uptake testing.

Production Date	Production Time of Day	Sample Label	Roller Pressure (psig)	Post Ribbon Mixer Feed Screw Setting (Hz)	Briquetter Feed Auger Setting (Amps)	Briquetter Roller Speed Setting (Amps)	Briquette Feed Temp (°F)	Post Compaction Briquette Temp (°F)
12/18/2018	8:58-9:03	CS-0	2900	25	4.8	18-20	80-100	100-120
12/18/2018	9:13-9:16	CS-1	2900	25	4.8	18-20	80-100	100-130
12/18/2018	9:40	CS-2	2900	25	4.8	18-20	80-100	110-135
12/18/2018	11:06	CS-3	2900	30	4.8	18-20	80-100	115-140
12/18/2018	12:18	CS-4	2900	30	4.8	18-20	80-100	115-140
12/18/2018	1:26	CS-5	2900	30	4.8	18-20	80-100	110-135
12/18/2018	2:39	CS-6	2900	30	4.8	18-20	80-100	120-145
12/19/2018	10:43	CS-7	2900	30	4.8	18-20	80-100	115-140
12/19/2018	12:36	CS-8	2900	30	4.8	18-20	80-100	115-140
12/19/2018	1:58	CS-9	2900	30	4.8	18-20	80-100	100-130
12/19/2018	3:18	CS-10	2900	30	4.8	18-20	80-100	120-140

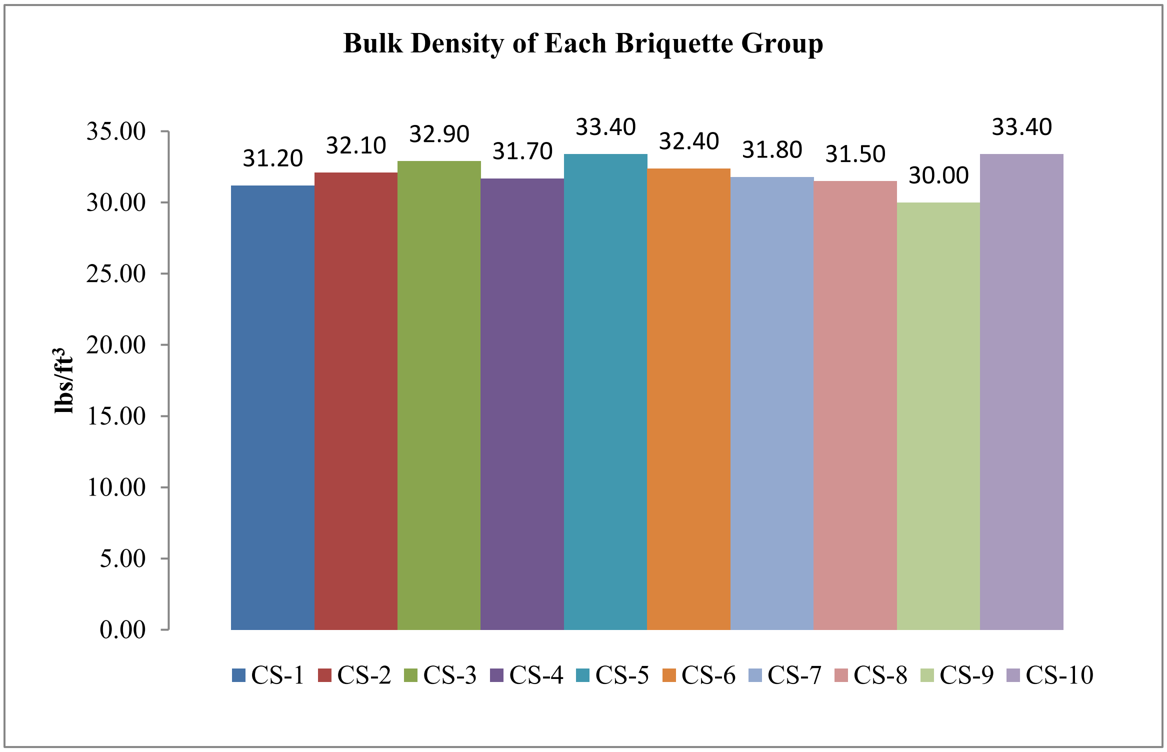

Figure 14. The bulk density of each briquette group within four hours of briquetting. Samples CS-5 and CS-10 were tested after 24 hours due to time restrictions. The densities (excluding CS-5 and CS-10) ranged from 30.0–32.90 lbs./ft^3 (480.6–527.0 kg/m^3) before curing.

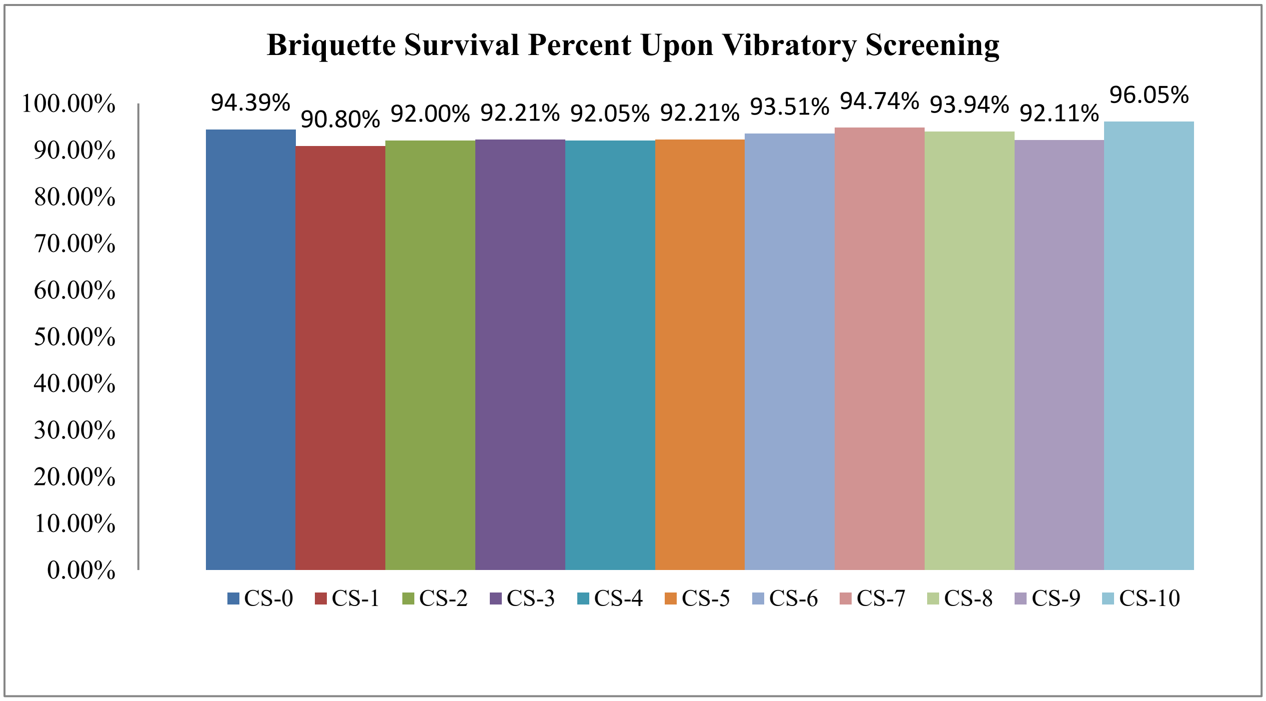

Figure 13. The percent survival of briquettes as they are cast across a 0.5 in. x 0.5 in. (12.7 mm x 12.7 mm) vibrating screen.

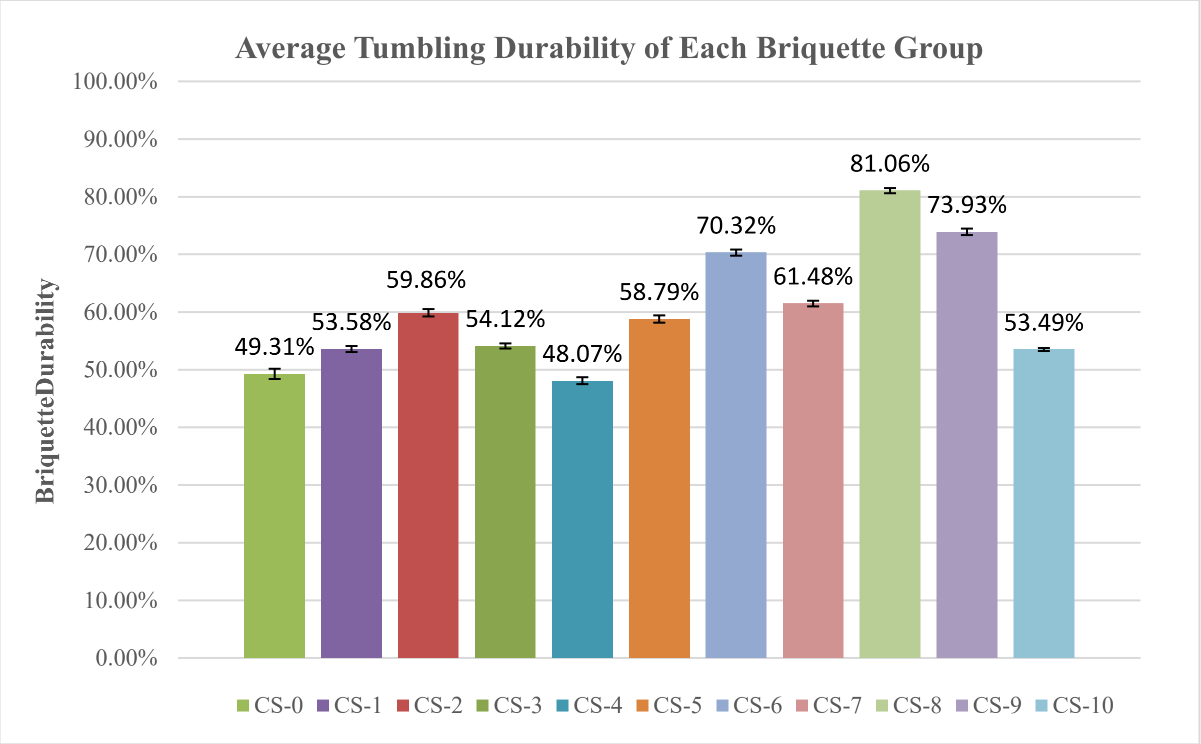

Figure 16. The average tumbling durability of each briquette group; standard error values shown.

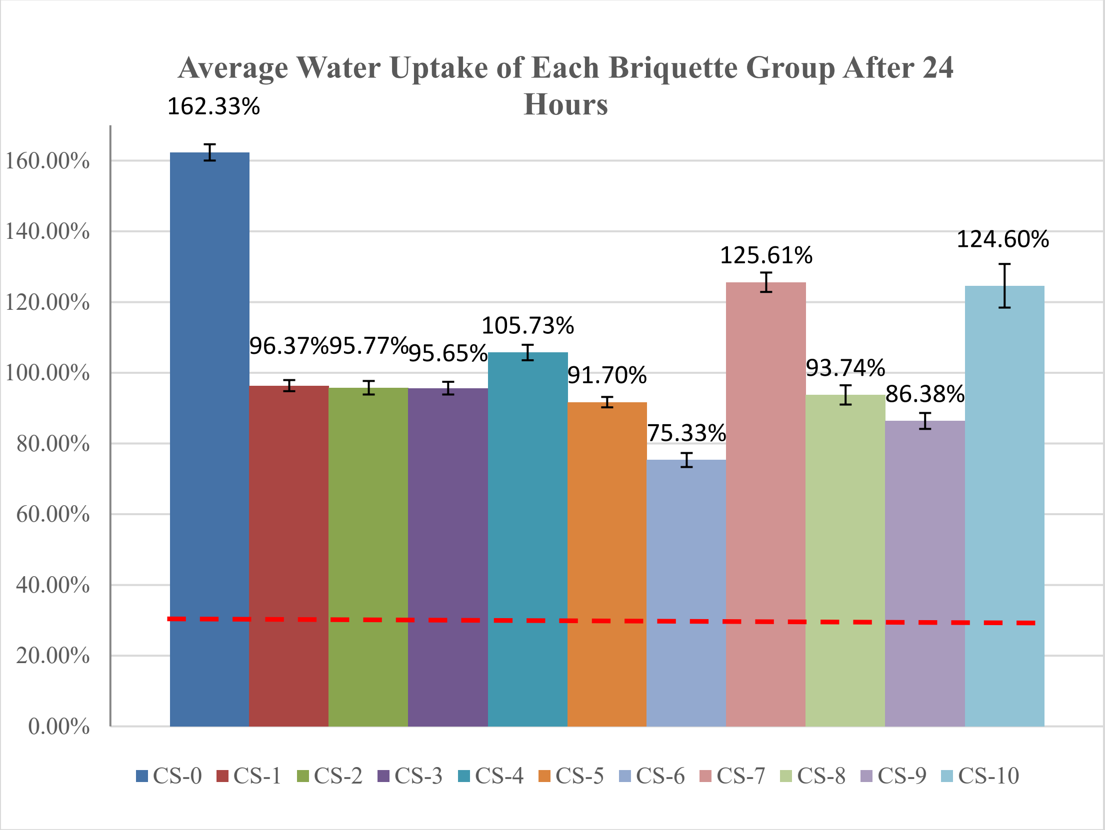

Figure 15. The average water uptake of each briquette group after 24 hours; standard error values shown.

Figure 17. CS-8 sample; this picture best represents the state of most of the briquettes after they are removed from immersion in water after 24 hrs.

Figure 18. CS-6 sample; this briquette group displayed the least amount of moisture uptake, and before immersion had a more specular (shiny) surface.

Figure 19. CS-10 sample; this picture best represents the level of disintegration that the samples CS-0, CS-7 and CS-10 displayed after 24 hours of water immersion.

Table 6. Final ranking of each batch.

Batch Label	Binder Percentage	Average Durability	Average Water Uptake	Rank
CS-0	0.0%	49.31%	162.33%	10
CS-1	0.0%	53.58%	96.37%	8
CS-2	1.0%	59.86%	95.77%	5
CS-3	3.0%	54.12%	95.65%	7
CS-4	1.0%	48.07%	105.73%	11
CS-5	3.0%	58.79%	91.70%	6
CS-6	3.0%	70.32%	75.33%	3
CS-7	3.0%	61.48%	125.61%	4
CS-8	3.0%	81.06%	93.74%	1
CS-9	2.2%	73.93%	86.38%	2
CS-10	0.0%	53.49%	124.60%	9

7.0 Discussion

The control samples CS-0 and CS-10 had to be drawn from torrefied and ground red oak inventory at the Biomass Conversion Lab (BCL). This was necessary because of the small sample volume – only 75 lbs – for the as-received control sample CS-1. As can be seen in Figure 10, the CS-0 and CS-10 briquettes had more of a brown color (left side), while the as-received control sample had a more blackened color. The brown coloration of CS-0 and CS-10 is due to the slightly lower heating value – 9,006 btu/lb and 8,649 btu/lb, respectively – from Table 3 recorded by the BCL and in Table 2, proximate analysis provided by Twin Ports Testing (TPT).

Table 3 lists the as-received moisture of the samples before they were conditioned with steam and after. The briquette moisture reflected in Table 3 generally shows a lower moisture content than the conditioned moisture taken at the mixer outlet. This is simply because the briquettes were hot as they exited the briquetter and lost some moisture upon cooling.

Figure 11 lists the average particle distributions for samples CS-1 through CS-9 compared to the control samples drawn from BCL torrefied oak inventory, CS-0 and CS-10. In general, the CS-0 and CS-10 control sample has more material passing a 20–30 mesh fraction and smaller proportion passing the 40 mesh fraction. The differences are attributed to the grinding equipment. The CS-1 through CS-9 samples were all prepared using a hammermill equipped with a 1/8-inch screen. The CS-0 and CS-10 samples were drawn from existing inventory of ground oak torrefied wood that was processed and ground through a turbulizer.

The mass balance closure for each briquette run CS-1 through CS-10 is depicted in Figure 12. In general, the mass recoveries averaged ~94 % across all the samples collected. The high hold up and mass loss displayed in sample CS-2 likely represents some pocketed areas within the conveyance system that filled initially but then released.

The process operating conditions over which the steady-state samples were collected is shown in Table 5. These settings were held as constants throughout the trial to help define any differences noted in durability or moisture uptake as a function of dosage or binder type. The NRRI project team felt these settings yielded the most consistent output. The average feed rate across all of the trials was nominal 400 lbs/hr corresponding to an energy utilization of ~-70 kwh/ton. This is likely on the high side for this briquetting trial, as no attempt was made to optimize or raise throughput.

Figure 13 shows the bulk density of each briquette group. The briquettes selected for this test were high quality (created during steady state) and representative of the group. The densities ranged from 30.0–32.90 lbs/ft^3 (480.6–527.0 kg/m^3). CS-5 and CS-10 were slightly higher because they cured for a day prior to testing.

Figure 14 displays the performance of each briquette group when being screened after curing. The idea behind this test was to determine if any briquette groups generated more fines than others (indicating poor binding). The result of the test was that 90.80%–96.05% of briquettes were retained on the 0.5 in. x 0.5 in. (12.7 mm x 12.7 mm) screen across all sample groups. No significant difference in screening performance was noted between samples (one sample bucket was done for each group). In general, this demonstrates that the recirculation of any fines or flashing fed back to the briquetting line would likely be in the 4%–5% range.

Figure 15 shows the results of the tumbling durability test. Five samples were done for each group (see Appendix A: Raw Data). The three controls (CS-0, CS-1, and CS-10) performed relatively similarly, with durability values in the range of 49.31%–53.58%. CS-4 was the worst batch with a binder (1.0% inclusion), with an average durability value of 48.07%. The five blends with 3.0% binder yielded higher durability results; the champion batch was CS-8, which averaged 81.06% survival. CS-9 had a lower binder inclusion (2.2%) yet had the second highest durability average at 73.93%.

Figure 16 shows the results of the water uptake test that were done in replicates of five. In previous hot briquetting trials with torrefied red oak, the NRRI has shown operating outlet temperatures in the 150°F–175°F (65°C–79°C) range, with moisture uptake levels of less than 30%. With moisture uptake of less than 30%, the briquettes are likely to better resist weathering, can potentially be stored outside and have a specular (shiny) surface that appears to aid moisture resistance. None of the briquette groups demonstrated uptake levels of less than 30% in this trial, and briquette temperatures with the new equipment layout never migrated past 145°F (63°C). However, it is worth noting that samples CS-6 had the lowest uptake, the most specular surface and the highest temperature range – 120°F–145°F (48°C–63°C) – and may be a candidate for further trials if moisture resistance is a requirement for a given application. The three controls (CS-0, CS-1 and CS-10) performed dissimilarly, with CS-0 and CS-10 having final uptake values in the range of 124.60%–162.33%. CS-1 absorbed 96.37% of its mass over 24 hours. The difference in control performance can be attributed to the degree of torrefaction and particle distribution. CS-7 was the worst batch with a binder (3.0% inclusion), with an average absorption value of 125.61%.

Figure 17 shows the state of the briquettes after they were immersed in water 24 hours – batches CS-1 through CS-5 and CS-8 and CS-9. In general, the briquettes in these groups kept their shape without collapsing. Figure 18 shows the CS-6 sample, which had the lowest moisture uptake recorded. Figure 19 shows the higher degree of disintegration seen in CS-0, CS-7 and CS-10. CS-4 had a higher water uptake value (105.73%) but also had a lower binder level at 1.0%. CS-6 performed significantly better than all other sample groups with the lowest absorption value of 75.33%. CS-6 briquettes were noted as having a shiny specular surface compared to other groups. CS-9 performed well at a lower binder inclusion level than CS-6 (2.2%) with the second-lowest absorption amount of 86.83%.

Table 6 displays the performance of each batch in both durability and water uptake level. The top three performers in the durability survival category were CS-8 (81.08%), CS-9 (73.93%) and CS-6 (70.32%). The top three performers with the least amount of moisture uptake category were CS-6 (75.33%), CS-9 (86.38%) and CS-8 (93.74%). The best performer in durability with the least amount of moisture uptake was CS-8.

8.0 Conclusions

The following conclusions were drawn from this briquetting trial:

1. The top three performers in the durability survival category were CS-8 (81.08%), CS-9 (73.93%) and CS-6 (70.32%).
2. The top three performers in the moisture uptake category were CS-6 (75.33%), CS-9 (86.38%) and CS-8 (93.74%).
3. CS-4 was less durable than all three controls, indicating a negative impact on bonding between the torrefied particles. CS-3 had a binder concentration of 3.0% and performed as well as the control CS-1 and CS-10, indicating no binding performance was gained.
4. CS-5, CS-6, CS-8 and CS-9 all absorbed significantly less water than CS-1 (the control with the same t-wood properties), indicating some gained hydrophobicity from these binders. CS-6 briquettes were quantitatively and qualitatively the most moisture resistant. CS-4 and CS-7 gained more water than CS-1, indicating the binder is hydrophilic or easily prone to re-wetting in a high-moisture environment.
5. The range of bulk densities generated in this trial ranged from a low of 30 lb/ft^3 for samples CS-9 and to a high of 33.4 lb/ft^3 for samples CS-5 and CS-10, well within the range of commercial briquettes.

9.0 Recommendations

The project team at the NRRI believes a larger-scale trial with one of the selected champion binders (CS-6, CS-8 or CS-9) would be an appropriate next step in the research process. It is worthy to note that the sample CS-6 had the most specular and shiny surface, had the highest noted temperature range – 49^{o}C–63^{o}C (120^{o}F–145^{o}F) – and demonstrated the least moisture uptake. A larger briquetting campaign with batches of at least 273 kg (600 pounds) could be done to definitively determine the differences between each binder or further optimize moisture uptake profile. This higher volume of material would also allow proper heating of the process equipment and yield a higher-grade product while also exposing the behavior of the starch under higher heat conditions. The specular surface imparted to the briquette may help to drive better weatherability and moisture resistance. In addition, manipulation of the binder chemistry should also be considered. Grafting on a hydrophobic tail to the starch could perhaps bring greater moisture resistance and open up new markets where conventional white wood or torrefied wood briquettes or pellets can be formulated with enhanced moisture resistance profile for ultimate outdoor bulk storage.

Appendix A: Raw Data

Table 7. Particle distribution data (see Fig. 11).

Raw Material Tested in Coleraine							
		Trial 2: CS-0			Trial 3: CS-10		
Mesh	**Diameter (mm)**	**Grams Retained**	**% Retained**	**% Passing**	**Grams Retained**	**% Retained**	**% Passing**
8	2.38	5	1.8%	98.2%	0	0.0%	100.0%
16	1.19	4	1.4%	96.7%	0	0.0%	100.0%
20	0.841	13	4.7%	92.0%	0	0.0%	100.0%
30	0.595	16	5.8%	86.2%	12	7.5%	92.5%
40	0.42	113	40.9%	45.3%	69	43.1%	49.4%
50	0.297	22	8.0%	37.3%	12	7.5%	41.9%
Pan		103	37.3%	0.0%	67	41.9%	0.0%
		276	Total		160	Total	

Table 8. Particle distribution data (see Fig. 11).

Raw Material Tested in Duluth							
		Trial 1: CS-5 Sample			Trial 2: CS-8 Sample		
Mesh	**Diameter (mm)**	**Grams Retained**	**% Retained**	**% Passing**	**Grams Retained**	**% Retained**	**% Passing**
8	2.38	0.18	0.2%	99.8%	0.49	0.5%	99.5%
16	1.19	3.81	3.9%	95.9%	7.25	7.4%	92.1%
20	0.841	5.74	5.8%	90.1%	8.79	8.9%	83.2%
30	0.595	7.51	7.7%	82.4%	9.56	9.7%	73.5%
40	0.42	10.22	10.4%	72.0%	11.73	11.9%	61.6%
50	0.297	10.06	10.2%	61.8%	10.49	10.7%	50.9%
Pan		60.64	61.8%	0.0%	50.11	50.9%	0.0%
		98.16	Total		98.42	Total	

Table 9. Particle distribution data (see Fig. 11).

Raw Material Tested in Duluth							
		Trial 3: CS-3 Sample			Trial 4: CS-2 Sample		
Mesh	Diameter (mm)	Grams Retained	% Retained	% Passing	Grams Retained	% Retained	% Passing
8	2.38	0.38	0.4%	99.6%	0.54	0.5%	99.5%
16	1.19	5.09	5.2%	94.5%	6.17	6.3%	93.2%
20	0.841	6.63	6.7%	87.7%	7.29	7.4%	85.8%
30	0.595	8.08	8.2%	79.6%	8.27	8.4%	77.4%
40	0.42	10.53	10.7%	68.9%	10.71	10.9%	66.5%
50	0.297	10.20	10.3%	58.6%	10.03	10.2%	56.3%
Pan		57.85	58.6%	0.0%	55.44	56.3%	0.0%
		98.76	Total		98.45	Total	

Table 10. Particle distribution data (see Fig. 11).

Raw Material Tested in Duluth							
		Trial 5: CS-7 Sample			Trial 6: CS-4 Sample		
Mesh	Diameter (mm)	Grams Retained	% Retained	% Passing	Grams Retained	% Retained	% Passing
8	2.38	0.71	0.7%	99.3%	0.42	0.4%	99.6%
16	1.19	8.05	8.1%	91.1%	5.21	5.3%	94.3%
20	0.841	9.20	9.3%	81.8%	7.34	7.4%	86.8%
30	0.595	10.18	10.3%	71.6%	8.68	8.8%	78.0%
40	0.42	12.41	12.5%	59.0%	11.54	11.7%	66.3%
50	0.297	10.75	10.9%	48.1%	11.20	11.4%	55.0%
Pan		47.63	48.1%	0.0%	54.23	55.0%	0.0%
		98.93	Total		98.62	Total	

Table 11. Briquette mass balance data (see Fig. 12).

Batch Label	Binder Percentage	Pounds of Material Into Briquetting Circuit	Pounds of Material Recovered After Briquetting	Percent of Mass Recovered
CS-0	0.0%	N/A	N/A	N/A
CS-1	0.0%	79	84.2	106.6%
CS-2	1.0%	147	88.1	59.9%
CS-3	3.0%	145.5	125.2	86.0%
CS-4	1.0%	154.5	132.3	85.6%
CS-5	3.0%	98	93.7	95.6%
CS-6	3.0%	150.5	158.8	105.5%
CS-7	3.0%	155.5	148.8	95.7%
CS-8	3.0%	154.5	124.2	80.4%
CS-9	2.2%	75.5	89.4	118.4%
CS-10	0.0%	104	116.6	112.1%

Table 12. Bulk density data (see Fig. 13).

Batch Label	Bulk Density (lbs/ft^3)	Bulk Density (Kg/m^3)
CS-0	N/A	N/A
CS-1	31.20	499.78
CS-2	32.10	514.19
CS-3	32.90	527.01
CS-4	31.70	507.79
CS-5	33.40	535.02
CS-6	32.40	519.00
CS-7	31.80	509.39
CS-8	31.50	504.58
CS-9	30.00	480.56
CS-10	33.40	535.02

Table 13. Briquette vibratory screening data (see Fig. 14).

Batch Label	Pounds of Material Before Screening	Pounds of Material Retained on 0.5 Inch Screen	Pounds of Material Passing 0.5 Inch Screen	Percent of Mass Recovered	Percent of Mass Retained on 0.5 Inch (12.7 mm) Screen
CS-0	21.4	20.2	1.2	100.00%	94.39%
CS-1	17.4	15.8	1.4	98.85%	90.80%
CS-2	15.0	13.8	1.4	101.33%	92.00%
CS-3	15.4	14.2	1.4	101.30%	92.21%
CS-4	17.6	16.2	1.4	100.00%	92.05%
CS-5	15.4	14.2	1.2	100.00%	92.21%
CS-6	15.4	14.4	1	100.00%	93.51%
CS-7	19.0	18.0	1.2	101.05%	94.74%
CS-8	19.8	18.6	1.2	100.00%	93.94%
CS-9	15.2	14.0	1.2	100.00%	92.11%
CS-10	15.2	14.6	0.8	101.32%	96.05%

Table 14. CS-0 tumbling durability data (see Fig. 15).

Sample Description	**CS-0**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	499.00	268.85	53.88%
2	505.05	244.57	48.42%
3	500.43	261.47	52.25%
4	502.82	243.43	48.41%
5	501.06	218.30	43.57%
Average	501.67	247.324	49.31%
Standard Deviation	2.33	19.55	4.00%
Standard Error			1.79%

Table 15. CS-1 tumbling durability data (see Fig. 15).

Sample Description	CS-1		
Sample Number	Initial Mass	Mass Retained on Test Sieve After Tumbling	Durability (%)
1	503.24	284.32	56.50%
2	495.92	270.85	54.62%
3	501.94	254.92	50.79%
4	499.98	258.79	51.76%
5	501.80	272.28	54.26%
Average	500.58	268.232	53.58%
Standard Deviation	2.85	11.71	2.30%
Standard Error			1.03%

Table 16. CS-2 tumbling durability data (see Fig. 15).

Sample Description	CS-2		
Sample Number	Initial Mass	Mass Retained on Test Sieve After Tumbling	Durability (%)
1	504.17	308.74	61.24%
2	504.86	310.08	61.42%
3	501.73	301.13	60.02%
4	503.36	306.40	60.87%
5	499.86	278.77	55.77%
Average	502.80	301.024	59.86%
Standard Deviation	2.01	12.90	2.35%
Standard Error			1.05%

Table 17. CS-3 tumbling durability data (see Fig. 15).

Sample Description	CS-3		
Sample Number	Initial Mass	Mass Retained on Test Sieve After Tumbling	Durability (%)
1	495.94	279.00	56.26%
2	499.70	278.61	55.76%
3	498.03	267.18	53.65%
4	500.71	261.49	52.22%
5	504.83	266.06	52.70%
Average	499.84	270.468	54.12%
Standard Deviation	3.32	7.90	1.81%
Standard Error			0.81%

Table 18. CS-4 tumbling durability data (see Fig. 15).

Sample Description	**CS-4**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	498.97	246.26	49.35%
2	500.40	249.88	49.94%
3	497.91	216.97	43.58%
4	500.69	236.38	47.21%
5	500.07	251.52	50.30%
Average	499.61	240.202	48.07%
Standard Deviation	1.15	14.25	2.78%
Standard Error			1.25%

Table 19. CS-5 tumbling durability data (see Fig. 15).

Sample Description	**CS-5**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	495.90	287.76	58.03%
2	504.94	307.91	60.98%
3	503.91	281.04	55.77%
4	499.86	288.60	57.74%
5	504.20	309.83	61.45%
Average	501.76	295.028	58.79%
Standard Deviation	3.83	12.99	2.38%
Standard Error			1.06%

Table 20. CS-6 tumbling durability data (see Fig. 15).

Sample Description	**CS-6**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	498.01	353.76	71.03%
2	504.52	365.49	72.44%
3	500.17	350.93	70.16%
4	497.97	349.12	70.11%
5	496.08	336.48	67.83%
Average	499.35	351.156	70.32%
Standard Deviation	3.23	10.39	1.68%
Standard Error			0.75%

Table 21. CS-7 tumbling durability data (see Fig. 15).

Sample Description	**CS-7**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	501.41	316.12	63.05%
2	500.82	310.57	62.01%
3	505.45	317.60	62.84%
4	498.64	304.05	60.98%
5	501.50	293.48	58.52%
Average	501.56	308.364	61.48%
Standard Deviation	2.46	9.88	1.84%
Standard Error			0.82%

Table 22. CS-8 tumbling durability data (see Fig. 15).

Sample Description	**CS-8**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	502.11	412.6	82.17%
2	501.84	407.5	81.20%
3	503.27	399.03	79.29%
4	503.44	404.44	80.34%
5	495.77	407.91	82.28%
Average	501.29	406.296	81.06%
Standard Deviation	3.16	5.00	1.27%
Standard Error			0.57%

Table 23. CS-9 tumbling durability data (see Fig. 15).

Sample Description	**CS-9**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	499.41	382.07	76.50%
2	505.23	368.91	73.02%
3	503.05	362.41	72.04%
4	496.91	366.61	73.78%
5	505.43	375.46	74.29%
Average	502.01	371.092	73.93%
Standard Deviation	3.74	7.74	1.67%
Standard Error			0.75%

Table 24. CS-10 tumbling durability data (see Fig. 15).

Sample Description	**CS-10**		
Sample Number	**Initial Mass**	**Mass Retained on Test Sieve After Tumbling**	**Durability (%)**
1	500.77	266.99	53.32%
2	505.71	279.93	55.35%
3	498.23	264.41	53.07%
4	497.55	266.16	53.49%
5	502.42	262.30	52.21%
Average	500.94	267.958	53.49%
Standard Deviation	3.31	6.93	1.15%
Standard Error			0.52%

Table 25. CS-0 Water uptake data (see Fig. 16).

Sample Description	**CS-0**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	76.91	75.86	76.24	77.32	74.30
24 hours	125.64	123.91	124.60	128.05	122.23
Mass of Net/Hook	46.83	46.39	46.21	46.96	44.05

Table 26. CS-1 Water uptake data (see Fig. 16).

Sample Description	**CS-1**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	75.78	76.99	72.66	76.14	74.05
24 hours	105.90	105.83	99.23	104.86	101.60
Mass of Net/Hook	46.23	46.97	43.81	46.57	44.93

Table 27. CS-2 Water uptake data (see Fig. 16).

Sample Description	**CS-2**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	76.61	74.17	75.88	76.00	75.87
24 hours	106.41	102.02	104.36	102.59	103.37
Mass of Net/Hook	47.13	45.34	46.92	46.29	46.40

Table 28. CS-3 Water uptake data (see Fig. 16).

Sample Description	**CS-3**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	73.74	75.27	76.19	77.17	75.58
24 hours	102.66	104.07	104.09	104.38	103.00
Mass of Net/Hook	44.93	46.20	46.26	46.98	46.86

Table 29. CS-4 Water uptake data (see Fig. 16).

Sample Description	**CS-4**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	74.62	72.69	72.29	74.87	75.73
24 hours	102.57	102.84	101.61	105.87	107.52
Mass of Net/Hook	46.41	44.07	44.12	46.57	46.99

Table 30. CS-5 Water uptake data (see Fig. 16).

Sample Description	**CS-5**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	77.33	77.53	75.48	75.50	78.77
24 hours	104.10	104.00	104.07	102.39	106.91
Mass of Net/Hook	47.63	47.19	45.70	45.76	49.05

Table 31. CS-6 Water uptake data (see Fig. 16).

Sample Description	**CS-6**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	77.34	77.51	78.26	76.23	78.12
24 hours	102.87	99.93	99.53	98.51	99.82
Mass of Net/Hook	47.44	47.68	48.15	46.02	47.86

Table 32. CS-7 Water uptake data (see Fig. 16).

Sample Description	**CS-7**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	78.35	77.78	76.95	78.10	76.82
24 hours	114.71	114.61	116.00	113.18	115.21
Mass of Net/Hook	48.66	48.49	46.91	48.66	47.44

Table 33. CS-8 Water uptake data (see Fig. 16).

Sample Description	**CS-8**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	76.54	78.46	78.44	78.00	77.51
24 hours	103.39	104.24	105.97	106.01	108.24
Mass of Net/Hook	46.89	48.72	48.40	48.85	47.88

Table 34. CS-9 Water uptake data (see Fig. 16).

Sample Description	**CS-9**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	77.29	77.01	76.04	77.51	74.84
24 hours	100.24	103.94	100.40	102.91	100.16
Mass of Net/Hook	47.47	48.06	47.97	48.28	46.14

Table 35. CS-10 Water uptake data (see Fig. 16).

Sample Description	**CS-10**				
Time	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**	**Mass + Net/Hook**
0 min	78.34	77.87	75.83	76.57	79.58
24 hours	121.18	114.15	113.70	115.39	114.59
Mass of Net/Hook	47.78	48.06	45.61	45.89	47.54