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Assessing the Potential of Bio-based Coatings for Secondary Bundle Packaging

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Abstract

In recent years, there has been a notable shift from plastic packaging to fibre-based alternatives. Ensuring that fibre-based packaging maintains all functionalities of its plastic counterpart is essential. This research focuses on a specific aspect of this transition: the resistance to water and moisture.

A critical divergence in material properties between LDPE (Low-Density Polyethylene) and fibre-based materials lies in water resistance. The inherent lack of natural water resistance in fibre-based materials underscores the importance of coatings in the success of fibre-based packaging. To address this challenge, two specially designed coatings were developed in collaboration with chosen companies. Following to a promising lab testing phase, a dedicated testbench was constructed for practical real-life evaluations.

Close cooperation with a coating research company played a key role in unveiling the true potential of these coatings. Particularly, a bio-based coating emerged as a viable solution to enhance water resistance in paper packaging.

Keywords: Cobb test; water barrier; Recyclable; coating; sustainability

Introduction

In prior research [1], a search for substitutes for collation shrink bundle packaging (Figure 1a) was performed. The objective was to find a packaging concept adaptable to a broad spectrum of bundles, ranging from four to eight products. Roman et al. together with the expertise of the VPK company [2] in fibre-based materials, resulted in a novel packaging called the Ecobundle, shown in Figure 1b.

The lack of resistance to moisture and rain is one of the main disadvantages of paper when compared to plastic [3]. Applying a PE coating, which involves adding a thin film layer to the surface, could address the issue. However, this solution doesn't align with sustainability goals as it complicates the paper recycling process [4].

The study evaluates the water barrier of bio coating of fibre based secondary packaging, more specific the Ecobundle and standard collation shrink film. Testing is divided into two pillars. One part of testing is lab-scale testing. This provides extensive data sets that can be used to determine the best performing coating. In addition, predictions can be made of how the coating will perform in practice. However, there are no predetermined benchmarks available for the lab tests, making field tests unavoidable for drawing conclusions and convincing potential interested stakeholders. Therefore, the second test phase contains testing with the Human Walking Simulator (HWS), a novel test bench, specifically designed for this purpose. By adding rainfall to the simulator in addition with the simulated walking forces, practical situations can be simulated.

Figure 1: (a) Collation shrink film (b) Ecobundle.

A fibre based packaging like the Ecobundle can come with a paper based handle. The researchers state that the fibre based material is strong enough [1], but doesn't mention the influence of rain of humid environments. Therefore, next to the Ecobundle itself, the paper based handle is also coated and tested.

Materials and Methods

Coating material

Subeco [5], a Belgium-based company, specialised in barrier technology for the fibre-based packaging industry, developed the 'ter-coat VPK1'. Emulco [6], a lab specialised in complex emulsions, proposed three types of coating. Table 1 gives an overview of the specifications for each emulsion. After consultation and some minor tests, it is concluded that an anionically charged emulsion results in better adhesion. This is because the anionic emulsion binds better with the anionic binders in the paper. In addition, low melting temperature of emulsions makes it impractical for packaging use under hot weather conditions. The decision is made to continue testing with Emulco's coating 40A-0103-001 and Subeco's Ter-Coat VPK1.

Company	***Subeco***	***Emulco***	***Emulco***	***Emulco***
Type	Ter-Coat VPK1	40A-0103-001	40A-0203-001	50A-0101-001
Dry residue [%]	42,5 – 44,5	39,9	39,99	49,52
Ph (25°C)	8 - 9	9,7	7,4	9,7
Viscosity (20°C LV 62-50rpm) [mPa.s]	100– 1000	158,00	68,00	43,00
Density 20°C [g/cm^3]	1,00	0,99	0,99	-
Static electric charge	anionic	anionic	anionic	cationic
Melt temperature [°C]	-	70	32	-

Table 1: Coating types.

Paper types

Roman et al. [1] performed various stability tests to select the carboard type with the most potential of a stable bundle. Table 2 provides an overview of carboard types with their specifications. Papers M, K and W are recycled liner papers which are used for corrugated board. They selected paper M with flute thickness of 1,5 mm, without testing the water barrier properties, therefore, all paper types are used for these tests. For these papers the upper side differs from the bottom side due to different treatments in the manufacturing process. Since cardboard needs to be moist resistant in some degree, the outer surface is treated with starch-based solvents [7]. The other side does not have the same requirements since it will be glued to other layers, thus remains susceptible for moist and water. Tests with papers M, K and W are executed on the treated side.

Board type	***Flute name***	***Board thickness***	***Line paper***
NEN	E	1,5	M
NBN	B	3	M
NCN	C	4	M
VCV	C	4	K
WCW	C	4	W

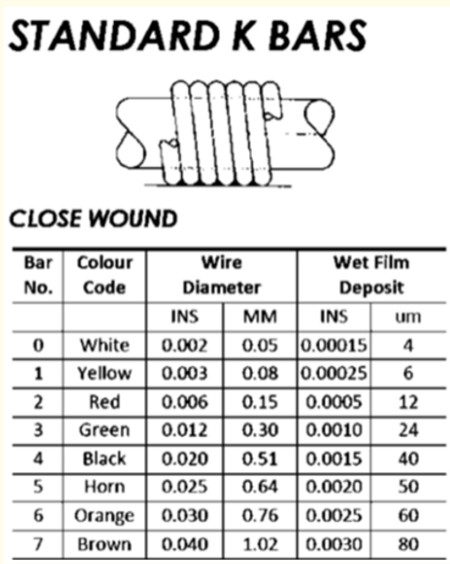
Table 2: Cardboard types.

In previous research, mechanical properties of an extensive range of paper types were tested. Paper B came out as the strongest paper with high stretchability and is selected for the handle.

Coating equipment

Samples are coated with different thicknesses of coating, which is done by hand using standard coating bars [8] as shown in Figure 2. The coating bars consist of a stainless steel wire drawn around a steel rod. Different wire sizes will create different gap sizes and deliver wet film, ranging from 4 to 80 micron thickness, depending on the wire size.

A sheet of paper gets clamped on the impression bed, which has a coating area of 220x340 mm. This bed has a rubber layer that avoids possible air gaps between the steel rod and the paper, which would cause more wet emulsion deposit than required. After applying a line of emulsion at the top of the paper over the entire width, the steel bar is pushed downward at a constant speed and pressure by hand.


STANDARD K BARS

CLOSE WOUND

Bar No.	Colour Code	Wire Diameter		Wet Film Deposit	
		INS	MM	INS	um
0	White	0.002	0.05	0.00015	4
1	Yellow	0.003	0.08	0.00025	6
2	Red	0.006	0.15	0.0005	12
3	Green	0.012	0.30	0.0010	24
4	Black	0.020	0.51	0.0015	40
5	Horn	0.025	0.64	0.0020	50
6	Orange	0.030	0.76	0.0025	60
7	Brown	0.040	1.02	0.0030	80

Figure 2: Standard K-Bars [8].

With the required grammage and density of the coating emulsion, the wet film deposit can be calculated, and the correct coating bar can be selected. For example, for the first test with Emulco coating and a desired dry coating grammage of 2 g/m^2:

Required coating grammage: 2 g/m^2 = 2 E-6 g/mm^2

Density coating: 0,99 g/ml = 0,99 E-3 g/mm^3

$$\rho\,.\,f = \frac{m}{V} = \frac{m}{A.\,d} = \frac{\rho_A}{d} \;\leftrightarrow\; d = \frac{\rho_A}{\rho}.\frac{1}{f} = \frac{2/1.000.000\ g/mm^2}{0{,}99/1.000\ g/mm^3}.\frac{100}{39{,}9} = 0{,}005\ mm = 5\ \mu m$$

Where:

ρ = density coating.
ρ_A = required area density coating.
m = wet mass coating.
V = wet volume coating.
A = coated surface area.
d = required wet film thickness.
f = dry rest factor.

Description of experiments

Cobb test

The Cobb test (ISO 535) [9] determines the amount of water a material can absorb by the surface in a certain amount of time. Firstly, the weight of the paper test sample with the dimensions of 125x125 mm is determined. Secondly, the test sample gets tightly clamped under a metal cylinder that covers 2500 mm^2 of the test sample. The cylinder, shown in Figure 3, is filled with water for 60 seconds (Cobb60) and emptied directly after that period. The samples with better test results are also subjected to a Cobb1800 test that lasts thirty minutes. After removing the excess water on the surface of the paper, the weight of the test sample, is determined again, as can be seen in the example of Figure 4. The difference in mass is the amount of absorbed water.

The water absorptiveness or Cobb value gives the mass of water absorbed in a certain time and is expressed in g/m^2.

To calculate the water absorptiveness A, the following equation is used:

$$A = (m_2 - m_1).\ 400$$

Where:

m_1 = the dry mass of the test sample [g].
m_2 = the wet mass of the test sample [g].

Figure 3: Cobb test cylinder.

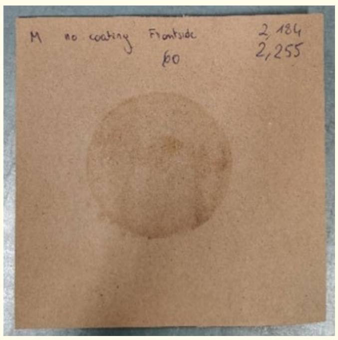


Figure 4: Cobb test sample.

Friction test

Since coating alters the surface texture of the material, the effects of coating on the friction coefficient are examined. The test is based on the horizontal plane friction test in accordance with ISO 15359 [10], but due to its unique design it does not fully comply with said standard. The test is executed on a linear tensile testing machine. A sheet of paper is clamped on the support block at the same height as the tensile machine's clamps as shown in Figure 5. Another sample and an incompressible steel block are placed on top and function as a sled. The mass of this block provides the normal pressure between the paper surfaces. The machine pulls the sled across the bottom sheet, creating friction. A load cell detects the force needed in the machine direction (MD) for the paper to move, which is required to calculate the friction coefficient. Figure 6 shows the setup that is built to perform the tests.

- Machine: Zwick bi-axial tensile testing machine.
- Movement speed: 75 mm/min.
- Travel distance: 25 mm.
- Sample width: 100±0,2 mm.
- Surface area: 100x120 mm.
- Sled mass: 2076 g, which applies a normal pressure of 1,70 N/mm^2.
- Clamp tightened to 12 Nm.

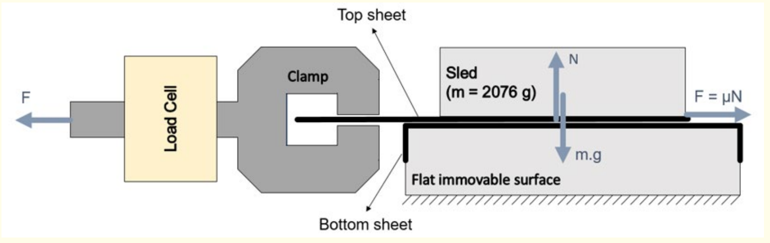


Figure 5: Schematically representation of friction test.

Figure 6: Friction test setup.

Five different scenarios are being tested:

- Frontside paper uncoated on frontside paper uncoated.
- Frontside paper coated on frontside paper uncoated.
- Frontside paper coated on frontside paper coated.
- Frontside paper uncoated on plastic label.
- Frontside paper coated on plastic label.

For each sample, five consecutive tests are conducted to consider the deterioration and change of the surface.

To calculate the friction coefficient, the following equation is used:

$$\mu = \frac{F}{N} = \frac{F}{m.g}$$

Where:

μ = friction coefficient [/].
F = friction force (MD) [N].
m = mass of the sled [g].
g = gravitational acceleration (9,81 m/s^2).

Each test generates a curve as shown in Figure 7, which shows the friction coefficient as a curve over the travelled distance of the surface. The static coefficient μs is derived from the maximum force in MD in the first part of travel (0-5 mm), while the kinetic coefficient μk is calculated from the average value in the zone where the curve stagnates (5-25 mm).

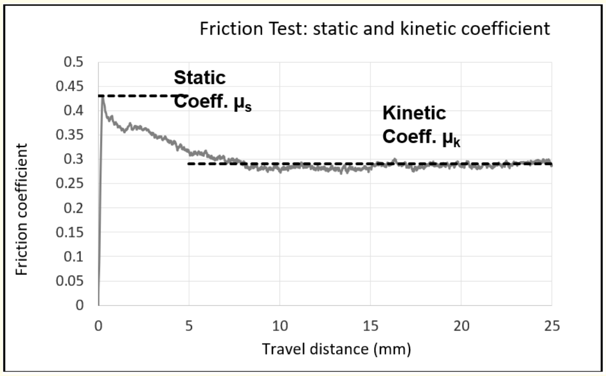


Figure 7: Friction test: static and kinetic coefficient.

Human Walking Simulator (HWS)

Since lab tests are very interesting to gain insights and compare two solutions, but do not offer the possibility to extrapolate the results to real-life situations, a new test bench with accompanying test protocol designed. The testbench is built to simulate walking forces with the possibility to add rain to the test. The simulator consists of a motor that can create a linear motion by an eccentric axis as shown schematically in Figure 8. This is controlled so that the forces experienced by the pack correspond to the forces on a pack during an average walking pattern of an average person. Tests were done beforehand where subjects walk with a pack of 6x1.5 l PET bottles equipped with an 'Endaq s4' accelerometer. This data was used to train the simulator to simulate the same accelerations. Afterwards, the sensor was also used to test if the simulator had the correct acceleration. The spread on forces during people walking is very large so average values were chosen.

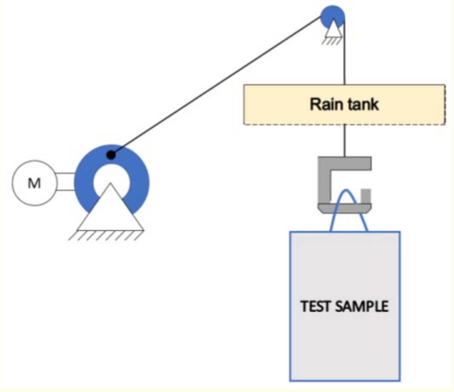


Figure 8: Schematically representation of HWS.

Next to the waling forces, the test bench simulates average rain by having the “rain tank,” indicated in Figure 9, containing small holes through which waterdrops can escape. Drop formation can be easily controlled by adjusting the water level in the tank. USGS researchers have defined average rainfall as 0.5 to 4 mm/hour [11]. Those average numbers have been the basis to determine the flow rate of the rain tank. Once calibrated at 2mm/hour, the rain tank’s flow rate is considered a constant during testing.

Figure 9: HWS.

With this test, not only the strength of the handle but also the strength of the tray is compromised. Therefore, this test is subdivided into a test for the handle where the tray is reinforced (Figure 10.a) and a test for the tray where the handle is reinforced (Figure 10.b).

The result is noted as the number of cycles the bundle has withstood.

Figure 10: Test sample (a) Enhanced tray (b) Enhanced handle.

Results

Cobb test

Cobb tests were conducted on all paper types discussed in 2.1 paper types. Where 'saturated' is indicated in the second column, the paper was too damaged by the water for correct results. In the case of Emulco's coating, the application method has not yet been determined. Different thicknesses are still possible and being tested. The Subeco coating was only tested in 1 configuration because the Subeco coating is applied using a FLEXOprinter [12], which fixes the thickness of the coating at 4µm when wet.

		COBB60 [G/M²]	***COBB1800 [G/M²]***
paper B (Mondi)	No coating	33.6	70.4
	Emulco 4µm	15.2	73.2
	Emulco 6µm	12.8	70.4
	Emulco 12µm	15.2	70.8
	Emulco 80µm	2.8	51.6
	Ter coat vpk	/	/
paper M (NCN)	No coating	28.4	Saturated
	Emulco 4µm	9.6	Saturated
	Emulco 6µm	5.2	Saturated
	Emulco 12µm	16.8	Saturated
	Emulco 80µm	0	Saturated
	Ter coat vpk	0	15.5
paper K (VCV)	No coating	21.2	Saturated
	Emulco 4µm	7.2	Saturated
	Emulco 6µm	11.2	Saturated
	Emulco 12µm	14.4	Saturated
	Emulco 80µm	12	Saturated
	Ter coat vpk	3	21.4
paper W (WCW)	No coating	30.2	Saturated
	Emulco 4µm	/	Saturated
	Emulco 6µm	/	Saturated
	Emulco 12µm	/	Saturated
	Emulco 80µm	/	Saturated
	Ter coat vpk	0	6.7

Table 3: Cobb test data.

When coating with Emulco's substance, the coating was tested through the K-bars in different thicknesses. It is clearly visible that greater water repellency is obtained with a thicker coating layer.

The last and most important observation is a clear difference between the Cobb values of the samples coated with emulsions of Emulco and Subeco. The Subeco coating has a water repellency score of 0 for 2 of the 3 paper types, indicating a complete water barrier. The Emulco coating, at the same thickness, still has a cobb value of 9.6 indicating a small absorption of water.

The Cobb1800 test, which lasted 1800 seconds or half an hour was only noted for the emulsion of Subeco. The test with the Emulco emulsion resulted in completely dissolved paper, which made the test corrupt and not possible to register. The longer the surface was exposed to water, the more it absorbed. The values for Cobb1800 are considered relatively low.

Friction test

In addition to making paper water repellent, the coating has another important consequence. Because of the coating, the coefficient of friction of the material changes. This is important because friction is supposed to hold the bottles together with the band and ensure that a bottle cannot slide out easily.

Table 4 shows a summary of all tests performed. As expected, static and kinetic friction decreases when conducting the test again on the same test samples due to the changing microstructure. This effect is shown in Figure 11, which shows five curves of the consecutive tests. By sliding the surfaces of the paper over each other, the rough peaks in the structure of the surface are flattened, resulting in a lower friction force. Except for coated paper on the plastic label, an increased friction force for each type of paper can be observed.

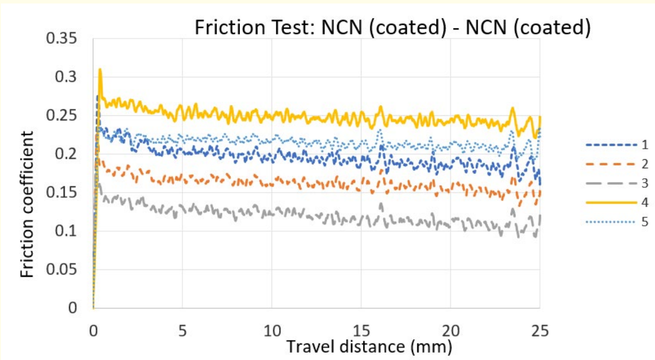


Figure 11: Friction test generated graph.

Adding a coating increases the friction between paper and both plastic and rubber. While it has no significant effect on the friction between two identical materials; the friction between two coated layers is on average the same as the friction between two uncoated paper surfaces. The friction decreases when these two are combined and coated paper is rubbed against uncoated paper. This last situation is uncommon since the cardboard is either coated or not. The increase in friction between paper and plastic after coating positively affects the stability of bundle packaging.

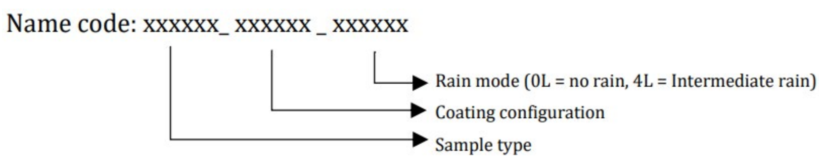
Material 1	***Material 2***	***µs***						***µk***					
		1	***2***	***3***	***4***	***5***	***avg***	***1***	***2***	***3***	***4***	***5***	***avg***
uncoated N	uncoated N	0.36	0.28	0.58	0.31	0.25	0.35	0.35	0.23	0.56	0.24	0.26	0.33
Subeco N	uncoated N	0.35	0.41	0.18	0.18	0.21	0.26	0.06	0.12	0.12	0.12	0.11	0.11
Subeco N	Subeco N	0.53	0.33	0.36	0.34	0.39	0.39	0.33	0.22	0.25	0.23	0.25	0.26
uncoated N	Plastic label	0.19	0.15	0.17	0.18	0.11	0.16	0.17	0.14	0.15	0.17	0.09	0.15
Subeco N	Plastic label	0.38	0.42	0.42	0.4	0.4	0.4	0.34	0.33	0.35	0.37	0.36	0.35
Emulco N	Plastic label	0.22	0.31	0.29	0.28	0.28	0.28	0.2	0.3	0.28	0.27	0.27	0.26
Emulco N	Emulco N	0.28	0.23	0.18	0.31	0.23	0.25	0.19	0.16	0.12	0.25	0.21	0.19

uncoated W	uncoated W	0.36	0.31	0.23	0.12	0.18	0.24	0.17	0.21	0.13	0.09	0.15	0.15
Subeco W	uncoated W	0.3	0.19	0.16	0.16	0.16	0.19	0.19	0.15	0.14	0.13	0.14	0.15
Subeco W	Subeco W	0.27	0.22	0.22	0.21	0.22	0.23	0.21	0.18	0.18	0.18	0.19	0.19
uncoated W	Plastic label	0.12	0.2	0.19	0.19	0.19	0.18	0.13	0.17	0.19	0.18	0.18	0.17
Subeco W	Plastic label	0.3	0.42	0.45	0.46	0.49	0.43	0.28	0.37	0.42	0.42	0.44	0.38
Emulco W	Plastic label	/	/	/	/	/	/	/	/	/	/	/	/
Emulco W	Uncoated W	/	/	/	/	/	/	/	/	/	/	/	/
uncoated V	uncoated V	0.36	0.4	0.52	0.5	0.46	0.45	0.26	0.33	0.46	0.42	0.4	0.37
Subeco V	uncoated V	0.41	0.21	0.21	0.18	0.18	0.24	0.19	0.14	0.14	0.13	0.13	0.15
Subeco V	Subeco V	0.43	0.39	0.4	0.39	0.36	0.39	0.38	0.35	0.36	0.36	0.28	0.35
uncoated V	Plastic label	0.15	0.17	0.17	0.16	0.16	0.16	0.15	0.16	0.17	0.15	0.16	0.16
Subeco V	Plastic label	0.71	0.73	0.71	0.65	0.71	0.70	0.62	0.58	0.61	0.56	0.54	0.58
Emulco V	Plastic label	0.3	0.19	0.19	0.34	0.19	0.24	0.29	0.47	0.48	0.34	0.48	0.41
Emulco V	Emulco V	0.33	0.22	0.19	0.13	0.14	0.20	0.29	0.16	0.12	0.09	0.08	0.14
uncoated B	uncoated B	0.2	0.17	0.15	0.16	0.1	0.16	0.15	0.15	0.12	0.13	0.09	0.12
Subeco B	uncoated B	/	/	/	/	/	/	/	/	/	/	/	/
Subeco B	Subeco B	/	/	/	/	/	/	/	/	/	/	/	/
uncoated B	Plastic label	0.25	0.25	0.22	0.22	0.25	0.24	0.23	0.2	0.18	0.2	0.2	0.20
Subeco B	Plastic label	/	/	/	/	/	/	/	/	/	/	/	/
Emulco B	Plastic label	0.31	0.3	0.25	0.28	0.27	0.28	0.27	0.28	0.23	0.26	0.27	0.26
Emulco B	Emulco B	0.28	0.25	0.27	0.25	0.23	0.26	0.23	0.21	0.22	0.2	0.19	0.21

Table 4: Friction test results (Tests marked with '/' were not performed or had corrupt results).

Field tests

After the lab-scale tests, tests are also conducted using the HWS to simulate real-world scenarios. From the lab tests, it was clear that Subeco builds up the best water barrier. Therefore, next tests were performed with the Subeco coating.



Description	*Test*	*Score*
TRAY_COATING_1side_4L	1	137
	2	150
	3	117
TRAY_COATING_2SIDE_4L	1	315
	2	298
	3	257
TRAY_NO COATING_4L	1	120
	2	115
	3	80

Vertical-HANDLE_NO COATING_4L	1	25
	2	18
	3	13
Vertical-HANDLE_COATING_4L	1	181
	2	256
	3	224
Horizontal-HANDLE_NO COATING_4L	1	35
	2	19
	3	24
Horizontal-HANDLE_COATING_4L	1	293
	2	125
	3	276

Table 5: Rain test results.

When water is added to the tests, the number of steps drops significantly. By splitting the tests into handle tests and tray tests, it is clear that the handle is the most water sensitive without coating. After the coating is applied, the tray and handle score is equivalent to an average of 220 steps for the handle with coating and 290 steps for the tray with coating.

Conclusion

All types of recycled liner papers from VPK were tested. The corrugated board NCN with matching liner M (as selected in paper [1]), has one of the top scores when considering moisture resistance with coating. The Cobb tests presents the level of water absorption for the tested surface. The first test series with a duration of 60 seconds, clearly show that different types of paper have different levels of water absorption. NCN and WCW score a Cobb value of 0, making them 100% water repellent for 60 seconds. VCV also scores a very low Cobb value. Cobb1800 values are remarkably low, meaning the coating does not dissolve in the first 30 minutes.

The friction tests showed that the static and kinetic coefficient of friction increased in the case of coated paper rubbing on a plastic label. This is a positive effect, due to the fact that the concept relies in part on the friction between paper and the bottle, this will ensure an even more rigid bundle. Lab-scale tests are positive and promising. But because there is no existing standard, there is no known requirement that the paper must meet to “function” in a practical environment such as a humid sunny day or a rainstorm. Lab tests are ideally suited to compare the two coatings. The Subeco coating scored best in the lab tests and this coating is used to proceed to practical tests with the HWS (Human Walking Simulator).

The HWS expresses the water resistance using a number of steps walked in what is called ‘average rain’ [6] with an ‘average walking pattern’ [13]. The simulator clearly shows, that the Ecobundle concept does require coating to use the packing method in a practical environment. Especially the handle cracks almost immediately after an average of 18 steps when raining.

When Subeco’s coating is applied to both sides of the plano, about 220 steps can be taken in the rain (290 for the tray and 220 for the handle). Still, there is no benchmark by which we can calibrate our Ecobundle and state whether the coating is adequate or not. But now, there is a clear link to the real-world situation. The 220 steps achieved correspond to 165 meters walked, calculated with an average step length of 75 cm [13]. It can be said that with coating, the packaging will be accepted by the market and the customer.

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