

Design of an absorbent and comfortable sanitary napkin for applications in developing countries

By

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ABSTRACT

Menstrual hygiene is an often-ignored problem in international development: lack of access to sanitation keeps women out of schools and the labor force. Sanitary napkin solutions to this issue normally focus on supply chain and manufacturing. This study aims to look at solutions from a materials perspective, assessing available materials for the properties needed for a good napkin, and reviewing the literature for comparison between these and other materials. Tests for absorption, comfort, durability, and drying time are measured on materials ranging from foam to traditional cottons both individually and in combination. These tests include microscopy observations, retention and wicking rate, tensile resistance, stiffness, and roughness. Though no single design emerges as the most effective for this application, clear differences emerge across materials that narrow down the options for optimal design. This information, in conjunction with user testing, can be used to inform local designs for sanitary napkins across borders.

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Introduction

Limited attention has been paid to the role of menstrual hygiene as a barrier to women's health and participation in society in the developing world. However, the effects on quality of living are substantial. Inadequate access to sanitation has been linked to school absenteeism, productivity declines, rashes and infections, and seclusion and embarrassment. (Bharadwaj, 2004). In fact, Poureslami et al (2008) found that 14% of girls studied between ages 15-18 in Iran stated that dysmenorrhea interfered with their daily life activities and caused them to be absent from school one to seven days per month.

Despite increasing innovation in this area of development, there has not been a generalized characterization of the types of materials or even properties that would be optimal for this application. Instead, most on-the-ground innovation focuses on streamlining the supply chain or the manufacturing process. Those that don't are often Western solutions that could never be produced locally, such as a menstrual cup. This study seeks to characterize and quantify properties of materials that are available in developing regions in order to determine the optimal sanitary napkin composition as a complement to user studies. Specifically, the region of study is rural Zambia, where access is available to markets that sell very basic materials. This study is a follow-up to a project from the International Development and Design Summit in Lusaka, Zambia in July 2013. During this project, local innovators were challenged with designing locally produced sanitary napkins. The project team relied on user feedback to understand the

effectiveness of their designs. This study seeks to complement such real-live testing in assessing the material properties that contribute to good napkin design.

Theory and Background

Estimate of need

The number of pads used by women during their estimated 32 reproductive years is staggering. Assuming thirteen menstrual cycles in a given year, with a requirement of eleven napkins per cycle, the average woman requires 4,500 napkins throughout her lifetime (Vostral, 2008). Currently, many of the women in developing countries rely on using old rags that propagate disease and that are insufficient in protecting from leakage (Bharadwaj, 2004). Further, and perhaps beyond the scope of this study, cultural taboos surrounding menstruation in many countries prevent large-scale or public changes.

A reusable solution is most logical for eliminating waste and for enabling affordability given the tangential problem of sustainability in development. Many modern technologies turn to the propagation of menstrual cups in order to fill these requirements. In many regions however, the use of invasive absorbents is culturally inadmissible. In addition, an economically feasible solution would ideally be one that is produced locally.

Existing technologies

The development of the sanitary napkin in the west has a long history that takes advantage of a number of innovations in materials and materials processing. Prior to the 1920s, American women hand-produced napkins from cotton, gauze, flannel, or rags to be pinned to undergarments and hand-laundered (Vostral, 2008). In essence, these were similar to the types of “napkins” that this study seeks, though again a well-grounded

understanding of the types of materials that were best to use was likely unknown.

Johnson and Johnson mass-produced disposable gauze-covered towels in 1890, and improved disposables that took advantage of advances in hydrogels entered the market in the 1970s (Bharadwaj, 2004).

A number of patents highlight the characteristics (and disadvantages) of modern pad design. Traditionally filled pads use hydrophilic wood pulp and rayon, though on their own these materials are slow to absorb fluids. Recently, super absorbent polymers (SAPs) have been incorporated into designs, which are lightly crosslinked polymers that swell when wetted. Non-woven pads containing SAP fiber absorb fluid faster while minimizing thickness (Zohuriaan-Mehr et al, 2010). Superabsorbent materials are subject to failure on their own, and many resilient materials are abrasive (Cadieux and Levesque, 1995).

Several designs focus on combining materials and structures that increase quick and high capacity absorption. Sodium carboxymethylcellulose, for example, is coupled with a cavernous structure to increase surface area, using a transverse webber in the molding process (Hujber and Walters, 1996). A unitized sanitary napkin achieves absorbance through a low-density cover layer, a higher density transfer layer, a very high density reservoir layer, and then finally an impermeable barrier layer (Cadieux and Levesque, 1995). In a more basic design, a primary absorbent layer of uncreped cellulose is layered with an embossed blend of coform fibers. (Dilnik et al, 1998). Save et al (2005) integrates superabsorbants based in attapulgite (aluminum silicate with hydroxyl groups at the surface) with fluff in a material that absorbs and retains about thirty times its weight under mechanical pressure of one to five kPa. He increases the specific surface

area by using porous agglomerates of smaller particles and incorporates a separation layer of nonwoven polypropylene fibers between an absorbent core and a porous cover sheet.

As might be expected however, the availability of advanced technologies such as super-absorbent hydrogels is limited in the target market. Therefore, substantial work is being done currently in order to improve menstrual hygiene options for women in developing countries where Western solutions are inaccessible. However few, if any, of these new solutions perform a rigorous analysis of materials in order to optimize for the properties that contribute to a successful pad. Studies that do explore materials properties generally focus on unusual materials that are available in very remote areas that lack access to cotton, eg banana fibers (Licht, Omran & Zhou, 2009).

There are a variety of new companies and products that are attempting to fill this need. Organizations such as ZanaAfrica, iCare, and Saathi pads work to localize production of reusable pads in order to provide income and increase sanitation. However, these technologies focus strictly on the production process, and do not take into account optimizing for material properties. As previously mentioned, many technologies applicable to developing regions are a cup design, which may be inappropriately invasive and cannot be locally reproduced. Example brands that are popular in the West include the Diva Cup ®, Mooncup ®, Lunette ®, and Sckoon ®. Finally, popular reusable brands in the US, notably Lunapad®, takes advantage of fleece-like materials that are unavailable in developing markets.

Characterization of fabrics

At their core, fabrics are characterized across a number of dimensions. The ASTM lists hundreds of standards ranging from material performance, tolerance,

identification of fibers, thermal resistance, and many more (Textile standards, 1996). Weaves are defined according to their warp and weft (the longitudinal versus transverse threads), their thread or yarn, and their ends per inch for tightness. Kawabata (1988) defines 16 standards to characterize the hand, or the “feel “of the fabric. The yarns are further measured according to a set of various units such as the denier (mass density), super S number (fineness of fiber), etc (Collier, 1970).

Given the immense amount of variation possible, this study is restricted to materials that are available in the market for less than the equivalent of 1 USD per meter in rural Zambia. In particular, the material properties that this study seeks to optimize are narrowed to those that would be most relevant to successful pad design. Save et al (2005) summarizes the requirements for an effective design, including the need to absorb and retain discharge, be in contact with the user without irritating skin, and a high wicking and fluid-retaining interior with a waterproof exterior. In addition, high porosity, tolerance to salts, low linting, and comfort are necessary. In a reusable design for the developing world, this study adds to this list durability (which would influence sustainability and affordability of a final product) as well as rudimentary drying time. The latter is included because a significant problem for the application is that, even if women and use and wash pads, it is inadmissible to dry them in public and therefore materials requiring minimal drying time are optimal. For this study, materials are tested specifically to maximize affordability, absorbance, durability and reusability, comfort, and drying time.

Absorption

Absorption is characterized in both the speed of uptake and the amount of liquid that the material can hold, and is dependent on both material properties and organizational structure. In addition, particle size, relative composition, and orientation may influence a material's absorptive ability. Gudmundsdottir et al (2009) measure the average total menstrual flow in the West (substantially lower in developing countries where nutrition levels are much lower) as approximately 51g during a menstruation period. Many studies quantify the absorption of fabrics through different measurements. Beskisiz, Ucar, and Demir (2009), for example, use the water absorption value (ratio of mass of material when saturated with water over mass of dry material) and drying time to determine the effectiveness of super absorbent fibers. Professor Steven Warner at the University of Massachusetts, Dartmouth (Personal interview, Feb 2014) discusses the rate of vertical wicking as critical to measuring speed of uptake, as well as the contact angle in order to measure wetting.

Comfort

Kawabata (1988) quantifies comfort as a measure of fabric performance through a series of sixteen measurements that define handle judgment, essentially the "feel" of a fabric. These measurements have standardized an objective measure for the "hand" of fabrics. These parameters include include koshi (related to bending stiffness), numeri (smoothness), "fullness and softness", shari (crispness), and hari (anti-drape stiffness). The full list may be found in figure 1.

Parameters		Description	Unit
Tensile	LT	Linearity of load/extension curve	none
	WT	Tensile energy	gf cm/cm ²
	RT	Tensile resilience	%
	EM	Extensibility, strain at 500gf/cm of tensile load	none
Bending	B	Bending rigidity	gfcm ² /cm
	2HB	Hysteresis of bending moment	gf cm/cm
Shearing	G	Shear stiffness	gf cm/deg
	2HG	Hysteresis of shear force at 0.5° shear angle	gf/cm
	2HG5	Hysteresis of shear force at 5° shear angle	gf/cm
Compression	LC	Linearity of compression/thickness curve	none
	WC	Compressional energy	gf cm/cm ²
	RC	Compressional resilience	%
Surface	MIU	Coefficient of friction	none
	MMD	Mean deviation of MIU	none
	SMD	Geometrical roughness	µm
Thickness	T	Fabric thickness	mm
Weight	W	Fabric weight	mg/cm ²

Figure 1: Mechanical and surface parameters of fabrics measured to standardize hand values and interpret comfort (Kawabata, 1988).

Behera et al (1997) and Radhakrisnaiah et al (1993) use Kawabata's fabric evaluation system to measure the tactile and thermal comfort properties of spun yarns and woven fabrics respectively, using a standard Instron tensile tester to measure tenacity and breaking. Bagherzadeh et al (2007) measures comfort properties for Spacer fabrics through quantifying air and water permeability, fabric bending, compression, and surface characteristics. Ibrahim et al (2010) and Kane et al (2007) measure the comfort of cotton fabrics and jerseys, respectively, through assessing air permeability, heat transmittance, hydrophilicity, and water absorbance.

Materials

This analysis uses two different sets of fabrics. First, the raw fabrics collected from shops in rural Zambia are measured across dimensions as a baseline. Table 1 lists

these materials, the notation that will be used for the rest of the study, and several key properties. Note that specific material identities are unknown,

Table 1: List of raw materials. ¹Fiber length is determined from imaging (see results). ²Assumed compositions determined from typical material compositions in the United States

Label	Standard material name	Density (average, g/cc +/- .01)	Fiber width ¹ (mm +/- .01 mm, mean)	Assumed composition ²	Structure
F	foam	0.011	0.142 (pore size)	polyurethane	porous
CB	cotton balls	0.061	0.016	cotton	non-woven, spun
M	mutton cloth	0.278	0.400 (bulk), 0.008 (individual thread)	cotton	weave
CC	cotton cloth	0.552	0.113 (bulk), 0.009 (individual thread)	cotton	weave
I	interfacing/stiffener	0.610	.009	polyester	non-woven web
P	plastic	0.975	N/A	polyethylene	amorphous



Figure 2: Raw materials used for testing. From left to right by row: foam, cotton balls, mutton cloth, cotton cloth, interfacing/stiffener, and plastic

Second, combinations of the raw fabrics are tested in order to determine changes on material properties based on potential combinations that might be developed for use.

As previously addressed, a realistic pad design would combine several materials (for example an absorbent layer, a waterproof layer, and a retaining layer) in order to effectively capture and hold flow. Table 2 lists the combinations selected. Note that the interfacing is excluded from all combinations because testing reveals a strong lack of durability, as addressed in the results. The materials are very loosely bonded together: Layers are stitched together on two opposing edges, with an additional knot stitched through the middle of the materials.

Table 2: Layer identities for combination samples. The first material listed is treated as the bottom of the pad

Mix number	Layer identities
1	Plastic, foam, mutton (P-F-M)
2	Mutton, foam, mutton (M-F-M)
3	Mutton, cotton balls, mutton (M-CB-M)
4	Cotton cloth, foam, cotton cloth (CC-F-CC)
5	Cotton cloth, cotton balls, cotton cloth (CC-CB-CC)
6	Plastic, cotton balls, cotton cloth (P-CB-CC)

Methods

Absorption, durability, comfort, and drying time of fabrics and their combinations are measured through a variety of mechanisms.

Absorption

Absorption is tested via three different metrics, all using tap water as the liquid. First, a basic pad absorption test is performed in which the ratio of the mass of a fabric saturated with water over the mass of dry fabric is measured (pad absorption = $m_{\text{saturated}}/m_{\text{dry}}$). This is repeated for all fabrics and then for combinations. No wringing of

the fabric is done in testing basic absorption. Rather, they are allowed to hang until dripping stops.

Second (and arguably more significantly), retention under weight is measured. A mass of 16.2 kg (force of 158.8 Newtons) is used to compress the fabrics and the test pads, and $m_{\text{squeezed}}/m_{\text{dry}}$ is recorded. Squeezed refers to wetted than dried, and dry is the initial, unaltered material.

Third, the fabrics are held in tension and the wicking rate is measured. 1 cm wide samples of fabric (four of each type) are suspended in air, with approximately one centimeter submerged in dyed water. Progression of water is measured each half hour up to 3 hours for each sample. See Figure 3 for schematic.

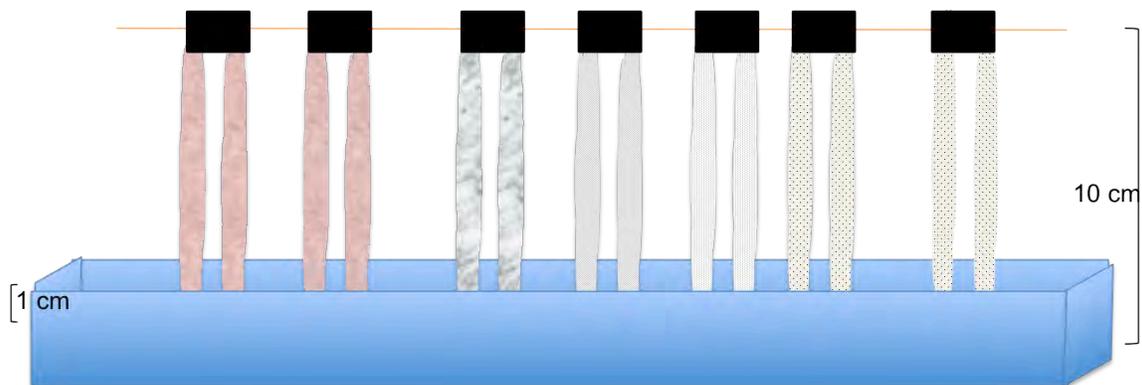


Figure 3: Setup for wicking rate test. Samples are suspended above a layer of water and water transfer rate is recorded.

Durability

Durability is quantified through two different major metrics. First, the combined samples are tested in tension using an Instron in order to determine resistance to force. The elastic modulus is determined in order to understand a material's resistance to movement and response to wear. A 500N load cell is used with a 50% load range with a 40mm deformation range in calibration at a crosshead speed of 7 mm per minute.

The combined samples are washed and dried repeatedly and vigorously in order to determine their durability. They are then imaged using a Hirox KH-8700 Digital Microscope at 160x magnification and the fracturing pattern (or lack thereof) is analyzed.

Comfort

Kawabata's research suggests a number of tests that may together give a quantitative measure of comfort. This data scratches the surface by combining the information from tensile testing with testing for bending stiffness. The flexural rigidity is first calculated using the elastic modulus and the area moment of inertia. Second, the samples are tested using the Instron under a 50 Newton load cell at a 50% load range, to a max displacement of 25mm at a crosshead speed of 5mm per minute.

In addition, a three-dimensional depth profile is recorded to get an idea for surface roughness from the Hirox KH-8700 digital microscope at 280x magnification. Though not included in Kitagawa's measurement of hand (feel), the deviation from the mean of the material gives an indication for the roughness and therefore comfort.

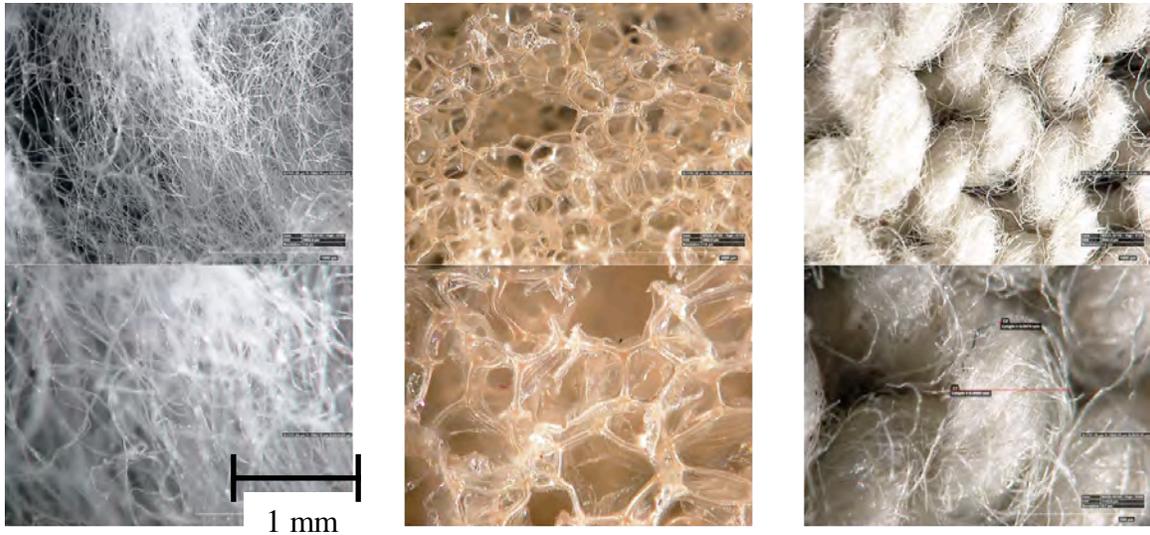
Drying time

A very rudimentary drying test is done to quantify the approximate time required for a saturated sample to dry. Initially, all materials were let out to dry on a uniform towel at room temperature. Drying times are approximate as the samples were checked every 10 minutes. Dryness was tested by touch, and time to dry was recorded when no sense of moisture was detected.

Results

Magnified images

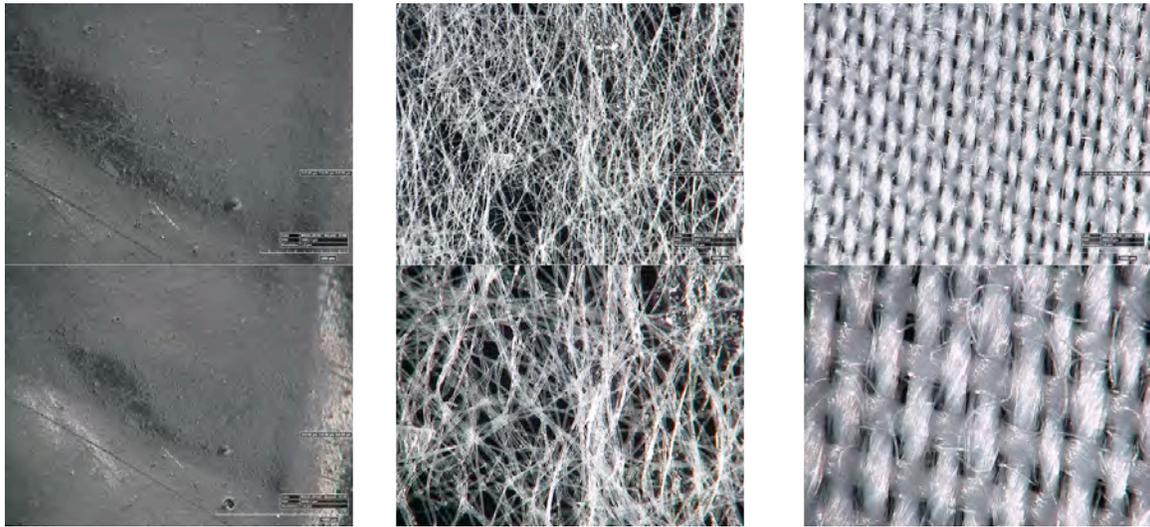
Figure 4 shows magnification of both 120x and 280x for the six basic materials used across this study. The images show substantial variation in composition, weaving/bonding pattern, and unit size. A summary of these differences is found in Table 1 in the materials section. In particular, cotton-based materials all have similar base width of cotton fibers, though the fibers are spun into varying size yarns and subsequent weaves.



a) cotton balls

b) foam

c) mutton cloth



d) plastic

e) interfacing

f) cotton cloth

Figure 4: 120x (top) and 280x (bottom) magnification of materials. Differences in bonding, composition, and unit size are summarized in the previous section.

Absorption

Pad absorption values

The absorption values are recorded in Figures 5 and 6 as described previously. The error bars represent the standard deviation in the range of recorded values for absorption of the given material. Without any sort of applied force, materials absorb

anywhere from 1.0 to 28.0g of fluid, with cotton and foam able to absorb the most fluid.

See Appendix 1 for detailed table of values.

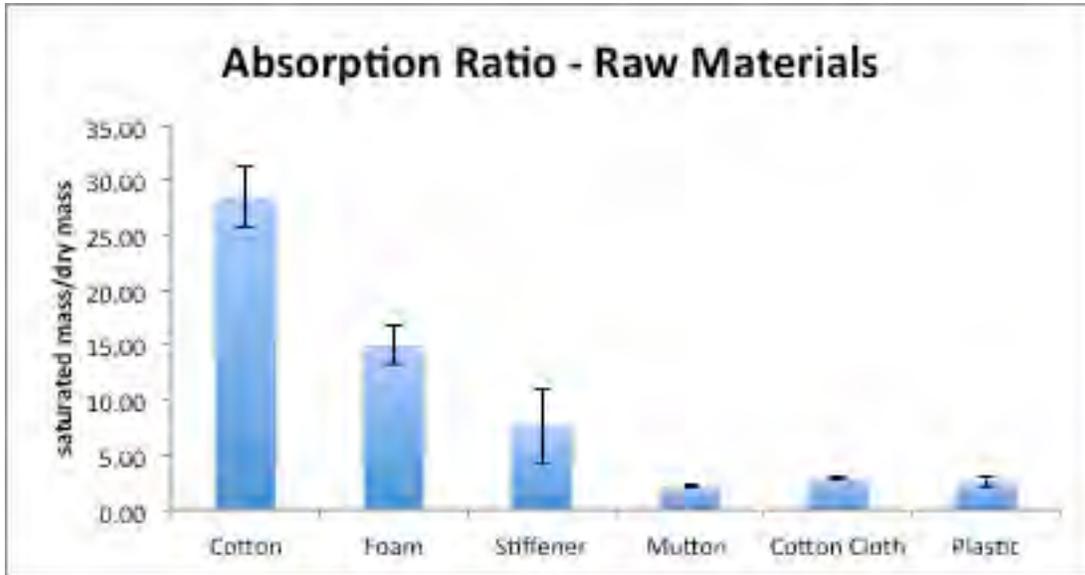


Figure 5: Absorption ratio of raw materials. Within error bars, cotton is by far the most absorbent material.

The same test is repeated for the six combinations of materials listed previously. As expected, the absorption ratio is generally in the middle range of the raw materials because each one is a combination of at least one of the less absorbing and one of the greater absorbing materials. Combinations 5 and 6, which have both cotton cloth and cotton balls, are unsurprisingly at the higher end of the spectrum of absorption.

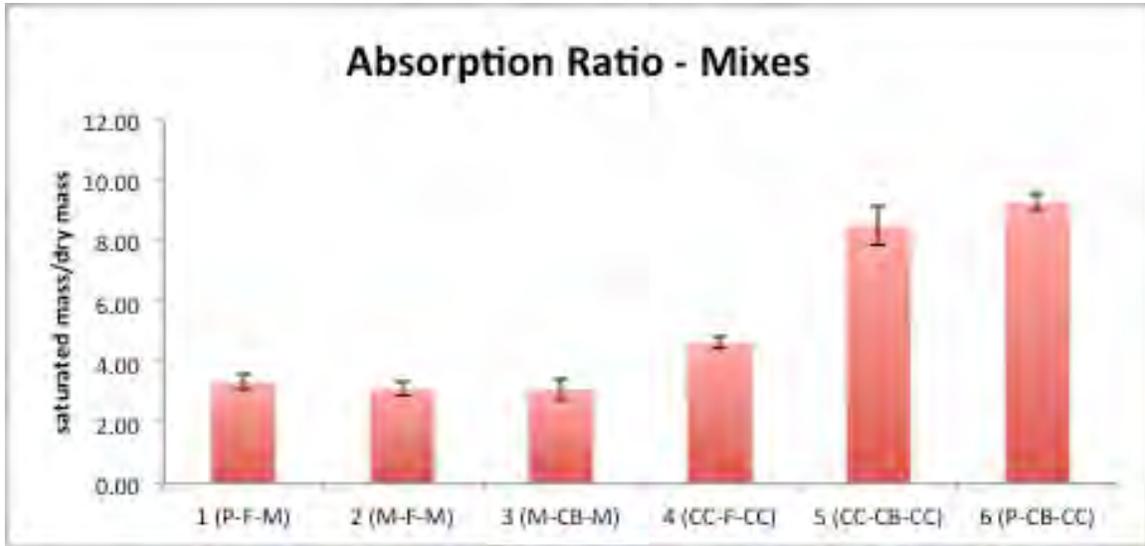


Figure 6: Absorption ratio of material combinations. Most values fall within the mid-range of absorption values expected by raw materials.

Finally, an interesting comparison to make is between the absorption values of the combinations as measured against the absorption value that would be obtained by merely summing the values obtained from the individual raw materials comprising each composition. In Figure 7, “sum of raw materials” refers to the ratio $\frac{\sum m_{saturated}}{\sum m_{dry}}$ across the materials in the relevant combination material. Across all of the materials, the absorption of the directly measured sanitary napkin is significantly lower than that predicted by the sum.

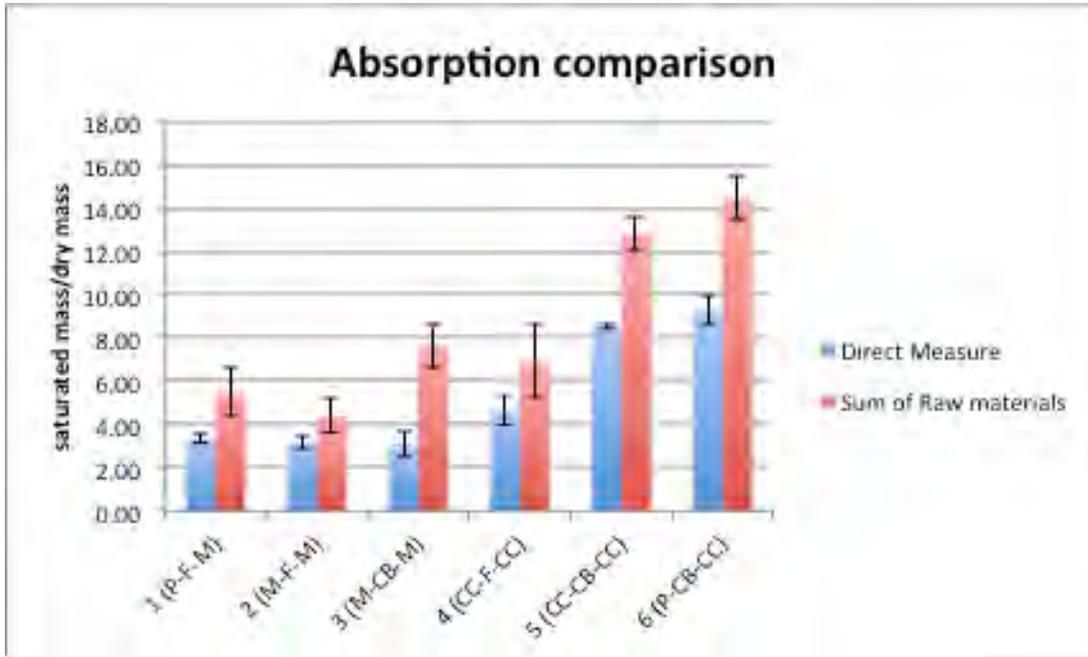


Figure 7: Absorption comparison between material combinations measured directly vs. the predicted absorption as measured by the sum from the individual raw materials. The direct measure ratios are significantly lower than predicted ratios.

Retention ratios

Absorption values are arguably less valuable than retention values, because in any practical application, force will be applied to the sanitary napkin during regular wear.

Retention value is measured as $m_{\text{squeezed}}/m_{\text{dry}}$, under applied force of approximately 158.8 Newtons. The relative ranking between materials remains approximately the same in retention as in absorption, as would be expected (Figure 8). Plastic is excluded from this test, as the theoretical value for retention is 0 as it is completely waterproof. Again, the error bars represent the standard deviation of values obtained for the retention ratios for the given material.

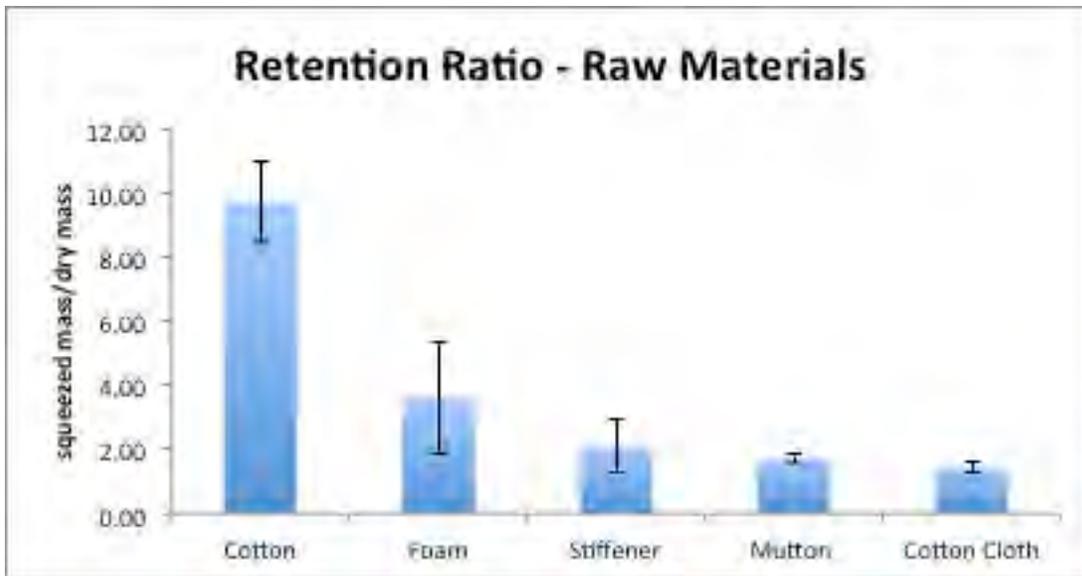


Figure 8: Retention ratio for raw materials.

The same test is repeated for the combinations of materials listed previously. Again, the ratios for mixes are in the mid-range of those of the raw materials, as would be expected.

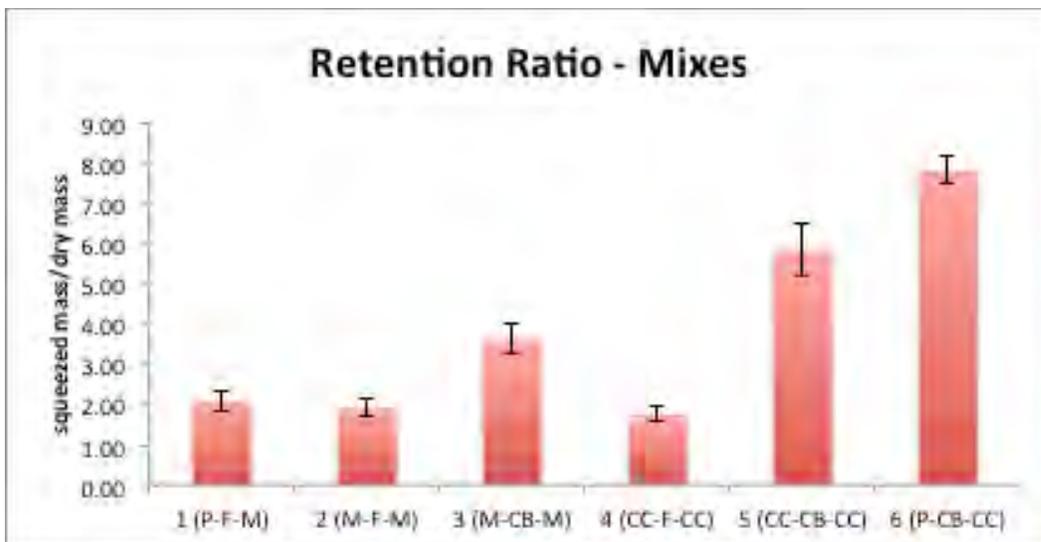


Figure 9: Retention ratio for combination of materials.

Finally, similar to absorption ratio comparison, a retention ratio comparison is done between that determined from a direct measurement, and that calculated from the

sum of raw materials. In this case however, no generalizations can be drawn about a systematic relationship between the two values.

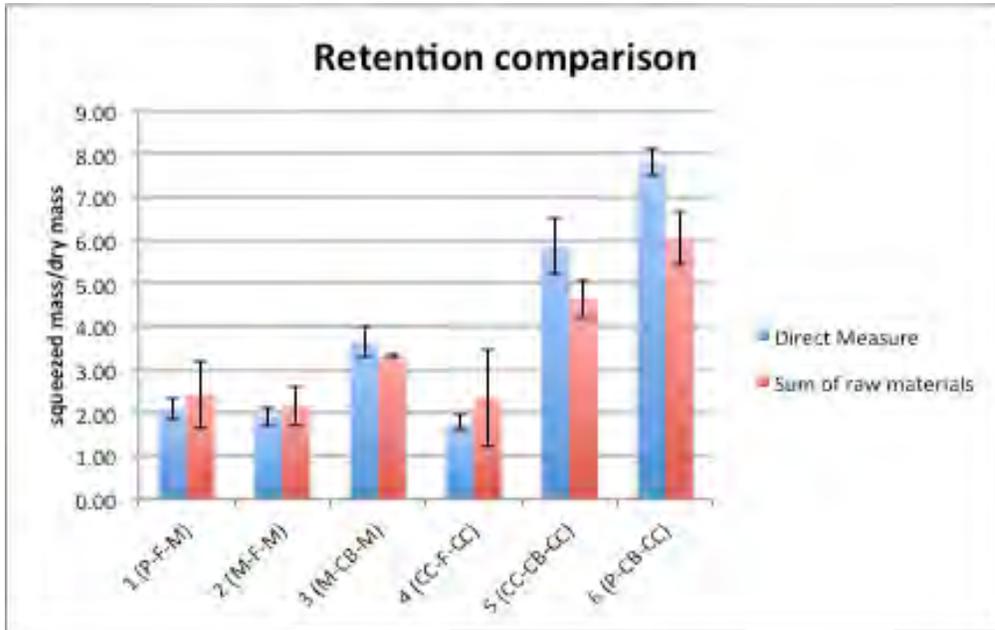


Figure 10: Comparison of retention ratios between directly measured compositions and predictions from the sum of raw materials. No generalization can be drawn about the relationship between the two.

Appendix 1 contains the means and standard deviations contributing to these tables.

Vertical wicking

Following Warner’s study, the rate of vertical wicking is used as a proxy for measuring the ability of materials to uptake liquid. This is a particularly important quality in a top layer, so that menstrual waste might be immediately absorbed from the user.

Figure 11 shows the setup used to measure vertical wicking. Cotton balls are excluded due to the lack of compatibility with this experimental setup.



Figure 11: Setup for vertical wicking, four samples for each material. From left to right (two samples per clip): Foam, cotton cloth, mutton cloth, interfacing, mutton cloth, interfacing, foam)

Figure 12 shows the test 2.5 hours after initiation. The primary result is that after this amount of time, the cotton cloth is the only material to exhibit any vertical wicking. Indeed, while none of the other five materials show any evidence of wicking at all, the liquid has travelled through about 9 cm of cotton in 1.5 hours (rate of 1 mm per minute).



Figure 12: Results of vertical wicking test after 2.5 hours. Only cotton cloth exhibits signs of significant wicking.

Durability

Tensile strength

Next, the six composite materials are strained under force in order to determine their modulus and yield points. The samples are tested in tension in order to measure durability. Figure 13 shows a sample of Composition 1 (P-F-M) during strain.



Figure 13: Strain of Mix 1 (plastic, foam, mutton cloth) in Instron. Fracture of the plastic is evident before other materials.

Stress-strain plots for the six curves are shown in Figure 14.

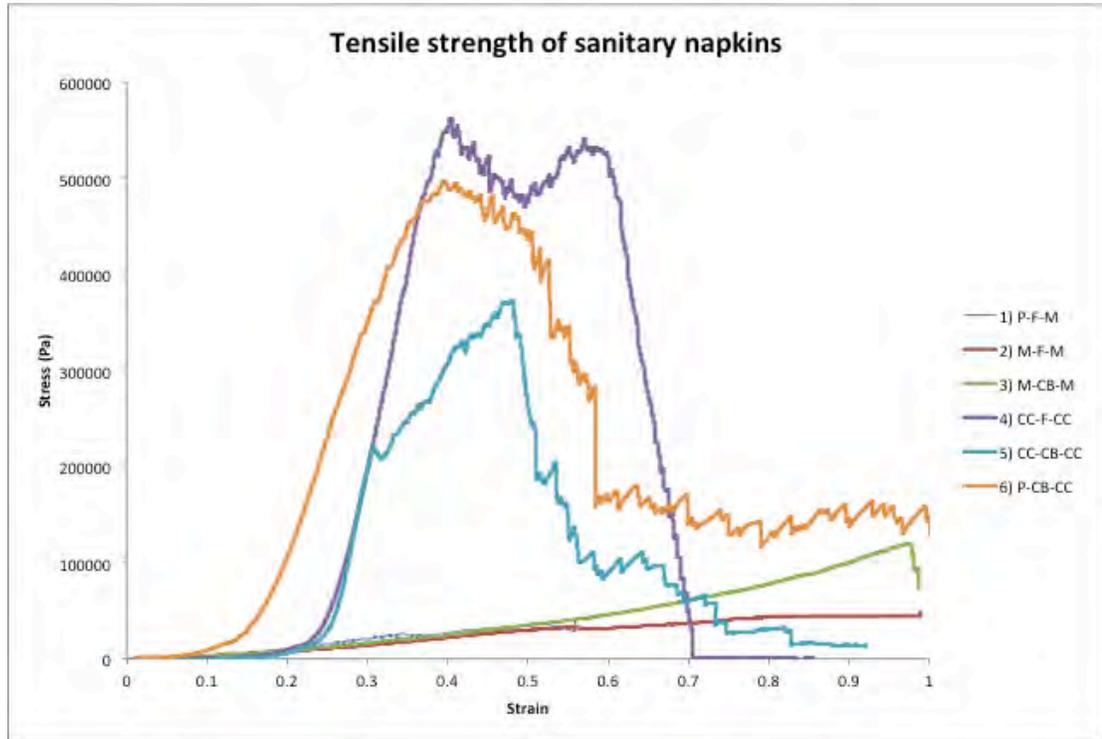


Figure 14: Tensile strength of sanitary napkins. Two distinct patterns emerge: one for cotton cloth-based materials and one that is mutton-based.

Mixes 4-6 have considerably higher elastic moduli than mixes 1-3, which is logical as mixes 4-6 have coatings comprised as cotton cloth, where as 1-3 are made of mutton, which is much more flexible. The different yield points are related to the yielding of the different layers – as each layer yields, applied stress experiences a sudden decrease. This suggests that the strength and elastic moduli of each material are dependent strictly on the most limiting material.

From these plots, an approximate yield point and Young’s modulus can be measured for the materials. The Young’s modulus gives an indicator to a material’s stiffness, both in terms of comfort/ease of movement and in terms of resistance to plastic deformation. The modulus is found by finding the slope of the linear region of each stress-strain curve, as depicted in Figure 15. Table 3 shows the resultant moduli and yield strengths for each material. As mentioned previously, the cotton cloth-based mixtures

have significantly higher elastic modulus, corresponding to increased stiffness that is perhaps linked to discomfort. All materials have a fairly high resistance to yielding, which is optimal in application.

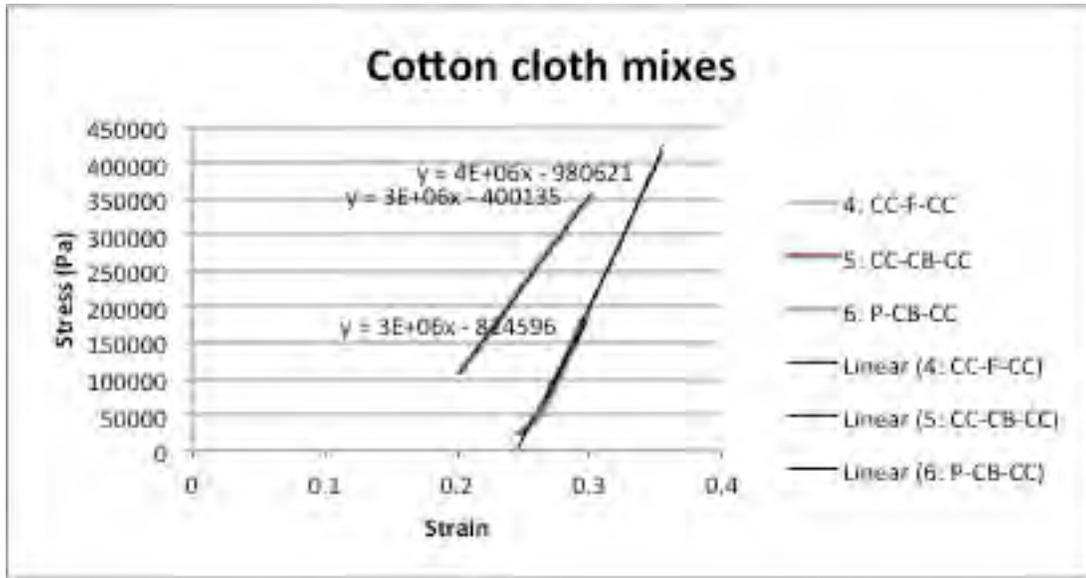


Figure 15: Calculating modulus for mixes 4-6

Table 3: Elastic modulus and yield strength for mixes.

Mix	Elastic modulus and yield strength	
	Elastic modulus (Pa)	Yield strength (Pa)
1	1.01E+05	--
2	6.40E+04	--
3	7.98E+04	--
4	4.00E+06	5.48E+5
5	3.00E+06	3.65E+5
6	3.00E+06	4.89E+5

Images of fracture

A visible difference can be seen between the combined materials before and after being pulled in tension. Most specifically, outer layers of cotton cloth and plastic are the first to fracture. In addition, though cotton balls are unlikely to fracture in the plastic, traditional sense, they are subject to permanent deformation that makes them slightly less

ideal as an absorbent. Mutton cloth and foam combinations have a very high yield strength, withstanding strains of over 100%, and are resistant to fracture..

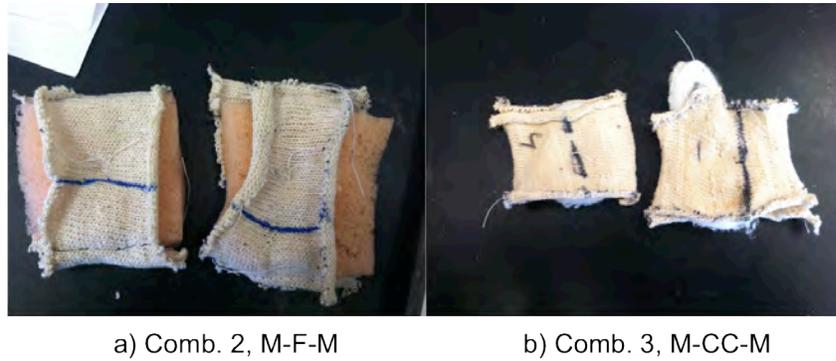


Figure 16: Comparison of mixed samples before (left) and after (right) being subject to tension.

The raw materials from these samples are imaged at varying degrees magnification to understand the fracture pattern. The resulting images are shown in Figure 17. The varying magnifications are used depending on the most effective magnification for seeing the difference between the fractured and unfractured portion of sample. Under tension, many of these materials exhibited almost no visible change. In particular, the best conclusion that might be reached about the mutton and foam is that they are very resilient to the amount of deformation that might expected from repeated use, and therefore they would perhaps be excellent materials for a pad.

Overall, imaging through a microscope shows almost no change, which is logical given the fibrous structure. In particular, the cotton fabrics and foams could be strained under both high and repeated loads with limited plastic deformation, relative to the plastic. The foam maintains porosity, though the pores get larger and progressively more transparent through continual tension. In the case of the cotton cloth, both the weave and the threads of the yarn loosen in “yielding.” Fracture in the mutton cloth and cotton ball is almost invisible as the loose and irregular structures of both of these materials is not changed. Finally, the plastic shows a distinctive yielding pattern in which individual bonds appear to break in close proximity, leaving behind gaping holes that serve as the origin for further breakages.

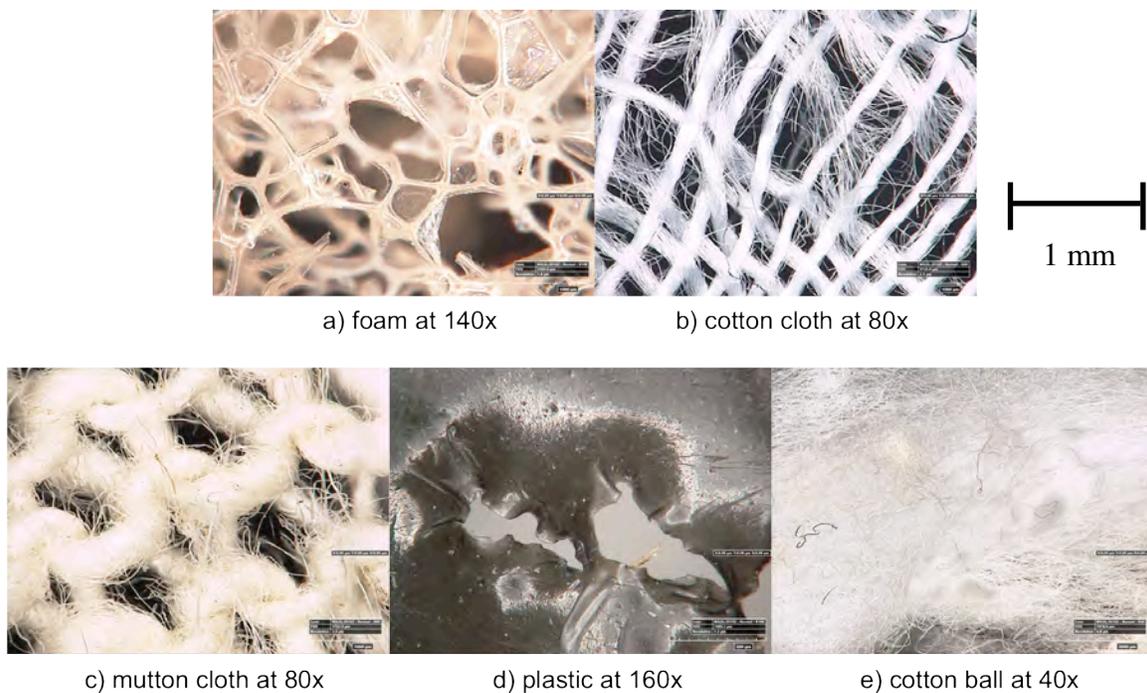


Figure 17: Varying magnification of material fractures patterns.

Comfort

Bending stiffness

Kawabata uses bending stiffness as one of his 16 standards for hand (feel). The bending stiffness of the six is subsequently calculated in two ways. First, we use the elastic moduli determined from tensile strength testing along with the moment of inertia for a rectangular solid to determine the flexural rigidity, EI . The results for the bending stiffness of each material are shown in Table 4.

Table 4: Bending stiffness of mixed samples. All samples have low stiffness.

Bending stiffness			
Mix	Makeup	I (m ⁴)	EI - flexural rigidity (N*m ²)
1	Plastic Foam Mutton	2.16E-07	0.022
2	Mutton Foam Mutton	2.13E-07	0.014
3	Mutton Balls Mutton	1.06E-07	0.008
4	Cloth Foam Cloth	9.59E-08	0.384
5	Cloth Balls Cloth	1.39E-07	0.416
6	Plastic Balls Cloth	4.06E-08	0.122

Each sample is also compressed under a three-point bending test, which provides a visual representation of both stiffness and shear. Results are in Figure 18.

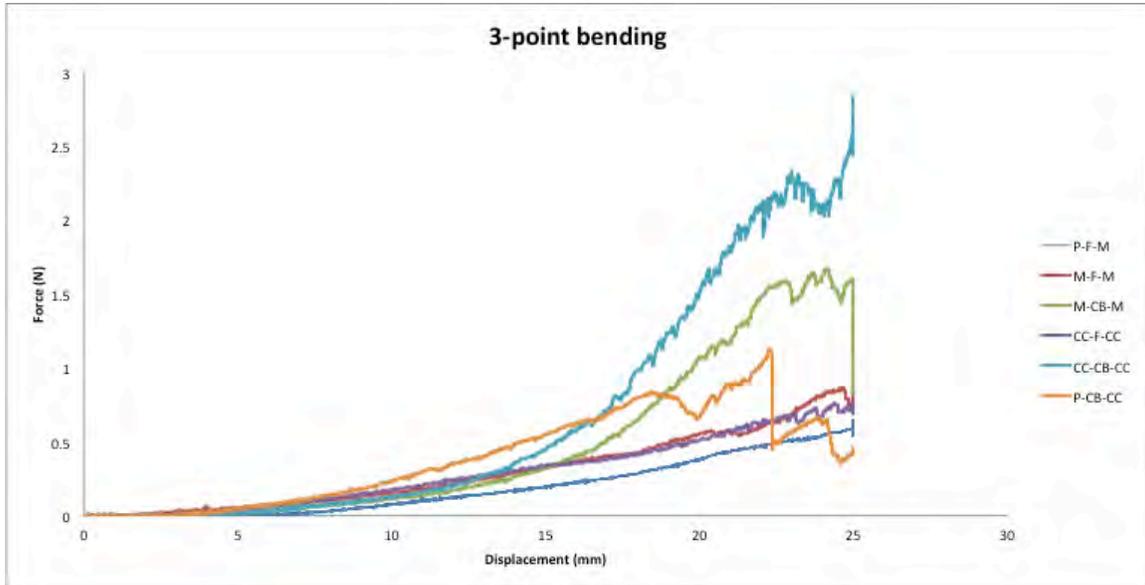


Figure 18: 3-point bending test of mixed samples. All samples have very low stiffness, particularly foam-based samples.

Both of these calculations demonstrate that all samples are relatively flexible, meaning that the applicability of the bending test is limited. However, mixes 1, 2, and 4 bend particularly easily. All three of these samples contain foam in their cores, which is less dense than the cotton balls are more amenable to movement, both before and after washing.

Surface roughness

Figure 19 shows depth profiles of five of the raw materials. Greater variation should theoretically indicate greater roughness, which is measured as generally the average distance of the surface from its mean. Cotton balls are excluded, as there is no mean depth on a surface from which to measure roughness. As expected, the plastic and interfacing show little variation in their depth profiles, while mutton cloth and foam show very substantial variation.

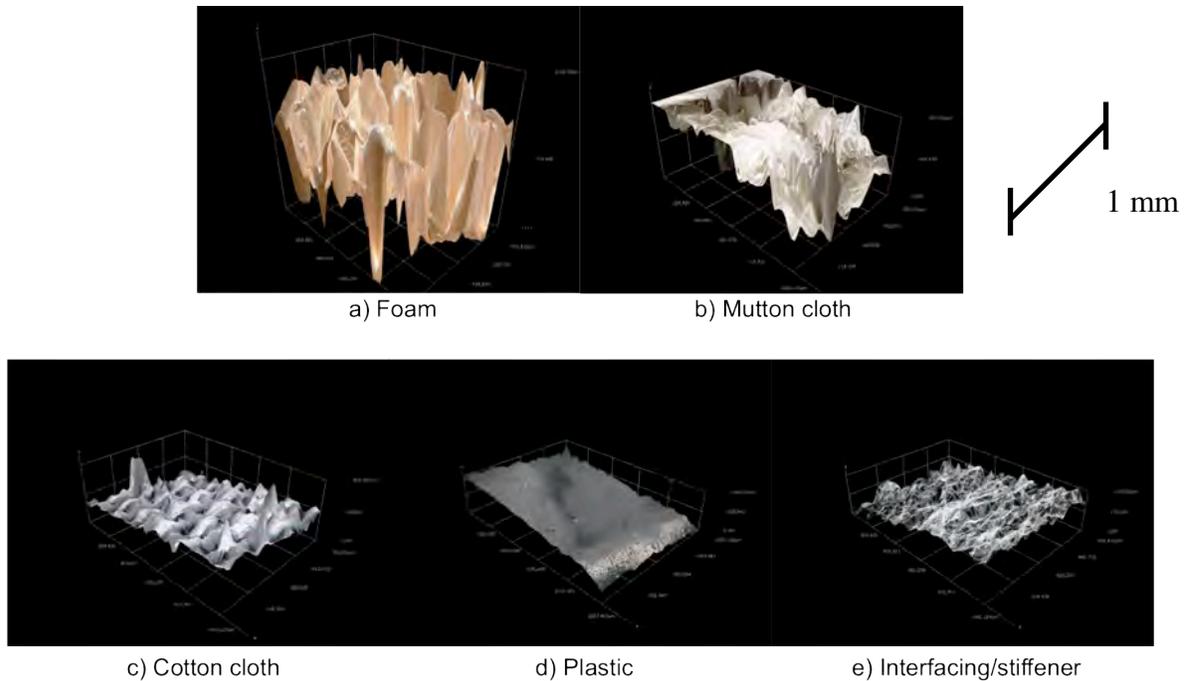


Figure 19: Depth profiles of raw materials at 280x magnification.

The implications of these differences on comfort are rather ambiguous. Key limitations exist with using surface roughness as an indicator of comfort. First, the “roughness,” as measured by average deviation of a point on the surface from the mean, does not necessarily correspond to softness, which is more likely a product of how the roughness responds to touch. It is more likely rather, that comfort is some combination of low roughness and low modulus of fibers. Second however, the deviation of a point on the surface from the mean is almost impossible to measure for these types of materials. As can be seen in Figure 4, many textiles have almost a fractile-type structure, in which a yarn is comprised of fibers is in turn comprised of fibers and so on. Natural folds in the fabric further obfuscate this calculation. The “mean” that is measured then is completely dependent on the roughness being used. Nevertheless, these depth profiles help to demonstrate and characterize the vast differences that exist across these material structures.

Drying time

As alluded to previously, drying time is particularly important for any application of reusable menstrual hygiene pads. One of the main barriers to menstrual hygiene in many developing countries, including Zambia, is embarrassment. Instead of hanging used rags in the sun to dry, women will tuck them away discreetly, allowing grounds for disease. Thus, an informal test is done to determine relative drying time (normalized by mass). Results are in Figure 20.

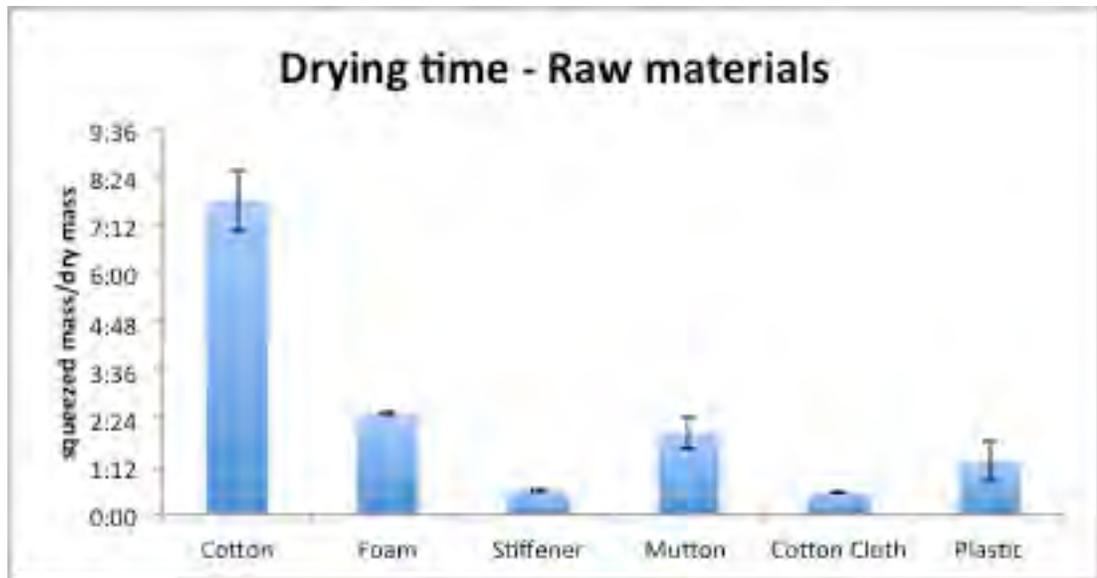


Figure 20: Drying time of raw materials.

Surprisingly, plastic drying time is relatively slow, though this could be attributed to condensed water droplets that evaporate slowly. Also unexpectedly, cotton balls require a drying time that is hugely greater than any other, even foam. In addition to being particularly slow to dry, pure cotton also responds uniquely to drying. In particular, it encounters irreversible deformation under force by remaining condensed. As an additional note, washing and drying demonstrates the weakness of interfacing. In one cycle, the interfacing effectively falls apart, likely due to its lack of weaving.

Discussion

Cotton-based materials substantially vary depending on how they are weaved, even if comprised of the same initial thread. However, weave (as expected) does inform absorption – both the cotton cloth and mutton have a similarly low absorption, partially due to a constant weave that leaves no room for holding of liquid, unlike in the cotton ball structure.

As previously mentioned, pad absorption is directly related to pad retention. However, the relative difference between retention and absorption is not constant. In particular, while loose cotton absorbs about three times as much liquid as it retains, foam absorbs about four times as much. Cotton cloth and mutton, perhaps because they absorb so little fluid to begin, absorb and retain almost the same amount of liquid.

The high rate of vertical wicking seen in the cotton cloth may be informed at least partially by its stiffness, as measured by tensile strength testing. The capillary action that leads to vertical wicking is more successful for a fabric held in tension, as is the case of the stiff weave of the cotton cloth. In the tests done here, outside of the results of tensile strength, the cotton cloth and mutton are overall fairly similar.

Though the surface roughness serves only somewhat effectively as a measure of comfort, the roughness corresponds well to the absorption and retention of the different materials. In particular, cotton balls and foam, easily the most “rough” surfaces, are also the most absorbent. Similar to hydrogels, these materials have the ability to expand when exposed to liquid.

Interestingly, drying time does not correspond linearly to absorbance, retention, or roughness. The required time for cotton to dry is much greater on the scale for drying

time than foam for example. Mutton has a much greater drying time than cotton cloth, despite the similar weave and absorption.

Errors and limitations

All of these tests are subject to limitations and errors. The most significant is in limited sample size. Each of these tests is limited to five or fewer samples, which may draw question to the conclusions.

Across the absorption tests, consistency in conditions is a constant limitation. The weight used in retention experiments, for example, may not be equally distributed across all samples. Level of saturation may vary when measuring pad absorption according to the level of water runoff allowed. Wicking rate is dependent on the level of tension in the materials; in this test, they are merely suspended in air and often have a natural and inconsistent fold.

In terms of measuring tensile resistance, the materials are almost never tested completely to failure, resulting possibly unrecorded trends. In addition, as alluded to previously, few conclusions can be drawn from the depth profiles. Even in quantifying, the value will depend on the parameters set. In bending, the samples used had relatively low span-to-depth ratios of between 3 and 4, which meant that realistically both bending and shear were captured in the final results.

Drying times, though important, are biased in a few ways. First, proximity to a particularly absorbent material led to greater drying times systematically (eg stiffener next to cotton would take longer to dry). Second, touching the materials to test dryness clearly speeds up the drying process in an uncontrolled way. Finally (and perhaps most

importantly), surface area across the samples is inconsistent, and is likely the greatest driver in increasing drying time.

Conclusions

We are able to successfully select and measure materials and properties for application as reusable sanitary napkins to combat a lack of menstrual hygiene in developing countries. Through a variety of tests of absorption, durability, and comfort, materials properties measurement contributes to user feedback in informing appropriate solutions. This study contributes to literature that opens the discussion of this problem from a materials science perspective.

None of the tested combinations are very obviously the most effective across all metrics. For the most part, these results instead provide insight into the types of tradeoffs that one might be required to make in selecting materials. However some (perhaps surprising) generalizations and recommendations might be made. For example:

- Loose cotton filling may deform and condense substantially and become less effective and more uncomfortable over time.
- Cotton cloth may make the best surface material, as it absorbs fluid at by far the most rapid rate, dries quickly, and is resistant to deformation.
- Mutton cloth and foam are both very durable, flexible, and absorbent materials that might be applicable for use as a middle layer
- Interfacing, though seemingly appropriate in providing shape and protection, is insufficiently durable for practical application in a sanitary napkin

- Plastic, though waterproof for blocking layer applications, is susceptible to fracture that can propagate and then let liquid through easily. Thus it may be appropriate to lie the plastic in such a way that it can be replaced once worn.

It should be made clear that these quantitative results in no way stand alone. In any test for a product that will be used by people, no measurement replaces the value of human feedback. However, these results can very well be combined with user feedback in order to provide user feedback into the types of properties that inform the most successful designs. In particular, these results provide a baseline that can be made universal across regions and availability. More importantly however, these results open the discussion into looking at menstrual hygiene solutions – and more generally technology solutions for the developing world – from a materials perspective.

Future Work

Substantial room exists for future work. First, Katagawa's tests for hand offers an extensive list of quantifiable attributes for measuring materials for sanitary napkin applicability. This study includes no mention of permeability or thermodynamic touch, for example.

Perhaps most obviously, all of these tests can be performed with increasing rigor in order to solidify results and better inform materials quality. In addition, they could be used in conjunction with user feedback in order to develop an alignment of materials properties measurements to success as a sanitary napkin.

This work might be used to develop standards against which materials around the world might be compared in order to assess the optimal choices for applications in

menstrual hygiene and more generally. Alongside user feedback, they might inform, for example, the weave required of raw cotton that could be produced in the developing world for production of sanitary napkins.

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Appendix

Appendix 1: Tables for retention and absorption ratios

		Absorption		
<u>Raw Material</u>	Mean	Std Dev		
Cotton	28.45	2.72		
Foam	14.99	1.72		
Stiffener	7.68	3.38		
Mutton	2.16	0.15		
Cotton Cloth	2.90	0.18		
Plastic	2.60	0.44		
<u>Mixes</u>	Mean	Std Dev	Makeup	
	1	3.35	0.21	Plastic Foam Mutton
	2	3.12	0.30	Mutton Foam Mutton
	3	3.11	0.61	Mutton Balls Mutton
	4	4.65	0.67	Cloth Foam Cloth
	5	8.51	0.09	Cloth Balls Cloth
	6	9.28	0.65	Plastic Balls Cloth

		Retention		
<u>Raw Materials</u>	Mean	Std Dev		
Cotton	9.72	1.27		
Foam	3.61	1.78		
Stiffener	2.11	0.82		
Mutton	1.72	0.14		
Cotton Cloth	1.45	0.16		
Plastic	0.00	0.00		
<u>Mixes</u>	Mean	Std Dev	Makeup	
	1	2.10	0.26	Plastic Foam Mutton
	2	1.92	0.22	Mutton Foam Mutton
	3	3.64	0.35	Mutton Balls Mutton
	4	1.75	0.19	Cloth Foam Cloth
	5	5.85	0.65	Cloth Balls Cloth
	6	7.82	0.33	Plastic Balls Cloth

Retention (Compared)						
<u>Mixes</u>	<i>Direct test</i>		<i>From raw materials</i>		Makeup	
	Mean	Std Dev	Mean	Std Dev		
1	2.10	0.26	2.43	0.78	Plastic Foam Mutton	
2	1.92	0.22	2.17	0.46	Mutton Foam Mutton	
3	3.64	0.35	3.31	0.02	Mutton Balls Mutton	
4	1.75	0.19	2.34	1.11	Cloth Foam Cloth	
5	5.85	0.65	4.64	0.44	Cloth Balls Cloth	
6	7.82	0.33	6.06	0.63	Plastic Balls Cloth	

Absorption (Compared)						
<u>Mixes</u>	<i>Direct test</i>		<i>From raw materials</i>		Makeup	
	Mean	Std Dev	Mean	Std Dev		
1	3.35	0.21	5.50	1.15	Plastic Foam Mutton	
2	3.12	0.30	4.40	0.77	Mutton Foam Mutton	
3	3.11	0.61	7.65	1.02	Mutton Balls Mutton	
4	4.65	0.67	6.92	1.70	Cloth Foam Cloth	
5	8.51	0.09	12.81	0.79	Cloth Balls Cloth	
6	9.28	0.65	14.47	1.05	Plastic Balls Cloth	

Appendix 2: Drying time

<u>Raw Materials</u>	Mean (h:mm)	Std Dev (h:mm)
Cotton	7:50	0:45
Foam	2:30	0:02
Stiffener	0:37	0:02
Mutton	2:03	0:24
Cotton Cloth	0:32	0:00
Plastic	1:20	0:30