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Effects of Staling of Bread Crumb on Mechanical Properties and Cell Morphology

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Effects of Staling of Bread Crumb on Mechanical Properties and Cell Morphology

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by

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Abstract

Bread crumb is a viscoelastic foam consisting of a random distribution of open and closed cells. This project analyzed the properties of bread as a function of time through the process of staling. Utilizing Stereo microscopy the average open to closed cell ratio and basic cell geometry was determined; the cell wall length and thickness were also measured. These data was compared to Gibson & Ashby mathematical models for foams to determine accurate cell geometrical structure. Making use of an Instron machine tensile testing was conducted on bread samples, cut to specific dimensions, to determine the elastic modulus and ultimate tensile strength. Video of destructive tensile testing was obtained to determine fracture patterns, and to view real time deformation of the cellular structure. From the analyzed data, it was observed that the Young's modulus and yield strength of the bread crumb increases and the cell wall lengths become smaller as the bread stales.

Acknowledgments

We would like to thank Professor Satya Shivkumar for all his guidance, patience, and advice during the course of this project. Also, we would like to thank Professor Gibson with his help on obtaining supplies and guidance for the image analysis portion of the project. We would also like to thank Carl Raatikainen for access to and instruction in the use of the stereo microscopes in Washburn shops. In addition, we would like to thank Lisa Wall for allowing us to access the Biology department's Instron machine for tensile testing.

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Introduction

Today, food science is a growing field that has gained more attention. Having a repeatable and quantifiable method of determining quality is sought by food producers. By performing staling analysis on foods you can obtain data that may be used to improve its quality, taste, and shelf life. The purpose of this MQP was to observe and analyze the change in the structure of bread and its mechanical properties as it stales. This was done through image analysis and experimentation.

Bread has been the foundation of the human diet. It has such a large influence that a lack of bread implies hard times, while an abundance of bread represents prosperous times. Bread is considered such an important item that the Russian word for hospitality is a concentration for the words bread and salt.[1] Quality and texture of bread throughout history has conveyed ones social status. Also, some claim that social order was founded on bread in eighteenth century France.[2]

Bread crumb is a highly porous visco-elastic solid. Gibson and Ashby have reasoned that the relative density of a material is the primary structural characteristic that affects the elastic and mechanical properties of cellular materials. Other parameters affecting the mechanical behavior are expected due to the breads heterogeneous structure. This heterogeneity comes from non-periodic ordering of cells, variation in cell wall, and imperfections due to broken cell walls. These defects will have a large effect on the mechanical behavior of bread.[3] The agents that cause staling in bread are not well known despite all the studies that have been done on the subject. Though each study claims a trend for certain components of staling the studies generally contradict one another or show varying degrees of contribution to staling[4-8].

This project seeks to provide evidence for the changes in bread crumb as it stales over time through four main objectives. Our first objective is a basic understanding of the cellular structure and characteristics of bread. This preliminary goal will allow us to delve further into bread properties and to develop a model to determine the basic cell distribution of bread. This will also allow us to identify the structure of bread, size and characteristics of the bread cells. The second objective is to determine the distribution of open to closed cells within the bread. The third objective is to test and analyze the bread under tensile and compressive stresses. Stress strain

data will be acquired through the compressive and tensile testing. The fourth objective will be to analyze and interpret the fracture patterns from the samples used in objective three. All of our processes will be recorded so that anyone can recreate any of our experiments if necessary.

Literature Review

Bread Forming

When looking at bread you can see that it consists of two phases, a fluid or air, and solid material. It is important to understand how these two phases develop when making bread. The basic formula for bread includes flour, water, and a leavening agent such as yeast. To create the dough for bread the ingredients previously mentioned are mixed together and then allowed to ferment for a time. These two processes occur simultaneously when the dough is mixed in a mixer. Also, when the dough is being mixed air is introduced into the dough. The air is trapped in the flour mass and obstructs further generation of gas cells from the leavening agents. The gas released from the leavening agents form gas cells and reduces the density of the dough. When the dough is baked in an oven the final bread crumb structure is set. [1]

Commercial breads as opposed to homemade bread is much more consistent in its overall structure. Industrial bread manufactures use a highly robust system for the production of their bread. The differences between taste and texture of different bags of the same brand of bread cannot be easily noticed. When looking at homemade bread you will notice large variations in pore size as well as texture and taste. This is due to the large number of factors that can affect the properties of bread. That is why when choosing a bread sample, commercially available bread should be chosen.

Cellular Solids

The size, shape, and topology has been an area of research for many years. Cellular solids', such as bread, properties depend greatly on the size, shape, and structure of the cells. According to Ashby and Gibson, the most important structural characteristic of a cellular solid is its relative density. Relative density is denoted by $\frac{\rho^*}{\rho_s}$. Rho star is the density of the foam material while the subscript "s" represents the material as a solid. When looking at importance of variables for a cell the shape of the cell is usually much more important than the size of the cell.[9]

When studying cells, it is important to study them as a two dimensional structure and not just a three dimensional structure. Modeling of properties in two dimensions is much simpler than modeling them in three. However, two dimensional modeling can be applied to more complex geometries by making assumptions that allow for simplification.[9]

Three dimensional analysis makes additional assumptions between open and closed cells. Closed cells are closed off from the surrounding cells by a membrane-like face. Open cells allow for cells to interconnect. An example of a closed cell foam is Styrofoam, which does not allow fluids to pass through it. An open cell foam allows all fluids to pass through it freely.[9]

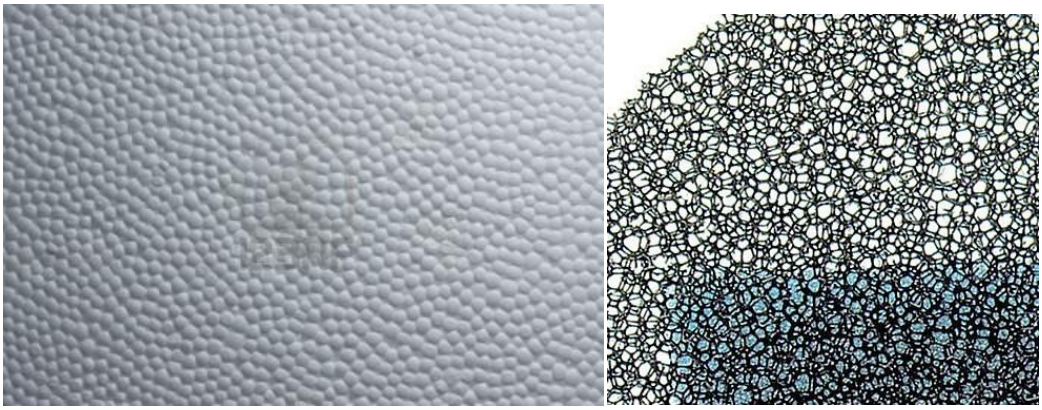


Figure 1 - On the left a closed cell foam, and on the right an open cell foam

http://us.123rf.com/400wm/400/400/anest/anest0902/anest090200010/4272139.jpghttp://img.directindustry.com/images_di/photo-g/pur-foam-panel-366342.jpg

Honeycomb

One of the most interesting structures observed by man is the bee's honeycomb. They are one of the most studied and observed structures to date. A honeycomb structure can be made with hexagonal, triangular, or square cells. However, the cell shape that uses the least material for the same pore volume is the hexagonal honeycomb. Hexagonal honeycombs have three cell edges meet at every vertex, as is the case with many manmade honeycombs, such as bread. [9] Figure 2 shows two different honeycomb structures that exhibit tight packing.

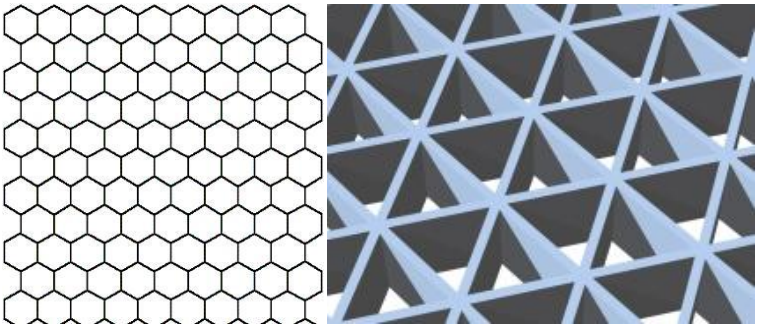


Figure 2 - On the left a hexagonal honeycomb, and on the right a triangular honeycomb

http://satishsankaran.com/Projects/honeycomb.JPG, http://www.ipm.virginia.edu/newres/pcm.manuf/pcm.manuf.triangles.jpg

The honeycomb structure is used to pack cells together to fill space. This packing is not as uniform as one may expect. A number of different cell shapes will be incorporated to fill space. When looking at three dimensional cells these include triangular prisms, rectangular prisms, hexagonal prisms, rhombic dodecahedra, and tetrakaidecahedra. [9]

Cell imaging

Scalon et al. has summarized a number of studies relating to the image analysis of bread crumb. Most of the images of the bread crumb have been obtained through the use of reflected light techniques although other techniques exist such as . To obtain images of the structure and organization of bread crumb cellular structure that can be analyzed accurately, lighting is crucial. Optimization of the contrast between the cell wall bread crumb and the air pockets provides the best images to be analyzed. It is extremely difficult to measure cell sizes due to the complex texture of bread crumb[1].

Visual interpretation of the bread crumb texture by observation is highly subjective of the viewer. There are also various methods for analyzing the cell sizes with various levels of discrepancies. There is generally a large distribution of small cells and a lower distribution of larger cells but the larger cells have a great effect on the average cell size which can lead to a slightly skewed observation of cell sizes. Analyzing the distribution of cell sizes allows for a more descriptive view[1].

Mechanical Properties Studies

The elastic properties of bread are closely associated with the quality of bread. Scanlon and Zghal summarize this quite nicely [10]. In their paper they discuss the merits of examining the elastic properties of bread crumb and the difficulties of gathering accurate test date due its heterogeneous nature which develops stress concentrations when placed under any sort of load be it compressive, tensile or shear. Compressive tests while the simplest to perform, simply cutting a cube and placing it between two parallel plates and applying a compressive load. This test creates a stress concentration in the center of the sample, which is the source of fracture and as a result is difficult to observe and thus not ideal. Tensile testing of materials consists of attaching the sample to a machine and pulling it apart at a graduated rate and measuring the force. Testing with this approach presents unique difficulties because bread crumb will fracture at the attachment point if the stress is not evenly distributed to the sample, and there is little

information available pertaining to standards to follow for the tensile testing of bread crumb. However once both of these obstacles are surpassed, the data gathered gives clear indications of material properties specifically the elastic modulus and ultimate tensile strength. These two values will be tracked as bread crumb experiences its staling process.

The most recent evidence of tensile testing of bread crumb located was Chen, Lester and Peleg [11]. In their analysis they used a cutout in the shape of a bone as seen in Figure 3 - Schematic View of the shape and dimensions of a tensile test specimen [11]to create the standardized sample size used for testing. The gray areas of the figure were wrapped in masking tape and mini alligator clips were placed on the masking tape. The masking tape spread out the holding force of the alligator clips enough such that when a tensile load was applied, the sample consistently broke in the 10 millimeter wide section. At the end of the article Chen, Lester and Peleg suggest that if a wider template is used the distribution of larger cells in each sample will be more uniform and produce more accurate results. This theory is put to use in designing the template for this articles tensile testing specimens.

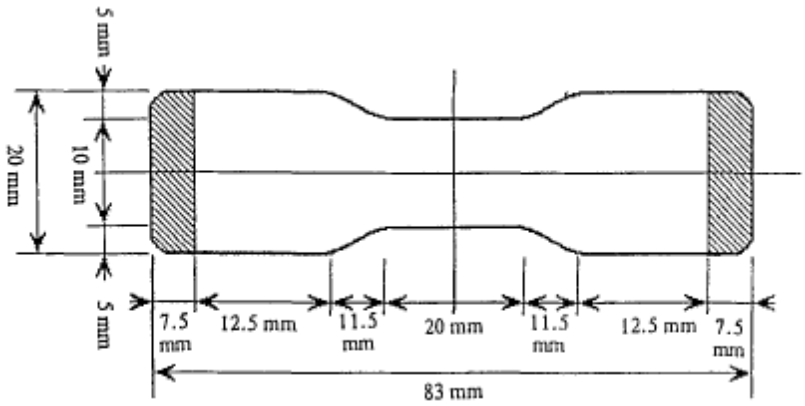


Figure 3 - Schematic View of the shape and dimensions of a tensile test specimen [11]

Theoretical Modeling of a foam

Bread is an anisotropic material, meaning that its properties are direction dependent. As opposed to isotropy which implies homogeneity in all directions. [2] One of the most important values to obtain for bread is the relative density. The equation for a two dimensional hexagonal honeycomb:

$$\frac{\rho^*}{\rho_s} = \frac{2}{\sqrt{3}}\frac{t}{l}\left(1 - \frac{1}{2*\sqrt{3}}\frac{t}{l}\right)$$ Eq. (1)

where t and l are the cell-wall thickness and the cell-edge length respectively. [9]

Another study done by Liu and Scanlon shows the relative density for two dimensions as:

$$\frac{\rho^*}{\rho_s} = 2 * C_t\frac{t}{l} - C_t^2\frac{t^2}{l^2}$$ Eq. (2)

where $C_t=3^{-0.5}$ for hexagonal honeycomb structures.[2] This is greatly simplified from Ashby and Gibson's model. This is mostly due to their investigation into bread crumb and its effect on the theoretical modeling. Their model takes into account that bread crumb is extremely heterogeneous and that many of the cell walls are missing.

The equations above do not take into consideration whether it is an open or closed cell structure. For an open cell hexagonal prism the general equation from Ashby and Gibson is:

$$\frac{\rho^*}{\rho_s} = \frac{4}{3*\sqrt{3}}\frac{t^2}{l^2}\left(1 + \frac{3}{2A_r}\right)$$ Eq. (3)

The aspect ratio or A_r is the height of the prism over the base length of the prism.[9] For a closed cell hexagonal honeycomb the relative density can be calculated from

$$\frac{\rho^*}{\rho_s} = \frac{2}{\sqrt{3}}\frac{t}{l}\left(1 + \frac{\sqrt{3}}{2A_r}\right)$$ Eq. (4)

This equation is similar to the previous except that its coefficients are different and its variables are of a lower order. These equations begin to break down when the relative density is greater than 0.2.[9] .

Figure 4 below is that of a closed rectangular prism but it shows the general layout for a cell and its dimensions used in the above equations:

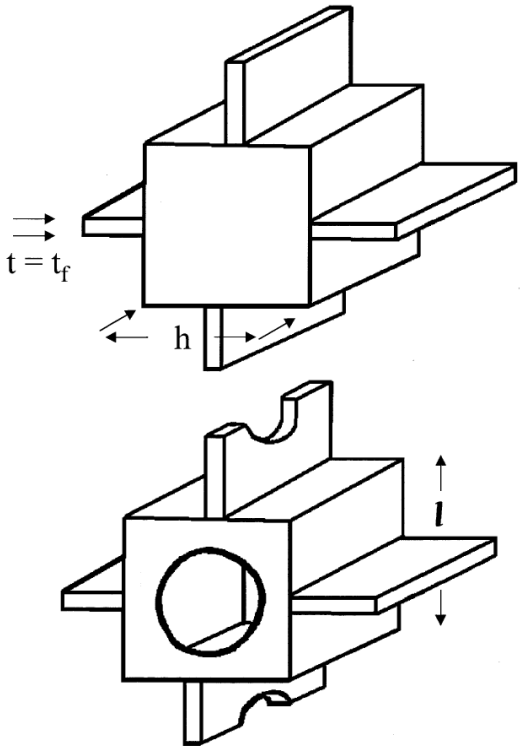


Figure 4 - Unit Cell Dimensions for Cellular Solids (Bread Crumbs)

it shows the cell-wall thickness, cell-edge length, and the height for a closed-cell foam. These values can be determined by looking at a bread crumb cell underneath a microscope and measuring these values using imaging analysis or current software.

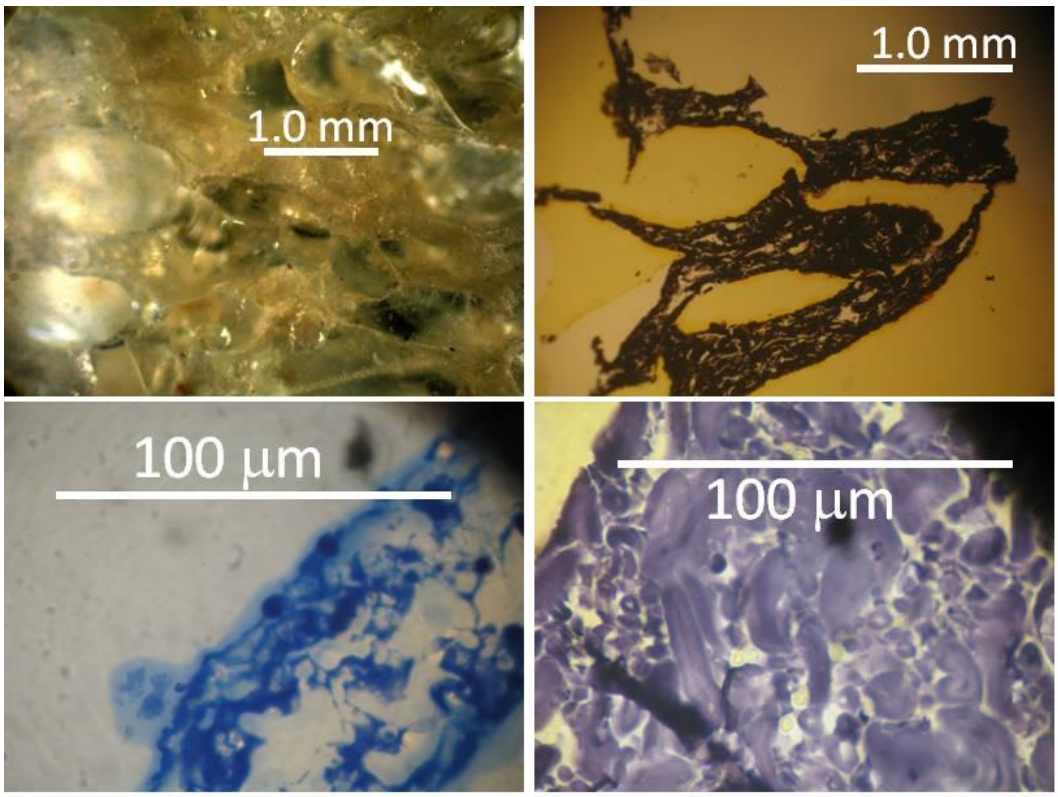
Staling

Staling with respect to bread is a series of chemical and physical changes that effect the texture, taste, smell [8] and independent of microbial action [4, 12]. Staling occurs in both the crust and crumb but generally more attention is given to the crumb as it effects the consumers perception of the bread [4]. Staling of bread crumb is also known as the firming of bread and the level of staling is measured by the firming rate [4, 12].

The process in which bread stales is complex and no conclusive process has been developed as there are many discrepancies between studies. There are three main components of the staling process that have been studied by various persons. One of the staling agents that has been proposed is the retro gradation of starch molecules specifically the amylopectin fraction of starch [4, 7]. Another possible staling component is the proteins in the bread, the gluten [4, 7]. The third main component said to effect staling is the non-starch polysaccharides in bread or "Pentosans"

and are thought to inversely effect staling[4]. The concept of pentosans is quite difficult to understand and therefore only the first two staling components were looked into further.

The retrogradation of starch molecules is when the starch molecules begin to rearrange themselves directly after baking. The starches supposedly gelatinize during baking due to the moisture in the bread dough and the temperature. Starches are observed to retrograde at room temperature. Though this is thought to be a prevalent agent of staling it is under speculation as to whether this process has a substantial effect on the change in mechanical properties[4, 7]. The moisture present in the bread is also used by many other hydrophilic molecules present in bread and therefore not enough moisture is present to fully gelatinize all the starch [7]. One study done in 1969 found that at storage temperatures above 21°C the retrogradation of starches is less important for staling[4]. Figure 5 is a picture of the starch molecules in a commercial white bread.



Clockwise from top left: Face of trimmed block of bread infiltrated with LR White acrylic resin; semithin (1 μm thick) section of resin-embedded bread, stained with iodine to show starch distribution, low magnifcation; iodine-stained section at high magnification (oil immersion) High magnification of section stained with toluidine blue, showing non-starch matrix.

Figure 5 - Starch Cells

Gluten protein is attached to the starch molecules and is thought to have an effect on the staling process. Studies related to the effects of gluten on staling have concluded dissimilar answers to this[4, 5]. Some state that gluten has a major effect on the staling of bread while others find there is no correlation with studies stating varying degrees of effect in between. In a study done by Every et al. on the effects of gluten additions to bread it was concluded that a combination of gluten-starch and starch-starch interactions are a likely candidate for the staling of bread [5]. Unfortunately no pictures of gluten for the bread samples used were able to be obtained with the equipment available.

Moisture loss in bread crumb is generally known as the major proponent of staleness and is associated with all the staling processes aforementioned[4, 7]. In a study done by Baik et al. bread was stored with crust and without crust and there was a noticeable increase of crumb firmness in the bread with crust. Assuming no loss of moisture to the atmosphere moisture is redistributed to the crust as the bread crumb stales[4, 7].

Methodology

The purpose of this project is to understand the relationship between the cellular structure of bread and how it deforms when under a given stress. Four main objectives describe the scope of the project.

- Cellular Structure of Bread Crumb - First and foremost the basic cellular characteristics of bread through image analysis must be obtained and modeled. This includes determining the average open-closed cell ratios, relative density, and shape of bread crumb cells.
- Staling effects on Bread Crumb Cell Morphology - The next objective is to observe any changes in geometry and dimensions of the bread crumb cells as the bread stales
- Changes in Mechanical Properties of bread crumb as it stales - Test and analyze the bread under a given strain rate and record the amount deformation both through visual observation and numerical data.
- Fracture Patterns - The samples from the tensile tests were analyzed and characterize the fracture and deformation patterns.

All these objectives serve an overall purpose of finding empirical evidence that bread properties are different over the aging process of the bread.

The bread that was used in all the tests is a commercial white bread. In this case we used Shaw's brand white bread. The commercial white bread used gave the most homogenous bread samples due to the robust production process. The cell structure will not vary greatly throughout the bread and the bread retains its packaged properties longer than non-commercial breads. This makes these breads ideal for testing since there will be less error in the data due to the heterogeneous nature of the bread samples. The commercial bread is made in such a way that it is almost the same composition every time.

Another factor to consider in all tests of the bread is the freshness of the bread. We wanted to test the bread soon after it is made and we wanted all the first tests of bread to be close to the same freshness. According to our research bread is delivered fresh to most grocery stores every day. We obtained the bread with the corresponding tag for the day that we got the bread to ensure

maximum freshness. It would also be necessary to determine for sure if the grocery store we purchase bread from has daily deliveries.

In order to maintain validity throughout all the experiments we will have to store the bread in a humidity and temperature controlled environment. One method is to keep the bread tightly sealed in its plastic package and place it in a container in a dark area. The bread should be used in the experiments on the day that it is baked since the freshness of the bread is expected to correlate with the mechanical properties. The bread would be tested afterward for set periods of time afterward to observe the changes in the bread as it stales.

Image Analysis

The models developed were based on functions of the cell wall thickness, length, density, and shape. Several of these values were determined by image analysis. The overall objective of the experiments and data was to determine if there was empirical differences between fresh and stale bread. For the image analysis a loaf of Shaw's white bread was analyzed over a month twice a week at rather random intervals due to accessibility to the labs. The loaf was bought on a day when it was delivered so it was as fresh as possible and analyzed that day to obtain the first set of data. The bread loaf was kept in the bag to maintain as much moisture as possible and to model a realistic set of bread conditions in the US. No family uses bread that has been left out of the bag for a month and from the literature review studies on staling of bread retain the moisture in the bread to ensure that moisture leaving into the atmosphere does not affect results.

The samples for viewing were simple to prepare. The slices of bread were de-crusted using a fine-tooth saw. De-crusting was done by cutting the crust and adjacent breadcrumb half an inch from the rest of the crumb. This was a necessary step since the breadcrumb near the crust would likely be deformed due to tensile and compressive forces of the crust hardening. Two slices were prepared and placed into an airtight container to maintain moisture while preparing microscope and viewing other samples. The bread was observed on the pre-cut face of the bread slices. It was assumed that this side would be the least deformed and damaged as the machine used by the manufacturer to cut the bread is designed to cut slices with minimal disturbances to the bread.

A Nikon SMZ 1500 Stereo Microscope with a Nikon DXM 1200F digital camera attachment was used to take pictures at 30x. Figure 6 shows the stereo microscope setup used for image analysis.

Figure 6 - Nikon SMZ 1500 with Camera Attachment

http://imaging.bates.edu/origin/files/images/smz1500_gs.preview.jpg

The camera software was ACT 1. The pictures needed to have mostly complete and non-deformed cells so that analytical data would be accurate. At least forty pictures were taken for every period of microscopy and only the twenty best of each set were analyzed. Therefore twenty images for each test period were analyzed for dimensional properties.

The images were analyzed using image analysis software. To determine the scale of the measurements a metric ruler was placed under the microscope on each sample used for the first picture of every sample. A scale was set by using the millimeter marks on the ruler. Figure 7 is an image of the bread crumb under the microscope with a millimeter scale ruler.

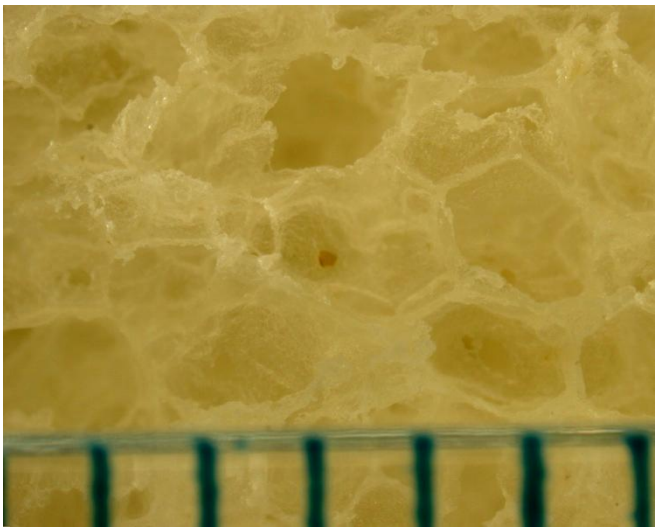


Figure 7 - Bread Crumb with scaling Ruler 20x

With a valid scale the dimensional properties of the cells were determined. The thickness of the cell walls, and the average cell area were the values analyzed through image analysis.

Open-Closed cell ratio

By taking the obtained Nikon SMZ 1500 stereo microscope images at 10x of several sections of a given bread loaf we can determine the number of closed and open cells. These pictures were taken with a similar procedure to the one for image analysis and used the same samples. Finding the open and closed cells is a difficult process as it is hard to determine what cells are open and what cells are closed. The number of closed and open cells must be counted accurately and no less than 3 times for every sample. When, at least, 20 samples are taken a ratio will be composed as the average of the ratios for all 20 or more samples. To count which cells were open and closed a blue and red marker was used respectively. Each cell that was counted was marked to keep track and avoid recounting of the same cell. Figure 8 shows a sample with all the cells counted.

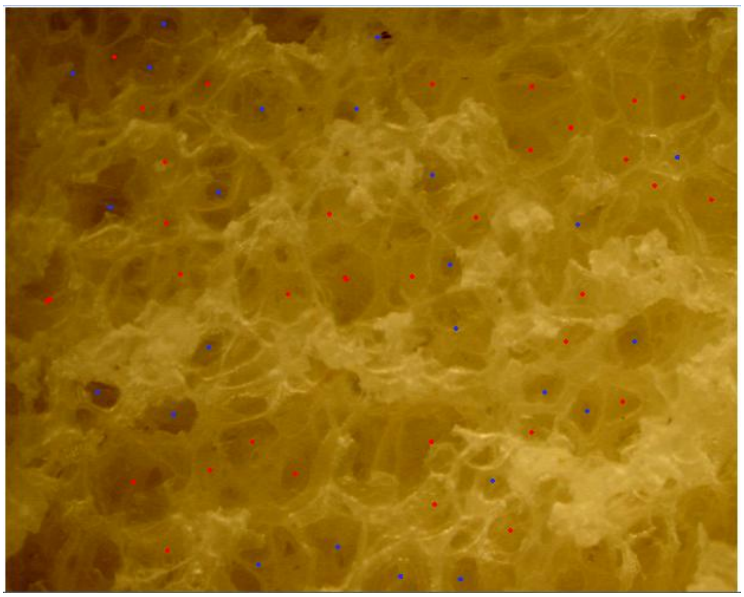


Figure 8 - Open-Closed Ratio Method

Another set of samples was set up to analyze the open-closed cell ratio. An LR-White epoxy resin as shown in Figure 9 was used to encase a square piece of bread.

Figure 9 - LR White

http://www.tedpella.com/chemical_html/18181.jpg

The resin was set for 24 hours in a refrigerated environment to allow the bread to absorb the resin. The bread submerged in resin was then placed in the oven at 77°C to cure. The cured resin was then cut using a tungsten blade to a mirror finish. The resin should have filled in all the open cells and not the closed cells so a ratio can be obtained with less human visual error. The method of marking the open and closed cells was the same as the non-resin samples.

The pore uniformity of the bread was an issue to consider. The bread can have abnormally large pores throughout the bread. The areas with these irregularities were not considered for observation, only observing sections with a seemingly uniform structure. Using a commercial bread sample that is produced with a robust process will yield more precise open to closed cell ratios.

Tensile Stress Tests

Using the recommendations of Chen, Lester and Peleg [2] a template for tensile testing samples was created with the following dimensions.

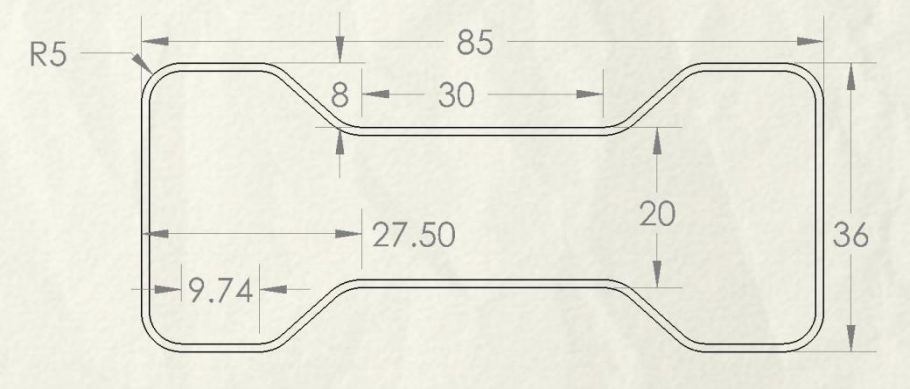


Figure 10 - Dimensions of the tensile testing sample (all dimensions in mm)

The template was constructed by bending 1mm galvanized steel into the profile and tabs were folded down facing outward and screwed to a block of wood to strengthen the template and to aid in maintaining the exact shape. The top edge was sanded flat and then sharpened to make a clean, even cut when pressed into a slice of bread while the slice is on a hard surface.

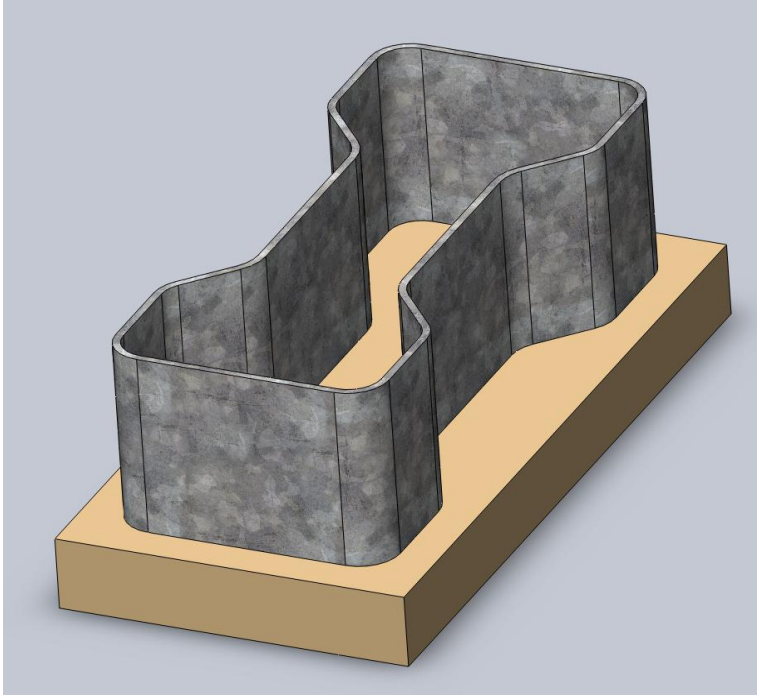


Figure 11 - 3-D model of bone shaped sample cutter

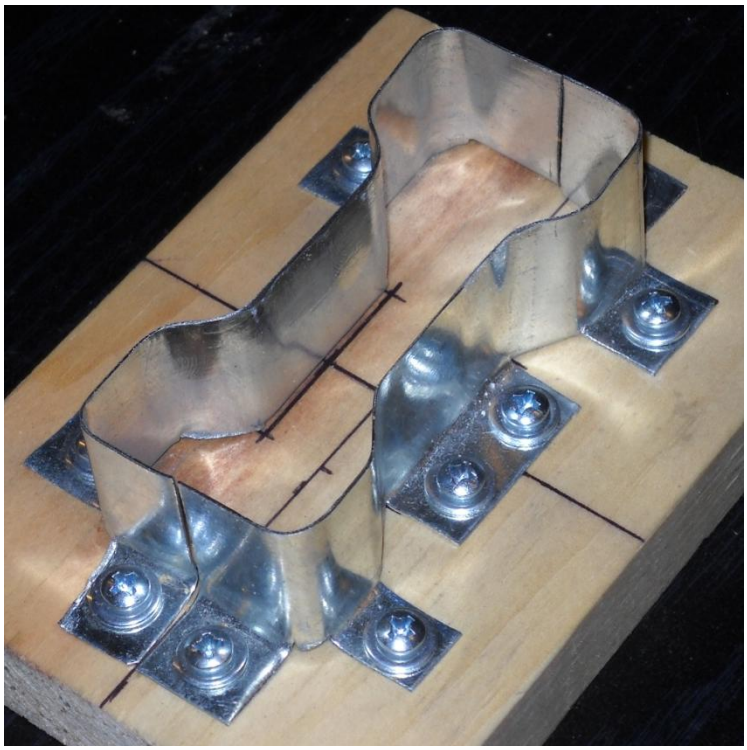


Figure 12 - Constructed Cutter

The same steps, mentioned previously for the image analysis concerning maintaining freshness of the samples, were followed while conducting the tensile tests.

Figure 13, Instron 5544 Tensile Testing Machine

Once removed from the plastic storage bag the bread slices were cut using the bone template. The samples were then clamped into the Instron 5544 machine, being careful to only clamp the upper and bottom-most 10mm of sample. Tensile testing was conducted on the samples recording the age, force and displacement data for each. Testing was performed at a strain rate of 1.0 mm/min and data was sampled at a rate of 1 kHz and samples were deformed until failure. Each day of testing consisted of 30 samples to minimize the effect of uncontrollable variables and to generate a suitable sample size. After testing, the samples were then quickly placed in a sealed enclosure to maintain freshness while awaiting image analysis of the fractures.

Fracture Characteristics and Patterns

Two sets of fractures were to be analyzed, a bending fracture and a tensile loading fracture. The bending fracture was obtained by dipping the bread samples into liquid nitrogen as shown in Figure 14.

Figure 14 - Freezing Bread Samples with Liquid Nitrogen

After about 15 seconds of being submerged in the liquid nitrogen the bread was removed and fractured by a bending moment. The sample would then be placed in an airtight bag to be observed later. Once all the samples were obtained they were viewed under the SMZ 1500 microscope. Images were taken of the fracture area both parallel to the fracture plane and perpendicular using the Nikon DMX 1200F digital camera at 20x and 7.5x optical zoom.

The tensile loading fractures were a result of the tensile testing done on the Instron machine. The samples of bread fractured by the Instron machine were directly transferred to an airtight container. The samples were cut with a fine tooth saw to half an inch from the lowest point of fracture. The only piece of the samples that were of concern was the area that encompassed the fracture. These samples were then analyzed in the same way that the liquid nitrogen samples were.

Theoretical modeling

To model the relative density using the equations mentioned previously in this report. The general cell shape, size, and cell ratio first had to be determined. To calculate relative density of Shaw's white bread both the density of the bread as a foam and as a solid had to be calculated. This was done by first making a simple punch to cut the samples into circles to hasten the process. A metal cylinder was used. After cutting out the bread foam, using the previously mentioned punch, the thickness was measured using a caliper. Figure 15 shows that the bread

crumb was cut in the middle of the slice of bread so as not to get any of the crumb distorted by the crust.

Figure 15 - Bread Slice After Removal of Sample

The caliper was accurate to 0.001 inches. The mass was also measured using a Denver Instrument A-250 mass balance. The mass balance was accurate to 0.0001 grams. After each sample was measured and recorded the sample was then crushed inside the circular punch using approximately 50 lbs of force distributed equally over the surface of the bread crumb so the bread would experience complete plastic deformation and densification. Figure 16 shows the completely crushed bread sample.

Figure 16 - Crushed Bread Samples

The thickness and mass was then re-measured and recorded.

After accomplishing these prior tasks, the values were substituted into the theoretical modeling equations. These were then plotted along with actual data to show discrepancies between the theoretical and actual data. By manipulating the equations and changing the coefficients within the equations it is possible to have the theoretical equations more accurately model the actual data. To observe these trends Microsoft Excel was used. This would allow us to see whether bread could be accurately modeled without the use of Finite Element Analysis software, which has been proven to accurately predict the behavior of bread crumb.

Analysis and Results

Cell structure

From multiple samples viewed under the SMZ 1500 stereo microscope the majority of cell structures appears to be a hexagonal honeycomb. A few 30x optical zoom pictures were taken to isolate single cells to clearly view this cell structure. Some cells appear to be missing cell walls which is common in materials produced through random physical processes but it is generally clear how the cell walls would be connected to make a complete shape. Figure 17 is microscope pictures taken at 30x optical zoom viewing individual cell structures.

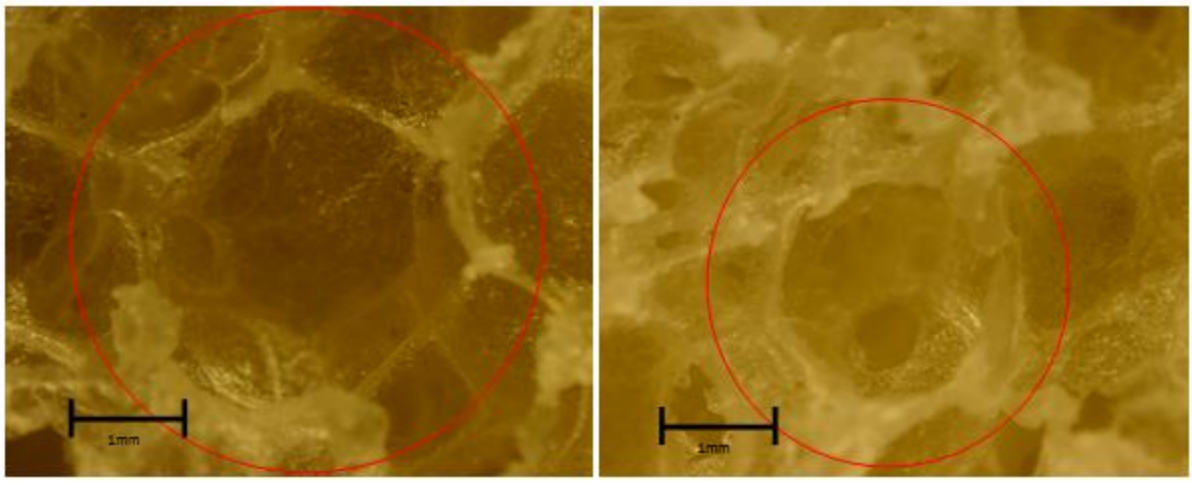


Figure 17 Cell structures 30x

The cell structures being discussed can be seen inside the circles. The right figure clearly shows a hexagonal cell surrounded by several adjacent hexagonal cells that are cut off by the viewing plane and the left figure shows another hexagonal cell highlighted by the circle. There are other structures present in the cells that were noticed but many are difficult to distinguish as many appear distorted or are missing cell walls or other cells intrude into the cell in question.

Sometimes at the higher magnifications it is difficult to see and discern what is being viewed. Most of the pictures taken are at 20x optical zoom. Although this zoomed out view does not isolate individual cells it allows a greater depth of viewing than the 30x optical zoom which has focusing issues. Figure 18 is the bread crumb viewed at 20x optical zoom.

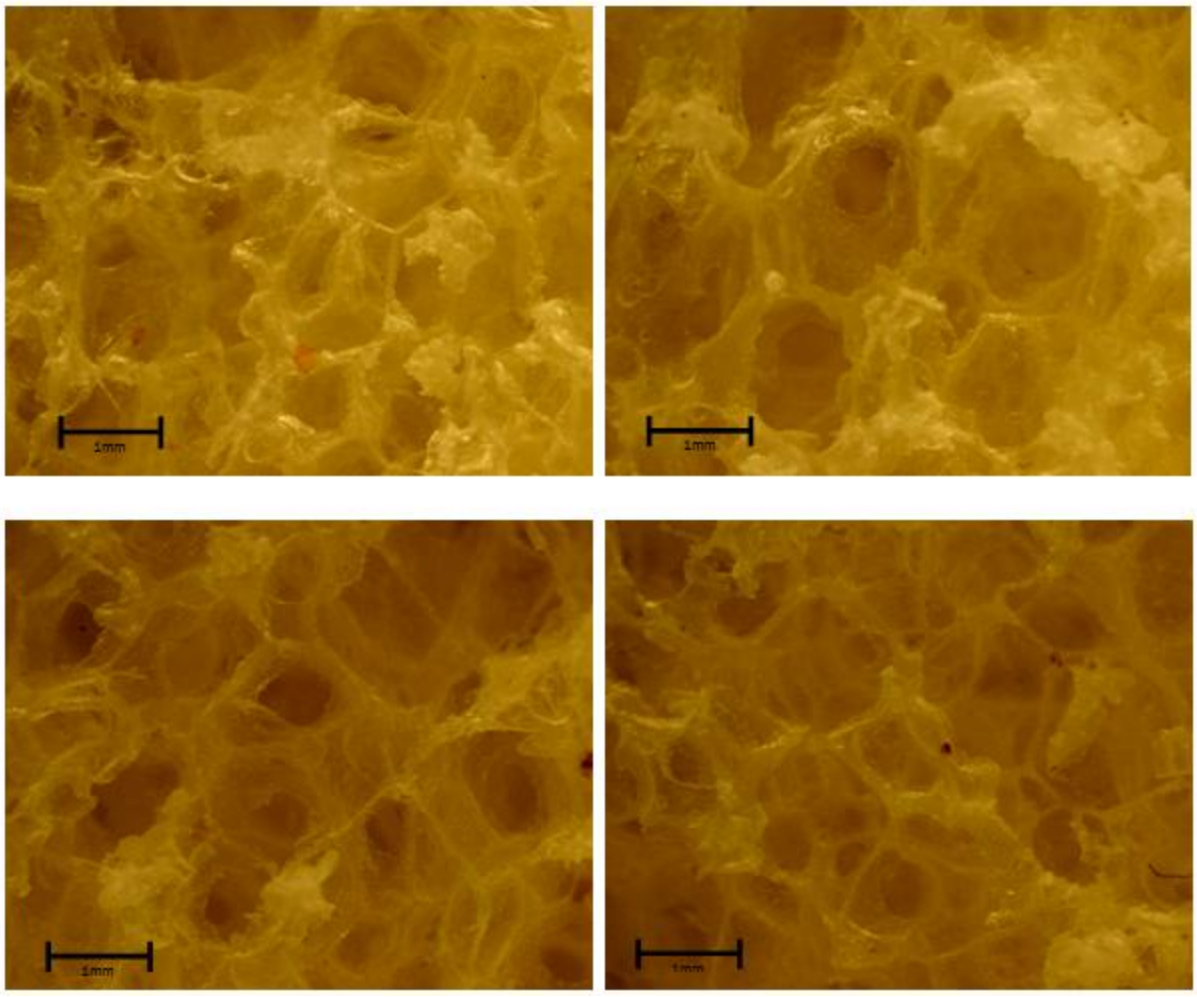


Figure 18 Cell Structures 20x

The random shapes and distribution of cells can be seen in the four samples of Figure 18. There are cells missing cell walls and a few different shapes represented in addition to distorted hexagons and indeterminable shapes. Pentagons are another prevalent observed shape and some rhombuses as well as octagon cross sections which are not seen in Figure 18. Some of the smaller sized cells present in the bread crumb are hard to discern their shape but appear to be hexagonal. These cells also had distortion or intruding bodies of dough into the cell structure.

Open Closed Ratio

20 samples of fresh bread were viewed under the SMZ 1500 stereo microscope to obtain data for the open-closed cell ratio. Knowing that bread is produced through random processes it was expected that the distribution of data would be broad. From the 20 samples viewed under 10x optical zoom an open closed cell ratio was determined. Between each sample the number of cells and the ratio of open to closed cells (OCR) had a wide variation. **Error! Reference source not found.** shows the distribution of open and closed cells.

Table 1 - Open-closed cell ratio

Sample	Open	Closed	Ratio	Total cells	% open	%closed
5	30	43	0.697674	73	0.410959	0.589041
20	24	34	0.705882	58	0.413793	0.586207
1	22	29	0.758621	51	0.431373	0.568627
2	25	32	0.78125	57	0.438596	0.561404
4	23	29	0.793103	52	0.442308	0.557692
10	23	29	0.793103	52	0.442308	0.557692
12	17	21	0.809524	38	0.447368	0.552632
3	27	33	0.818182	60	0.45	0.55
6	28	33	0.848485	61	0.459016	0.540984
9	20	22	0.909091	42	0.47619	0.52381
16	22	23	0.956522	45	0.488889	0.511111
13	25	26	0.961538	51	0.490196	0.509804
7	29	28	1.035714	57	0.508772	0.491228
8	22	20	1.1	42	0.52381	0.47619
14	24	21	1.142857	45	0.533333	0.466667
18	24	21	1.142857	45	0.533333	0.466667
19	24	19	1.263158	43	0.55814	0.44186
15	27	21	1.285714	48	0.5625	0.4375
17	20	13	1.538462	33	0.606061	0.393939
11	29	12	2.416667	41	0.707317	0.292683
Avg Ratio			0.933515			
STD			0.187393			
% open			47.83825			
%closed			52.16175			

The ratio was calculated for each sample and the initial OCR and standard deviation of the ratio was calculated to see which values to omit. Any value that was twice the standard deviation from the calculated average OCR was omitted. The OCR with all the samples was calculated as 1.038 and the standard deviation was .3937. this resulted in Sample 11 being omitted from the data. The standard deviation and OCR average were calculated as 0.2290 and 0.965 respectively and therefore sample 17 was also omitted. The Standard deviation and OCR was recalculated to check if the remaining values were within the deviation. With a standard deviation of .187 and an OCR average of .933515 the remaining 18 samples were within the deviation. The percentage of open cells is 47.838% and the percentage of closed cells is 52.162%. Surprisingly the open-closed cell ratio is almost even which goes against research stating it is mostly open. The open-closed cell ratio and basic cell structure was used to develop a model for the actual structure of the bread. Appendix D contains all the samples used to determine the open-closed cell ratio.

For the LR-white resin samples, the open-closed cell ratio was also analyzed. Figure 19 shows a cross section of the bread encased in LR-White epoxy resin.

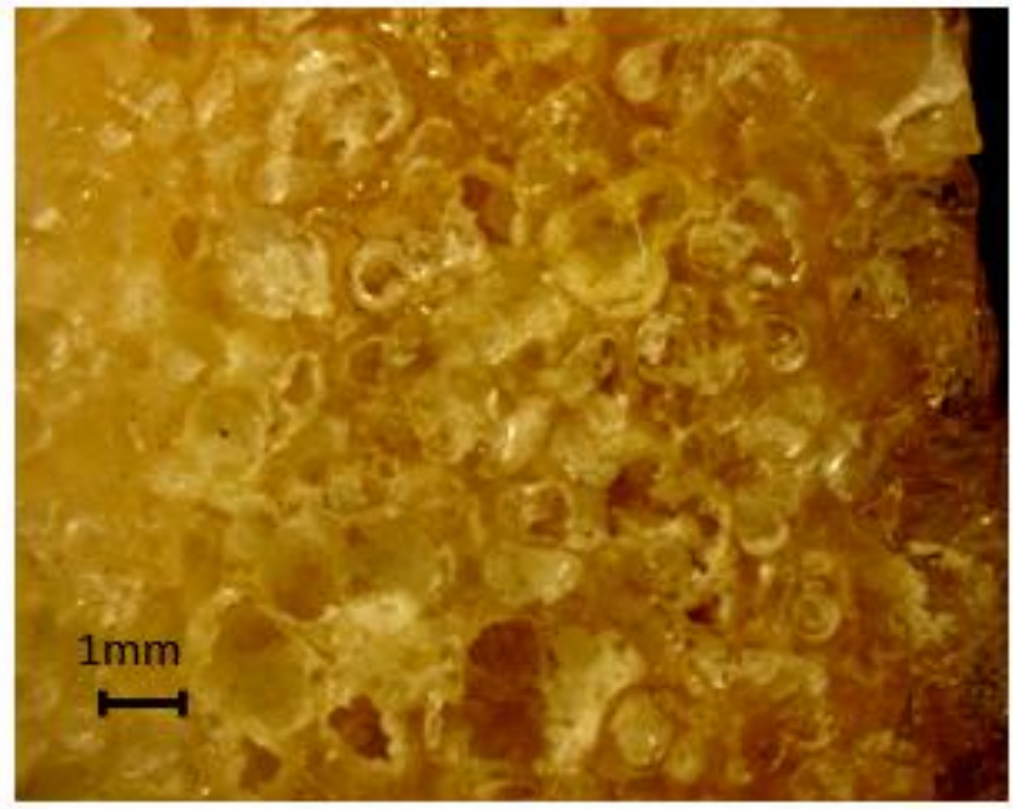


Figure 19 - Bread crumb in LR-White Epoxy Resin

With the resin the open cells are ones that are filled with resin and the closed cells are the empty spaces. These samples are easier to discern which cells are open and which are closed when compared to the samples viewed without resin. Another benefit of the resin was samples could be cut thin and the crumb structure remained undisturbed. The problem with the resin was when preparing the sample the bread became baked which may change the cell ratio. Another issue was there appeared to be air bubbles in the resin though it was unclear as to the mechanism that caused them. An air bubble could be mistaken as a cell. The open-closed cell ratio is calculated for the five resin samples in Table 2.

Table 2 - LR-White Resin Open-Closed Cell Ratio

Sample	Open	Closed	Ratio	Total	%open	%closed
1	39	11	3.545455	50	0.78	0.22
2	28	7	4	35	0.8	0.2
3	26	9	2.888889	35	0.742857	0.257143
4	34	8	4.25	42	0.809524	0.190476
5	20	5	4	25	0.8	0.2
6	35	12	2.916667	47	0.744681	0.255319
avg			3.600168			
STD			0.586191			
%open			0.77951			
%closed			0.22049			

The average open to closed cell ratio for the bread samples in resin was higher by approximately a factor of 3.6. The total number of cells counted was also higher in the resin samples even though the magnification was the same. The resin sample was thinner which might explain the larger amount of total cells but also a misinterpretation of air bubbles as cells could be another reason. The non-resin slices may have distorted cells from the manufacturers slicing which lowered the count of viewable cells of the data in Table 1. The data that was decided to analyze for modeling was the non-resin samples primarily because of the presence of air bubbles in the resin samples. Appendix E contains all the samples encased in LR White epoxy resin.

Changes in Cell Dimensions as Bread Stales.

Cell wall lengths and thicknesses were measured over the course of four weeks and monitored for any dimensional changes. It was not feasible to observe the cells for geometrical changes due to how the bread cells are so varied throughout every section of bread viewed. The missing cell walls and distorted cells would also make it difficult to determine the changes in cell geometry if there is any changes to be found. Measuring dimensional cellular properties is feasible though. It is generally clear where a cell wall ends regardless of what shape the cell is. The cells dimensions measured in this study were from the cells that appeared hexagonal for consistency and it produces more comparable data if cells with relatively the same shape are viewed. Figure 20 shows the fresh baked bread cells at 20x optical zoom.

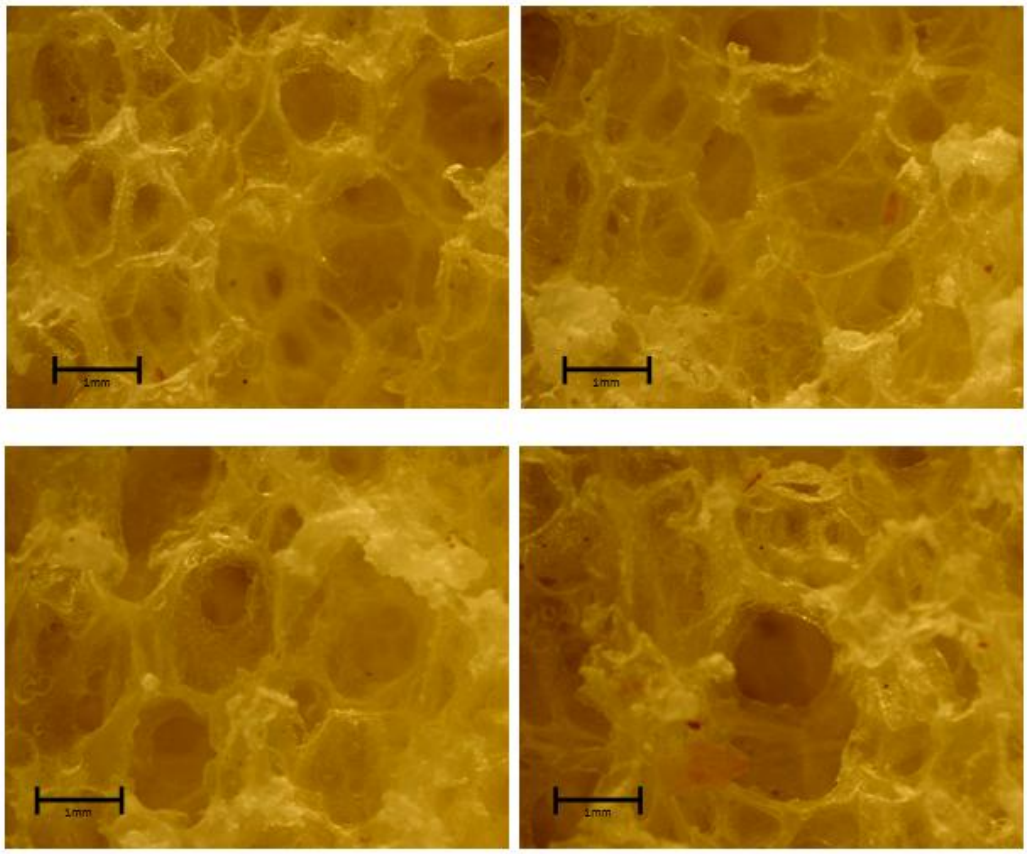


Figure 20 - Fresh Bread Crumb 20x

Table 3 shows the fresh baked bread sample measured the day that the bread was delivered to the store.

Table 3 - Day 0 Bread Crumb Cell Dimensions

Cell	Side 1(mm)	side 2(mm)	Thickness(mm)
1	1.3	0.95	0.075
2	0.8	0.8	0.125
3	0.85	0.75	0.05
4	0.85	0.65	0.05
5	0.725	0.85	0.075
6	0.55	0.65	0.075
7	0.75	0.7	0.05
8	0.5	0.45	0.075
9	0.75	0.75	0.075
10	1.05	0.6	0.1
11	0.5	0.65	0.1
12	0.475	0.55	0.05
13	0.85	0.9	0.075
14	1.15	1.15	0.075
avg	0.792857	0.742857	0.075
STD	0.248153	0.17959	0.021926

Side 1 and Side 2 lengths are the lengths of two adjacent cell walls of a hexagonal structured cell. Looking at Cell 10 shows a big length difference between the two adjacent cell walls. Many cells wall lengths are different meaning that the cells are not symmetrical, a result likely influenced by the random processes that create baked bread. The average cell wall length of fresh baked bread crumb for side 1 and side 2 was 0.7929 mm and .7429 mm respectively. The overall average cell wall length between the two sides is 0.7679 mm. The standard deviations for the two lengths were 0.2482 and 0.17959 respectively. Cell 1 side 1 was slightly above twice the standard deviation but all the other cell walls were within 2 standard deviations. The thickness of the cell walls averaged out to approximately 0.075 mm with a standard deviation of 0.02193. The thicknesses were measured from the same cell that the sides were obtained. Appendix A contains all the samples taken.

The next set of samples measured was the four week old samples. Figure 21 is the cells analyzed from this set of samples.

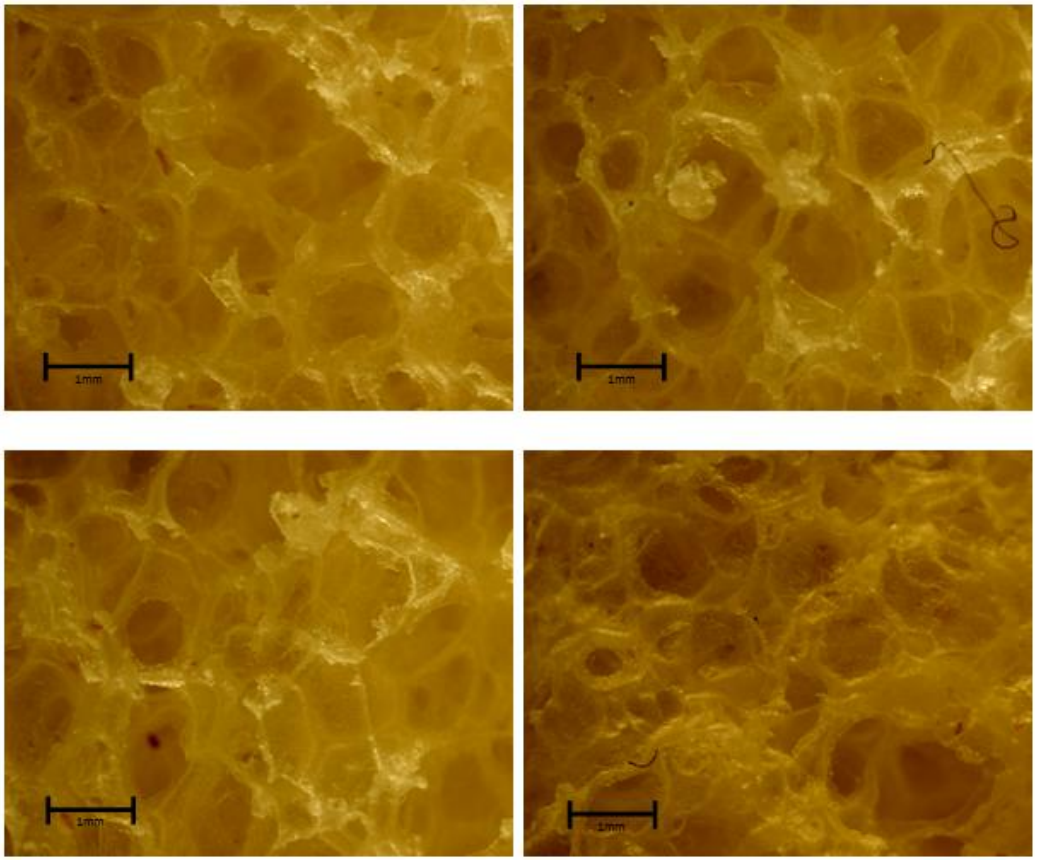


Figure 21 - 24 Day old Bread Crumb 20x

Table 4 is the cell wall lengths and thicknesses from 24 days of staling.

Table 4 - Day 24 Bread Crumb Cell Dimensions

Cell	Side 1(mm)	Side 2(mm)	thickness(mm)
1	0.8	0.7	0.075
2	0.85	0.5	0.075
3	0.65	0.6	0.05
4	0.45	0.45	0.1
5	0.75	0.8	0.075
6	0.7	0.5	0.1
7	0.4	0.55	0.075
8	0.5	0.7	0.1
9	0.75	0.8	0.05
10	0.45	0.6	0.075
11	0.8	0.55	0.05
12	0.6	0.55	0.05
13	0.45	0.5	0.075
14	0.55	0.55	0.075

avg	0.621428571	0.596428571	0.073214286
STD	0.15530898	0.111741952	0.018251148

The average cell wall lengths were 0.6214 mm and 0.5964 mm with standard deviation of 0.1553 and 0.1117 for side 1 and side 2 respectively. The overall average cell wall length is 0.6089 mm. All of the data points were within 2 standard deviations. The average thickness of the cells was 0.07321mm with a standard deviation of 0.01825. All the data points for cell wall thickness were within 2 standard deviations. Appendix C contains all the samples taken for 24 day old bread.

Comparing the results from table 2 and table 3 the bread cells are smaller in length when the bread is stale. The thickness also decreases slightly in the 24 day old bread though the data points themselves seem to show the thicknesses remaining relatively constant between the two times most of the thicknesses are 0.075 mm.

With the two sets of data previously discussed a change in cell dimensions could be determined, though with the high standard deviations and the small size of samples taken no real conclusion can be made with confidence. Analyzing only two sets of data does not justify a trend. The data from other days had to be viewed as well to solidify a data trend and see if the bread crumb cells change after staling.

The next set of samples analyzed were the 3rd week of samples taken. Figure 22 is the cells analyzed from this set of samples.

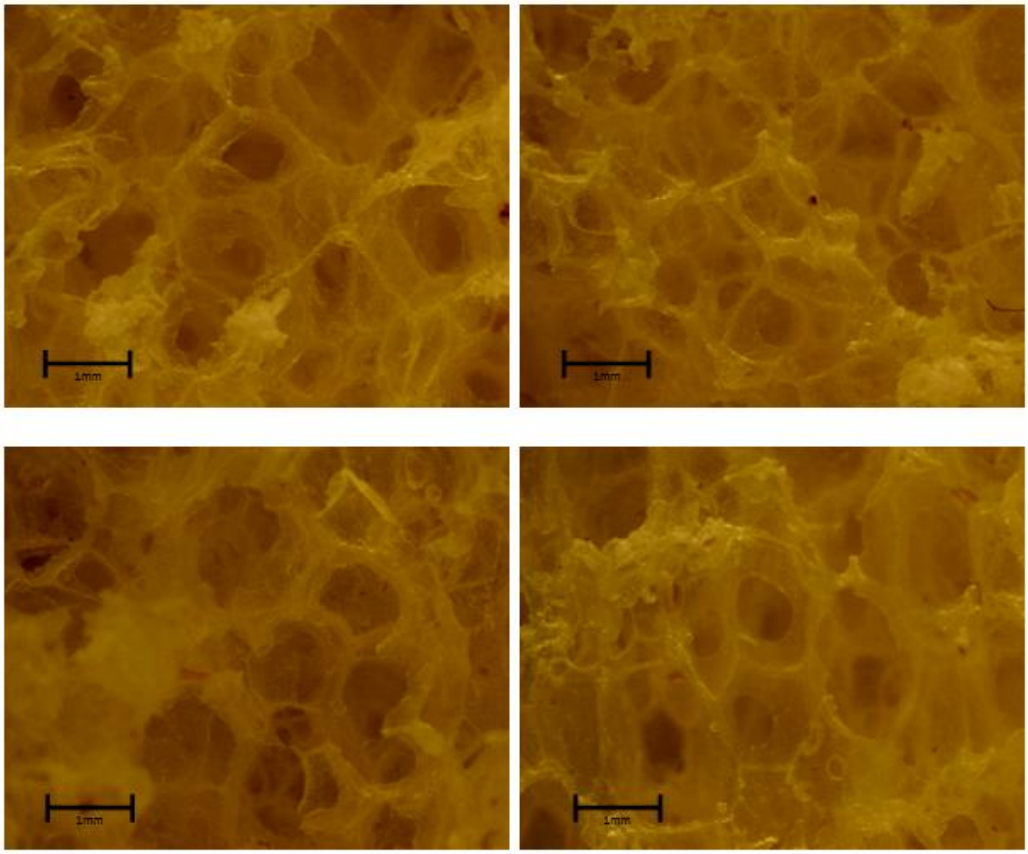


Figure 22 - 14 day old Bread Crumb 20x

Table 5 shows the cell wall lengths and thicknesses for 14 days of staling.

Table 5 - Day 14 Bread Crumb Dimensions

Cell	side 1(mm)	side 2(mm)	thickness(mm)
1	0.85	0.55	0.075
2	0.85	0.65	0.05
3	0.45	0.9	0.05
4	1.05	1.2	0.075
5	0.75	0.85	0.075
6	0.7	0.7	0.075
7	0.5	0.7	0.075
8	0.4	0.45	0.05
9	0.4	0.6	0.05
10	0.75	0.7	0.1
11	0.95	0.8	0.1
12	0.9	0.65	0.075
13	0.6	0.9	0.05
14	0.5	0.4	0.075

avg	0.689285714	0.717857143	0.069642857
STD	0.215886875	0.205320709	0.01748233

The data from table 4 has average cell wall lengths of 0.6893 mm and 0.7179 mm with standard deviations 0.2159 and 0.2053 for side 1 and side 2 respectively. The average overall cell wall length is 0.7036 mm. The average cell wall length is smaller than the fresh bread but larger than the 24 day old bread. This data gives reason to state a general trend that the bread crumb cell walls shrink as bread stales. The fact that moisture leaves the bread as it stales makes this trend seem likely and the data quantifies this. The thickness averages to 0.06964 mm which is significantly lower than the previous two data sets. Appendix B contains all the samples taken for 14 day old bread.

As stated in the review of literature, an average cell size does not portray an accurate image of the cells sizes due to the few large pores present. A histogram was developed for each set of samples and superimposed on one graph to compare the distribution of cells as seen in Figure 23.

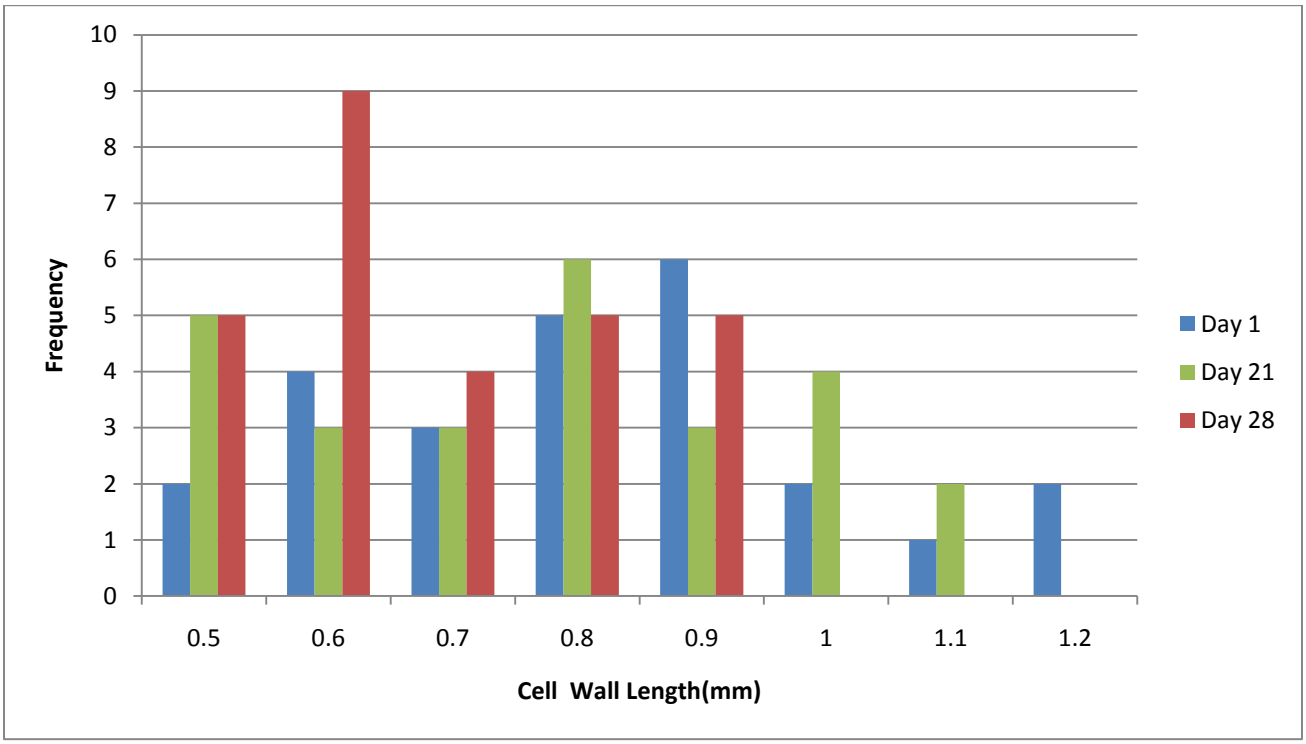


Figure 23 -Histogram Cell Wall Length over staling period

The distribution of cells for the fresh baked bread is more uniform then the distribution of the other two days and has a slightly higher frequency towards larger cell sizes in comparison. The highest frequency of cell lengths is about 0.9 mm. Compared to the average from the data table of 0.769 mm it is clear that the histogram is a better representation of the cell sizes. Fourteen day old bread has a less clear trend as the frequencies increase and decrease between lengths but it appears to have a generally lower cell size than the fresh baked bread. Twentyfour day old bread shows a significantly narrower range of cell sizes compared to the other two sets of data. The 24 day old bread has a higher frequency of small cells as well with most of the cell walls' lengths about 0.6 mm. The histogram shows that the cell wall lengths generally decrease as the bread stales similar to the averages calculated by the tables.

Measured Relative Density

The area used for calculating the relative density was 1.89 in^2. This was calculated by measuring the circumference of the metal punch. The measured thicknesses and masses can be seen in Table 6 below.

Table 6 - Measured thicknesses and Masses of Bread

#	Area (in^2)	Uncrushed (in)	Mass-un (g)	Crushed (in)	Mass-crush (g)
1	1.89	0.551	2.254	0.094	2.101
2	1.89	0.5675	2.679	0.0955	2.45
3	1.89	0.4349	1.83	0.0065	1.716
4	1.89	0.5759	2.141	0.0915	1.957
5	1.89	0.527	2.268	0.115	2.133
6	1.89	0.5269	2.381	0.1139	2.174
7	1.89	0.4876	2.013	0.1	1.892
8	1.89	0.482	2.145	0.109	1.962
9	1.89	0.518	2.198	0.1005	2.035
10	1.89	0.52	2.423	0.115	2.215
11	1.89	0.4905	1.894	0.106	1.786
12	1.89	0.4429	2.065	0.1069	1.88
13	1.89	0.5244	2.15	0.1033	2.03
14	1.89	0.565	2.475	0.13	2.26
15	1.89	0.515	2.092	0.101	1.964
16	1.89	0.508	2.238	0.1134	2.063
17	1.89	0.5	2.062	0.109	1.946
18	1.89	0.527	2.345	0.1146	2.134
19	1.89	0.4978	2.153	0.103	2.022
20	1.89	0.5025	2.165	0.0927	1.978

SDV	0.036655142	0.197937384	0.024175986	0.16782977
AVG	0.513195	2.19855	0.10104	2.0349

The average measured thicknesses for uncrushed and crushed bread crumb were 0.513 and .101 inches respectively. While measuring the mass for the bread crumb the staling process was noticeable. In order to obtain accurate data, the bread had to be quickly weighed. Even while weighing the bread, the mass was decreasing. This is most likely due to the bread crumb losing moisture. Also, the handling of the bread had to be taken into consideration. As the bread was measured and held, bread crumbs were falling off the sample. The opposite could also be said about unknown particulate attaching themselves to the bread crumb sample. Both of these would skew the data obtained.

The calculated density of the foam, solid, and relative density can be seen in the Table 7 below.

Table 7 - Density of Foam, Solid, and Relative Density

Den-Foam	Den-Solid	Measured Relative Density
2.164414869	11.8259597	0.183022344
2.497727432	13.57378321	0.184011148
2.226383004	139.6825397	0.015938878
1.967015511	11.31639055	0.173820045
2.277039848	9.813664596	0.232027478
2.390943936	10.0988986	0.23675294
2.184330117	10.01058201	0.21820211
2.354607126	9.523809524	0.247233748
2.245102245	10.71362763	0.209555747
2.465404965	10.19093628	0.241921341
2.043050769	8.914844764	0.229174015
2.466905831	9.305042046	0.265114958
2.169271811	10.3976193	0.208631586
2.317741256	9.198209198	0.251977445
2.149278266	10.28864791	0.208898029
2.33095863	9.625523735	0.242164343
2.182010582	9.446143391	0.230994861
2.354346757	9.852535158	0.238958473
2.288375732	10.38680845	0.22031558
2.279607255	11.28976102	0.201918114
	SDV	0.052122952

AVG	0.212031659

As you can see the density of the solid bread crumb is greater than that of the foam bread crumb. This is due to the cell walls being crushed together and the absence of the previous gas cells. The average relative density was calculated to be 0.212. This shows that the density of the solid bread crumb is approximately five times larger than that of the foam bread crumb.

Modeling of Relative Density

To model the relative density the cell ratio, cell shape, and cell size previously analyzed will be used. These values and the equations mentioned in the previous section were inputted into excel and plotted as a function of cell length. The full excel sheet can be seen in Appendix G. This can be seen in the Figure 24.

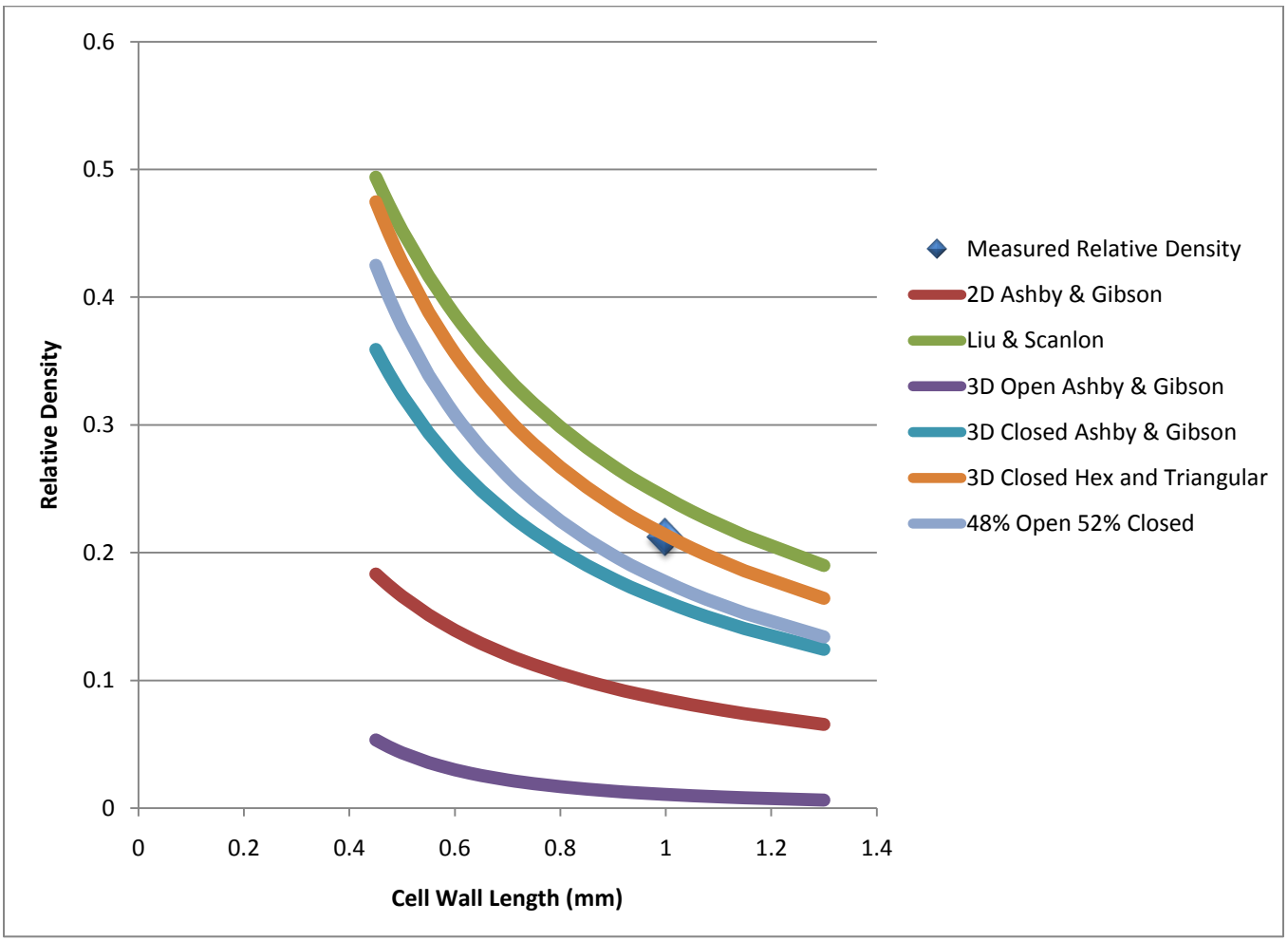


Figure 24 - Theoretical Relative Density as a Function of Cell Length

The above figure contains plots for several different equations. The purple line represents the Ashby and Gibson model for 100% open hexagonal prism structure. From our previous image analysis we know that this is not true. This can also be seen on the figure from the blue diamond representing the average measured relative density. From reading the graph the average measured relative density should have a cell wall length of approximately 0.97 mm. From the histogram showing the distribution of cell wall lengths, a large portion of cells have a cell wall length of approximately 0.9 mm. The 100% open hexagonal prism has too low a relative density to fit the actual data. The red line denotes the Ashby and Gibson two dimensional hexagonal honeycomb structure. This too has a low relative density compared to the measured data. The dark blue line is the 100% closed hexagonal prism structure. We had previously assumed that the general geometry for bread crumb was completely hexagonal. From the figure above we see that this is apparently not true. To try and fit the measured data the Ashby and Gibson models for both open and closed hexagonal prisms were combined using coefficients to get the appropriate open to closed cell ratio. However, this did not improve the model. To further improve the model, equations for open and closed triangular prisms were added. This resulted in the light blue line on the figure above. Even with a ratio of 90% triangular and 10% hexagonal prisms, which we know not to be true, it did not fit to the measured relative density. The theoretical model for three dimensional hexagonal prisms could not match the measured relative density.

This is most likely due to the fact that bread is not a perfect hexagonal honeycomb structure. Many of the cell walls are either missing or deformed. Also the majority of cells cannot be identified as a geometric shape.

To try and match the measured relative density with a theoretical model, a combination of 100% closed hexagonal and triangular prisms were modeled. This equation consists of 70% hexagonal and 30% triangular prisms, represented by the orange line. As you can see in the figure above, it fits the measured data. However, as previously mentioned bread crumb is not 100% closed cells. Therefore, this model is not accurate or applicable.

The model that most closely follows the measured data is the function produced by Liu and Scanlon. By utilizing experimental data they fit a second order function to measured values. This

model can be seen in the figure above represented by a green line. Their equation also incorporates the fact that some of the cell walls are missing or deformed. This was the expected outcome since their function was tailored to represent actual data from bread.

Tensile Testing

All of the data from the tensile tests, force vs. displacement, was used to calculate the stress strain curves seen below in Figure 25. Best fit trinomials were fitted to the data set for each day to graph the average of each data set. The data for each set for strain values from 0% to 0.05% were used to calculate a best fit line and generate the elastic modulus seen in Table 8. Also the stress at the end of the best fit trinomials was used for the ultimate tensile strength (UTS) also labeled in Table 8.

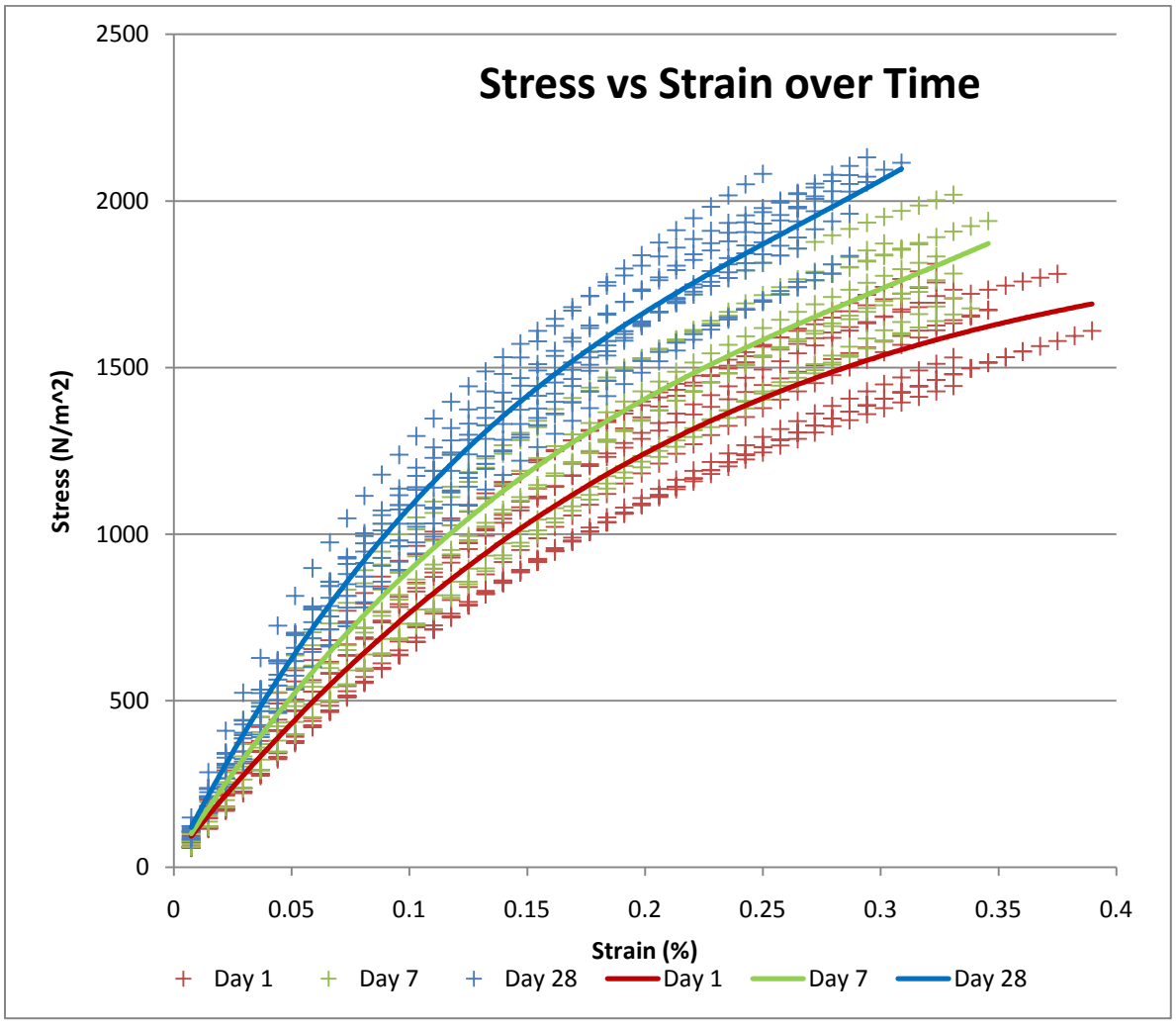


Figure 25 - Stress vs. Strain, Best fit lines and data points

Table 8 - Material Property Data

	Day 1	Day 7	Day 28
Elastic Modulus *E* (Pa)	8649	10242	12540
Ultimate Tensile Strength (Pa)	1700	1830	2100

From the stress strain curve and the preceding table it is evident that as bread crumb stales there is an increase in both the Elastic modulus and the UTS.

Fracture Patterns

Fractures were observed for samples subjected to bending and tensile loading. Figure 26 shows the facture pattern of a bending fracture sample outlined in red at 7.5x optical zoom perpendicular to the plane of fracture.

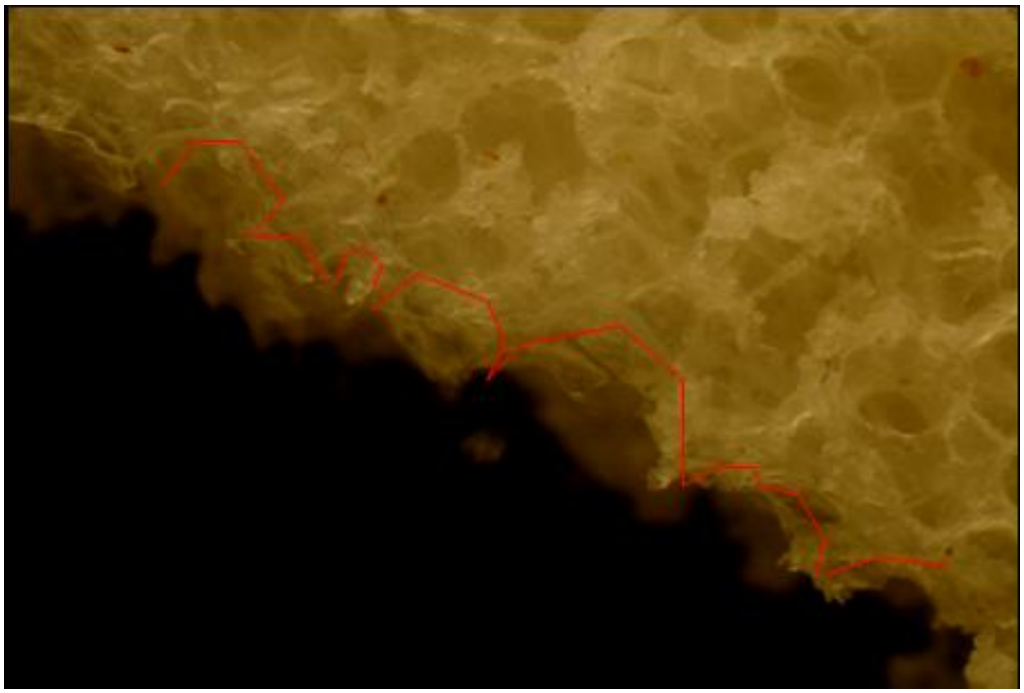


Figure 26 - Bending Fracture outlined at 7.5x

Figure 27 shows several other bending fractures perpendicular to the fracture plane at 7.5x optical zoom.

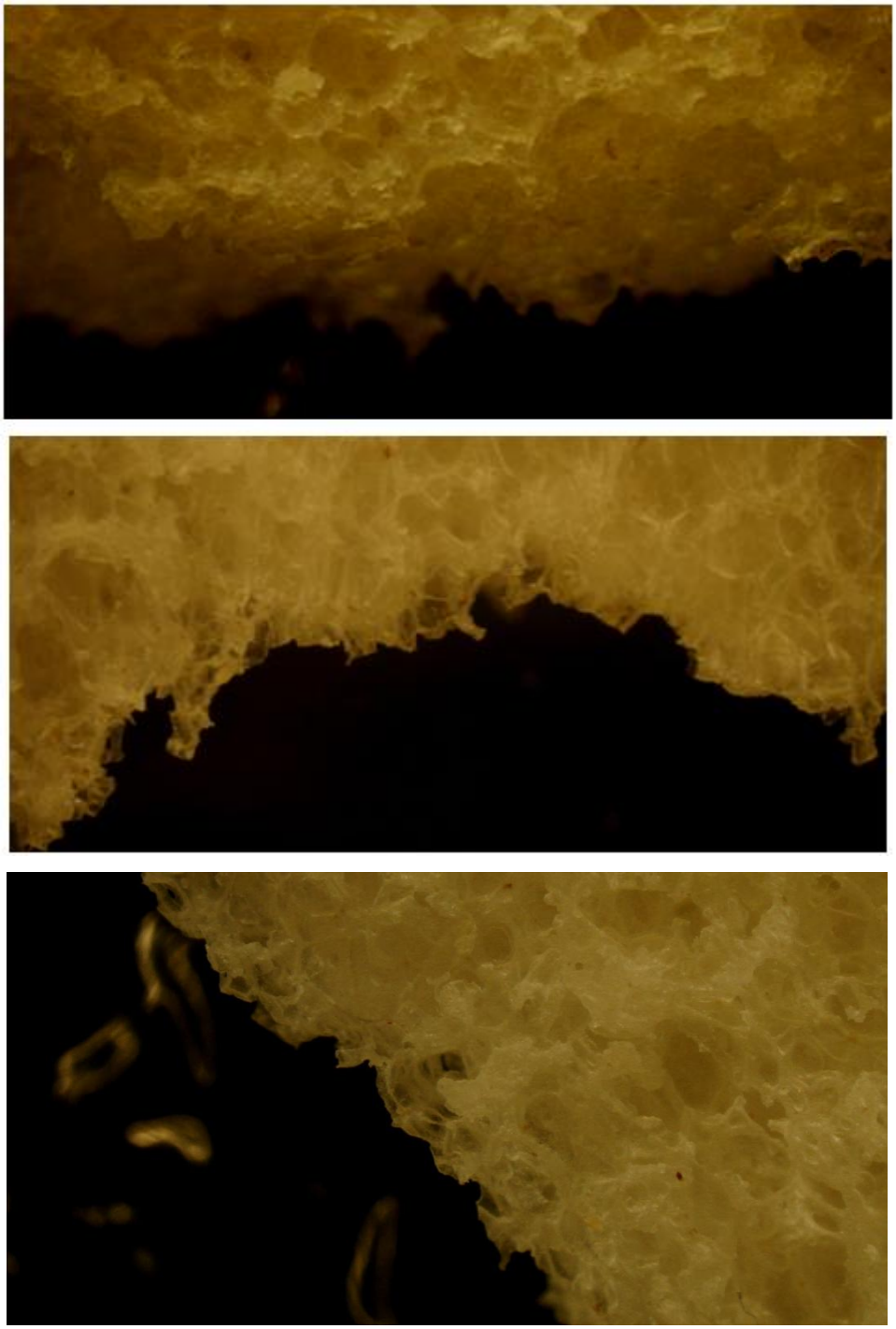


Figure 27 - Bending Fractures at 7.5x

From visual observation the fracture pattern appears to be trans-cellular from bending moments. Images were also taken parallel to the fracture plane and at higher magnifications but those were not feasible to analyze. Appendix F contains more pictures of the bending fracture samples.

After tensile testing was completed, the samples were photographed to analyze the fracture patterns. Below are three figures, Figure 28, Figure 29 and Figure 30 which demonstrate the three common types of fractures observed, cup and cone, transverse and oblique. At first inspection the type of fracture appeared random but upon closer inspection it was noticed that the fracture line would follow a line that contained the largest cells within the narrow section of the bone shaped template.

Figure 28 - Oblique Fracture

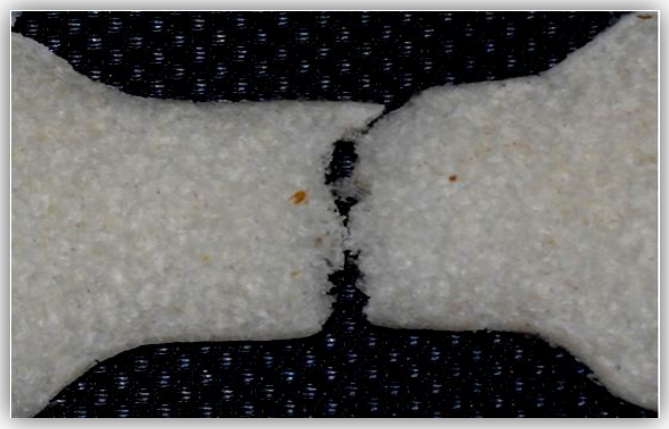


Figure 29 - Transverse Fracture

Figure 30 - Cup and Cone Fracture

A file submitted with this document contains video footage of bread fracturing under tensile loads. It shows the deformation of bread crumb cells as it is being pulled. They can be viewed below. The video recording device could not be zoomed in further than what is seen due to the limits of the recording device. Any video editing increased file size dramatically so it was not feasible to try and edit the video to include in this report. Looking at the video the bread plastically deforms significantly before fracturing. Cells elongate in proportion to the deformation, generally more elongation is seen at the area where bread will fracture.

Conclusion and Recommendations

Conclusions

From the samples taken the general cellular shape of the bread crumb was observed to be hexagonal honey comb, which corresponds with previous findings. The actual cell structure is much more complex due to the random processes involved in the formation of the crumb structure. Examples include missing cell walls, variations in cell shape and size and malformed cells. The general hexagonal honey comb structure was used in conjunction with further image analysis and modeling.

Another measured parameter was the ratio of the open to closed cells of bread crumb. Two sets of samples were observed, the first set consisted of 20 samples from the surface of the slice as cut by the manufacturer, and a second set that was encased in LR-White epoxy resin and cut using a tungsten-carbide saw to a mirror finish. There was a significant difference between the two types of samples. From the analysis of the first set of samples, the average ratio was determined to be 52% closed to 48% open. The LR-White epoxy resin samples had an average ratio of 22% Closed and 78% open. The ratios were determined by direct observation without the aid of image analysis software packages, and are subjective to the observer. Although observations of the the LR-White epoxy sample set was more defined between open and closed cells, a number of factors likely influenced the results; therefore the first sample set represents a more accurate portrayal of the actual ratio.

Cell wall lengths and thicknesses were measured over the course of four weeks to determine if there is a change in dimensions and shape. From the data collected there is trend that shows the cell wall lengths decreasing noticeably as it stale. Fresh bread had an average cell length of 0.7679mm, as opposed to the 14 week bread of 0.7036mm and the 24 day old bread of 0.6089mm. Both the maximum and range of cell wall lengths decreased in size over the period of study.

The relative density of bread crumb can be modeled using the Ashby and Gibson mathematical functions. These are based on the general cell shape and dimensions, and are taken as either 100% open or 100% closed foam cells. These functions were combined to match the open to closed cell ratio determined through image analysis. Due to discrepancies toward our assumption of a 100%

hexagonal honeycomb structure within the bread crumb the theoretical curve does not closely follow the actual data. Using coefficients and the incorporation of other shapes' functions, the curve can be skewed to follow the actual data. The final equation to describe the relative density of bread used was The relative density of bread crumb can be modeled using functions that are based on experimental data, such as the equation used by Liu and Scanlon. There equation is:

$$\frac{\boldsymbol{\rho}^{*}}{\boldsymbol{\rho_s}} = \mathbf{2} * \frac{1}{\sqrt{3}}\frac{\boldsymbol{t}}{\boldsymbol{l}} - \frac{1}{3}\frac{\boldsymbol{t^2}}{\boldsymbol{l^2}}$$

where the thickness and cell wall length are the two variables. Ashby and Gibson's models are not necessarily incorrect, but cannot be used with the information that we obtained. From there models we can see that bread is not a simple hexagonal honeycomb structure. It is in fact a wide variety of shapes and non-uniformities.

Bread slices were cut into "dog bone" shaped samples to be tested using an Instron machine using a constant strain rate. The tensile force and displacement data was collected from this test. Using dimensions of the bread samples the data collected was translated into stress and strain data. This data was graphed and the elastic modulus and yield strength were determined. Over the duration of staling the bread samples were measured to have a higher elastic modulus and yield strength. While the trend is noticeable, the data sets collected are broad and overlapping likely a result of the heterogeneous bread crumb structure.

Fracture Patterns were observed from bending and tensile loading to investigate how the fractures propagated throughout the bread crumb. Samples were frozen using liquid nitrogen and then fractured by bending. Fractures that were observed using this method demonstrated fracture through the cell walls, specifically brittle transverse trans-cellular fracture. Fracture patterns were also observed from the ductile strain induced tensile loading at room temperature. These tests demonstrated trans-cellular fracture, but followed three distinct patterns cup and cone, transverse, and oblique likely caused by the irregularities of the cells.

Through the image analysis the cell wall lengths decrease as bread stales. Tensile tests showed that as bread stales the elastic modulus and yield strength increase. As the average cell size decreases the elastic modulus and tensile strength increase due to densification of the bread crumb. Both of these effects are likely due to staling of bread. During staling moisture is redistributed from the crumb to the crust. It is important to note that this data cannot be

correlated to the mechanisms of staling due the lack of current research into understanding the staling of bread crumb.

Recommendations

There are several recommendations for the image analysis portion of this study. Appropriate image analysis software should be used to eliminate human error and would likely reduce the time it takes to analyze the cell dimensions allowing more data to be obtained. This leads to the second recommendation to obtain more data to further establish the trend of decreasing cell sizes as bread stales. Although a trend has been observed the amount of samples seems insufficient to safely conclude what is observed. Data should be obtained for more frequent intervals of time and the change should be plotted.

Specifically for determining the open-closed cell ratio more experiments should be done with the LR White epoxy resin to obtain samples that are not baked and reduce air bubbles. Using the LR white epoxy resin has potential to give accurate cell ratios and would probably be better to use with image analysis software. Another medium might also be worthwhile experimenting with to avoid having to heat the bread. More samples in general should be taken for the open-closed cell ratio. More samples obtained will give a more developed and credible average.

When measuring the bread crumb for relative density the bread staled extremely fast, looking at the mass balance the value would decrease continuously. This led to much of the data being partially inaccurate. To prevent this it is recommended that the bread crumb be measured in a closed environment with a set humidity and temperature. Also when measuring the thickness of the bread, a small force from the caliper would distort the bread and or remove some of the material. This was a result of the bread crumb being extremely soft. To prevent this the bread's volume would have to be measured without the use of a caliper or any other tool that comes in contact with bread.

The theoretical modeling of the bread did not have the results that were expected. This may be due to irregularities in bread geometry and size. Also, Bread crumb structure is not uniform so using any model based on set geometries would be inaccurate. When modeling relative density, thickness of the cell wall was held constant for simplification. To accurately model bread crumb,

the thickness would also change with cell wall length. If the most accurate model were to be obtained, it would have to be done through a software package, such as FEA, that could model bread structure accurately with a wide range of cell shapes and sizes.

References

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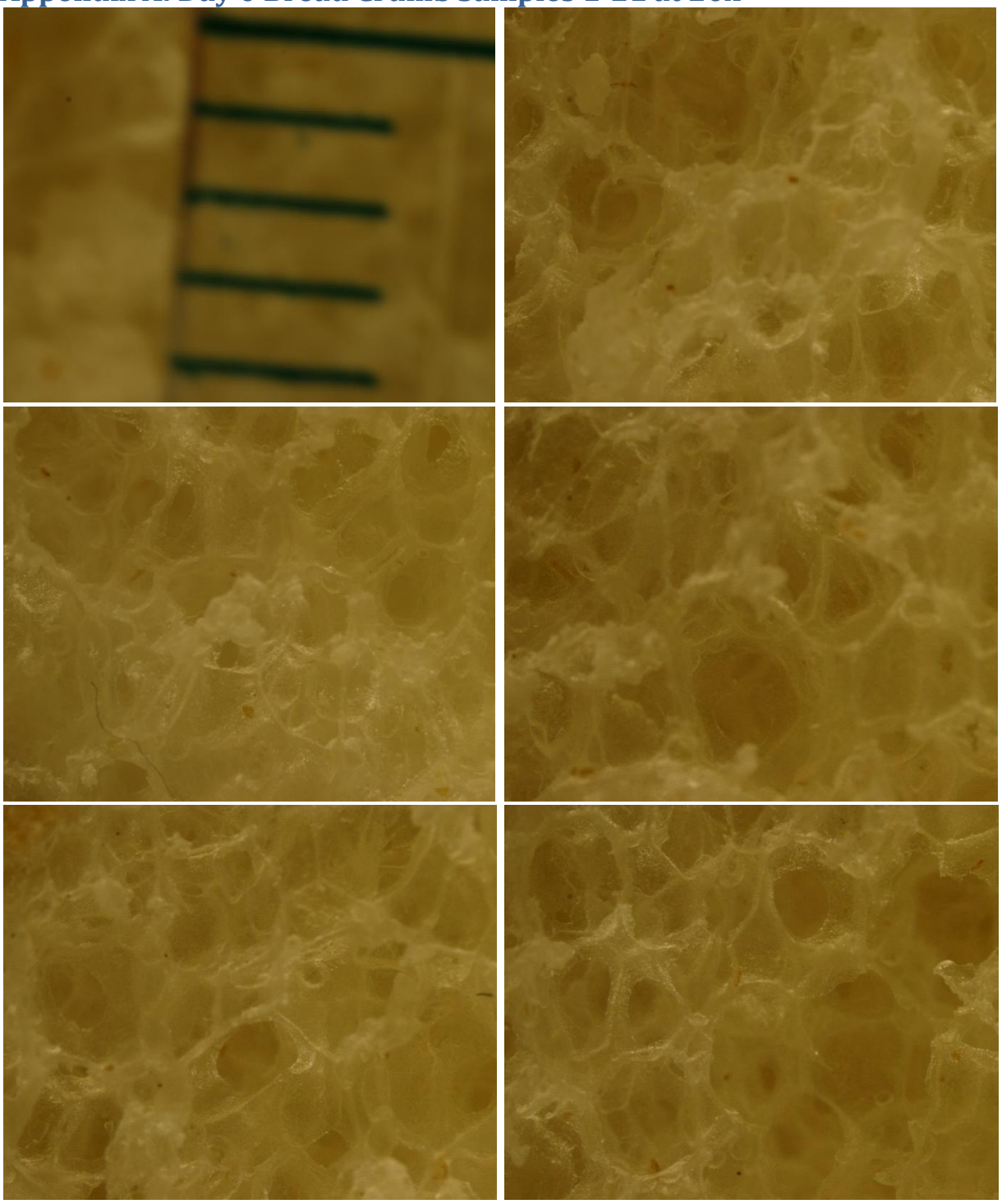
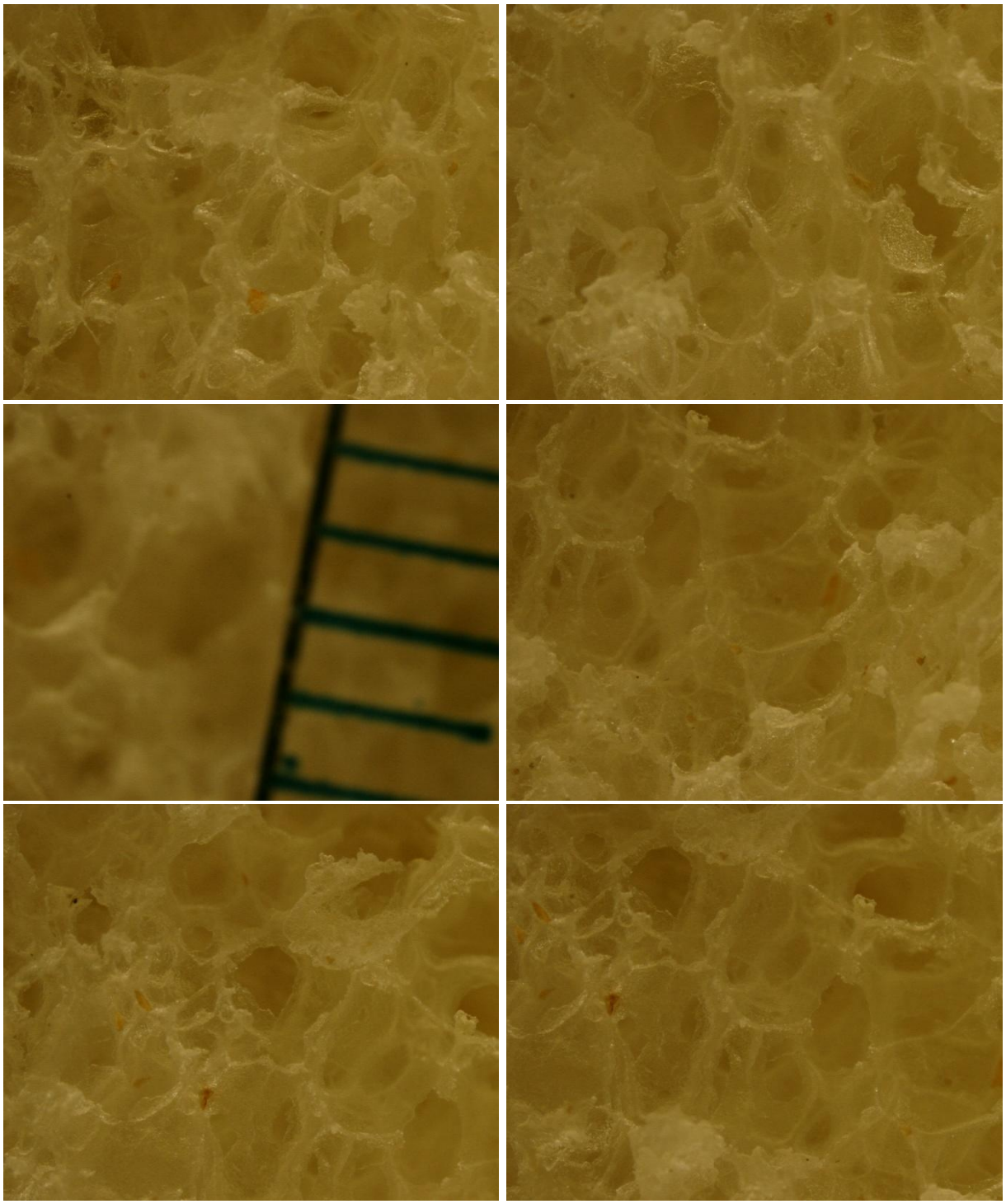
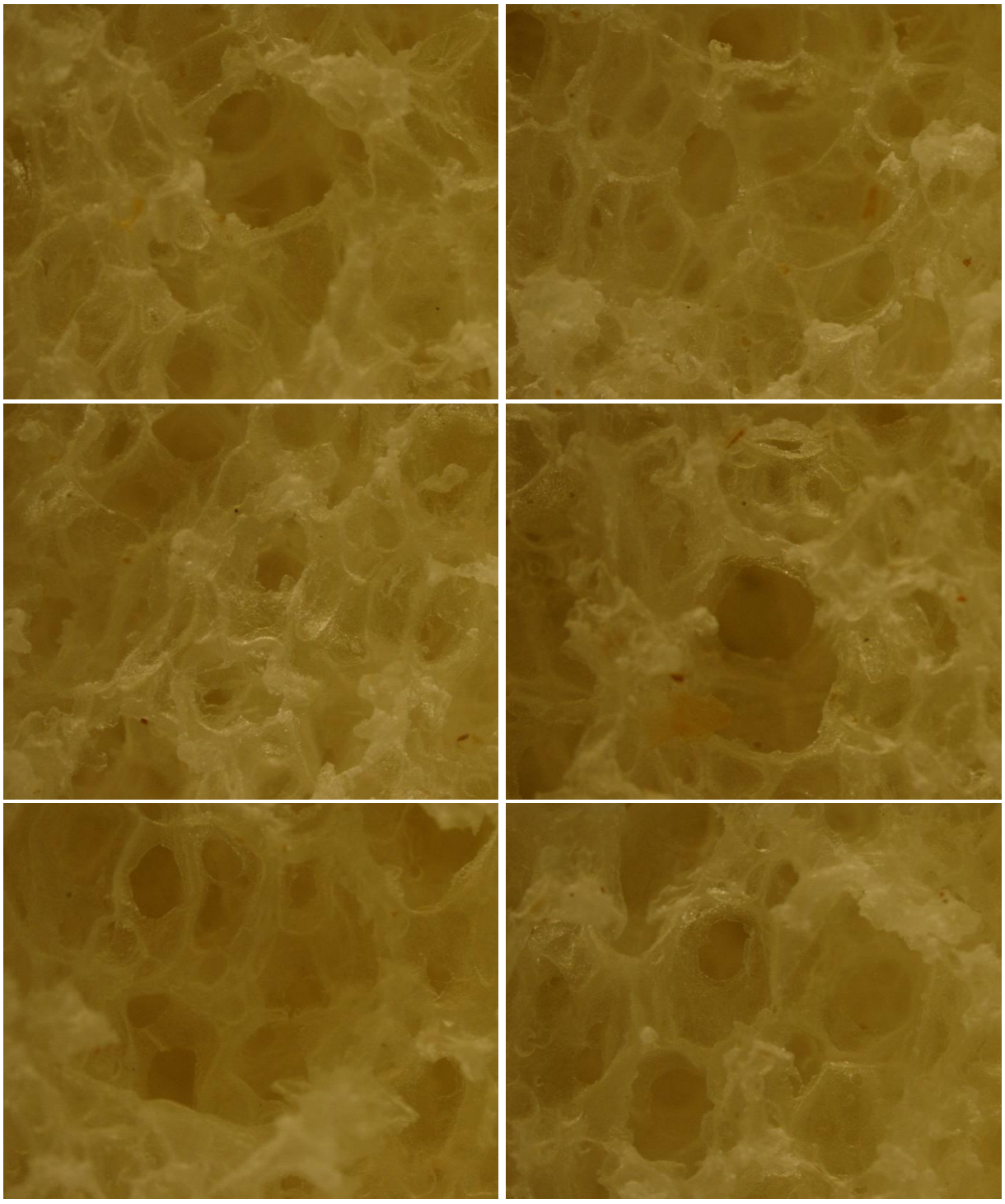
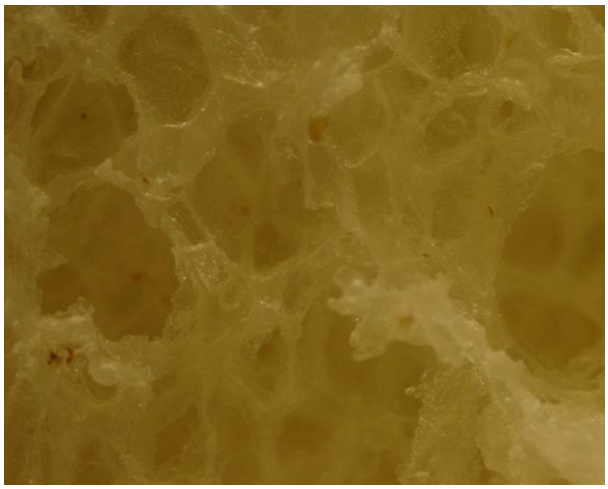
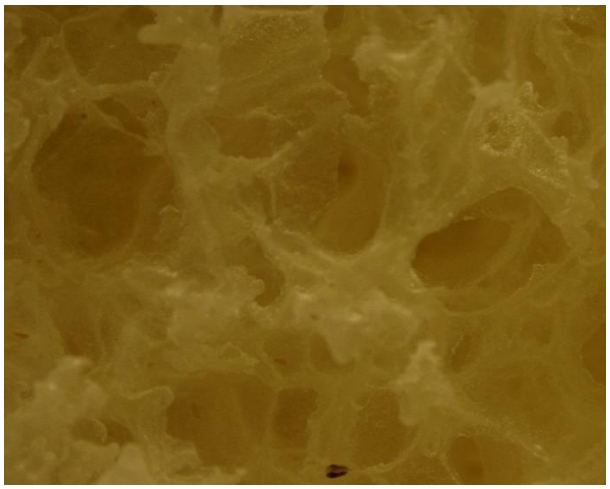
Appendix A: Day 0 Bread Crumb Samples 1-21 at 20x

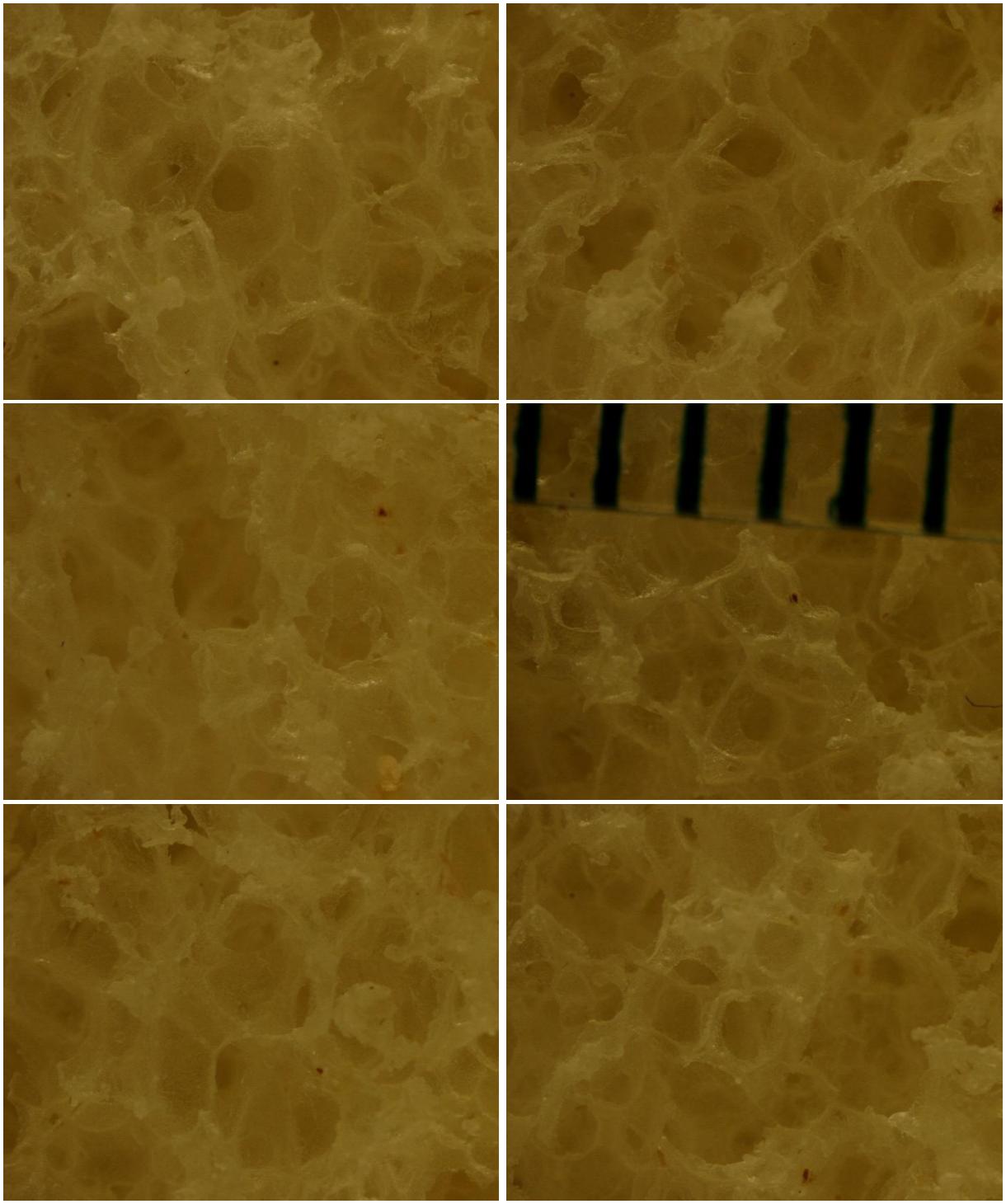


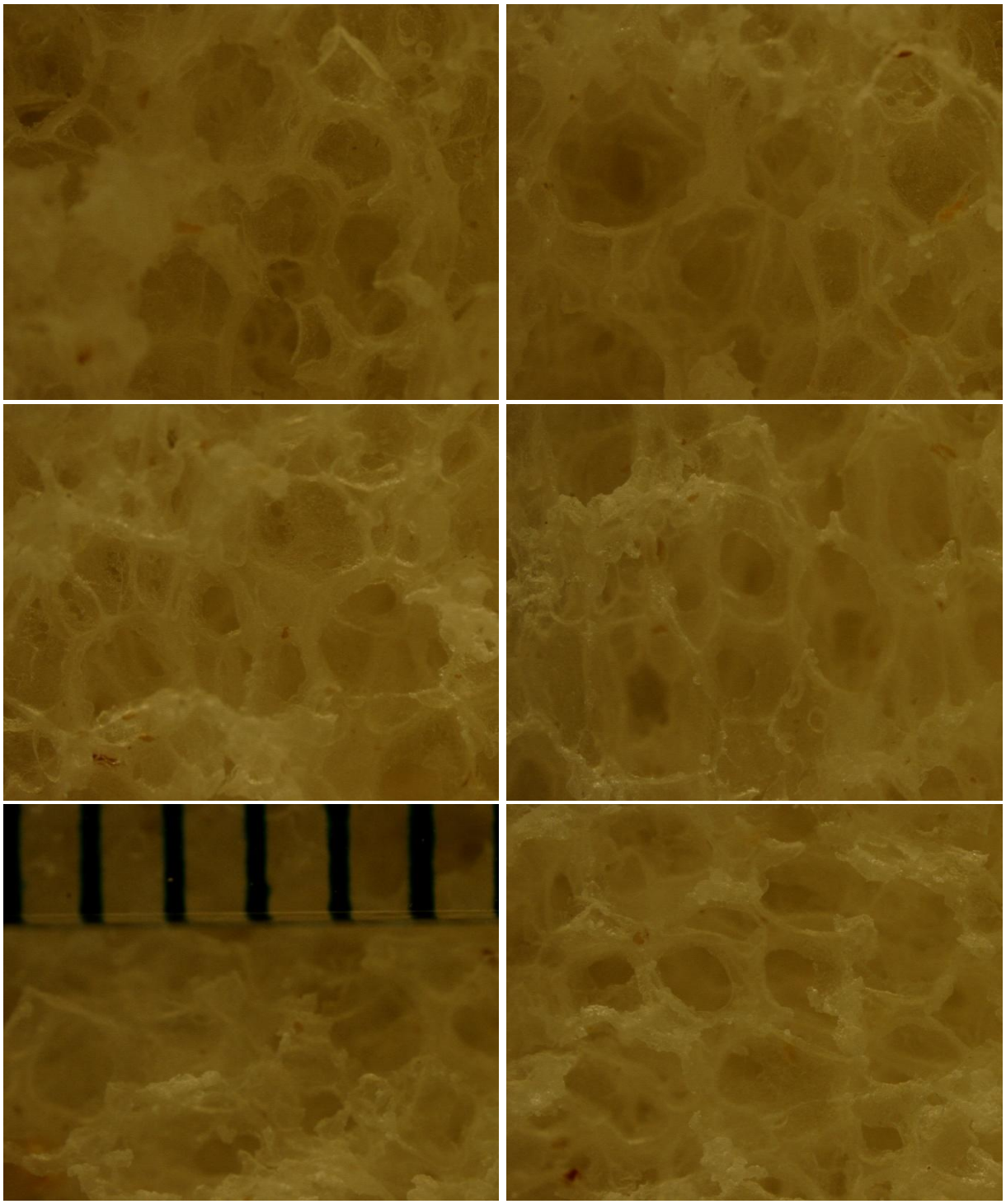


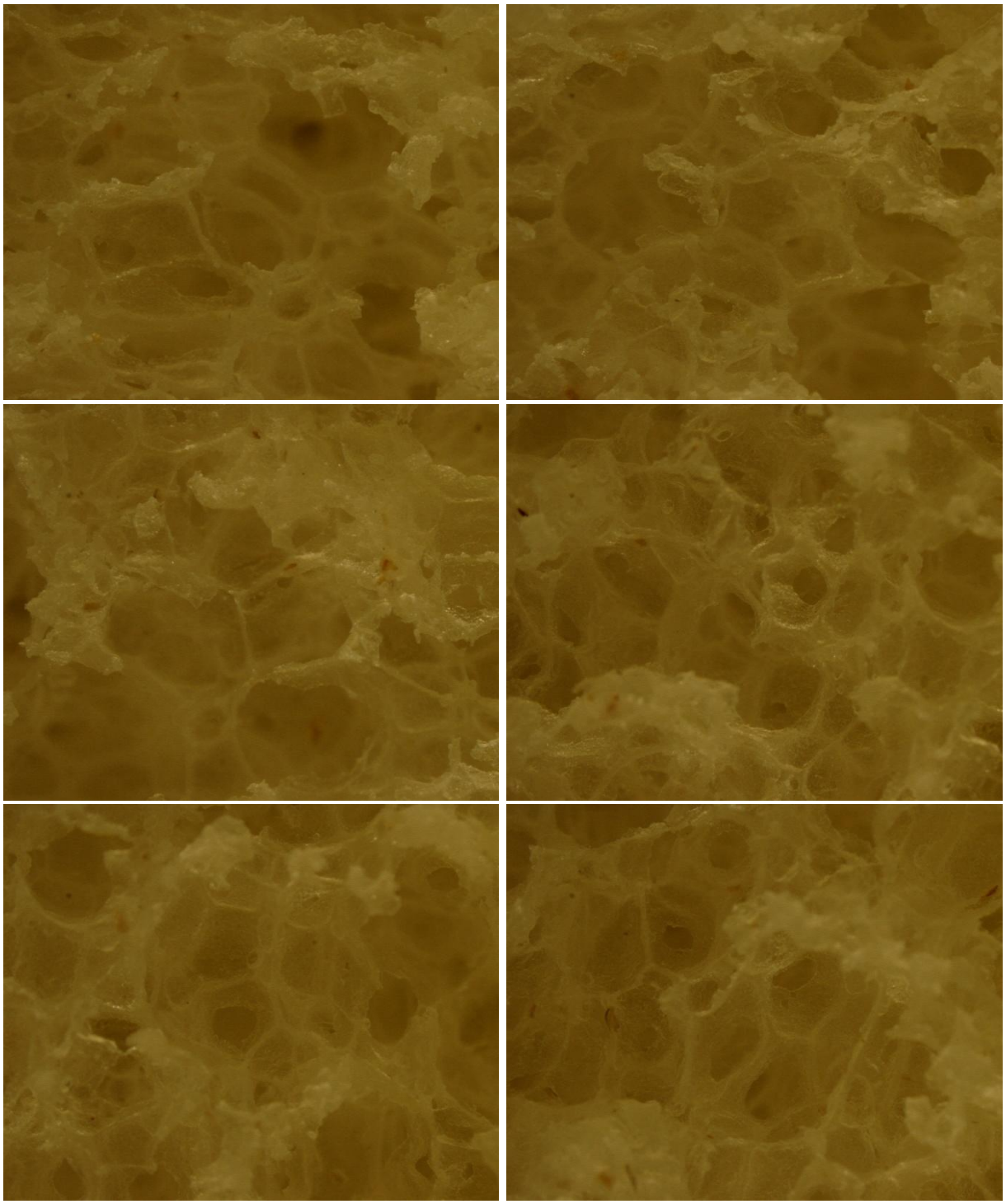


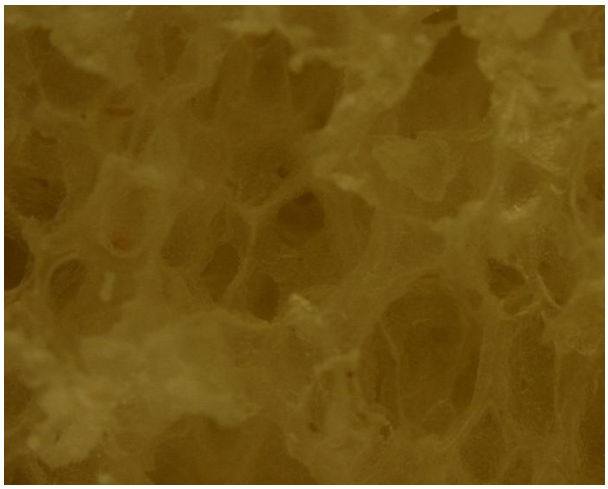



Appendix B: Day 14 Bread Crumb Samples 1-19 at 20x

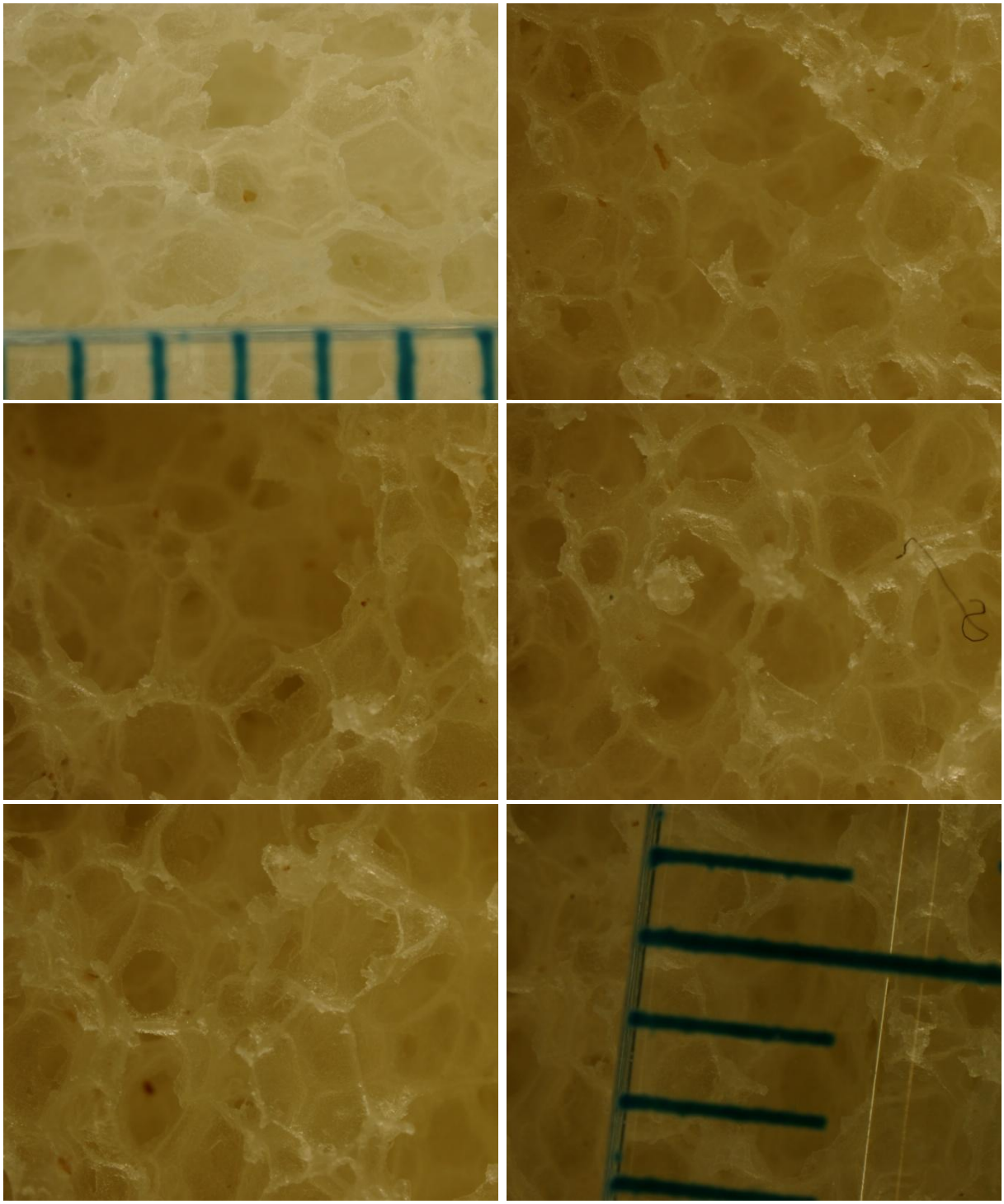


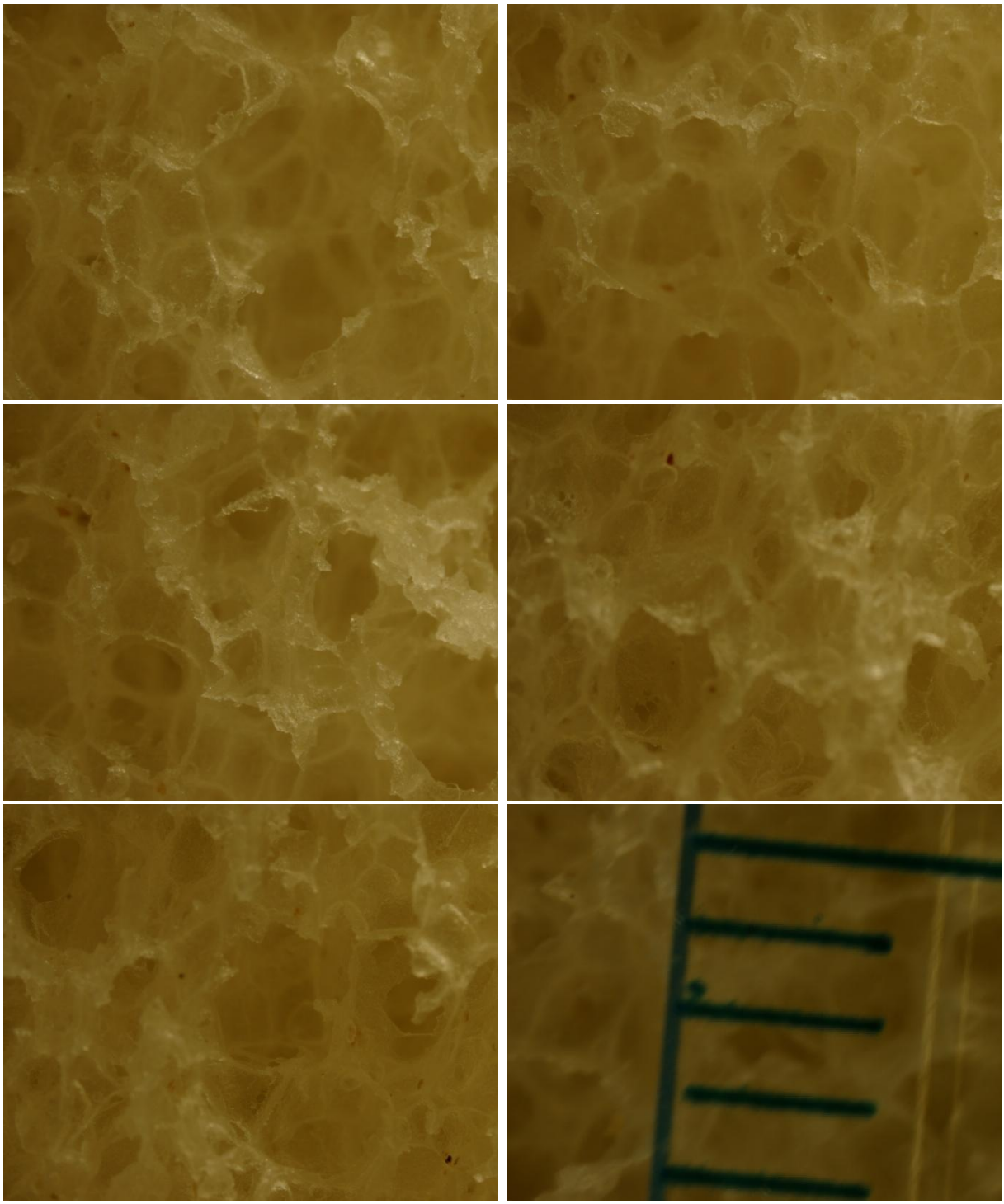


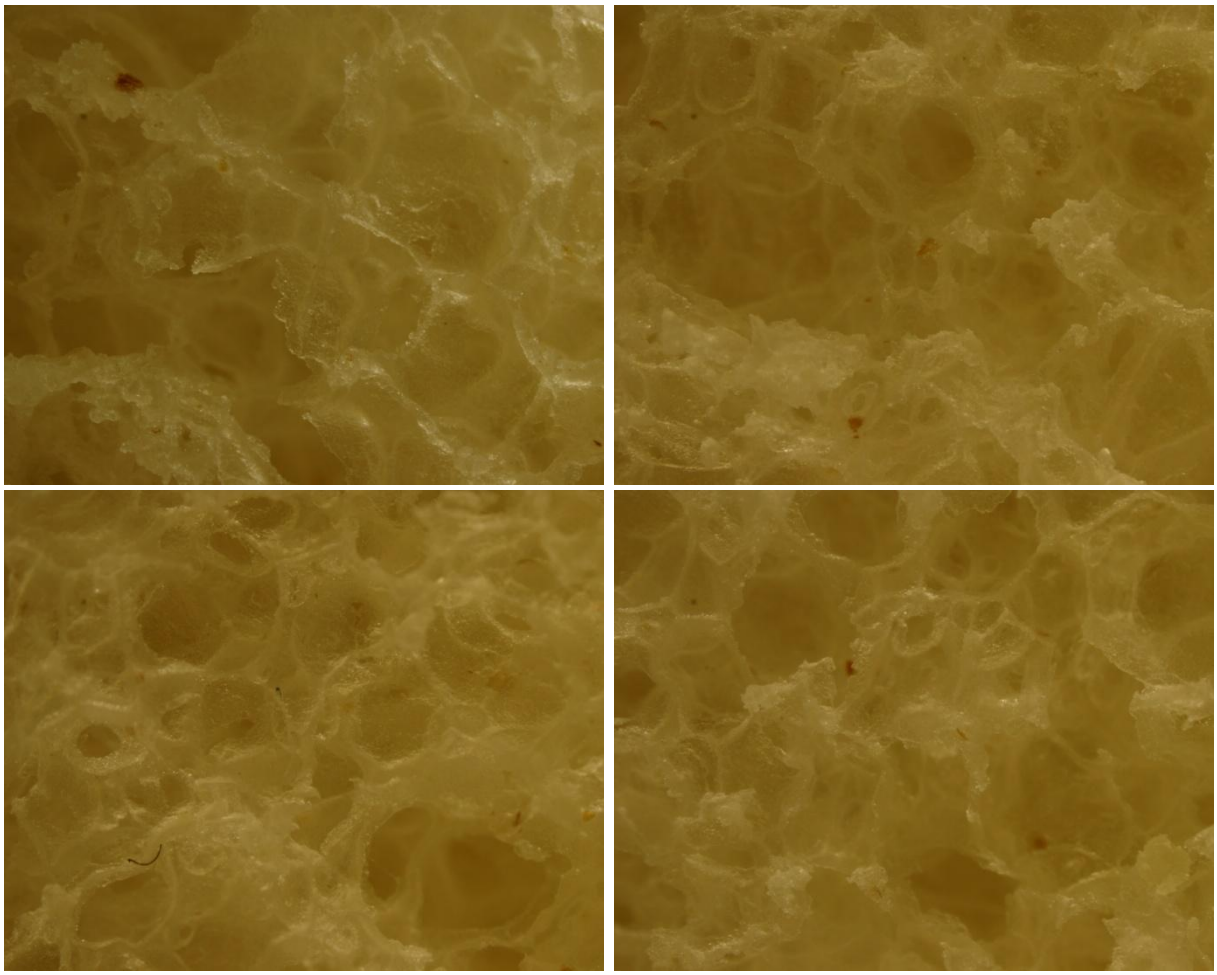




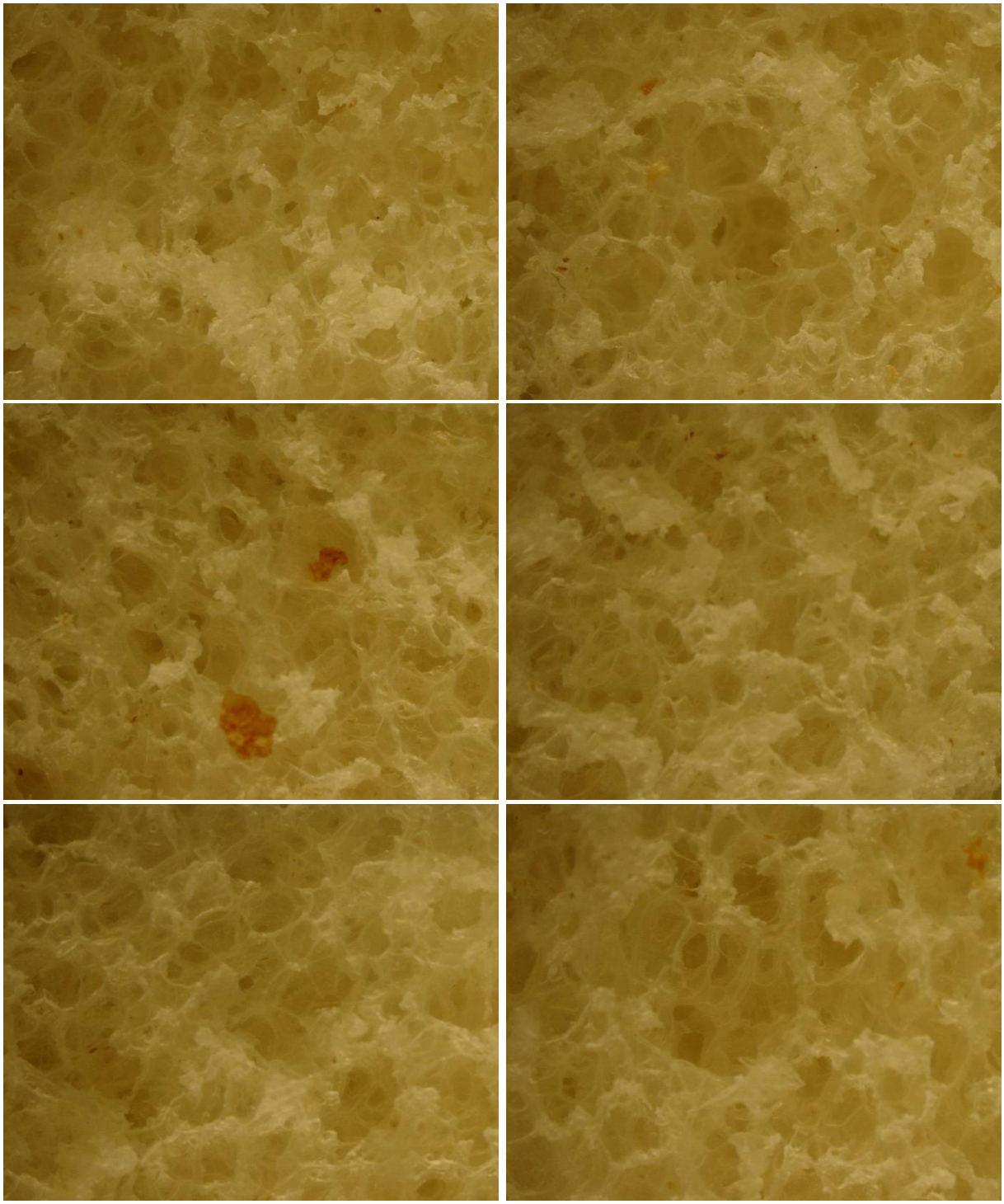
Appendix C: Day 24 Bread Crumb Samples 1-20 at 20x

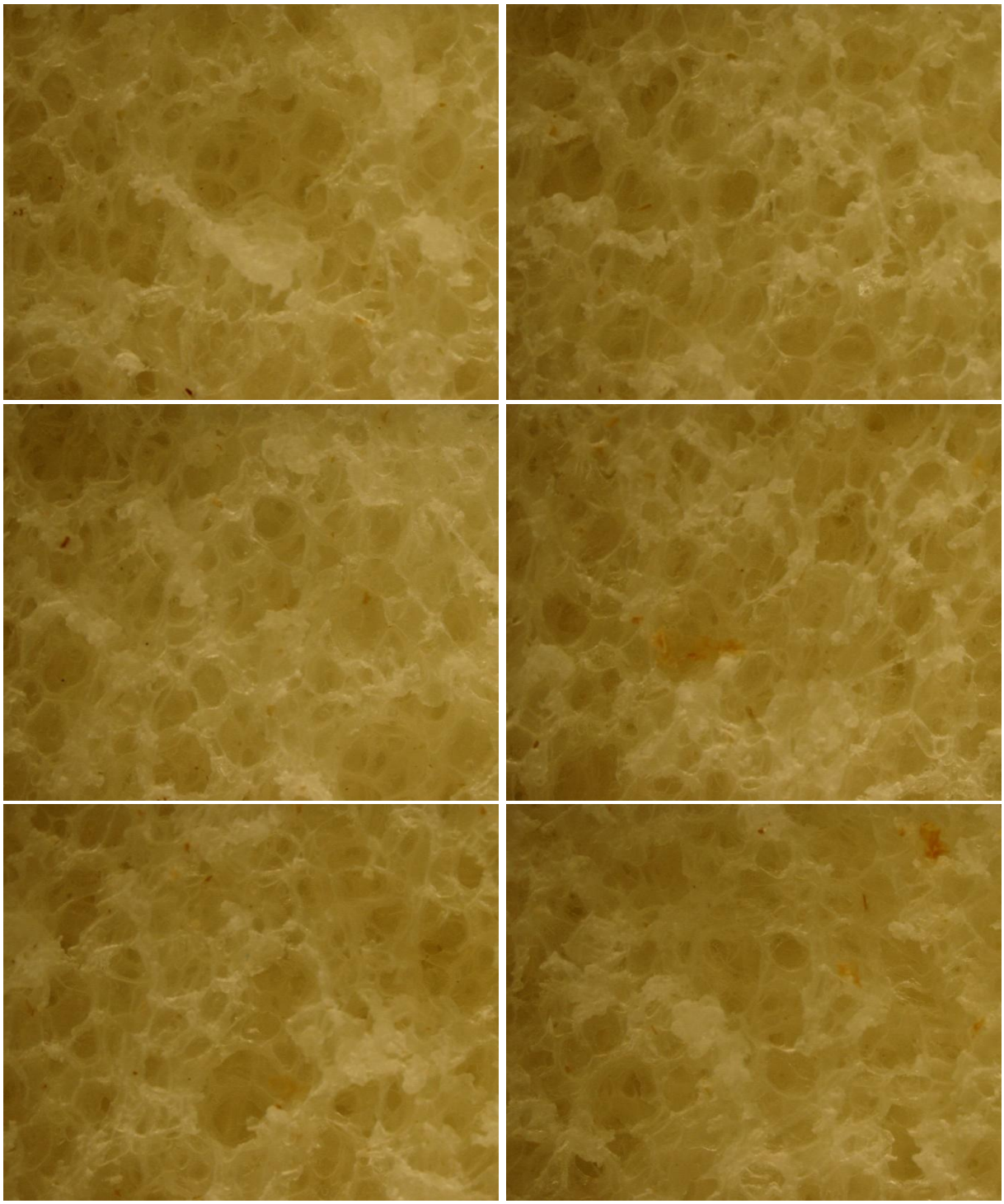


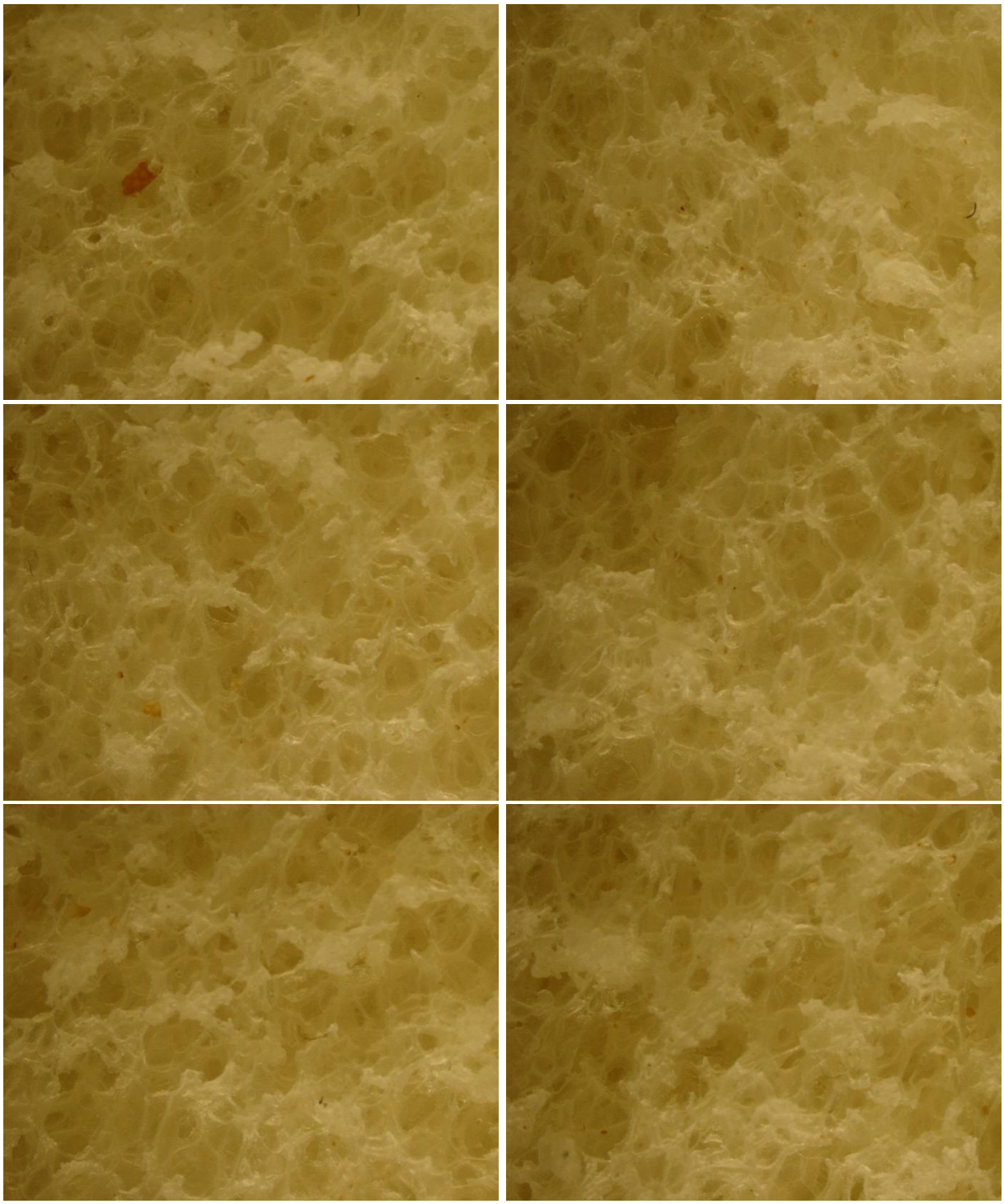


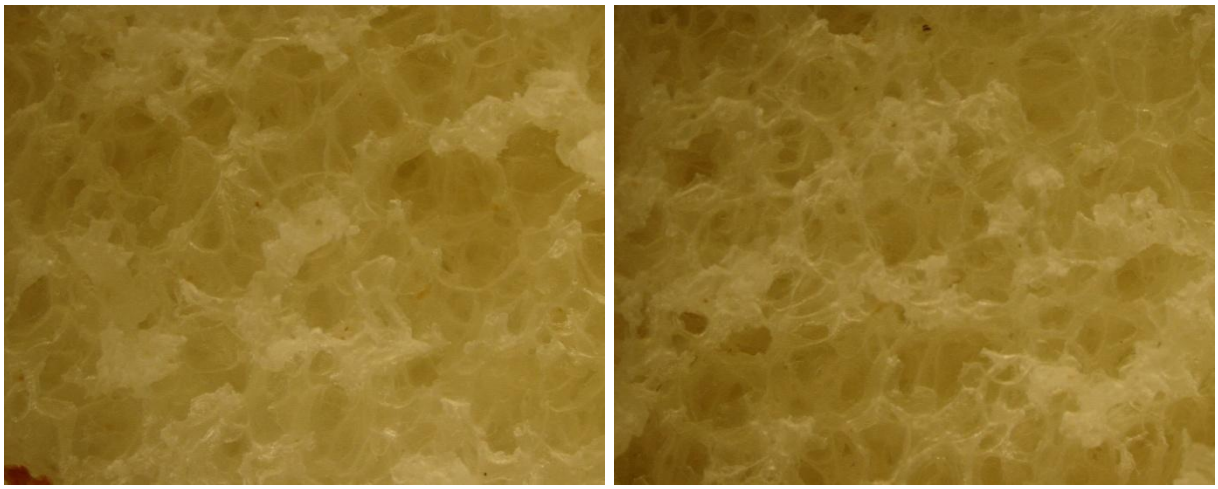


Appendix D: Non resin Open-Closed Cell Samples 1-20 at 10x

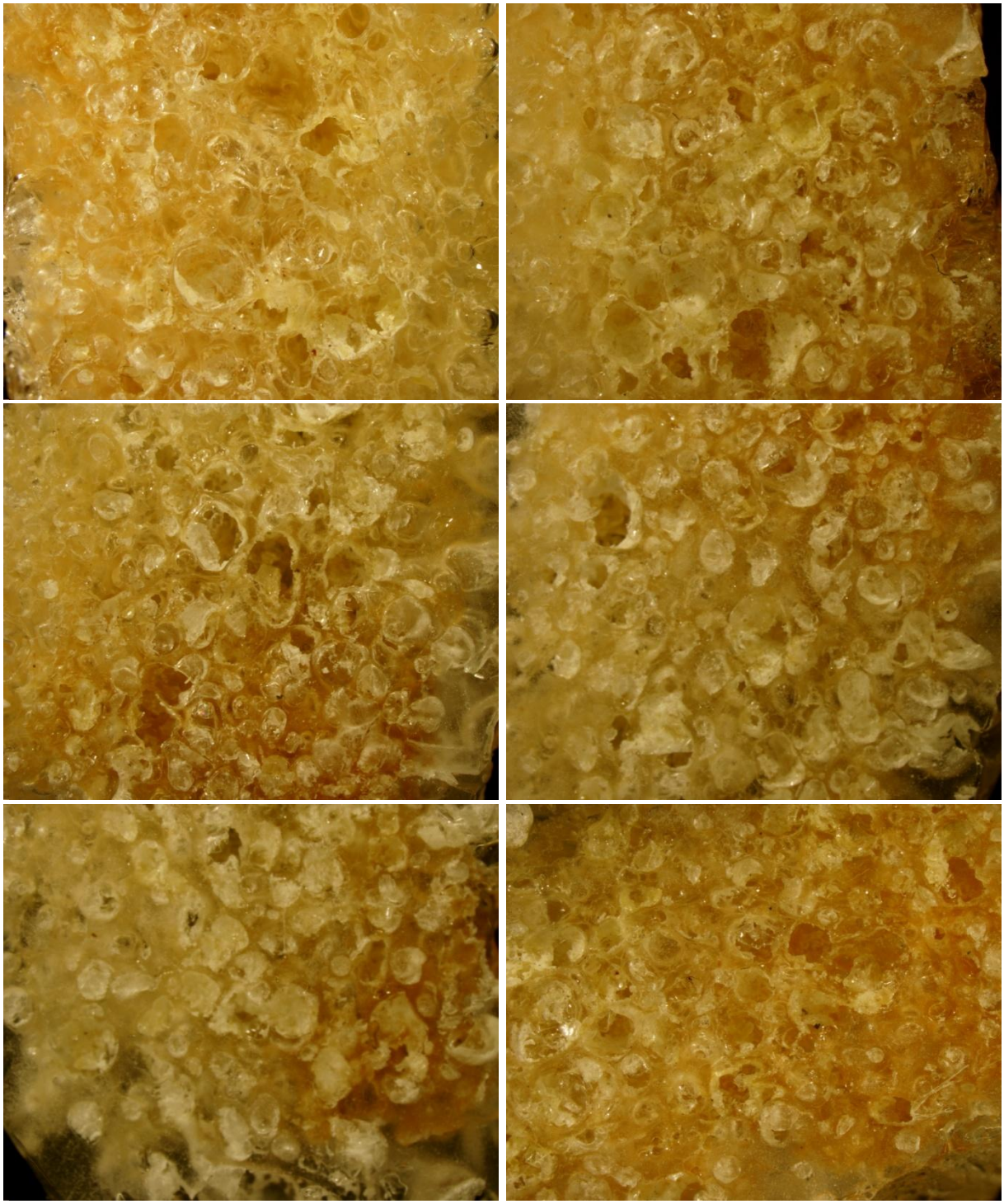




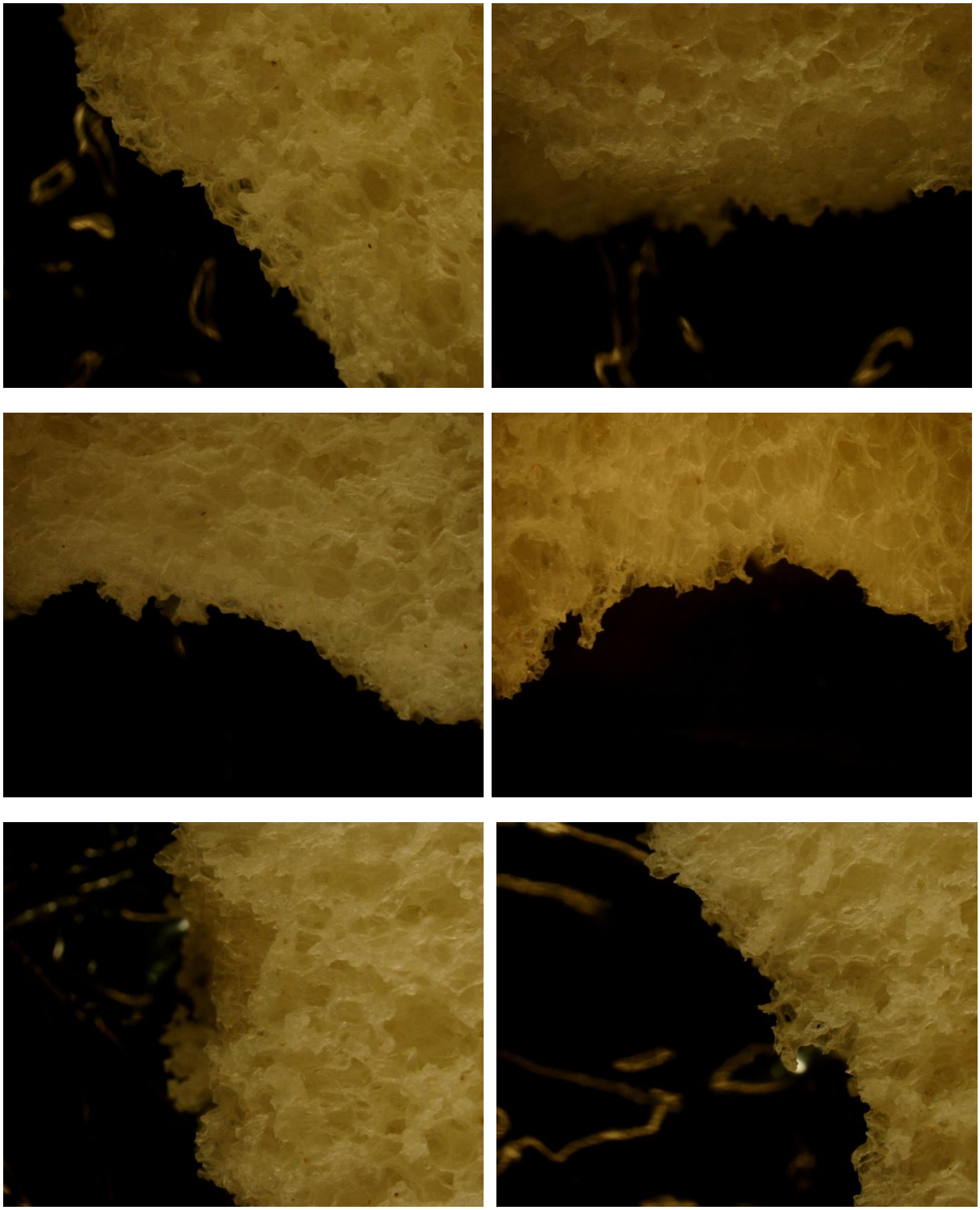




Appendix E: LR White epoxy resin Open-Closed Cell Samples 1-6 at 10x



Appendix F: Bending Fracture Patterns



Appendix G: Table of Models

#	1	2	3	4	5	6	7	8	9
Thickness	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
Length (mm)	0.45	0.475	0.5	0.5	0.55	0.55	0.6	0.65	0.65
2D Ashby & Gibson	0.183189948	0.174010091	0.165704357	0.165704357	0.151260213	0.151260213	0.139128072	0.128796365	0.128796365
Liu & Scanlon	0.494	0.472155125	0.4521	0.4521	0.416578512	0.416578512	0.386125	0.359751479	0.359751479
3D Open Ashby & Gibson	0.053458333	0.047979224	0.043301 25	0.043301 25	0.035786157	0.035786157	0.030070313	0.025622041	0.025622041
3D Closed Ashby & Gibson	0.3591117	0.340211084	0.323200 53	0.323200 53	0.293818664	0.293818664	0.269333775	0.248615792	0.248615792
3D Closed Hex and Triangular	0.474587474	0.449609185	0.427128726	0.427128726	0.388298842	0.388298842	0.355940605	0.328560559	0.328560559
48% Open 52% Closed	0.424871891	0.399618664	0.377165458	0.377165458	0.338995606	0.338995606	0.307780493	0.281788838	0.281788838

0.281788838	0.259817532	0.250060393	0.24100515	0.24100515	0.24100515	0.24100515	0.224719068	0.224719068	0.210484443	0.210484443
0.328560559	0.305091947	0.294571535	0.284752484	0.284752484	0.284752484	0.284752484	0.266955454	0.266955454	0.251252192	0.251252192
0.248615792	0.230857521	0.222896917	0.21546702	0.21546702	0.21546702	0.21546702	0.202000331	0.202000331	0.190117959	0.190117959
0.025622041	0.022092474	0.020595125	0.019245	0.019245	0.019245	0.019245	0.016914551	0.016914551	0.014983131	0.014983131
0.359751479	0.336704082	0.32624019	0.3164	0.3164	0.3164	0.3164	0.298382813	0.298382813	0.282290657	0.282290657
0.128796365	0.119890999	0.115884237	0.112136381	0.112136381	0.112136381	0.112136381	0.105323187	0.105323187	0.099289916	0.099289916
0.65	0.7	0.725	0.75	0.75	0.75	0.75	0.8	0.8	0.85	0.85
0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
10	11	12	13	14	15	16	17	18	19	20

0.210484443	0.210484443	0.197938045	0.186797366	0.167885929	0.152441474	0.152441474	0.133945721
0.251252192	0.251252192	0.237293737	0.224804593	0.203394632	0.185708142	0.185708142	0.164280279
0.190117959	0.190117959	0.17955585	0.170105542	0.153905014	0.14052197	0.14052197	0.124307896
0.014983131	0.014983131	0.013364583	0.011994806	0.009818878	0.008185491	0.008185491	0.00640551
0.282290657	0.282290657	0.267833333	0.254775623	0.232122449	0.213153119	0.213153119	0.189860947
0.099289916	0.099289916	0.093909987	0.089082786	0.080777745	0.073888631	0.073888631	0.065507745
0.85	0.85	0.9	0.95	1.05	1.15	1.15	1.3
0.075	0.075	0.075	0.075	0.075	0.075	0.075	0.075
21	22	23	24	25	26	27	28