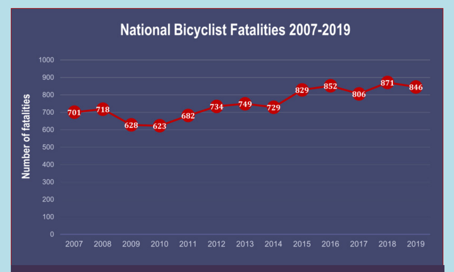
Nature's Super Shapes: How Voronoi Tessellations Affect Structural Strength

Research Question

Do Voronoi tessellations affect the structural strength of an object? According to the Centers for Disease Control and Prevention, "Nearly **1,000** bicyclists die and over **130,000** are injured in crashes that occur on roads in the United States every year." 75% of these deaths are direct results of head injuries. The significance of these injuries could be dramatically reduced if bicycle helmets were more durable. If Voronoi tessellations improve the structural integrity of an object, they could be implemented in things we use every day such as bicycle helmets.

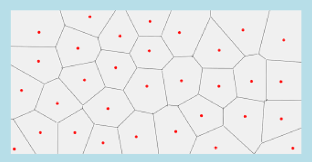


From Bay Area Bicycle Law

Background Research

What are Voronoi Patterns?

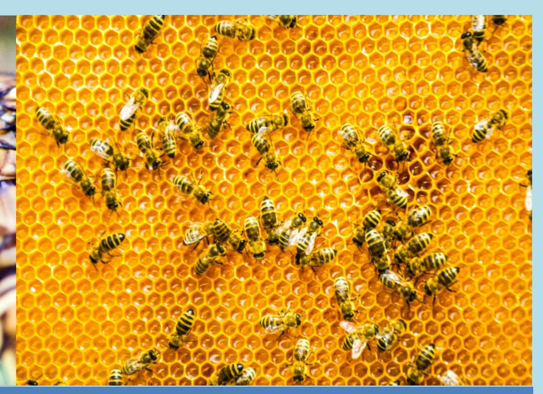
- Unique arrangement of polygons
- Tightly fitted with no gaps
- Follows the Nearest Neighbor Rule

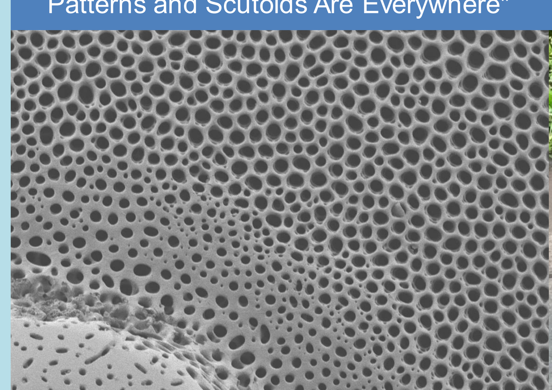

From JavaLab Science Simulations

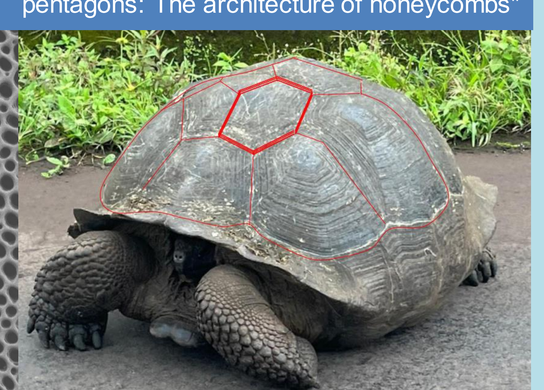
- Polygons are formed by bisecting imaginary segments created by pre-generated seeds (points)
- Segments are equidistant from each seed
- Weight Distribution: applied force is evenly distributed

Voronoi Patterns in Nature


From Scientific American's: "Voronoi Patterns and Scutoids Are Everywhere"


From ars Technica's: "Mergers, twists, and pentagons: The architecture of honeycombs"


From Journal of the Royal Society Interface: "Hexagonal Voronoi pattern detected in the microstructural design of the echinoid skeleton"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- Dragonfly wings: effectively maneuver by making the wings more lightweight while staying strong
- Honeycombs: found to prevent buckling
- Sea Urchin skeletons:
  - 82% match with a randomly generated Voronoi Pattern
  - Explanation for survival with water pressure
- Turtle shells: layer of protection

Why Voronoi Patterns?

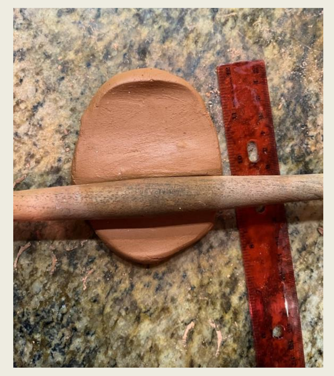
- Proven in nature to be lightweight and strong
- Principles of Biomimicry enforced by applying Voronoi tessellations to bicycle helmet models to test strength.

Hypothesis

This experiment aims to test the effect of Voronoi tessellations on the structural integrity of an object. Knowing how Voronoi tessellations affect strength would contribute to the development of stronger and more lightweight materials. The hypothesis states if bicycle helmet models are formed of Voronoi tessellations, then they will have improved structural strength.

Methods

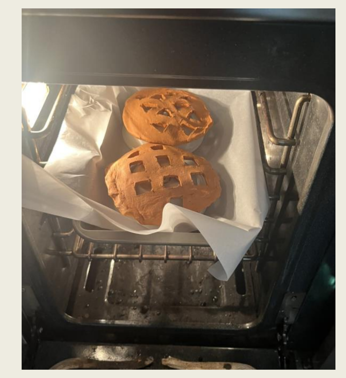
1.


150 gram pieces are rolled out into circles with diameters of 12.7 centimeters.

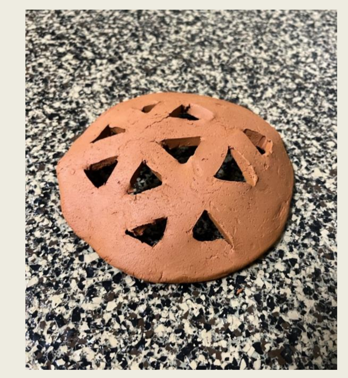
2.


Tessellations are cut out with 1.5 centimeters between them.

3.


Models are sculpted on a ceramic bowl and placed in the oven.

4.


After models cooled down until completely dry they are were dropped.

5.


The drop mimicked a bicycle helmet test drop, and data was collected.

Quantity	Materials
6000 gm	Natural Earth Clay
2	Ceramic bowls (diameter 14 cm)
1	Rolling Pin
1	Hexagonal Cookie Cutter (each side in 1.5 cm long)
1	Square Cookie Cutter (each side 1.5 cm in length)
1	Triangle Cookie Cutter (each side 1.5 cm in length)

Independent Variable

- Different tessellations cut out from models

Dependent Variable

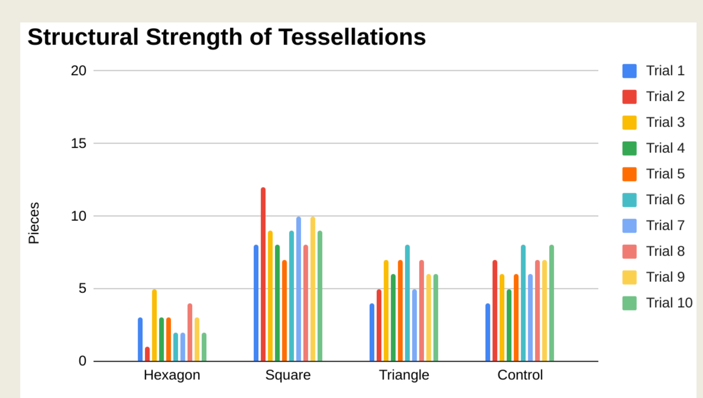
- How many pieces each model broke into

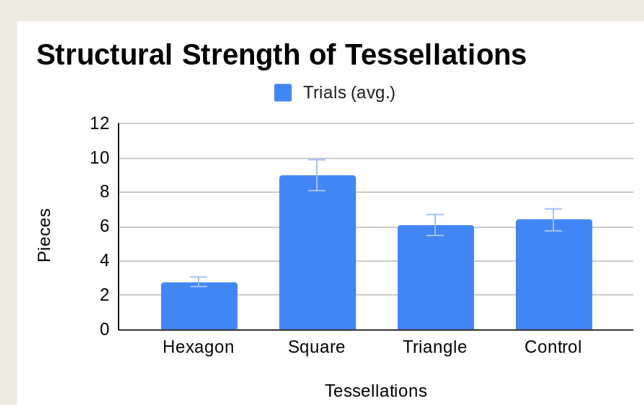
Controlled Variables

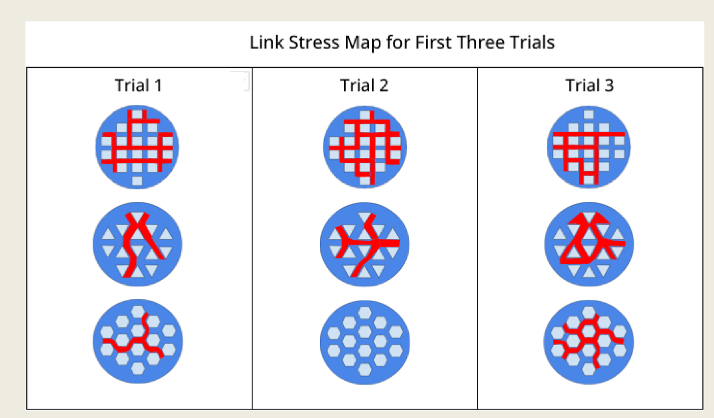
- Ceramic bowl dimensions
- Mass of models before tessellations were cut
- Distance between edges of polygons for each different tessellation
- Length of the edges for each polygon
- Minimum distance of tessellations from perimeter
- Diameter of models before baked
- Thickness of models before baked
- Temperature baked
- Amount of time each model was baked
- Amount of time each model was dried
- Height models are dropped at

All Methods photographs taken by Student Researcher

Graphs & Results







Models	Trial 1 (pieces)	Trial 2 (pieces)	Trial 3 (pieces)	Trial 4 (pieces)	Trial 5 (pieces)	Trial 6 (pieces)	Trial 7 (pieces)	Trial 8 (pieces)	Trial 9 (pieces)	Trial 10 (pieces)
Hexagon	3	1	5	3	3	2	2	4	3	2
Square	8	12	9	8	7	9	10	8	10	9
Triangle	4	5	7	6	7	8	5	7	6	6
Control	4	7	6	5	6	8	6	7	7	8

From the data we can see that on average the control broke into more pieces when dropped than the models with hexagonal tessellations, and slightly more than the models with triangular tessellations. Although, on average the models with square tessellations broke into more pieces than the control. The graph that averages the trials includes error bars to determine how significant the data is statistically. If the error bars overlap, then there is a higher probability that the data could be due to chance. The only overlap when comparing the error bars is when the triangle models and control are compared, which proves that the results of the triangle models are less likely to be statistically significant.

All graphs, tables, and maps created by Student Researcher

Applications

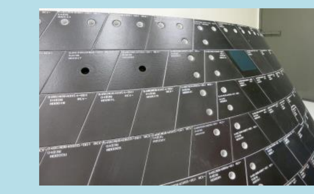
Bicycle Helmets

- Outer (hard) shell of helmet
- Implemented as air holes
- Cools head, stronger, & more lightweight
- Reduce casualties and severity of accident-related injuries


From Clip Art Images

Space Shuttle & Space Capsule Heat Shields

- Implemented as tight-fitting tiles
- Points are pre-generated on a plane, then boundaries are formed causing it to be tight fitting
- No holes during re-entry
- Prevent accidents


From NASA's Orion Capsule

Floor Tiles

- Compact Fixture
- Makes flooring non-porous for ship tankers
- Prevents mold and fungus from developing
- Jointless
- Reduces maintenance costs
- Safe & Durable with a long lifespan

Applicable Attributes of Voronoi Patterns

- Tight Fitting – Created around pre-generated points
- Stronger – Weight Distribution Property
- Lightweight – Decreased Mass

CAD Model Designs

(Left to right: Triangular, square, and hexagonal tessellations)


All Models created by Student Researcher

Conclusion

The hypothesis of this experiment states that if structures are formed of Voronoi tessellations, then they will have improved structural strength when dropped.

After rolling clay models out with equal size and mass, cutting out different shapes equally distanced as tessellations, molding the models, and dropping them from the same height we are able to observe that Voronoi tessellations have an effect on the structural integrity of an object. Different shapes influence the structural integrity of an object in unique ways, proving the hypothesis accurate.

Looking at the graphs we can see the models with hexagonal tessellations broke into less pieces on average when dropped than the control. On the other hand, the models with square tessellations broke into more pieces than the control. If bicycle helmets are made with hexagonal tessellations then they will have improved structural strength as opposed to if they had no tessellations at all, which would decrease the severity of injuries regarding bicycle incidents.

Voronoi patterns possess important qualities that will pave the way for the future of our materials through all types of applications, from space to every household.

Extensions

Randomly Generated Voronoi Patterns

- Tested in helmet models as air holes
- Results may vary with different arrangements of polygons

Digital Simulations

- Mimic bicycle incidents
- More realistic