2 Engineering Projects

2.1 Materials Engineering

My friend and I worked on a project to make the strongest concrete puck with a 4 cm diameter and varying thicknesses of 0.5 cm, 1.0 cm, and 1.5 cm. We experimented with different compositions of Type I–II cement, sand, gravel, and water to determine the optimal mixture for maximum strength.

2.1.1 Preparing Materials

Figure 1: Type I-II cement

First, I purchased Type I–II cement from Lowe's, which provided almost supply for the entire year. We also obtained garden gravel and sand; in retrospect, the garden gravel was not ideal due to inconsistent particle sizes.

Figure 2: Silicon lubricant applied on PLA molds

To cast the concrete pucks, we needed molds. We initially 3D-printed PLA molds, but the concrete was difficult to remove even with silicon lubricant as shown in **Figure 2**. We then switched to TPU filaments for their flexibility, which allowed the concrete to be released easily. Please see **Figure 3** for the TPU mold.

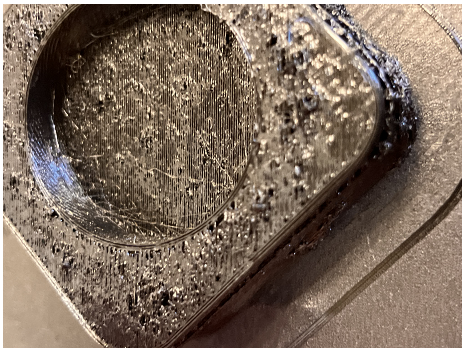

Figure 3: Printed TPU mold

2.1.2 Concrete Mixing Process

The concrete mixture always begins by combining all the dry components in a cup. We created a small cavity in the center and gradually added water, ensuring that the mixture was hydrated but not too watery. Typically, 4–5 spoons of water were sufficient for proper hydration. The consistency is important because overly wet concrete reduces structural integrity, while too dry a mixture prevents complete hydration.

Figure 4: Hydrated mixture in the TPU mold

2.1.3 Experimental Compositions

Number	Cement	Gravel	Sand
1	1	2	2
2	1	3	1
3	1	2	3
4	1	0	2
5	1	0	1
6	3	2	3
7	1	1	1
8	2	2	1
9	3	2	2
10	1	2	1
11	1	1	3
12	1	3	2
13	2	1	1
14	3	2	1
15	1	1	2
16	1	0	0
17	3	3	2
18	1	1	2
19	2	1	0
20	2	1	1
21	1	3	2
22	1	0	1
23	2	1	2
24	3	1	1
25	3	2	1

Figure 5: Different ratios of cement, sand, and gravel

We tested different ratios of cement, sand, and gravel (see **Figure 5**). The primary strength test involved dropping each concrete puck from varying heights, ranging from 10 cm to 100 cm above the ground, and evaluating its resistance to fracture. Specifically, we recorded the height at which each puck first exhibited structural failure.

Two main fracture modes were observed: complete fracture and surface chipping. Thicker concrete pucks were more prone to minor chipping, whereas thinner pucks experienced more severe and frequent chipping.

We found that certain compositions demonstrated superior strength. In particular, a 2:1:1 ratio of cement, gravel, and sand with significantly reduced water content (mixture 20) performed the best under high-impact testing.

2.1.4 Technical Insights

The strength of concrete comes from the hydration of cement. The primary chemical reactions involve the formation of calcium silicate hydrate (C–S–H) and calcium hydroxide ($Ca(OH)_2$):

$$2Ca_3SiO_5 + 7H_2O \longrightarrow 3CaO \cdot 2\,SiO_2 \cdot 4\,H_2O + 3Ca(OH)_2$$

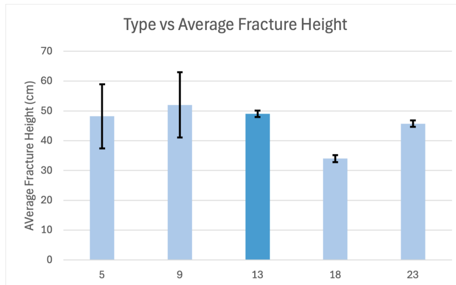

Figure 6: Fracture heights of the five strongest concrete mixtures with 2×SEM error bars

The C−S−H gel is the main binding phase that provides compressive strength. Adding sand fills voids between cement grains, increasing packing density, while gravel acts as coarse aggregate to reduce shrinkage and improve fracture resistance.

Fracture toughness of concrete reflects a balance between ductility and plasticity. A more ductile mixture is capable of absorbing greater energy during impact and is therefore less susceptible to sudden, brittle failure. Thus, I started exploring methods for enhancing these mechanical properties and I discovered that the solution might lie in the use of specialized additives!

2.1.5 Additives

Flexibility can be enhanced by adding polymers or rubber aggregates, which allow the concrete to deform slightly before cracking. Other additives, such as silica fume, directly improve compressive strength by reducing porosity and refining the microstructure. We experimented with both additives. Rubber significantly increased fracture resistance; however, it was highly susceptible to long-term stress. In other words, when stress was intentionally applied to the concrete for 5–10 seconds, it crumbled much more easily.

Such observations highlight a fundamental tradeoff between fracture toughness and yield strength. By increasing ductility with rubber additives, the concrete became better at absorbing impact energy, which improved fracture toughness and reduced brittle failure. However, the flexibility lowered the yield strength; in other words, it deformed more easily under sustained loads. As a result, while the rubber-modified concrete performed well under sudden impacts, it was less resistant to prolonged stress, causing earlier failure when a constant force was applied.

Meanwhile, silica fume significantly increased the fracture height without exhibiting the weaknesses observed in the rubber-modified concrete. We added

Figure 7: Silica fume used in the concrete mixture, purchased from Amazon

approximately 10 spoonfuls of silica fume per mixture, ensuring that it comprised at least 5% of the total mixture by weight.

2.1.6 Concrete Curing Methods

We experimented with multiple curing methods, including steam curing and water curing, beginning 12-24 hours after casting the concrete into molds. Each method offered distinct advantages and limitations.

Steam curing was tested to accelerate the hydration process by exposing the concrete to warm, moist conditions. While this method is often used in industrial settings to achieve early strength gain, we observed that steaming did not produce a significant improvement in fracture resistance for our concrete pucks. Additionally, improper temperature control may introduce microcracks, potentially reducing long-term durability.

Water curing, in contrast, proved to be far more effective. By submerging the concrete in water for up to two weeks, we ensured continuous hydration of the cement particles. This method significantly improved overall strength and fracture height performance. The prolonged moisture exposure prevented premature drying, reduced internal stresses, and allowed for more complete formation of calcium silicate hydrate (C–S–H), which is the primary contributor to concrete strength.

Comparison of Methods

- **Steam curing**
  - Pros: Faster early strength development
  - Cons: Limited long-term strength gain, risk of microcracking
- **Water curing**
  - Pros: Maximizes hydration, improves durability and fracture resistance
  - Cons: Requires longer curing time and water management

In the end, we applied water curing to every concrete puck we created and then allowed them to dry for an additional week. When we tested them afterward, we observed a significant improvement in performance!

The year I spent exploring materials engineering with concrete was one of the most exciting experiences of my life. I loved how chemistry, physics, and engineering all came together in a single project! While the hydration of concrete is fundamentally a chemical process, understanding its behavior required me to dive into many engineering concepts as well. Most importantly, I had a fantastic time mixing and experimenting with concrete almost every day with my friend! The hands-on experience was both fun and deeply educational. Please enjoy the photos of me mixing concrete!