Reinforcing the Future

I. Introduction

Cement is the second most used substance in the world, after water. Cement accounts for 8% of global greenhouse gas (GHG) emissions, and its high cost has dramatically exacerbated the effects of a severe housing crisis. This study investigates a novel cement that is lower in carbon emissions and lower cost than the currently-used Ordinary Portland Cement (OPC). However, to be used on a large scale, it must exhibit robust properties in a variety of applications (performance) such that companies are willing to use it as a replacement for OPC. Thus, a statistical test will be carried out to determine if using my novel cement to make concrete causes the mean performance score, determined by combining compressive strength and electrical resistivity (indicates susceptibility to chemical attack), to be significantly greater than concrete made with OPC. This test was carried out using a sample of 20 sets of starting materials and randomly assigning cement compositions to them. Then, 20 concrete samples were made by mixing starting materials and assigned cement composition, and measuring 5-day compressive strength and electrical resistivity of each sample. Since these metrics are in different units and scales, z-score normalization was used and the z-scores for each metric were added to receive a performance score for each experimental unit.

II. Statistical Question & Hypotheses

The statistical question I seek to answer is as follows: Does using novel cement to make concrete blocks similar to the novel concrete blocks used in the study cause a significantly greater performance score than concrete made from OPC similar to the OPC blocks used in the study?

To test this, the following hypotheses are used:

H_0: μPN = μPO

H_a: μPN > μPO

Where μPN is the mean performance score of concrete blocks similar to the 10 concrete blocks made from the novel cement, and μPO is the mean performance score from concrete blocks similar to the 10 blocks made from the OPC in the study.

III. Data Collection

A convenience sample of 20 sets of starting materials (a "set" includes 40g sand, 80g gravel, and 10g water) was taken in this study. The chemical compositions of the cements were then randomly assigned to the starting materials. Our novel cement was made of a 1:1 blend of sustainably sourced sodium silicate and calcium hydroxide (and found through our experimental results to be a viable composition for cement). These materials were sustainably sourced through novel reactions between calcium carbonate and sodium hydroxide (creates calcium hydroxide) and diatomaceous earth and sodium hydroxide (creates sodium silicate) at ambient temperatures. To randomly assign the treatments, twenty stations were set up each with one set of starting materials. Then, treatment Novel (representing novel cement) and treatment OPC (representing OPC) were written on 10 sticky notes each, for a total of 20 sticky notes. The sticky notes were placed upside down (such that I could not see the label), mixed well, and given out at random to each station. Twenty grams of the corresponding cement composition was given to the station with the matching treatment (Novel or OPC) on the sticky note. This method of random assignment eliminates confounding by ensuring both treatment groups are roughly equivalent with respect to all other variables that could affect performance scores.

Fig 1. Experimental setup of starting materials with random assignment of cement treatments

Air and water temperature were set constant for all samples by keeping them in the same room with the thermostat set to ~22 degrees C. Exposure to moisture was kept relatively constant as all samples were cured in a dark corner of the same room with the same exposure to air. Mixing time for each concrete block was kept constant (1 minute) to ensure no samples are over- or under-mixed relative to the others. The environment each sample was exposed to was also kept relatively constant, as they were all held in the same silicone container. Controlling these variables reduces variability in sample results (making them more precise to the population truth), because it prevents variables outside the ones tested (like air temperature) from affecting factors in the performance score (by keeping them constant across all experimental units).

Compressive strengths were determined by using a schmidt hammer, measuring rebound, and correlating rebound values to compressive strength values. Relative electrical resistivity was determined using an electrical circuit, arduino, and electrodes to find resistivity values of samples - these correlate to permeability and give insight into the sample's resistance to chemical attack.

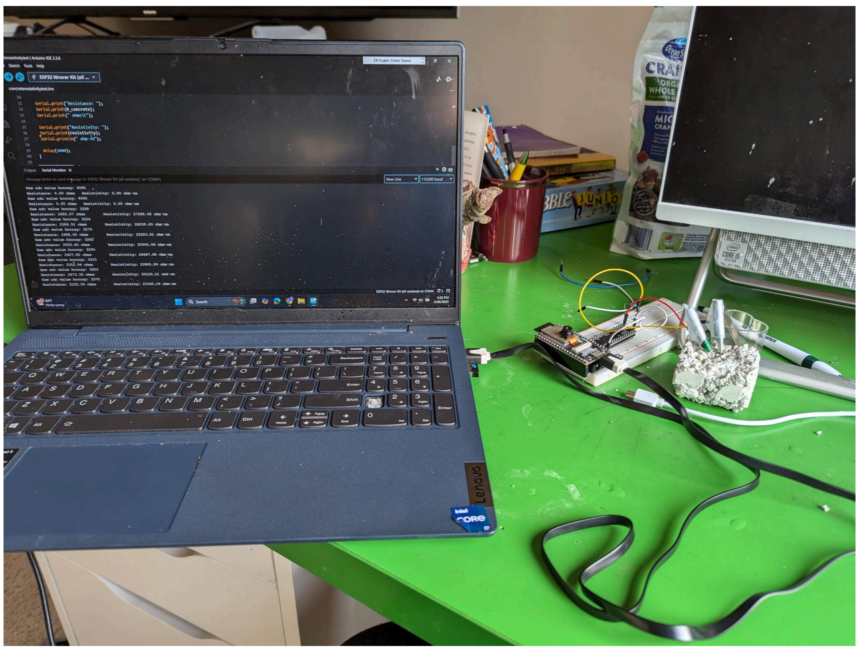

Fig 2. Experimental setup for resistivity measurement.

IV. Data Display

Strength (MPa)	12.3	12.1	13.1	13.9	11.7	15.4	14.0	13.5	14.3	13.6
Resistivity (Ohm · cm)	45625	52322	36440	34364	34840	34231	40946	39925	51538	55955
z(Strength)	-0.238	-0.410	0.447	1.13	-0.752	2.42	1.22	0.790	1.48	0.921

z(Resistivity)	1.10	1.65	0.342	0.171	0.210	0.160	0.714	0.630	1.59	1.95
Performance Score (zS + zR)	0.862	1.24	0.789	1.301	-0.542	2.58	1.934	1.42	3.07	2.871

Fig 3. Data from concrete made with novel cement. z(Strength) and z(Resistivity) refer to normalized 5-day compressive strength and electrical resistivity values when using z-score normalization for all 20 strengths and separately for all 20 resistivities.

Strength (MPa)	11.5	12.4	11.8	11.8	11.5	11.8	11.5	11.8	12.0	11.5
Resistivity (Ohm · cm)	21020	19310	24667	23078	19239	22854	24438	19099	25110	20948
z(Strength)	-0.924	-0.153	-0.667	-0.667	-0.924	-0.667	-0.924	-0.667	-0.295	-0.924
z(Resistivity)	-0.931	-1.07	-0.630	-0.761	-1.08	-0.780	-0.649	-1.09	-0.593	-0.937
Performance Score (zS + zR)	-1.855	-1.223	-1.297	-1.428	-2.004	-1.447	-1.573	-1.757	-0.888	-1.861

Fig 4. Data gathered for 10 concrete samples made from OPC. Z-score normalization done by finding mean and standard deviation of all 20 compressive strength values and all 20 resistivity values, subtracting individual values by the mean and dividing by standard deviation.

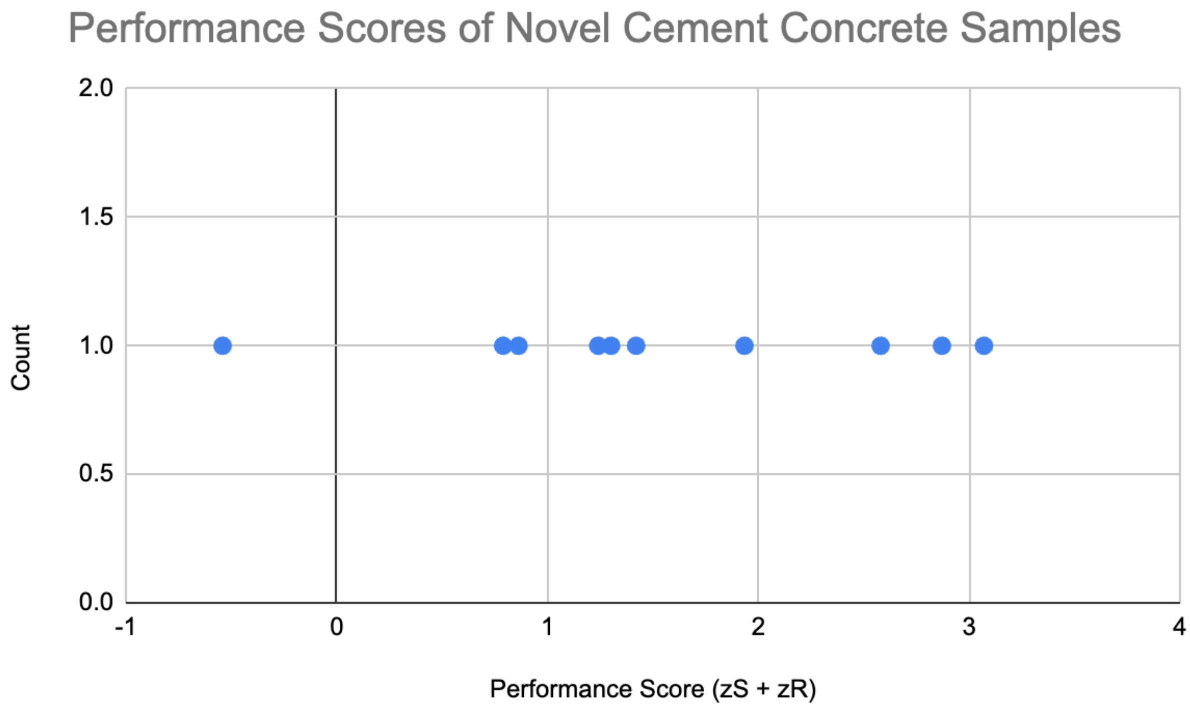

Fig 5. Performance scores, calculated by adding normalized 5-day compressive strengths and resistivities, of 10 concrete samples in the novel cement group.

The dotplot in fig 5 appears roughly symmetric, possibly slightly skewed to the left. The mean of the performance scores is 1.5525 and the standard deviation is around 1.099. Using the 2SD rule, there are no outliers (lower boundary: -0.6455, upper boundary: 3.7505). Most scores are concentrated between 1 and 3 (~6), with clusters of 2 dots each at scores of around 1.25 and 0.8.

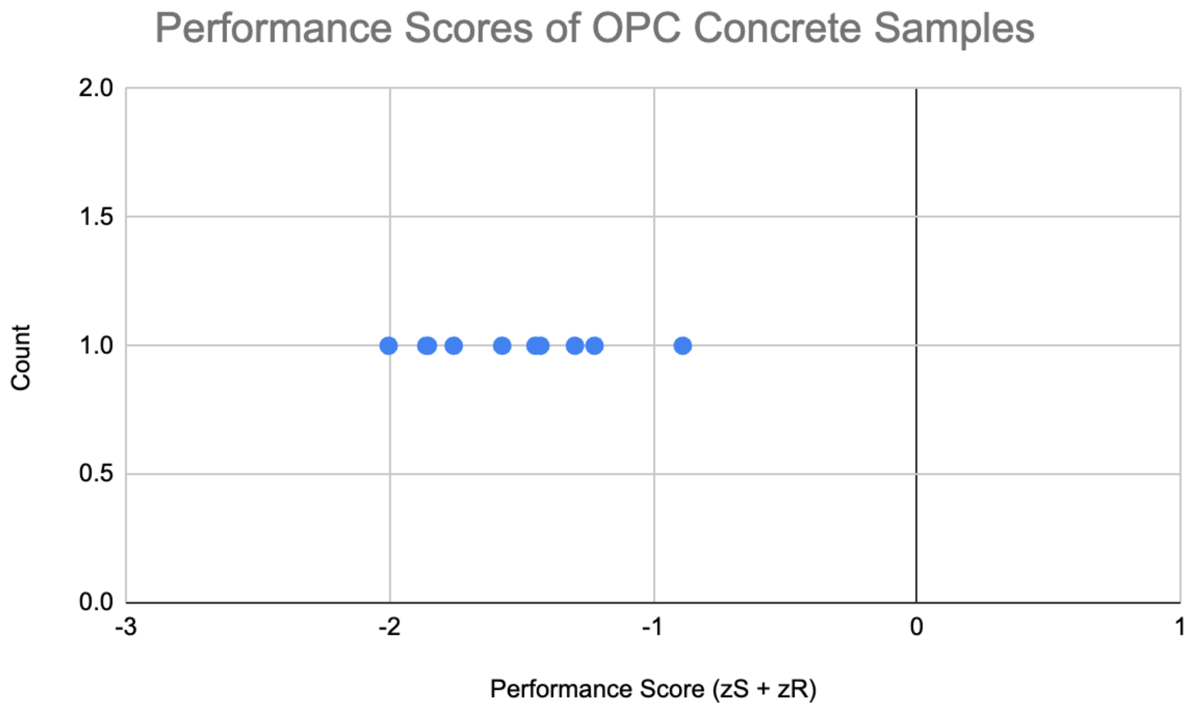

Fig 6. Performance scores, calculated by adding normalized 5-day compressive strengths and resistivities, of 10 concrete samples in the OPC group.

The dotplot in fig 6 appears roughly symmetric, with very slight skew to the right. The mean of the performance scores for the 10 concrete samples made from OPC is around -1.533, with a standard deviation of 0.345 (there is clearly less spread in this dotplot as opposed to the one with the novel cement). According to the 2SD rule, there are no outliers (lower boundary: -2.223, upper boundary: -0.8433). Most values are concentrated between -2 and -1.25 (~8), with clusters of 2 dots each at around -1.4 and -1.8. With a large difference of around 3.0855 in mean performance scores, and all of the values clustered on the left of 0 for OPC while on the right of 0 for the novel cement, it is likely to see a significantly greater performance score for concrete made with the novel cement.

V. Statistical Analysis

Conditions for a t-test for a difference in means

1. **Random:** The novel cement composition and OPC were randomly assigned to the starting materials for making the concrete, so this condition is met in the experiment.
2. **Independence (10%):** Does not need to be checked because random sampling was not used in the experiment.
3. **Normal:** $n_1 = 10$, $n_2 = 10$ not < 30. However, dotplots of the data for performance scores shown in figs 5 and 6 show no major skew or outliers using the 2SD rule.

Test procedure

$$t = \frac{(\bar{x}_1 - \bar{x}_2 - 0)}{\sqrt{\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}}}$$

$$t = \frac{1.5525 - (-1.533) - 0}{\sqrt{\frac{1.099^2}{10} + \frac{0.345^2}{10}}}$$

$$t = 8.4707$$

$$df = 10.7568$$

$$p - val = tcdf(lower: 8.4707, upper: 9999999999, df: 10.7568) = 2.195 * 10^{-6}$$

Conclusion

Because the p-value of $2.195 * 10^{-6}$ is less than $\alpha = 0.01$, we reject H_0. There is convincing evidence that using novel cement to make concrete blocks similar to the novel concrete blocks used in the study causes a significantly greater performance score than concrete made from OPC similar to the OPC blocks used in the study.

Errors

Since H_0 was rejected, there is a possibility that type I error occurred. In this context, type I error indicates that the test found convincing evidence for our novel cement to cause a significantly greater performance score for concrete blocks like the ones in the study, when in reality it does not. This could cause more resources to be put into expanding the concrete's production, even though it didn't show significantly greater performance. However, since α = 0.01 was used, the probability of type I error is relatively low at 1%. The power for the one-sided two-sample t test to detect a difference in performance scores of 3.0855, using a pooled standard deviation of 0.815 ($\sqrt{\frac{9(1.099)^2+9(0.345)^2}{18}}$), was estimated to be approaching 1.00. This means that given that the novel cement causes a significantly greater performance score of 3.0855 in concrete samples like the ones in the study than does OPC, the probability that our test would find convincing evidence for H_a: μPN > μPO, approaches 1.00.

VI. Reflection

In the midst of a growing housing crisis and rapidly increasing climate change, it has become ever more important to develop sustainable and cheap alternatives to common building materials. While many alternatives are being developed, including the one used in this study, they are often not adopted due to limiting factors in performance (such as strength and resistance to chemical attack). This study aims to address this problem by creating performance scores for concrete made from a novel cement and from OPC, and determining if using the novel cement caused a significantly greater performance score. While larger sample sizes than 10 for each cement would be preferred for more precise estimations of population truth, cost of materials in addition to lack of storage space were limiting factors. Random sampling would also be ideal to generalize results to the population of starting materials sampled from. However, convenience sampling was done instead because utilizing random sampling would require checking the 10% condition (meaning over 200 sets of starting materials would need to be obtained total). Consequently, the results of this study can only be generalized to concrete samples like the ones used in the study. Originally, I had planned to only test for a difference in compressive strength, but because a holistic view of concrete's performance requires looking at susceptibility to chemical attack and sorptivity, I decided to combine resistivity and strength into a performance score (and search for difference in performance). After collecting the raw data however, I realized that simply adding them into a performance score would not properly represent compressive strength, as each value of compressive strength was far lower (between 10 and 20) than electrical resistivity values (between 15,000 and 60,000). Thus, I decided to use z-score normalization for all 20 compressive strengths and all 20 resistivity values, and add the normalized values as they were in similar scales. Data collection also proved to be quite difficult and time-consuming, as to ensure consistency I had to make each of the 20 concrete samples individually with similar mixing times. I was surprised to not see more variability in compressive strengths, because while many factors were kept constant, there are countless factors (like particle sizes of gravel and sand, slight differences in the masses of the raw materials, etc.) that could make large differences in compressive strength even when using the same cement. For future research, it would be beneficial to explore even more factors such as temperature resistance and workability (which were not done in this study due to a lack of budget for specialized materials required). It would also be beneficial to control even more variables such as vigorousness of mixing in the future to ensure more precise estimations of the population truth. Further, future research could explore how changing the ratios of chemicals in the novel cement (comparing 1:3, 1:1, 3:1 etc.) affects strength and whether there is a significant difference in strength or workability between different ratios.