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Analysis and Comparison of NIR Pigments for "Cool" Coating Applications

Karey Steinmetz
kms406@uakron.edu

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4250:497 Honors Project in Corrosion Engineering

Karey Steinmetz

Sponsored by Dr. Qixin Zhou

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Abstract

The goal of this research is to compare our own formulation of near infrared radiation (NIR) pigment coating to commercialized ones. These near infrared coatings are designed to be used on roofs of buildings to keep the buildings from absorbing the heat from the sun's radiation. This would keep the building cooler and use less energy and money to cool the building. In this study, Styrofoam was used to build a lab-scale house and were put under heat lamps that mimicked the sun. Temperatures were taken at three different locations to determine the effectiveness of the pigmented coatings. Color and gloss of the coatings were also recorded. The synthesized coating was better at keeping the model building cooler than the Heuback HEUCODUR Black 953. The synthesized pigment performed worse than the Clariant Graphtol Black CLN and about the same as the Heuback HEUCODUR Black 9-100. The testing showed that the synthesized pigment performed better than a commercialized pigment. As more testing is completed, if the synthesized pigment is outperforming commercial pigments, then the synthesized pigment is ready to be taken to market.

Executive Summary

Problem Statement

Buildings heat up from the adsorption of heat from the sun's radiation. NIR pigments can be used to reflect the near infrared radiation and keep the building from getting so hot. These pigments can be added to coating systems to be applied to the exterior of the building. This decreases the amount of energy, and therefore cost, needed to keep the building the temperature it currently is. This project will explore the readiness of the synthesized pigment in the lab compared to commercial NIR pigments already on the market. This will be done by comparing the temperature of a small enclosure over an hour period covered in an aluminum panel coated in the coating system. Along with this, gloss and color will also be studied.

Summary of Results

The temperature of three different areas of the small building was recorded for every coating. The synthesized pigment performed better than Heuback HEUCODUR Black 953 for all three temperature locations. HEUCODUR Black 953 was the worst performer overall. The synthesized pigment performed worse than the Clariant Graphtol Black CLN for all three temperature locations. The synthesized pigment performed better than Heuback HEUCODUR Black 9-100 for temperature 3 but worse than for temperatures 1 and 2. The Heuback HEUCODUR 953 and 9-100 were similar except 9-100 is a blacker shade than 953 and the gloss of 953 was less than 9-100. The synthesized pigment shows promising results.

Conclusions

The synthesized pigment outperformed Heuback HEUCODUR Black 953 and performed similar to HEUCODUR Black 9-100. The Clariant Graphtol Black CLN outperformed the synthesized pigment which suggests the lighter color of CLN performs better than the black pigment synthesized. The Heuback HEUCODUR 9-100 performing better than Heuback HEUCODUR 953 suggests that gloss may help with near infrared reflection. The ability of the synthesized pigment to outperform one of the commercial pigments means that more testing is needed but the synthesized pigment looks promising for going to market.

Implications of Research

This research is very promising. This synthesized pigment has already outperformed a commercial pigment. This research shows that if this pigment were to go to market it would perform better than one of the pigments it was tested against. Taking this pigment to market could be a great source of revenue for the university. As a corrosion engineering student, it is beneficial to work on projects such as these to apply classroom learning and prepare for the world upon graduation. It was a great experience to put together all the knowledge learned in the past four years to get promising results.

Recommendations

The results from this study are promising, but more research should be done. The synthesized coating only outperformed one of the three commercial pigments it was tested against. It is recommended to test the synthesized coating against other commercial pigments. It is also suggested to test the coatings on different materials to determine if the results will differ. Buildings are made of all sorts of material so it would be important to have evidence supporting how it would perform.

Introduction

Temperatures across the globe are rising each year. These rising temperatures will cause an increase in energy and costs to keep buildings cool. Since, buildings are already responsible for about 40 percent of the world's energy consumption, it is imperative for technology to advance to decrease the energy need.[1] This is becoming more of an issue for every building but especially commercial ones. Many commercial buildings in cities experience the effects of "heat islands" which causes higher temperatures in cities compared to rural areas.[2-4] Many buildings have some sort of coating. These can be for protection of the material underneath, aesthetics, or other reasons.[5] Coatings can be designed to help keep the buildings cool. These are made using pigments designed to reflect near infrared radiation.[6-8] They are already for sale commercially. The goal of this project is to compare these commercial pigments to lab synthesized pigments to determine the readiness of the lab synthesized pigment for use.

Background

Two past honors projects were used as a basis for this project. They were completed in 2020. The first was "Design of Pigments for use in "Cool" Coatings" by Tyler Laughorn and the second was "Testing the Effectiveness of Reflective "Cool" Pigments" by Ashleigh Carpenter.[9,10] Through these tests, preliminary pigment synthesis and testing were completed. The synthesis method from their reports was repeated for the lab synthesized pigment.

For this testing, a pigment, $Ca_2Mn_{0.65}Ti_{0.15}Zn_{0.20}O_{3.80}$, was synthesized in the lab. From past projects, this was determined to be the most promising. This pigment is black, inorganic, and shown in **Figure 1**. Three other commercial pigments were tested along with the synthesized one. The first commercial pigment was Clariant Graphtol Black CLN. This pigment has a purple color and is an organic coating. It can be seen in **Figure 2**.

Figure 1. $Ca_2Mn_{0.65}Ti_{0.15}Zn_{0.20}O_{3.80}$ synthesized pigment.

Figure 2. Clariant Graphtol Black CLN.

The other two commercial pigments were both from Heubach and are both inorganic and black. The HEUCODUR Black 953 can be seen in **Figure 3** and HEUCODUR Black 9-100 can be seen in **Figure 4**. These two pigments are very similar except that 9-100 is a blacker shade than the 953.

Figure 3. Heubach HEUCODUR Black 953.

Figure 4. Heuback HEUCODUR Black 9-100.

Experimental Methods

Synthesis of Pigment

70.25 weight percent $CaCO_2$, 19.86 weight percent MnO_2, 4.21 weight percent TiO_2, and 5.68 weight percent ZnO were used for the pigment synthesis. This was thoroughly mixed using a coffee grinder until homogeneous. The powder was then placed in a furnace and heated to 1200 °C for 8 hours with a heating rate of 10 °C per minute.

Coating Design

Four different pigments were used in this testing. The coatings were made up of pigment, acetone, epoxy resin, hardener, defoamer, and wetting agent. The epoxy used was EPON Resin 828 and the hardener was EPIKURE Curing Agent 3164. The defoamer was BYK-141 and the wetting agent was BYK-333. The first pigment was synthesized in the lab while the other three were commercial pigments. Originally, 25.91 weight percent pigment, 12.95 weight percent acetone, 25.91 weight percent resin, 35.23 weight percent curing agent, 1 drop defoamer, and 1 drop wetting agent. Once the coating was thoroughly mixed, it was drawn down on aluminum Q-panels. The Q-panels were left to dry for 24 hours before baking in an over for 2 hours at 120 °C. After baking the coating was noticed to have defects that were clumps of pigment due to having too much pigment. This can be seen in **Figure 5** below. The formulation was adjusted to 6.48 weight percent pigment, 12.95 weight percent acetone, 34.14 weight percent resin, 46.43 weight percent curing agent, 1 drop of defoamer, and 1 drop of wetting agent. This formulation had a much smoother finish that can be seen in **Figure 6** below.

Figure 5. This panel is coated with the synthesized coating with 25.91 weight percent pigment.

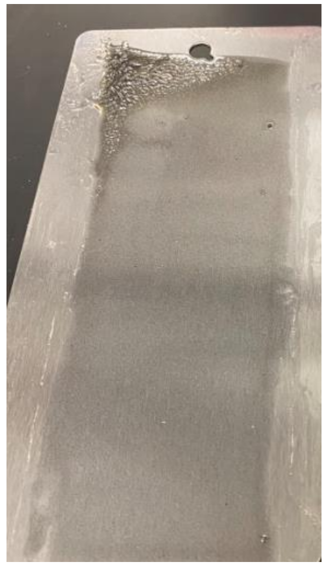

Figure 6. This panel is coated with the synthesized coating with 6.48 weight percent pigment.

The other two inorganic pigments, 953 and 9-100, were formulated using the same ratio as the synthesized pigment. This was 6.48 weight percent pigment, 12.95 weight percent acetone, 34.14 weight percent resin, 46.43 weight percent curing agent, 1 drop of defoamer, and 1 drop of wetting agent. The Clariant Graphtol Black CLN formulation was adjusted based on being an organic pigment. The formulation used for this was 0.4 weight percent pigment, 25 weight percent acetone, 31.6 weight percent resin, 43 weight percent hardener, 1 drop defoamer, and 1 drop wetting agent. All four of the coatings were mixed thoroughly then drawn down on clean aluminum Q-panels. This was done using draw down bar with a wet film thickness of 120 micrometers. 5 panels of each coating were used for testing. After drying for 24 hours, the panels were heated in an oven at 120 °C for 2 hours. Once they were cooled to room temperature, testing was able to begin.

Table 1. Pigment with corresponding pigment weight percentage.

Pigment	Pigment Weight Percent
Synthesized	6.48
Clariant Graphtol Black CLN	0.4
Heuback HEUCODUR Black 953	6.48
Heuback HEUCODUR Black 9-100	6.48

Another coating was prepared using the same formulation as the inorganic coatings but without the pigment. This was drawn down and heated the same way as the other panels. The four coatings containing pigment can be seen in **Figure 7**. This was used as a baseline for testing.

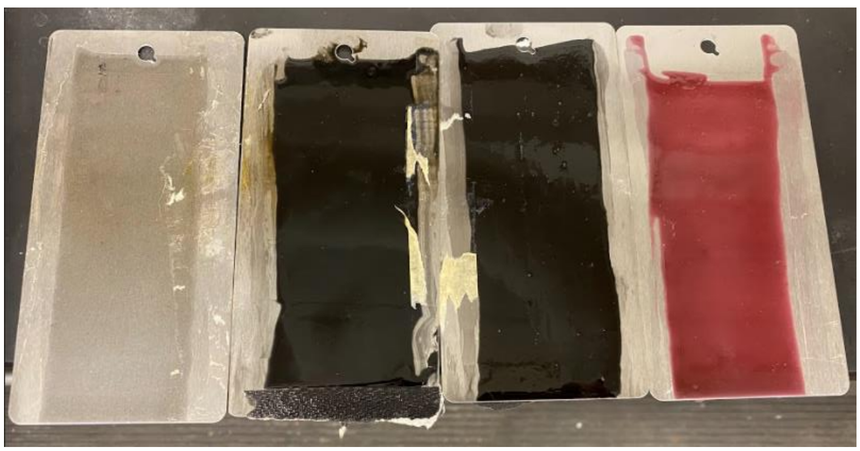

Figure 7. From left to right is the synthesized coating, HEUCODUR 953, HEUCODUR 9-100, Clariant Black CLN.

Testing Set-Up

This test was designed to mimic adding the pigment to a coating system and putting it on the top of a building. A small building was made from half-inch thick polystyrene boards and can be seen in **Figure 8** below. They were designed to be the length and width of the coated panel. These buildings were attached a wood base using tape. A heat lamp was used to simulate the sun's radiation. The light was a Philips BR 123 IR red 250-W light bulb. Two lights and buildings were set up next to each other so two tests could be run at the same time. Thermocouples were set up to measure the temperature at three different locations. These different locations can be seen in **Figure 9**. Temperature 1 is the temperature at the center bottom and inside of the house. Temperature 2 is the temperature from the bottom side of the coated panel. Temperature 3 is the temperature of the coating on top of the panel. Each thermocouple was held in place by tape.

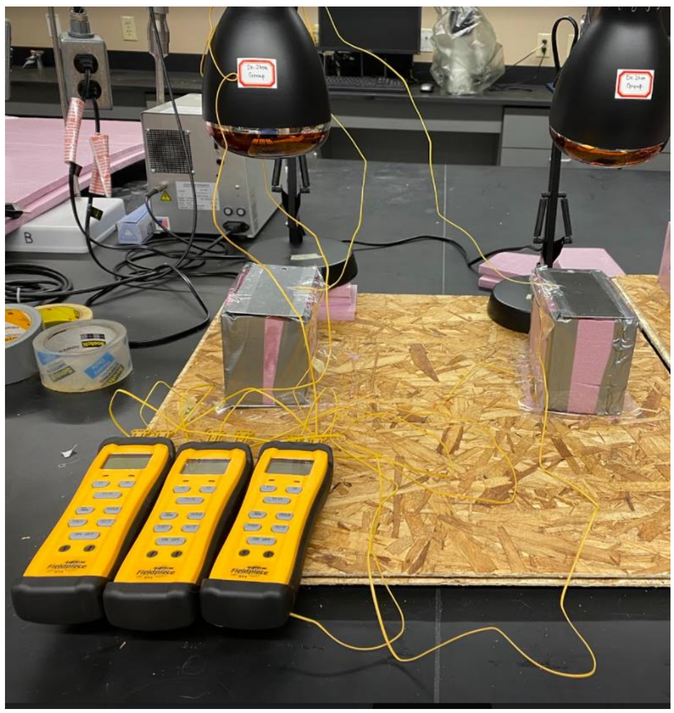

Figure 8. Testing set-up to run two samples at a time.

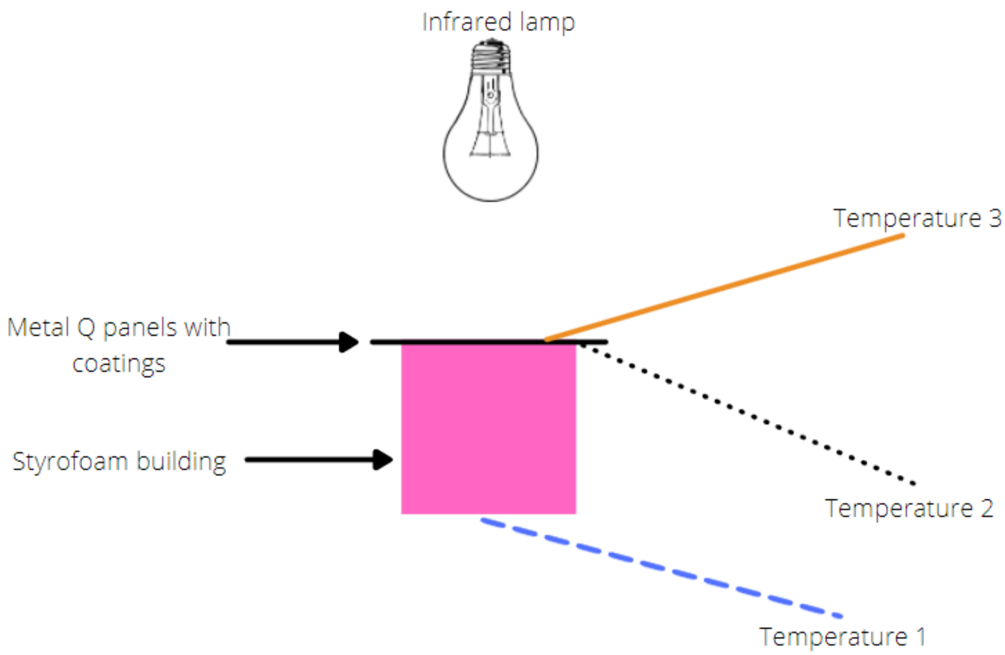

Figure 9. Detailed testing set-up showing the different temperature readings.

Testing

Once the samples were prepared, testing was performed using the test set-up. A coated panel was placed on top of the small building. Thermocouples were attached at the bottom of the house, the underside of the panel, and touching the coated part of the panel as showed in **Figure 9** above. A panel of two different samples was used on the two different enclosures and run at the same time. The temperature of all three locations were taken before the lights were turned on to get a start temperature. Then the lights were turned on and the temperature was recorded every 5 minutes for an hour. This was repeated for each coating and a blank Q-panel at least 3 times per coating for accuracy. The small buildings were returned to room temperature before more testing began.

Once the temperature testing was complete, the gloss and color of the coatings were taken and recorded. The gloss was taken by a Glossmeter, and the color was taken using a color spectrometer. These were used as another means of comparing the coatings.

Data and Results

Due to the large amount of data collected during this project, the data has been summarized for ease of presenting the data. The raw data collected throughout the experiment are provided in **Tables 12-35** in the Appendix section of this report. For each coating, the temperature at each time was averaged to give one average temperature for each 5-minute time interval. The average temperature is shown for each coating below in **Tables 2-7**.

Table 2. The average temperatures over the test period for the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	61.4	60.6	60.6
5	72.4	204.9	202.3
10	76.9	214.3	208.9
15	79.0	210.1	206.7
20	80.3	204.9	205.9
25	81.3	202.9	204.3
30	81.9	199.1	201.9
35	82.1	197.1	201.1
40	82.7	197.0	201.9
45	83.0	194.9	199.4
50	83.1	193.1	199.7
55	83.6	191.7	198.1
60	83.6	190.3	196.7

Table 3. The average temperatures over the test period for the Heuback HEUCODUR Black 953 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	61.4	60.6	60.6
5	72.4	204.9	202.3
10	76.9	214.3	208.9
15	79.0	210.1	206.7
20	80.3	204.9	205.9
25	81.3	202.9	204.3
30	81.9	199.1	201.9
35	82.1	197.1	201.1
40	82.7	197.0	201.9
45	83.0	194.9	199.4
50	83.1	193.1	199.7
55	83.6	191.7	198.1
60	83.6	190.3	196.7

Table 4. The average temperatures over the test period for the Heuback HEUCODUR Black 9-100 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	52.5	52.8	52.8
5	57.3	165.3	183.7
10	70.0	193.3	211.8
15	72.5	188.3	209.5
20	74.5	184.5	209.0
25	74.8	182.3	207.5
30	76.0	182.3	207.8
35	76.5	181.5	206.8
40	77.0	180.5	206.0
45	77.5	179.8	204.3
50	77.8	178.3	203.3
55	78.0	178.0	204.5
60	78.3	177.0	204.8

Table 5. The average temperatures over the test period for the Clariant Graphtol Black CLN coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67.7	67.0	67.0
5	75.0	182.0	179.0
10	77.3	188.7	188.7
15	78.7	190.0	197.3
20	79.3	189.0	196.3
25	80.0	186.7	194.3
30	80.0	185.0	191.7
35	80.3	182.7	189.7
40	80.3	179.7	187.0
45	81.0	180.3	187.7
50	81.3	182.3	189.7
55	81.0	180.3	188.3
60	81.3	179.0	186.7

Table 6. The average temperatures over the test period for the clear coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	59.1	59.1	59.0
5	70.3	185.8	181.0
10	77.1	201.1	203.7
15	79.6	201.0	209.0
20	81.3	201.0	208.9
25	82.4	201.0	205.9
30	83.6	200.6	209.7
35	84.3	200.4	208.9
40	85.0	200.3	209.0
45	85.3	200.4	209.6
50	85.7	200.0	209.1
55	86.3	199.7	208.6
60	86.6	199.4	208.3

Table 7. The average temperatures over the test period for the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	71.3	69.8	69.7
5	80.2	147.8	161.3
10	83.7	155.3	165.5
15	85.0	156.0	166.0
20	86.7	155.3	165.5
25	87.0	155.0	165.0
30	88.0	154.8	164.7
35	88.7	154.2	163.3
40	89.0	153.5	163.0
45	89.2	153.7	162.2
50	89.5	154.0	162.7
55	89.8	153.8	162.2
60	90.0	153.5	162.7

The data from **Tables 2-7** above are summarized in **Figures 10-12** below. The figures the average temperatures for each coating over the test period. The data will be analyzed further in the following section.

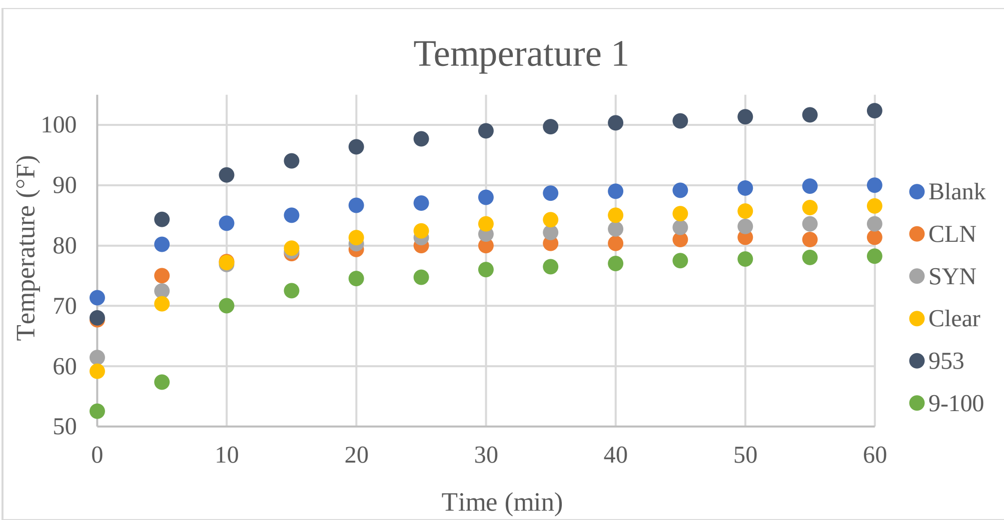

Figure 10. The change of the average Temperature 1 over the testing time. The Temperature 1 is the temperature of the bottom of the small house. CLN stands for Clariant Graphtol Black CLN,

SYN stands for the synthesized pigment, 953 stands for Heuback HEUCODUR Black 953, and 9-100 stands for Heubac HEUCODUR Black 9-100.

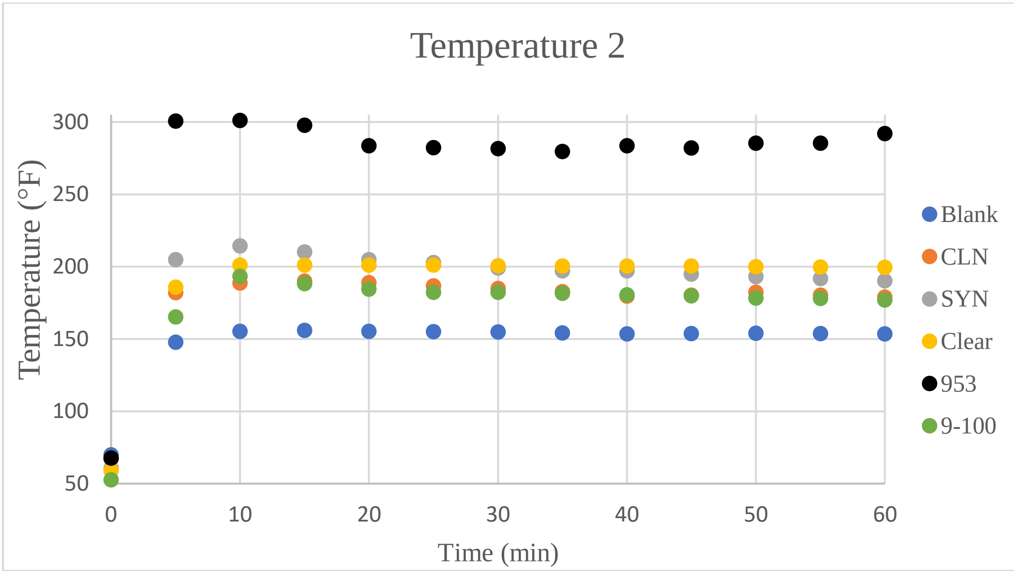

Figure 11. The change of the average Temperature 2 over the testing time. The Temperature 2 is the temperature of the underside of the Q-panel. CLN stands for Clariant Graphtol Black CLN, SYN stands for the synthesized pigment, 953 stands for Heuback HEUCODUR Black 953, and 9-100 stands for Heubac HEUCODUR Black 9-100.

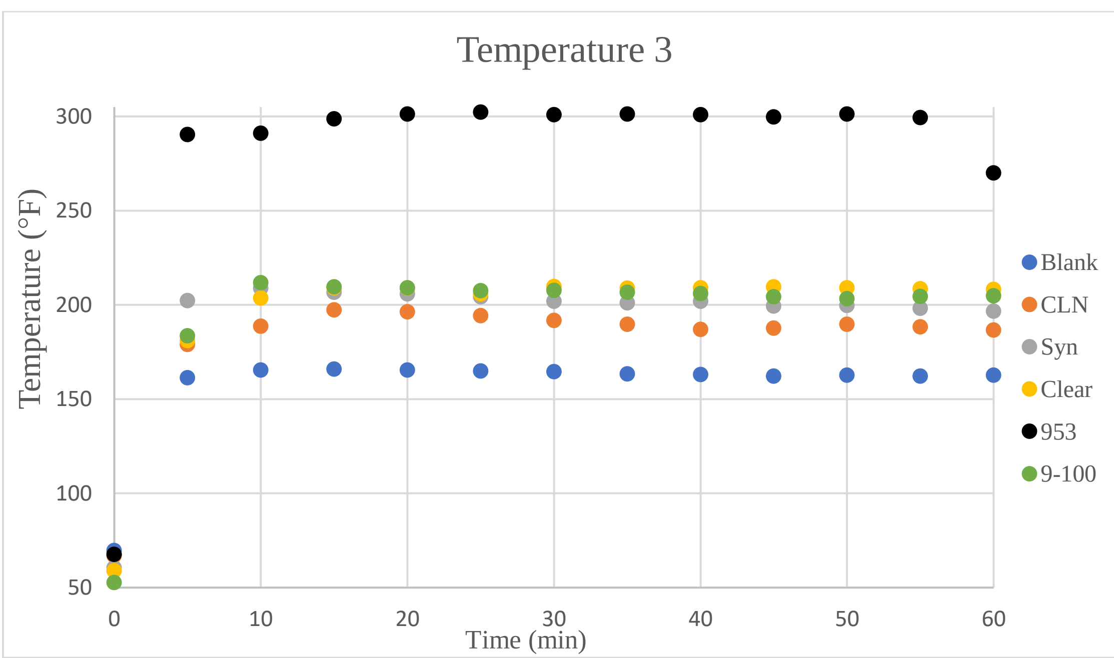

Figure 12. The change of average Temperature 3 over the testing time. Temperature 3 is the temperature of the coating on the Q-panel. CLN stands for Clariant Graphtol Black CLN, SYN stands for the synthesized pigment, 953 stands for Heuback HEUCODUR Black 953, and 9-100 stands for Heubac HEUCODUR Black 9-100.

The maximum temperature and average rate of change of temperature were recorded below to help differentiate the coatings. The maximum temperature for each coating is in **Table 8**. The average rate of change of temperature is in **Table 9**. The average rate of change in temperature was calculated by taking the final temperature minus the initial temperature divided by the time.

Table 8. The maximum temperature during the test period for each coating.

Coating	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
Synthesized	83.6	214.3	208.9
Heuback HEUCODUR Black 953	102.3	301	302.3
Heuback HEUCODUR Black 9-100	78.3	193.3	211.8
Clariant Graphtol Black CLN	81.3	190	197.3
Clear	86.6	201.1	209
Blank	90	153.5	162.7

Table 9. The average rate of change of temperature during the test period for each coating.

Coating	Change in Temperature 1 (°F/min)	Change in Temperature 2 (°F/min)	Change in Temperature 3 (°F/min)
Synthesized	0.22	1.30	1.36
Heuback HEUCODUR Black 953	0.57	3.74	3.37
Heuback HEUCODUR Black 9-100	0.43	2.07	2.53
Clariant Graphtol Black CLN	0.23	1.87	2

Clear	0.46	2.34	2.49
Blank	0.31	1.39	1.55

The gloss and color were taken and recorded for the coatings with pigment. The gloss is shown **Table 10** and color is shown in **Table 11**. Gloss and color cannot be taken of clear coatings.

Table 10. Gloss of the pigment coated panels.

Pigment	20 °Gloss (GU)
Synthesized	84.8
Clariant Graphtol Black CLN	75.6
Heuback HEUCODUR Black 9-100	64.9
Heuback HEUCODUR Black 953	60.8

Table 11. Color of the pigment coated panels.

Coating	Value	
Synthesized	L	37.95
	a	0.13
	b	2.20
Heuback HEUCODUR Black 953	L	25.49
	a	0.19
	b	0.35
Heuback HEUCODUR Black 9-100	L	27.79
	a	2.59
	b	0.71
Clariant Graphtol Black CLN	L	41.00
	a	9.70
	b	1.20

Discussion and Analysis

From the data above, the lab synthesized pigment does well in keeping the small structure cool. In all three temperature readings, the synthesized coating is cooler than the clear coating.

Not only does the synthesized pigment do better than the clear coating, it performs better than some of the commercialized pigments.

Temperature 1, the temperature of the bottom of the small house, over the time period for each coating is shown in **Figure 10**. Keeping this temperature low is the most important temperature as the goal of this research to be able to keep buildings cool. Heuback HEUCODUR 953 has the highest temperature readings throughout the testing time. Heuback HEUCODUR 9-100 had the lowest temperature readings throughout the testing time. The synthesized coating had a cooler temperature than the clear coating, blank panel, and the Heuback HEUCODUR 953. Out of the four different pigments, it performed the third best.

Temperature 2, the temperature reading from the underside of the panel, over the time period for each coating is shown in **Figure 11**. Heuback HEUCODUR 953 has the highest temperature readings throughout the testing time. The blank panel has the lowest temperature readings throughout the testing time. The synthesized coating was cooler than the Heuback HEUCODUR 953 and was similar to the clear coating. Out of the four different pigments, it performed the third best.

Temperature 3, the temperature of the coating on top of the panel, over the time period for each coating is shown in **Figure 12**. Heuback HEUCODUR 953 has the highest temperature readings throughout the testing time. The blank panel has the lowest temperature readings throughout the testing time. The synthesized coating was cooler than the clear coating, Heuback HEUCODUR 953 and 9-100. Out of the four different pigments, it performed the second best.

The Clariant Graphtol Black CLN pigment performed better than the synthesized pigment for all 3 different areas of temperature. This could be due to the color of the CLN pigment is a purple hue instead of black like the synthesized pigment. The colors were recorded in **Table 13**. Along with this, CLN is an organic coating, so the formulation was different than the other three inorganic coatings.

It is interesting that the Heuback HEUCODUR 9-100 performed better than the HEUCODUR 953 for all three different temperature areas since the 9-100 is a darker shade than the 953 and would be expected to perform worse. This is because darker colors absorb more light from the sun and therefore absorb more heat.[11] Although, the 9-100 did have a higher gloss as seen in **Table 10**. The synthesized coating had the highest gloss while the Heuback HEUCODUR had the lowest gloss.

The synthesized pigment had the lowest rate of change of temperature over time shown in **Table 9**. This means the same amount of time in the sun for all the pigments, the synthesized pigment should heat up the slowest. This would be beneficial if the coating would only be sitting in the sun for a short amount of time.

Conclusions

The synthesized pigment performed fairly well in testing when compared to commercialized pigments already on the market for keeping the small building cool. It outperformed Heuback HEUCODUR 953 for all three different temperature locations by keeping the temperature lower. The Clariant Graphtol Black CLN did outperform the synthesized coating throughout the testing, but the coating formulation was different and the CLN was a lighter color. Heuback HEUCODUR 9-100 did perform better than the synthesized coating for temperatures 1 and 2 but the synthesized coating was better at keeping the coating cooler than 9-100. The synthesized pigment did better than Heuback HEUCODUR 953, performed similarly to Heuback HEUCODUR 9-100 and did worse than Clariant Graphtol Black CLN.

Recommendations

The research conducted gives positive results, but more experimentation is needed to prove that the synthesized pigment performs well enough to take to market. This research showed that the pigment performed better than one already on the market, but it also did worse than another commercialized pigment. Since the pigment that was superior in testing was a different color and organic, it would be best to run more tests comparing the synthesized pigment to other black inorganic pigments. It would also be a good idea to continue the testing on other types of Q-panels. Not all buildings are made of aluminum so it is important to determine if the pigment will perform differently on different materials.

Design Constraints

Safety

Safety was important to keep in mind during the testing. During the synthesis of the pigment proper personal protective equipment (PPE) was worn. Safety glasses, long sleeves, and gloves were worn the whole time. Also, the synthesis was done under a fume hood to prevent the inhalation of the powdered chemical. PPE was also used while preparing the coating. The oven used for heating the pigment and panels was only opened when at room temperature. This prevented any risk of burns.

During testing, heat lamps were used. These and the panels got very hot during the testing. Caution was used to turn the lamps off after testing and panels were allowed to cool before being removed from the small buildings. Along with this, testing only ran for 1 hour to prevent the Styrofoam buildings melting which could lead to Styrofoam vapors entering the air of the lab. These preventative measures assured that the experiment was completed safely.

Intellectual Property

Heuback HEUCODUR Black 953 and 9-100 were used in this research. The safety data sheets for these two pigments were exactly the same. The technical data sheets were roughly the same with the only difference being a slight difference in density. It was hard to determine the difference between these two products. A representative of Heuback was contacted and they were asked the different. The exact composition of these pigments are intellectual property so when Heuback was contacted the only difference stated was that 9-100 is a blacker shade than the 953. Both are considered a black shade. The intellectual property makes it hard to determine why one of the Heuback HEUCODUR is performing better than the synthesized pigment but the other is performing worse. This is likely to be a reoccurring issue when testing against commercial products.

Marketing

This pigment would be easy to bring to market. With rising temperatures of the Earth, the need for a pigment that can help keep buildings cool is only going to grow. This black pigment would work well in an industrial setting where the goal of the coating is to keep the building cool to reduce energy needs. It would be important to keep costs at least the same if not lower than competitors. The lower the cost, the more likely a company would be to go with this product over others. Although, the pigment would be more difficult to market to the non-commercial industry such as houses in residential areas. The coating of houses relies on more than just how it can reduce energy use. There are other important factors such as color, texture, and application ease. A lot of homes are subject to home owner associations and require certain looks to houses. The ease of application is important as if the application is difficult that will drive up the overall cost of the product which could make the difference between going with this product or a competitor.

Acknowledgements

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Appendix

Table 12. The temperature for each time for the first run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	70	69
5	72	192	184
10	74	203	184
15	75	201	187
20	76	194	194
25	77	195	194
30	77	194	192
35	77	194	200
40	78	196	201
45	78	197	198
50	78	196	197
55	79	196	198
60	79	195	196

Table 13. The temperature for each time for the second run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	64	65
5	79	181	180
10	84	195	192
15	86	196	193
20	87	195	193
25	88	195	191
30	88	195	190
35	89	193	188
40	89	191	186
45	89	188	185
50	89	187	183
55	89	186	182
60	89	184	180

Table 14. The temperature for each time for the third run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	70	72	71

5	84	259	248
10	89	277	266
15	91	263	265
20	93	256	266
25	95	252	266
30	96	248	267
35	97	245	263
40	97	241	264
45	98	238	265
50	98	235	272
55	99	232	269
60	99	230	267

Table 15. The temperature for each time for the fourth run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	78	73	73
5	96	259	256
10	102	268	264
15	104	264	257
20	105	259	250
25	106	257	249
30	107	243	236
35	106	240	235
40	107	237	232
45	107	236	230
50	107	235	229
55	107	234	229
60	107	232	225

Table 16. The temperature for each time for the fifth run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	70	69	70
5	87	255	256
10	94	267	264
15	98	264	258

20	100	257	253
25	101	254	247
30	102	251	245
35	102	250	243
40	103	260	254
45	104	253	242
50	104	251	244
55	105	249	242
60	105	248	242

Table 17. The temperature for each time for the sixth run of the synthesized coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	78	76	76
5	89	288	292
10	95	290	292
15	99	283	287
20	101	273	285
25	102	267	283
30	103	263	283
35	104	258	279
40	105	254	276
45	105	252	276
50	106	248	273
55	106	245	267
60	106	243	267

Table 18. The temperature for each time for the first run of the HEUCODUR Black 953 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	66	66	66
5	84	271	251
10	93	287	254
15	96	287	276
20	99	287	282
25	101	285	277
30	103	284	280

35	104	284	280
40	105	283	279
45	105	283	280
50	106	285	286
55	107	285	281
60	107	285	283

Table 19. The temperature for each time for the second run of the HEUCODUR Black 953 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	71	69	69
5	87	315	295
10	93	300	294
15	95	299	293
20	97	297	288
25	98	296	299
30	99	293	293
35	100	284	294
40	100	286	295
45	100	285	293
50	100	284	294
55	100	283	292
60	101	284	295

Table 20. The temperature for each time for the third run of the HEUCODUR Black 953 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	68	68
5	82	316	325
10	89	316	325
15	91	307	327
20	93	267	334
25	94	266	331
30	95	268	330
35	95	271	330
40	96	282	329

45	97	278	326
50	98	287	324
55	98	288	325
60	99	307	232

Table 21. The temperature for each time for the first run of the HEUCODUR Black 9-100 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	76	77	77
5	88	255	281
10	94	245	280
15	96	230	276
20	98	220	274
25	98	215	270
30	99	218	273
35	100	217	272
40	100	214	269
45	100	213	267
50	101	210	268
55	101	210	267
60	102	208	269

Table 22. The temperature for each time for the second run of the HEUCODUR Black 9-100 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	67	67
5	84	241	270
10	90	244	278
15	94	238	273
20	96	233	274
25	97	230	273
30	99	226	267
35	99	224	268
40	100	222	267
45	101	220	261
50	101	218	261
55	101	216	263

60	101	214	263

Table 23. The temperature for each time for the third run of the HEUCODUR Black 9-100 coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	67	67
5			
10	96	284	289
15	100	285	289
20	104	285	288
25	104	284	287
30	106	285	291
35	107	285	287
40	108	286	288
45	109	286	289
50	109	285	284
55	110	286	288
60	110	286	287

Table 24. The temperature for each time for the first run of the Clariant Graphtol Black CLN coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	69	67	67
5	73	177	161
10	74	186	185
15	75	186	188
20	76	189	190
25	76	188	190
30	76	188	189
35	77	188	188
40	77	187	186
45	77	188	186
50	77	187	185
55	78	186	184
60	77	185	183

Table 25. The temperature for each time for the second run of the Clariant Graphtol Black CLN coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	70	68	68
5	76	186	192
10	76	185	186
15	77	193	214
20	77	191	213
25	78	190	212
30	78	189	211
35	78	188	211
40	78	186	209
45	79	185	208
50	79	184	209
55	79	182	208
60	79	182	208

Table 26. The temperature for each time for the third run of the Clariant Graphtol Black CLN coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	64	66	66
5	76	183	184
10	82	195	195
15	84	191	190
20	85	187	186
25	86	182	181
30	86	178	175
35	86	172	170
40	86	166	166
45	87	168	169
50	88	176	175
55	86	173	173
60	88	170	169

Table 27. The temperature for each time for the first run of the clear coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	66	67	67
5	79	238	215
10	84	248	227
15	87	243	259
20	89	243	260
25	90	247	259
30	91	248	260
35	92	250	260
40	93	251	259
45	93	252	261
50	94	253	260
55	94	253	259
60	95	253	258

Table 28. The temperature for each time for the second run of the clear coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	72	69	69
5	89	224	225
10	95	235	235
15	97	236	236
20	99	237	237
25	100	235	217
30	102	235	241
35	102	235	241
40	103	235	242
45	104	235	242
50	104	234	241
55	105	235	242
60	105	234	241

Table 29. The temperature for each time for the third run of the clear coating.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	67	69	69
5	82	205	187
10	89	218	225

15	93	221	227
20	95	223	226
25	96	223	228
30	98	223	229
35	99	223	229
40	100	223	231
45	101	225	231
50	101	224	230
55	102	225	230
60	102	225	231

Table 30. The temperature for each time for the first run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	66	66	66
5	70	114	134
10	71	115	135
15	72	115	135
20	73	115	134
25	73	115	136
30	75	115	136
35	75	115	135
40	76	114	134
45	76	114	131
50	76	115	132
55	76	114	132
60	77	114	132

Table 31. The temperature for each time for the second run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	66	64	64
5	70	124	134
10	71	126	139
15	71	126	137
20	72	126	138
25	71	126	138
30	71	126	139
35	72	125	137

40	71	124	137
45	71	126	138
50	71	125	137
55	72	124	134
60	71	124	136

Table 32. The temperature for each time for the third run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	71	70	70
5	84	155	186
10	89	164	179
15	91	161	178
20	93	158	176
25	93	156	173
30	94	154	166
35	95	151	161
40	96	149	159
45	96	148	157
50	97	152	162
55	97	151	161
60	97	150	162

Table 33. The temperature for each time for the fourth run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	78	74	74
5	88	171	178
10	92	181	187
15	93	184	189
20	95	183	187
25	95	183	187
30	96	183	188
35	96	183	188
40	97	184	190
45	97	183	188
50	97	183	188
55	97	183	187

60	98	182	188

Table 34. The temperature for each time for the fifth run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	69	70	69
5	79	164	173
10	84	176	182
15	86	179	184
20	88	179	186
25	90	179	185
30	91	180	187
35	92	180	187
40	92	179	185
45	93	180	187
50	93	179	185
55	94	180	186
60	94	180	185

Table 35. The temperature for each time for the sixth run of the blank panel.

Time (min)	Temperature 1 (°F)	Temperature 2 (°F)	Temperature 3 (°F)
0	78	75	75
5	90	159	163
10	95	170	171
15	97	171	173
20	99	171	172
25	100	171	171
30	101	171	172
35	102	171	172
40	102	171	173
45	102	171	172
50	103	170	172
55	103	171	173
60	103	171	173