Glowcrete

A Thin Layer Approach to the Development of Self-Illuminating Concrete

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Section 15 Team 3

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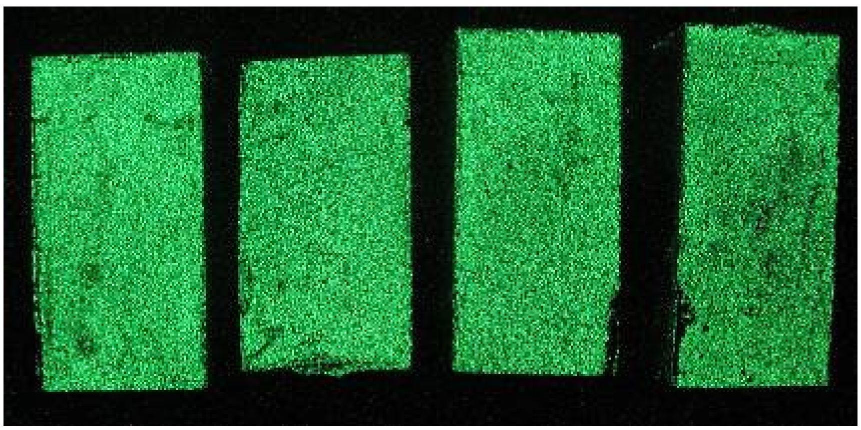

Paul Preissner
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June 7th, 2006
Northwestern University
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EXECUTIVE SUMMARY

Problem

Self-illuminating concrete is a novel concept that would provide safety and power efficiency in various applications, including parking garages, driveways, jersey walls and runways. Despite these useful applications, very little research has been conducted on developing self-illuminating concrete. For this reason, the mission of Team Glowcrete (EDC Section 15 Team 3; Spring 2006) was to determine if it were possible to produce a phosphorescent concrete material.

Due to the complexity of developing new materials, the investigation was divided into four parts:

- Researching possible ways for concrete to self-illuminate
- Developing methods for producing samples of phosphorescent concrete
- Developing methods for testing the properties of phosphorescent concrete
- Using these methods to determine the feasibility of this concept

Research

Based on preliminary research, expert interviews and cost analysis, the team pursued the application of a thin phosphorescent concrete layer to the surface of a bulk concrete sample. All tests were conducted with cement as a model for analogous testing with concrete.

Design

Drawing from expert interviews and preliminary lab testing, the team developed methods for producing and testing cement samples with a thin phosphorescent layer. Strontium aluminate ($SrAl_2O_4$), doped with europium (Eu) and dysprosium (Dy), was used as the phosphorescent additive. Adhesion tests, including a three-point bend test and compression test with a spherical indenter, were performed and analyzed using microscopy. Digital photography was used to investigate the phosphorescent properties, and a quantitative test with a light meter was designed.

Preliminary Results

Using these procedures, Team Glowcrete tested various water and glow powder ratios in the thin layer. Conclusions from these tests include:

- A thin layer can be used to produce a cement material that phosphoresces on top.
- Thickness does not affect the amount of light emission from samples.
- Compression tests with a spherical indenter is a reliable method for testing adhesion.
- Three-point bend tests do not provide any substantial data on adhesion.
- Samples do not phosphoresce for more than five minutes after charging for 10 minutes

Next Steps

The results of the preliminary testing indicate that concrete can be produced that self-illuminates. However, future work in the optimization of the glow powder and water ratios must be conducted in order to maximize the benefits of such a material. A new glow powder with longer glow time should also be explored. The tests outlined in this report (used on cement) can be extended to concrete samples. While cement results can be analogous to concrete, future tests must be conducted on concrete before the material can be used in structural applications.

INTRODUCTION

Paul Preissner of Qua'Virarch, an innovative architectural design firm, asked EDC Team 15.3 (Team Glowcrete) to explore the development of self-illuminating concrete. No concrete with this property is commercially available at present; however, it would be extremely useful for various individuals and organizations, including architects, designers, and city planning councils. Self-illuminating concrete could be used as a light source and safety measure in concrete structures such as parking garages, curbs, and jersey walls. In addition, because self-illuminating concrete is not a conventional material, there are no methods expressly created for testing its properties.

Therefore, the team's objective was to create a concrete that could withstand the forces experienced by normal structural concrete, as well as provide luminescent output for an appreciable duration. The full requirements of the design project are given in Appendix A.

This proposal details the findings of an eleven-week period from March 27th, 2006 to June 7th, 2006, during which Team Glowcrete developed novel approaches for producing and testing self-illuminating concrete. These goals were accomplished through researching possible additives and testing procedures, and then investigating those that were most promising.

This proposal also discusses the findings of Team Glowcrete in relation to the design problem. It contains pertinent research, and includes discussion of not only the creation of the samples, but also the design of the sample testing. The proposal concludes with a discussion of recommended next steps for further exploration into the use of self-illuminating concrete.

MAJOR REQUIREMENTS AND USERS

Concrete with self-illuminating capabilities is not commercially available at present, and the current method for making a concrete material glow is to apply a layer of phosphorescent paint on top. However, this paint wears away and chips off more easily than a layer of concrete would. Therefore, developing a self-illuminating concrete would provide new glowing materials to various potential users, including:

- Architects
- City planners
- Structural engineers
- Artists

To be feasible for such users, this concrete must meet the following requirements:

- It must have at least the compressive strength of normal concrete
- It must not be more expensive than typical lighting and concrete infrastructure
- It must glow for an appreciable duration (at least four hours)

These requirements have motivated the direction Team Glowcrete has pursued in the development and testing of self-illuminating concrete.

Appendix A provides a more comprehensive discussion of the potential users and project requirements.

Also, because there are no widespread testing methods for determining the properties of self-illuminating concrete, potential users of the developed testing procedures include architects and material engineers who wish to explore this topic.

BACKGROUND RESEARCH

Extensive research was performed during the development of the methods for producing and testing samples. This research, found from a variety of sources, provided essential insight into the characteristics of the materials we made and the standard techniques for testing them. The methods and results for this investigation are outlined below.

See References for complete bibliographical information.

Client Requirements

On April 6, 2006, the team met with the client, Mr. Paul Preissner, to discuss the project details and requirements. Further communications to refine the project definition and focus were accomplished via e-mail.

Previous Investigations

This research discusses whether phosphorescent materials can be used as illumination sources when other light sources are not present. Such research includes a study by the Federal Aviation Administration, which investigated whether phosphorescent materials could be used for escape path markings (McLean, et. al.). The study concluded that using phosphorescent materials as a source of lighting may be possible, and that strontium aluminate ($SrAl_2O_4$) is the recommended material.

Materials

Throughout the project, the team researched concrete and phosphorescent materials. This research was vital to the project because it guided the determination of which materials to use in the self-illuminating concrete and how to test its properties.

Concrete Materials

Research conducted on concrete materials provided basic background information required to complete this project. This information was found through online research and expert interviews.

Online Research: Several online organizations specializing in concrete provided detailed information on the characteristics of concrete. These sources included the websites for the University of Illinois' Materials Science and Technology Teacher's Workshop (MAST) and the Cement Association of Canada (CAC website).

Expert Interviews: Throughout this project, the team consulted with several concrete experts at Northwestern University and the Naval Surface Warfare Center, Carderock Divison:

- Dr. Hamlin Jennings – Professor, Department of Civil Engineering (Northwestern University)
- Mr. Curtis Martin – Material Scientist (Naval Surface Warfare Center, Carderock Division)
- Dr. Jeffrey Thomas – Professor, Department of Civil Engineering (Northwestern University)

The results of the research on concrete, including basic information on cement and concrete, can be found in Appendix B. One of the more important findings indicated that neat cement can be used as a substitute test for concrete, and will give analogous results (Maczura, et. al., & Martin).

Phosphorescent Materials

References in Phosphorescent Materials: These sources were written by experts in the field of phosphorescence or those who are active in the phosphorescent material industry. They provided greater understanding on the phenomenon of phosphorescence. These references included the *Phosphor Handbook* (Phosphor Research Society) and Glow Inc.'s website. Each of these sources indicated that strontium aluminate doped with europium and dysprosium ($SrAl_2O_4$: Eu^{2+}, Dy^{3+}) was a phosphor that produced above average phosphorescence in terms of intensity and duration. For a more detailed background discussion on phosphorescence, see Appendix C.

Glow Powder Analysis: The glow powder used for this investigation was purchased from a company that sells phosphorescent materials. The powder was characterized by Dr. James Zaykoski of the Technical Ceramic Science Group at the Naval Surface Warfare Center. Dr. Zaykoski characterized the sample for its chemical composition and structure using X-Ray Diffraction, Energy Dispersive X-Ray Spectrometry (EDS) and Scanning Electron Microscopy (SEM). These tests indicated that the glow powder used was $SrAl_2O_4$: Eu^{2+}, Dy^{3+}. The glow powder also had a particle size of 80μm with similar physical properties as sand. A discussion on these results can be found in Appendix D. The powder was also found to be powder is also safe to use.

Sample Production and Testing

Online Research: Several online organizations specializing in concrete provided detailed information on methods of testing materials. These sources included the Canadian Cement A.

Expert Interviews: In addition to the experts in concrete, the team contacted additional faculty members and graduate students at Northwestern University with backgrounds in testing materials:

- Mr. Mark Seniw – Technician, Department of Materials Science and Engineering (Northwestern University)
- Ms. Ni Wansom – Graduate Student, Department of Materials Science and Engineering (Northwestern University)

Each of these experts had significant experience in materials testing. Tests such as a three-point bend test and a compression test were discussed in detail. Appendix E provides an overview of these different tests.

THE DESIGN: A THIN PHOSPHORESCENT LAYER AND TESTING METHODS

Because the process for developing a new material is complex, the investigation was divided into four phases:

- Researching possible ways for concrete to self-illuminate
- Developing methods for producing samples of phosphorescent concrete
- Developing methods for testing the properties of phosphorescent concrete
- Using these methods to determine the feasibility of this concept

Approach for Self-Illumination: Thin Phosphorescent Layer with Doped Strontium Aluminate

The objective of this investigation was to determine whether a phosphorescent concrete could be produced. Of the various possible ways to make phosphorescent concrete, the addition of a thin phosphorescent concrete layer on top of pure concrete appeared to be the most promising. This material's phosphorescent layer contained doped strontium aluminate additives. The reasoning behind choosing this approach is discussed below, along with an analysis of the feasibility of this approach.

Thin-Layer Approach

Two methods for developing a self-illuminating concrete were considered: either mixing phosphorescent powder throughout the concrete or applying a thin phosphorescent concrete layer to the surface (Figure 1).

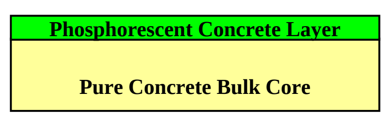


Figure 1: Diagram of Phosphorescent Layer Concept
(Image Drawn by Lauren Smith)

After analyzing the two alternatives, the thin-layer approach was pursued. There are three differences between the alternatives that make a thin layer more appropriate for this study:

- Phosphorescent material in the core of the sample will have little effect on the self-illuminating properties of the sample as a whole (light will not reach this region).

- The addition of phosphorescent materials throughout the sample could significantly decrease the structural properties of the concrete. In contrast, a thin layer on the surface of the concrete would have little effect on the structural properties (Jennings, Martin).
- Phosphorescent materials are generally expensive and addition of these throughout the entire structure would significantly increase the cost (see Appendix F for a cost analysis of the thin-layer approach).

Phosphorescent Material: Doped Strontium Aluminate ($SrAl_2O_4$: Eu^{2+}, Dy^{3+})

Various sources from the preliminary literature research indicated that $SrAl_2O_4$: Eu^{2+}, Dy^{3+} was the best candidate for self-illuminating concrete. The literature reports that this compound glows up to twelve hours and has an intensity about ten times the brightness of the common glow in the dark materials (usually composed of zinc-sulfide) (Phosphor Research Society). This decision was considered to be the best way to satisfy the client's requirement of the concrete phosphorescing for up to four hours.

Analyzing the Feasibility of this Approach

The feasibility of the thin-layer approach relies on two characteristics of the material: the ability of the thin layer to adequately phosphoresce, and the ability of the thin layer to adhere to the bulk pure concrete sample. To test these characteristics, samples with phosphorescent thin layers had to be made and tested. Because no previous research has been attempted on this type of material, both the methods for producing samples and testing them are unique to this investigation.

Methods for Producing Samples with a Thin Phosphorescent Layer for Testing

After determining to pursue the thin-layer approach with $SrAl_2O_4$: Eu^{2+}, Dy^{3+}, methods were developed to produce samples for testing its feasibility. For each of these samples, cement was used instead of concrete.

Using Cement for Tests Instead of Concrete

Cement samples were used throughout this investigation, as a way of indicating how corresponding concrete samples may behave. The reasons for using cement instead of concrete include:

- Testing samples of cement generates results analogous to testing samples with concrete (Maczura, Martin).
- Using cement produces samples with smooth faces (in contrast to the rough and uneven surfaces of concrete due to the sand aggregates). These flat surfaces are required for the tests discussed below.

Method for Producing Samples

In this study, cement samples were laid in a 25.4 mm x 25.4mm x 101.6 mm (1" x 1" x 4") mold. However all procedures can be adapted to a different mold size. In this procedure, a thin layer of cement and phosphorescent powder was laid on the bottom of the mold, and the bulk pure cement was poured on top to fill the remaining volume of the mold (Figure 2).

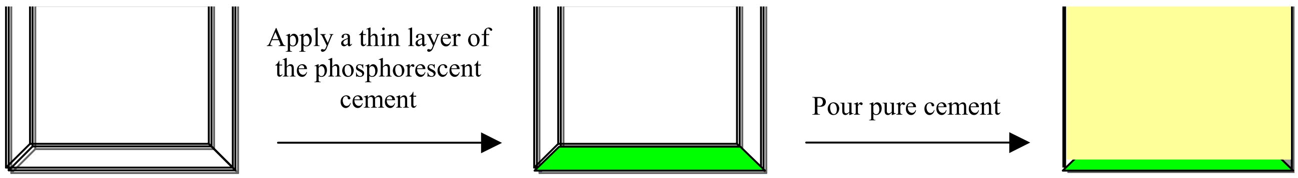


Figure 2: Diagram Describing Process for Applying Thin Phosphorescent Layer
(Image Drawn by Lauren Smith)

To ensure that the thin layer had a consistent depth for each sample that was produced, Team Glowcrete designed a device to smooth an even 1 mm phosphorescent layer on the bottom. This smoother (shown in Figure 3) fits around the mold, allowing for a straight-edge to be inserted and evenly scrape close to the bottom.

Figure 3: Perspective Diagram of the Smoother Device
Housing (left) and Scraper (right)
(Image Drawn by Adrienne Smith and Lauren Smith)

See Appendix G for orthographic projection of smoother device.

After both the phosphorescent and pure cement layers were laid, the samples were bounced gently to remove air bubbles. Failure to do so resulted in samples with highly irregular surfaces (Figure 4).

Figure 4: Samples with Irregular Surfaces Caused by Air Bubbles
(Photo Taken by Adrienne Smith)

Samples were wrapped in wet paper towels and stored in plastic bags for 16 hours.

After allowing the samples to harden for 16 hours, they were placed in water saturated with CaO for 8 days, to ensure that the hydration bonds in the cement continued to form.

Appendix H describes each of these methods used in greater detail.

Benefits of Methods for Producing Samples

There are many benefits to producing the phosphorescent thin-layer cement samples using the procedures described. These methods produce samples that:

- Have thin layers of consistent thickness, throughout the specific sample and between samples

- Have flat surfaces on top and minimizes air bubbles

Both of these characteristics are required for the phosphorescent and adhesion tests

Methods for Testing the Properties of the Thin Layer

After the samples were produced, tests were performed to determine whether the thin-layer approach would work. These test also served as methods to optimize the composition of the thin layer. Samples with different values for the thin-layer variables were produced, and then tested for phosphorescence and adhesion.

All samples were tested after eight days of curing. Although testing concrete or cement is generally performed after 28 days of curing (Cement Association of Canada), experts in the field indicate that tests after a week can be used to begin initial characterizations of the material (Jennings, Martin).

Thin-Layer Variables

Water Content and Phosphorescent Powder Content

Water content and glow powder content of the thin layer were the two variables tested in this study. Varying these was predicted to influence either the phosphorescent quality of the sample or the adhesion properties of the thin layer. The proportions used (seen in Table 1) were chosen as a result of expert interviews and visual observations of the dry powders.

Table 1: Water and Glow Powder Ratios Used in the Thin-Layer Tests

Ratio of cement to water by mass
2.40:1
2.10:1
1.90:1
1.70:1

Ratio of cement to phosphorescent powder by mass
5.00:1
2.50:1
1.70:1
1.30:1

Thickness of Thin Layer

Expert contacts had also indicated that the thickness of the layer may be an important variable. However, preliminary results suggested that the thickness of the layer did not influence the phosphorescent character of the material, because light did not penetrate past the outer surface of the samples.

Tests were performed on a small sample of cement with phosphorescent powder mixed throughout. The cross section of the sample was covered with electrical tape, while the top surface was exposed to light.

After 10 minutes of excitation, the light source was removed and the cross section covering tape was taken off. As depicted in Figure 5, the light had only excited a small depth into the surface (less than 1 mm). Therefore, thickness was not tested as a variable, because thickening the thin layer would not increase the intensity or duration of glow.

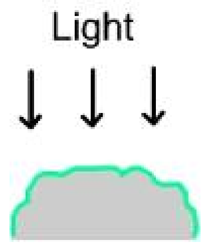


Figure 5: Penetration of Light into a Sample with Glow Powder Mixed Throughout (Cross Section Shown Above)
(Image Drawn by Lauren Smith)

Phosphorescent Properties Testing

Before any phosphorescent testing was performed, the thin-layer surface of the cement was sanded down gently, to remove any CaO build up that formed while the sample was setting in the CaO saturated water.

The self-illuminating nature of the thin-layer samples was examined using digital photography. To compare the phosphorescent intensity among the different glow powder and water ratios, samples were excited with either UV light or white light for a standard length of time (1 minute). Afterwards, the light source was removed and a picture was taken where the phosphorescence was the only light source present.

To characterizing the nature of the phosphorescence decay over time, samples were excited with either UV light or white light for 10 minutes. Photographs were then taken every minute after the light source was removed, until five minutes had passed. The full procedures for this test can be found in Appendix I.

A quantitative method for testing phosphorescence was also developed. This test used a light meter to measure phosphorescent output of the thin layer as a function of time. A more in-depth discussion can be found in Appendix J.

Layer Adhesion Testing

According to experts in the field, adhesion to the bulk cement sample was the most significant obstacle in developing the phosphorescent cement layer. Through online research and expert interviews, the most promising tests for adhesion were modified versions of a three-point bend test and a compressive strength test (these two basic tests are explained in Appendix K.

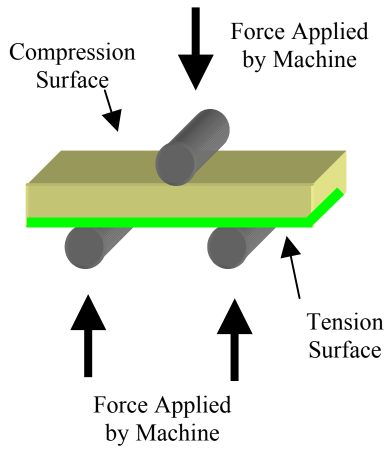
All testing was performed using a Sintech 20/G Materials Testing Workstation (Figure 6), which could be modified to apply either the three point bend test or the compressive test.

Before these tests could be run, the face of the sample opposite the thin layer was also sanded down, to create a smooth testing surface.

Figure 6: Test Frame Used (Sintech 20 G)
(Photo Courtesy of Mark Sinew)

Three Point Bend Test for Adhesion

The three-point bend test for adhesion used a standard three-point bend test, but put the thin layer in tension (Figure 7). A poorly adhered surface placed in tension was predicted to fracture along the boundary when the sample was breaking in half. Such cracking behavior could then be observed using microscopy and compared to the behavior of pure cement. The full procedures for this test can be found in Appendix K.



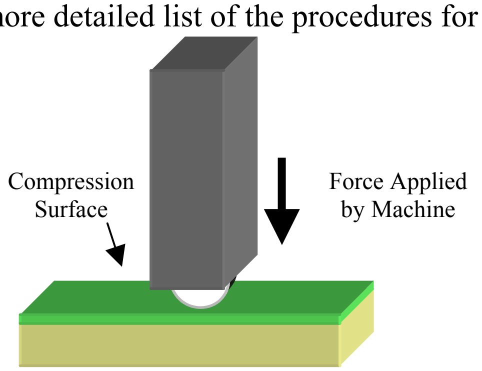
a. Diagram of Testing Setup – Position of the Thin Layer
(Image Drawn by Adrienne Smith)

b. Photo of Three Point Bend Testing Setup
(Photo Courtesy of Mark Seniw)

Figure 7: Setup for Three Point Bend Test for Adhesion

Compressive Test with Indenter for Adhesion

The compression strength test applies a compressive force to the thin layer through the indenter (analogous to the types of forces that will be applied to the material in real world applications). A compression test with a 15.88 mm (5/8 in.) diameter indenter was applied to the sample, with the indenter pushing directly on the thin phosphorescent layer (Figure 8). A poorly adhered thin layer placed under the indenter should show significant structural damage (such as cracking or crumbling) along the circumference of the indenter's crater. Such material deformation could then be observed using microscopy and compared to the behavior of pure cement (see Appendix K for a more detailed list of the procedures for this test).



a. Diagram of Testing Setup – Position of the Thin Layer
(Image Drawn by Adrienne Smith)

b. Photo of Compression Testing Setup
(Photo Courtesy of Mark Seniw

Figure 8: Setup for Compressive Test with Indenter for Adhesion

Benefits of Methods for Testing Samples

There are many benefits to testing the phosphorescent thin-layer cement samples using the procedures described.

- The phosphorescent test provides information on the intensity and duration of a sample's phosphorescence.
- The three-point bend test puts the thin layer in tension, which may provide information on the adhesion of the layer
- The compression strength test applies a compressive force to the thin layer through the indenter (analogous to the types of forces that will be applied to the material in real world applications).

<u>The Feasibility of a Phosphorescent Thin Layer – Preliminary Results</u>

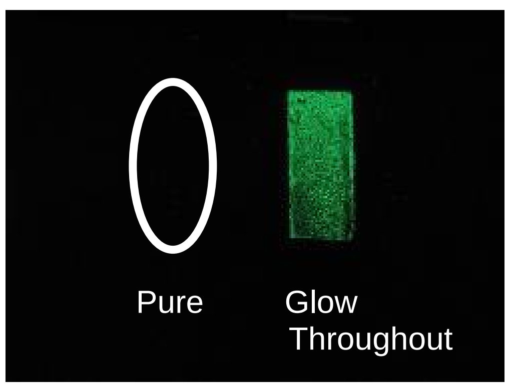
* All three point bend test and compression test pictures were taken by Andy Long; all phosphorescent pictures were taken by Adrienne Smith.

Phosphorescent Test

The phosphorescent properties of the samples were observed qualitatively, after exposing the samples to both white and UV light. A complete compilation of the pictures taken can be found in Appendix L.

Pure cement and a sample with 2.5:1 glow powder throughout were observed after being exposed to a light source for 1 minute. Samples containing pure cement did not glow, while samples containing glow powder throughout did (Figure 9). Furthermore, the sample with glow powder throughout did not glow differently than samples with a thin layer, thus justifying the choice of a thin-layer design.

White Light



UV

Figure 9: Phosphorescence of Pure Cement and 2.5:1 Glow Power, 2.1:1 Water Throughout Samples After 1 Minute Exposure

Other tests, including exposing the cross section of a thin-layer sample to a light source, indicated that using the smoother to even out the thin layer was accurate (Figure 10). One can easily see that the layer was of a consistent size.

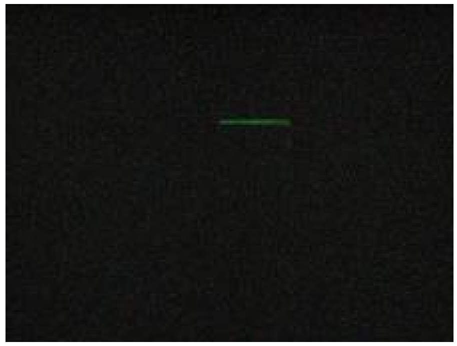
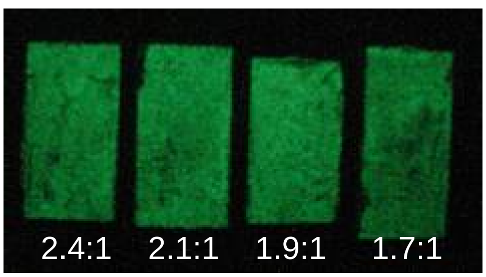
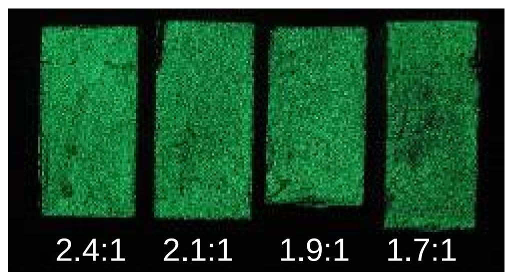


Figure 10: Phosphorescence of Cross Section - Example of Thin Layer
2.5:1 Glow Powder Ratio, 2.4:1 Water Ratio

Additionally, varying the ratios of water in the thin layer has no affect on the phosphorescence (Figure 11). This was true for all samples exposed to 1 minute of either white or UV light.



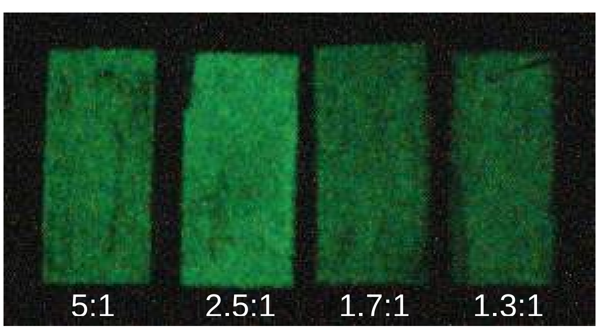
White Light 2.5:1 Glow Powder



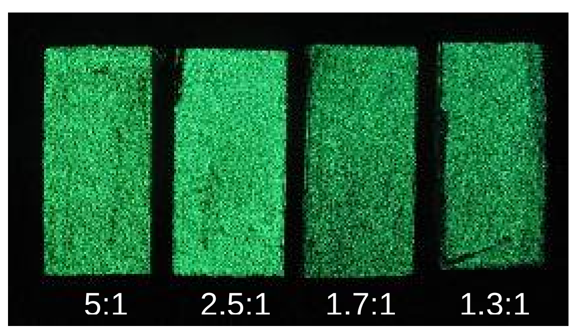
UV 2.5:1 Glow Powder

Figure 11: Phosphorescence of Samples Containing 2.5:1 Glow as a Function of Water Ratio

In contrast, varying the glow powder ratios in the thin layers did effect the phosphorescence (Figure 12). Samples containing a 2.5:1 glow powder ratio had a brighter glow compared to those containing the other ratios (including those that had less and those that had more glow powder).



White Light 2.1:1 Water



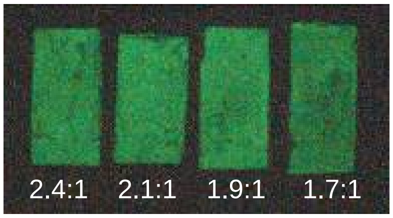
UV 2.1:1 Water

Figure 12: Phosphorescence of Samples Containing 2.1:1 Water as a Function of Glow Powder Ratio

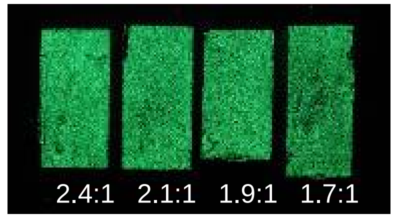
The phosphorescence of the samples was also tested as a function of time. Samples containing a 2.5:1 ratio were exposed for 10 minutes and pictures taken every minute thereafter for five minutes. As is seen in Figure 13, the phosphorescence of the samples quickly fades. After one minute, the light is significantly dimmer; after five, the light is almost undetectable.

2.5:1 Glow Ratio, White Light

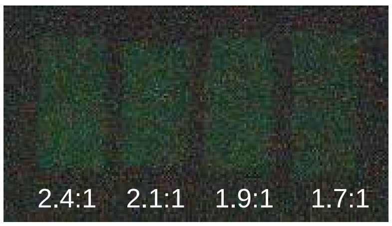
2.5:1 Glow Ratio, UV Light



Time Lapsed = 0 min

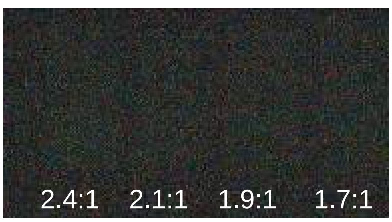


Time Lapsed = 0 min



Time Lapsed = 1 min

Time Lapsed = 1 min



Time Lapsed = 5 min

Time Lapsed = 5 min

Figure 13: Phosphorescence of Thin Layer Samples as a Function of Water Ratio and Time (2.5:1 Glow Powder Ratio)

Three Point Bend Adhesion Test

No conclusions could be made about the adhesion properties of the thin layer from the three-point bend test. After the samples were broken, the boundary layers were observed under a microscope. See Figure 14 for a picture of a representative sample. (All cross sectional pictures can be found in Appendix M). It was clear from these pictures that the thin layer did not separate from the bulk sample for any ratio of glow powder or water. There was mild cracking in some samples, however not along the boundary layer. Therefore, it was concluded that the three point bend test is may not provide any data on the adhesive properties of thin-layer cement samples.

Figure 14: Cross Section of 1.30:1 Glow Powder, 1.9:1 Water after Three Point Bend Test

Compression Strength Test

Through the use of the compression test, adhesion properties of the thin layers were observed. After the load was applied to the samples, the indent was observed using a macro lens camera. Team Glowcrete then compared the indents of these samples to those of the pure cement samples created under identical testing conditions. All photographs of such tests are shown in Appendix N. Figure 15 displays the control sample of pure cement, containing the ideal amount of water. There are no cracks around the crater and no flaking around the edges. Similar properties were seen in samples containing a 5:1 glow powder ratio entirely through. This indicates that any cracking or flaking was not due to the phosphorescent material failing, but due to poor adhesion.

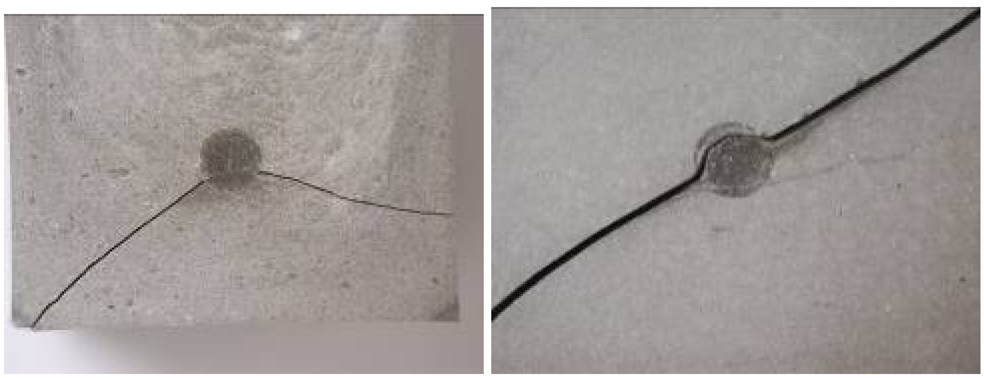


Figure 15: Compression Test of Control Samples
Pure Cement (left) and 5:1 Glow Powder Ratio Throughout, 2.1:1 Water Ratio (right)

Samples with good adhesion should have similar properties to that of pure cement. Therefore, samples were analyzed for the presence of cracks and flaking. Figure 16 compares a sample that has poor adhesion properties with a sample that has good adhesion properties.

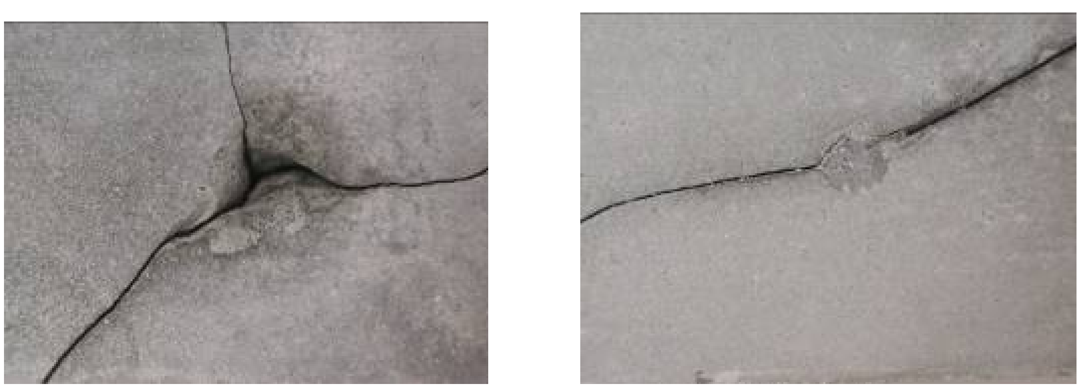


Figure 16: Representative Compression Test Results – Poor and Good Adhesion
1.30:1 Glow Powder Ratio, 1.7:1 Water Ratio– example of poor adhesion (left); 2.5:1 Glow Powder Ratio, 2.1:1 Water Ratio – example of good adhesion (right)

The amount of distortion and cracking was measured and used to help evaluate the adhesive properties of the samples. The results of this analysis can be found in Table 2. See Appendix O for how the layer adhesions were evaluated.

Table 2: Strength of Layer Adhesion

Phosphorescent Powder Ratio*	Water Ratio*	Layer Adhesion
5.00:1	2.40:1	Weak
5:00:1	2.10:1	Strong
5.00:1	1.90:1	Strong
5.00:1	1.70:1	Strong
2.50:1	2.40:1	Strong
2.50:1	2.10:1	Strong
2.50:1	1.90:1	Strong
2.50:1	1.70:1	Strong
1.70:1	2.40:1	Strong
1.70:1	2.10:1	Strong
1.70:1	1.90:1	Weak
1.70:1	1.70:1	Weak
1.30:1	2.40:1	Strong
1.30:1	2.10:1	Weak
1.30:1	1.90:1	Weak
1.30:1	1.70:1	Very Weak

*All ratios are by mass of cement to mass of phosphorescent powder or mass of water.
This data shows that insufficient and surplus water can cause the layer adhesion to be weak.

Discussion of Results

From the data obtained from the testing, the following can be concluded:

- A thin layer can be made that produces the same glow as samples with glow powder throughout.
- A thin layer can be successfully made using the smoother.
- Phosphorescence dies out in less than 5 minutes after being removed from the light source.
- Compression test with a spherical indenter is a good method for testing adhesion.
- The three point bend test is not a usable method for testing the adhesion of a thin layer, because it does not provide any noticeable change in cross section of the material (even if the compression test indicates that adhesion is poor).
- A 2.5:1 ratio of cement to glow powder provides the brightest glow.
- Optimal amount of water for adhesion decreases with the increase of glow powder content.

The last two conclusions warrant further study. These results are interesting but cannot be explained at present. More samples should be made in the future to replicate these tests. Experts should also be consulted in order to help explain the cause of these results.

Characterizing the phosphorescent decay of the samples also showed significant results. While the samples glowed, and the thin layers adhered, the lifetime of the phosphorescence was short. Within 5 minutes, the intensity died out and required recharging. This has implications for the use of this product for any extended amount of time. More research should be conducted on identifying another source of phosphorescence that does not decay in such a short amount of time.

RECOMMENDED NEXT STEPS

Team Glowcrete has made significant steps in developing methods for synthesizing and testing phosphorescent concrete. More work must be conducted, however, in the following areas:

- Repetition of cement tests to confirm results
- Consultation of experts
- Application of quantitative phosphorescence testing
- Search for longer-lasting glow powder
- Production and testing of analogous concrete samples
- Quantitative compressive strength tests
- Durability tests
- Large scale tests

Repetition of Cement Tests

Samples tested for this investigation included only one data point for each combination of variables. In the future, more samples for each combination of variables should be tested. A broader range of glow powder and water ratios should also be tested on order to better determine the relationship between these variables and adhesion / phosphorescence. This would allow future researchers to report on the effects of adding phosphorescent powder with more accuracy.

Consultation of Experts

The preliminary results obtained form the testing performed indicate that a 2.5:1 glow powder ratio is optimal, and that the optimal water amount decreases with increasing glow powder quantities. Both results were unexpected and should be investigated further. Experts in the cement field should be consulted to try to determine the cause of such results.

Analogous Production and Testing of Concrete Samples

All samples for this project were made with cement rather than concrete. Given that cement is a large constituent of concrete, the procedures and results should be analogous. However, the work conducted with cement can only be interpreted as a proof of concept. In order for phosphorescent concrete to be used in any real world application, these tests must be repeated using concrete.

Quantitative Compressive Strength Tests

A majority of this project focused on the adhesion of the thin phosphorescent layer to the bulk sample. Based on expert opinions, the thin layer was not believed to adversely affect the total material's compressive strength. However, before Glowcrete can be used in structural applications, the compressive strength must be verified (especially if structural failure could potentially cause bodily harm).

Durability Tests

Due to time and facility constraints on this project, only adhesion and phosphorescent properties were tested. However, Team Glowcrete strongly suggests that more work be conducted in characterizing the durability properties. Some tests include:

- Thermal shock (freeze-thaw, then compressive tests)
- Microhardness (Vicker's hardness)
- Resistance to common environments for applications (monitor weight/ thickness when reacting with sulfuric acid)

Large Scale Tests

All samples for this project have been made on a small scale. The procedures are analogous to how the material would be laid in real life on a large scale. However, time should be spent to verify that these production methods, testing procedures, and preliminary results translate to a large scale. Failure modes and effect analysis have been conducted for large scale applications (Appendix P). Therefore, these tests must also be conducted in order to verify that the failure modes can be prevented.

CONCLUSION

In eleven weeks, Team Glowcrete has made significant advances in developing methods for making and testing phosphorescent concrete. While all testing was conducted on cement, the results and methods should be analogous to those of concrete.

This study indicated that one method for creating a phosphorescent cement sample is by applying a thin layer of phosphorescent cement to the surface of a pure cement object before hardening. The glow powder added to make this phosphorescent layer was chosen to be strontium aluminate doped with europium and dysprosium, because the literature indicated that this is the brightest and longest lasting phosphor on the commercial market.

Methods were also developed to test the adhesion of the thin phosphorescent layer. While the three point bend test was inconclusive, the compression test proved to be a good measure of adhesion. A qualitative method for testing phosphorescence using photographic comparisons was developed and used. A quantitative test was also developed, and is recommended for future research.

This testing conducted on cement samples allowed for the analysis of the effects of thickness, glow powder content and water content of the thin layer. Results showed that the thickness did not change the phosphorescence of the material, because light does not penetrate deeply into the surface. The phosphorescent lifetime of these samples was also found to be very short (approximately 5 minutes) and much lower than the client's requirements for the concrete. More research should be conducted to identify a phosphorescent material with a longer glow time.

The following relationships between glow powder, water content, adhesion, and phosphorescence were also found:

- Water content does not affect the phosphorescent properties
- Optimum water content for adhesion decreases with the increase of phosphorescent powder
- Samples with a 2.5:1 glow powder ratio had the best adhesion for the water ratios tested
- Samples with 2.5:1 glow powder ratio phosphoresced more than other samples which contained either less or more glow powder

From these results, Team Glowcrete suggests that more research be conducted on this topic. The preliminary results collected should be verified, and the ratio range for glow powder and water expanded. If confirmed, experts should be consulted to help determine the cause of such relationships. These tests should also be carried out on cement, in order to prove that the results and methods are analogous. Lastly, more testing on strength, durability and large scale applications should be conducted.

Overall, the work conducted indicates that there is a possibility for the development of a phosphorescent concrete material; the methods developed were proven to work. And while the length of time that the material phosphoresced was short, the adhesion tests and phosphorescent test prove that a thin phosphorescent cement layer can be applied to cement. These results indicate that with future research, potential users such as architects, designers, and city planning councils may be able use phosphorescent concrete as a feasible construction material.

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APPENDICES

Appendix A: Project Definition

The following document is the project definition. It includes the project's mission statement, constraints, users and stakeholders, and a table of requirements and specifications.

Mission Statement

The mission of the team is to determine whether methods can be developed for making self-illuminating concrete by adhering a separate phosphorescent layer to the concrete core. This material may be used in applications such as parking garages and runways.

Constraints

- Must be more cost-efficient than normal concrete and normal lighting
- Must not inhibit structural concrete from resisting a compressive force of at least 3400 psi
- Must be safe for users to utilize the final product

Users and Stakeholders
- Qua'Virarch
- Paul Preissner
- Other architects
- Other civil engineers
- Construction companies
- Artists
- City planners
- Lighting companies

Requirements	Specifications
• Must be strong enough to use in place of normal concrete, if used structurally	• Must have at least 3400 psi of compressive resistance • Upwards of 4000-6000psi is acceptable
• The top phosphorescent layer must adhere to the concrete core	• After sample is snapped by bend test, top phosphorescent layer must still be attached concrete core • Must resist chipping of only top phosphorescent layer after compressive test with spherical indenter
• Must phosphoresce for a lengthy duration	• At least 4 hours per night • Should have lifetime of 23 years (the average lifespan of a building)

Appendix B: Summary of Cement Findings

This appendix describes an overview of what cement and concrete are.

Concrete is a composite material containing a filler and a binder. The filler consists of fine and coarse aggregates and the binder consists of cement (Figure 17). When water is added with the filler and binder, the solution undergoes hydration, causing the concrete to harden. The amount of water used in this reaction is essential because if too much water is added the strength of the concrete will reduce and if too little water is used the concrete will be unworkable.

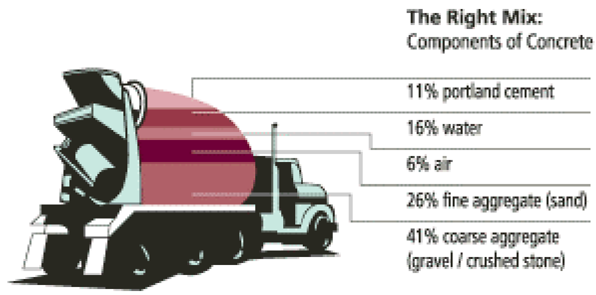


Figure 17: Components of Concrete
(Image Courtesy of Cement Association of Canada)

Concrete also contains aggregates, substances that are held together by the cement. The aggregates range from ultra-lightweight to heavyweight and can influence the density of the concrete. Admixtures are all other substances added to the concrete. These additives can have several effects such as air entraining, superplasticizers, retarding, accelerating, coloring (MAST). A phosphorescent powder additive would be considered an admixture.

Appendix C: Summary of Phosphorescent Findings

This appendix details some background information on what phosphorescence is, and materials that have phosphorescent properties.

Phosphorescence refers to the type of light emission that lasts for a relatively long time after external light has been removed. This illumination is due to substances known as phosphors. Phosphors consist of a host lattice doped with an activator ion (Phosphor Research Society). External radiation, usually in the form of light, is transmitted to the phosphor. The activator ion stores the energy and emits photons as seen in Figure 18.

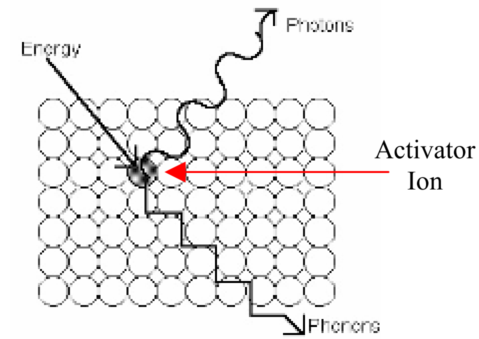


Figure 18: How Light is Emitted from a Phosphor
(Image Courtesy of McKittrick)

Within the last century, lots of research has been conducted with different substances as the activator ion. The Phosphor Handbook, compiled Table 3 shown below to depict the brightness and illumination time for several materials. Clearly, the strontium aluminate doped with europium and dysprosium surpassed all other materials in brightness as well as lasting for a long time.

Table 3: Characteristics of Common Phosphorescent Materials

Composition	Luminescence Color	Luminescence Wavelength at peak (nm)	After-glow brightness (after 10 min) (mcd m^{-2})	After-glow persistence time (min)
CaSrS:Br^{3+} (Sr,10-20%)	Blue	450	5	Semi-long (about 90)
CaAl2O4: Eu2+,Nd3+	Blue	440	35	Long (over 1000)
ZnS:Cu	Yellow-green	530	45	Semi-long (about 200)
ZnS:Cu,Co	Yellow-green	530	40	Long (over 500)
SrAl2O4:Eu2+	Green	520	30	Long (over 2000)
SrAl2O4:Eu2+, Dy3+	Green	520	400	Long (over 2000)
CaS:Eu2+,Tm3+	Red	650	1.2	Short (about 45)

Appendix D: Summary of Glow Powder Analysis

This appendix details the chemical and physical properties of the glow powder used, as well as the safety characteristics of the material.

Results of Glow Powder Analysis – Chemical and Physical Properties

Results from the analysis of the glow powder used for this investigation indicate that the powder is $SrAl_2O_4$ doped with Eu and Dy (Zaykoski). X-Ray Diffraction data supporting conclusion are found in Figure 19. It indicates that the material is mostly a strontium aluminate, with residual strontia and alumina.

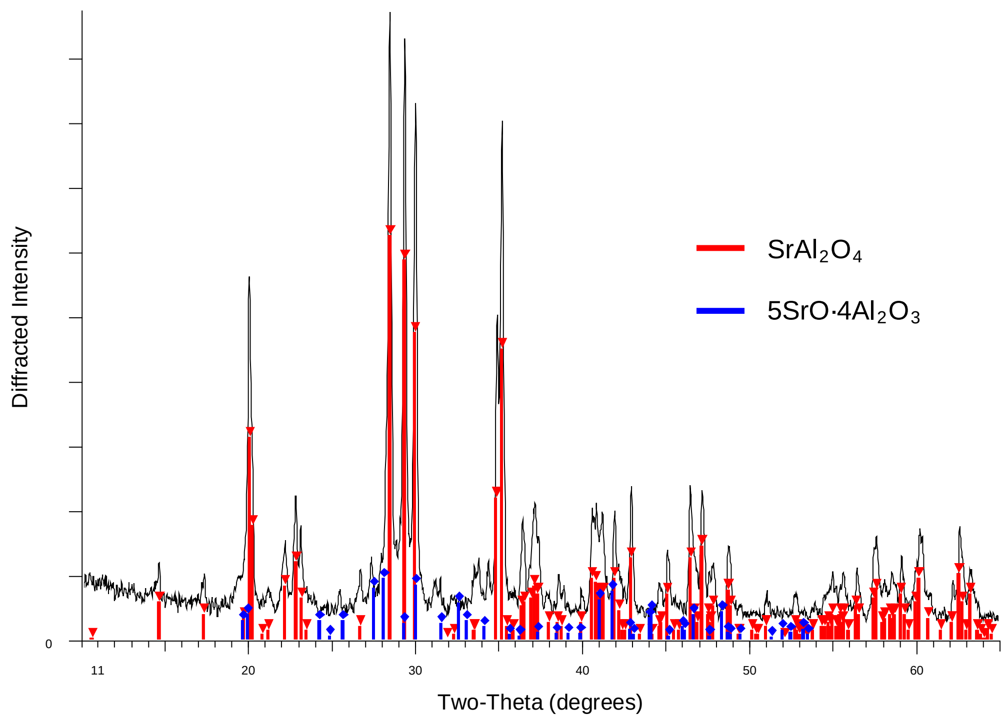


Figure 19: X-Ray Diffraction of Glow Powder Used

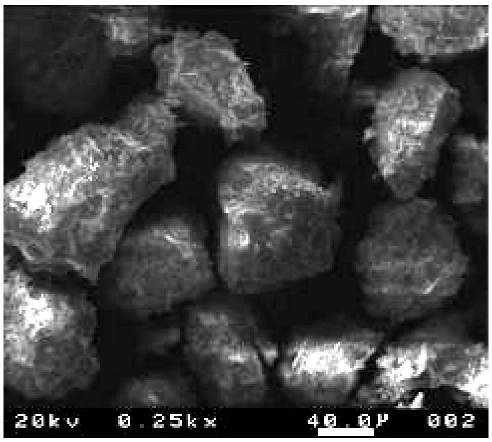
Table 4 includes the elemental composition breakdown of the material found using EDS. This analysis indicated the presence of potassium in the sample as well. This may by attributed to the "water-proof coating" that the supplier stated is present on its powder.

Table 4: Elemental Composition of Glow Powder Used

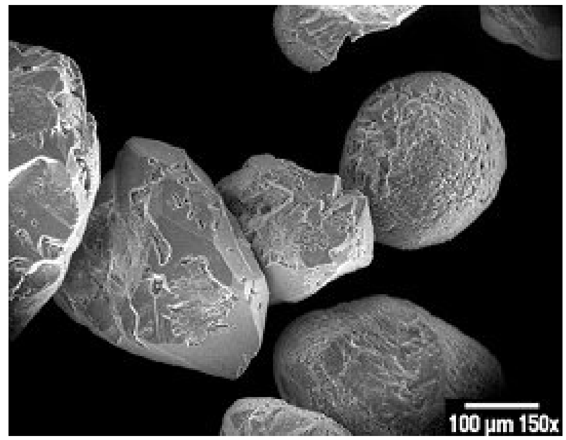
Element	Atoms%	Compound	Weight%	Error(±)	Norm%
O	42.62	O	20.08	0.09	20.08
Al	36.62	Al	29.1	0.11	29.1
K	3.24	K	3.73	0.1	3.73
Dy	0.55	Dy	2.64	0.54	2.64
Sr	16.64	Sr	42.94	0.32	42.94
Eu	0.34	Eu	1.51	0.37	1.51

The structure of the glow powder was also analyzed using an SEM (Figure 20). Conclusions from this analysis and discussion with Zaykoski include:

- average grain size of the material is 80 microns – comparable to that of sand commonly used in concrete (75-150 microns) (Cardigan)
- the shape of both particles (seen below) are similar
- this glow powder (assuming no chemical reactions) should act similarly to how sand acts as a fine aggregate in concrete



a. Micrograph of Glow Powder *
(Image Courtesy of Zaykoksi)



b. Micrograph of Sand *
(Image Courtesy of Bell)

Figure 20: SEM Micrographs Comparing the Shape of Glow Powder vs. Sand

* note: The magnification of these micrographs are different. The sand shown has a significantly larger grain size than the type of sand used in cement. These micrographs are to be used only as a comparison for particle structure/shape.

Safety of Glow Powder

The safety of the glow powder was also investigated. The MSDS sheet posted by the supplier indicates that the substance is inert and is not harmful (except for the fact that it is a small particle powder and should not be inhaled.) Furthermore, the glow powder does not degrade or polymerize into any harmful material, making it safe for users when placed in the concrete.

Identity (Trade Name):	
CAS:	Al2O3, SrCO3, Eu2O3, Dy2O3, TiO2
Chemical Family Name:	Alkaline Earth Metal Aluminate Europium Doped

This Material Safety Data Sheet (MSDS) has been preparted in compliance with the Federal OSHA Hazard Communication Standard 29 CFR 1910.1200.

This Product is considered to be a Non-Hazardous substance under that standard.

Sara 313 Title III, Toxic Substance Control Act (TSCA):
All ingredients in this product are listed on the U.S EPA TSCA inventory of chemical substances.

Section I - Contact Information

Responsible Party: Glow Inc.	Emergency and Informational Telephone Number: 410-551-4874
Address: **1539 Florida Ave.** **Severn, MD 21144**	Date Prepared: **Februrary 4, 2004**

Section II - Hazard Ingredients/Identity Information

Hazardous Components (Specific Chemical Identity; Common Name(s))	OSHA PEL	ACGIH TLV	Other Limits Recommended	%(optional)
As Inert Dust	3mg/m3	2mg/m3	n/a	n/a

Section III - Physical/Chemical Characteristics

Boiling Point	n/a	Specific Gravity (H2O = 1)	**3.0 - 3.6**
Vapor Pressure (mm Hg.)	n/a	Melting Point	**1200 C**
Vapor Density (AIR = 1)	n/a	Evaporation Rate (Butyl Acetate = 1)	n/a
Solubility in Water: **Soluble**			
Appearance and Odor: **Light green powder with no odor**			

Section IV - Fire and Explosion Hazard Data

Flash Point (Method Used): n/a	Flammable Limits: n/a	LEL: n/a	UEL: n/a
Extinguishing Media: **Water**			
Special Fire Fighting Procedures: **Fire fighters should wear self-contained breathing apparatus when fighting chemical fires.** **Use water spray to cool nearby containers and structures exposed to fire**			
Unusual Fire and Explosion Hazards: **This product will not burn easily. Use appropriate techniques to fight surrounding fire.**			

Section V - Reactivity Data

Stability: **Stable**	
Conditions to Avoid: **Contact with Acids**	
Incompatibility (Materials to Avoid): **Acids**	
Hazardous Decomposition or Byproducts: **Will not occur**	
Hazardous Polymerization: **Will not occur**	

Section VI - Health Hazard Data

Route(s) of Entry: **Inhalation, Skin and Ingestion**			
Health Hazards (Acute and Chronic): **May cause irritation to eyes, skin and mucous membranes**			
Carcinogenicity: **None**	NTP? n/a	IARC Monographs? n/a	OSHA Regulated? No
Signs and Symptoms of Exposure: **May cause irritation to eyes, skin and mucous membranes**			
Medical Conditions Generally Aggravated by Exposure: **None**			
Emergency and First Aid Procedures: **Skin: Wash off with soap and water, to wear gloves when handling.** **Eyes: Flush with water for 5 minutes.** **Inhalation: Remove to fresh air.** **Ingestion: Drink quantities of water and induce vomiting.**			

Section VII - Precautions for Safe Handling and Use

Steps to Be Taken in Case Material is Released or Spilled: **Wear appropriate protective equipment, avoid the generation of dust with vacuum or shovel. Material must be placed in closable container for disposal.**
Waste Disposal Method: **Dispose in accordance with state and local regulations.**
Precautions to Be taken in Handling and Storing: **Store closed in cool dry area.** **When handling wear protective clothing and respiratory protection.** **Avoid scatter into air.**

Other Precautions: **Maintain a schedule of regular housekeeping to insure cleanliness.**

Section VIII - Control Measures

Respiratory Proctection: Ventilation: **Local Exhausted or General Mechanical, Proper Breathing Apparatus**	
Protective Gloves: **Plastic or Neoprene**	Eye Protection: **Chemical Glasses**
Other Protective Clothing or Equipment: **Lab Coat**	
Work/Hygienic Practices: **Keep a clean work area and avoid scattering product into air**	

Appendix E: Description of Testing Methods (Three Point Bend and Compression Test)

Three-Point Bend Test

A three point bend test is a mechanical test that is traditionally used to determine the tensile strength and Young's modulus of a material. As seen in Figure 21, it causes one side of the sample to be in compression, while the other to be in tension. The test strains the sample until it breaks (EngSys).

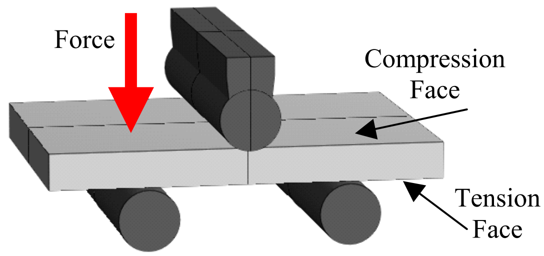


Figure 21: Diagram of Three-Point Bend Test
(Image Courtesy of Applied Research Associates and Lauren Smith)

Compression Test

A compressive test determines the behavior of materials under crushing loads, which is the type of load which concrete usually experiences. As seen in Figure 22, it causes the entire sample to be in compression, by sandwiching the sample between a moving head and a fixed head (Instron).

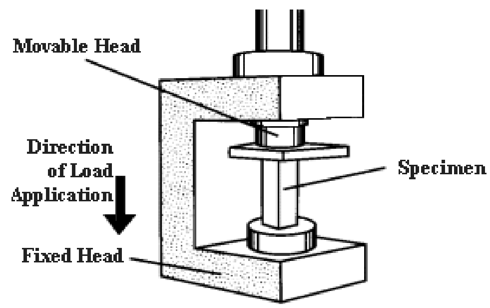


Figure 22: Diagram of Compression Test
(Image Courtesy of MatWeb)

Appendix F: Cost Analysis

Selected Cost Analyses

The following are calculations to determine the cost of adding a phosphorescent layer using a ratio of 2.5:1 of cement to glow powder, by mass, to jersey wall and sidewalk. Of special interest is the jersey wall, where phosphorescent properties could enhance road safety.

Price of glow powder in bulk

50 Pounds = \$1,905.89 → 1g = \$0.084
(Source: Glow Inc.)

Jersey Wall – 4 feet long (See Figure 23)

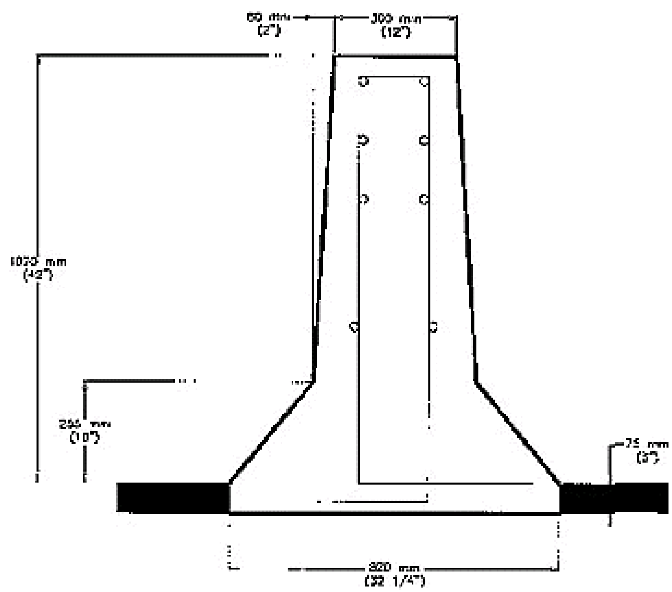


Figure 23: NJ Turnpike Authority's Heavy-Vehicle Median Barrier
(Image Courtesy of McDevitt *)*

Surface Area of both sides and top of jersey wall = 33437 cm^2
Volume of phosphorescent cement needed to coat jersey wall (with thickness .1 cm) = 3344 cm^3

Using a ratio of cement: glow powder: water
1 : .4 : .48

Density of cured Portland Cement = D_c = 1.5g/cm^3
(Source: http://www.simetric.co.uk/si_materials.htm)

Approximate Density of glow powder= D_{gp} = 3.5 g/cm^3

Density of water = D_w = 1.0 g/cm^3

Mass of cement phosphorescent cement needed to coat 4 feet of jersey wall is given by:

$$3344 \times \left(\frac{1 \times D_c}{1 + .4 + .48} + \frac{.4 \times D_{gp}}{1 + .4 + .48} + \frac{.48 \times D_w}{1 + .4 + .48} \right) = 6012\,\text{g} \qquad \text{(Eqn. 1)}$$

Mass of glow powder needed:

$$6012 \times \frac{.4}{1 + .4 + .48} = 1279\,\text{g} \qquad \text{(Eqn.2)}$$

Cost of glow powder:

$$1279\text{g} \times \frac{\$0.084}{\text{g}} = \$107.45 \qquad \text{(Eqn. 3)}$$

Additional material cost of adding a thin layer of phosphorescent cement to 4 feet of jersey wall:

$107.45

Sidewalk

Volume of phosphorescent cement to coat a 45in x 60in rectangle (with .1cm thickness) = 1742 cm^3

Mass of phosphorescent cement (analogous to Eqn. 1): = 3132 g

Mass of glow powder needed (analogous to Eqn. 2): = 666 g

Cost of glow powder (analogous to Eqn. 3): = $55.97

Additional material cost of adding a thin layer of phosphorescent cement to a 45in x 60in sidewalk rectangle:

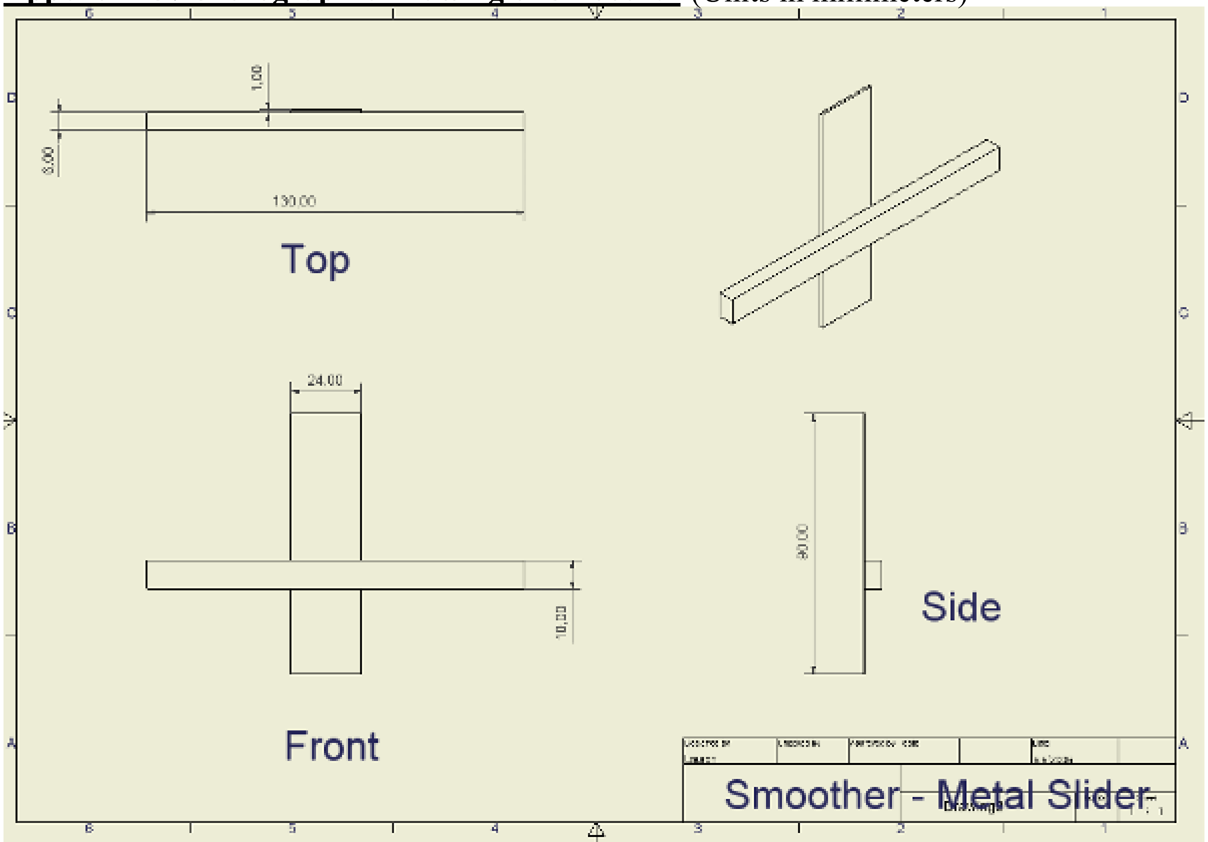
$55.97

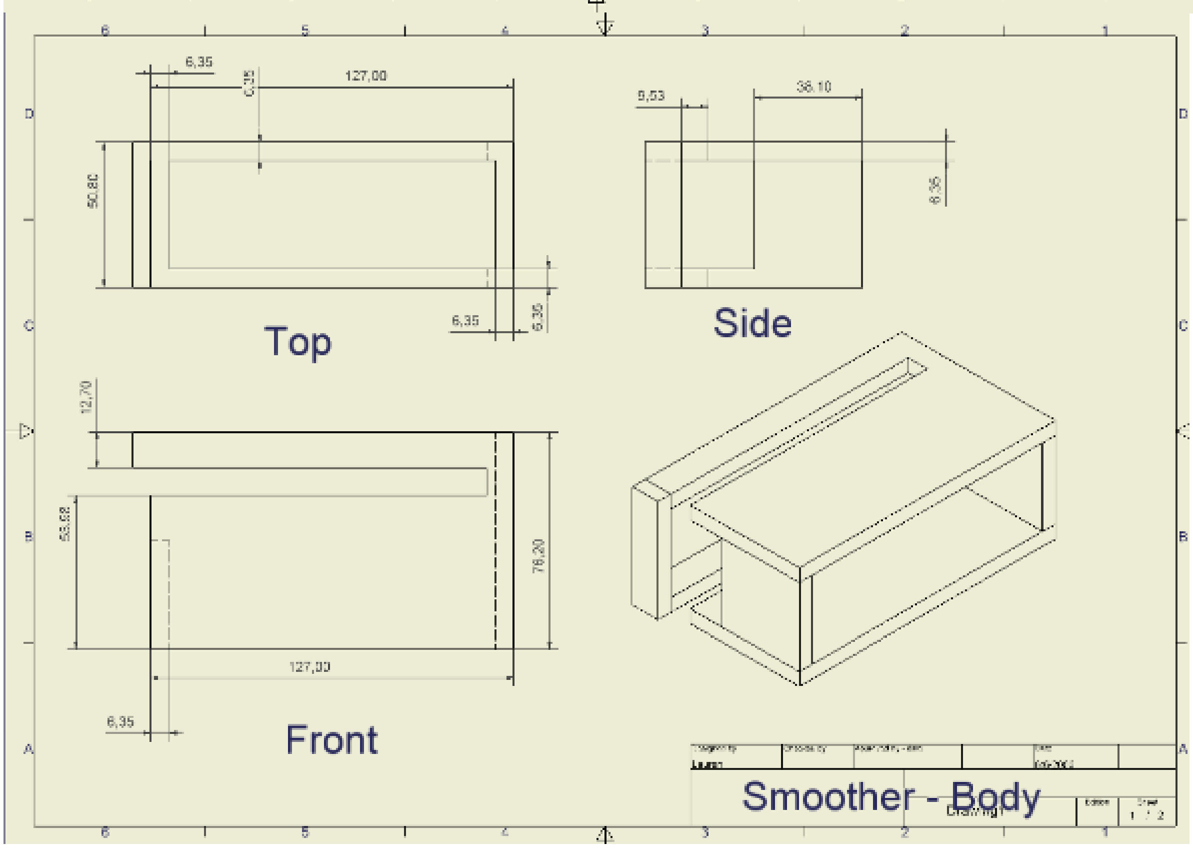
Cost of concrete for a 45in x 60in sidewalk rectangle, at $4.65/sq ft (City of Oxnard Sidewalk Repair Program):

$87.19

Therefore, the price would be increased by 56%.

Appendix G: Orthographic Drawing of Smoother (Units in millimeters)





Appendix H: Procedures for Making Thin Layer Samples

This appendix outlines the procedures used to make a thin phosphorescent layer on a cement bulk material.

Part A
Preparing the Mold

1. Put mold together.
2. Use electrical tape to tape edges.

Part B
Making a Thin Layer of Cement and Phosphorescent mixture

1. Obtain dry materials for given combination (20 g cement, X g of glow powder).
2. Mix dry materials in plastic cup.
3. Obtain amount of water needed for combination.
4. Mix contents with water in cup until consistent.
5. Add to bottom of mold.
6. Use smoother to make consistent 1 mm layer.
7. Gently bounce mold to remove air bubbles from layer.

Part C (can be completed at simultaneous to Part A in separate container)
Making Cement Mixture

1. Place cement (150 g) in cup.
2. Add 40 mL of water
3. Mix until consistent
4. Pour cement mixture on top of thin layer in mold.
5. Use straight edge to level top.
6. Gently bounce mold to remove air bubbles form layer.
7. Lightly place lid on top.
8. Wrap in wet paper towels.
9. Place samples in plastic bags.
10. Wait 8 days before proceeding to part D.

Appendix I: Qualitative Procedures for Observing Phosphorescence of Thin Layer Samples

This appendix includes the qualitative procedures used to observe the phosphorescence of samples.

Light sources used:

- white light: Phillips TLD 15W/08 bulb
- UV light: Ott-Lite 13W bulb

Charging times tested:

- 1 minute
- 10 minutes

1. Set up camera.
2. Place black cloth around camera closing off outside light.
3. Place four samples being tested under camera.
4. Discharge phosphorescent properties of four samples.
5. Turn on light source and set according to charging time.
6. Turn off light source and take a picture (without flash).
7. Take a picture every minute until samples stop phosphorescing.

Appendix J: Procedures for Quantitatively Testing Phosphorescence of Thin Layer Samples

This appendix contains the procedures to quantitatively measure the phosphorescence of samples.

Light sources used:

- white light: Phillips TLD 15W/08 bulb
- UV light: Ott-Lite 13W bulb

Charging times tested:

- 1 minute
- 10 minutes

1. Obtain light meter.
2. Leave samples in dark room to discharge samples.
3. Expose thin phosphorescent layer of cement to light for charging time.
4. Remove light and use light meter to record luminescence until luminescence terminates.
5. Normalize these values based on surface area.
6. Repeat for each sample.

Appendix K: Procedures for Testing Adhesion of Thin Layer Samples

This appendix contains the procedures used to test for the three point bend test and compression test.

1. Remove samples from molds.
2. Use sand paper to make level top.
3. Conduct three point bend test.
4. Store broken parts of each sample separately in plastic bags with CaO water.
5. Conduct compressive test.
6. Analyze broken samples under a microscope.
7. Analyze the thin layer to see if the layer adhered to the normal cement.
8. Compare to control sample.

Appendix L: Phosphorescence Testing Results

This appendix contains photographs taken for phosphorescent testing. Samples are shown as a function of glow powder composition, water composition, and time. All pictures were taken by Adrienne Smith.

For samples as a function of glow powder, the format is:
(left) 5:1, 2.5:1, 1.7:1, 1.3:1 (right)

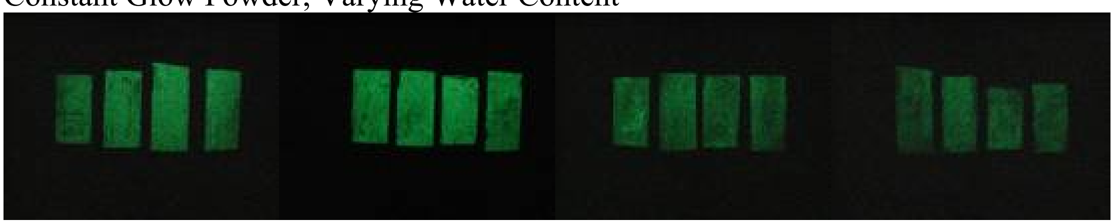
For samples as a function of water, the format is
(left) 2.4:1, 2.1:1, 1.9:1, 1.7:1 (right)

For the controls, the format is
(left) pure, 5:1 glow powder throughout (right)

Unless otherwise stated, all samples were charged for one minute.

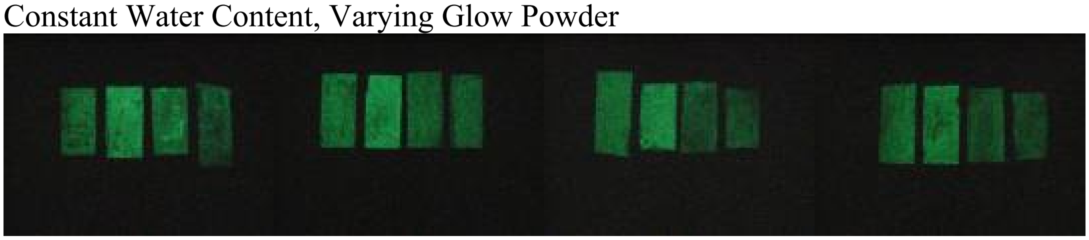
WHITE LIGHT

Constant Glow Powder, Varying Water Content



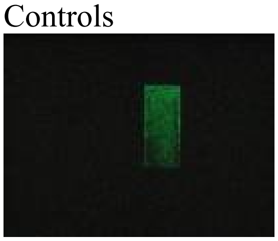
5:1 Glow | 2.5:1 Glow | 1.7:1 Glow | 1.3:1 Glow

Constant Water Content, Varying Glow Powder



2.4:1 Water | 2.1:1 Water | 1.9:1 Water | 1.7:1 Water

Controls



Pure Cement and 5:1 Glow Throughout 2:1 water

Cross Section of 2.5:1 Glow, 2.4:1 Water

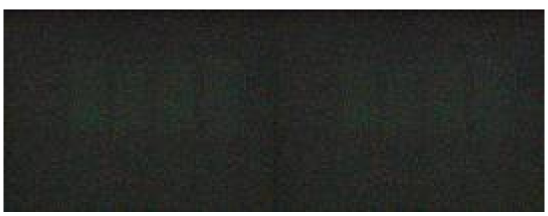
Time Elapse 1 Min Charge, Constant Glow (2.5:1), Varying Water Content

T = 0 min T = 1 min T = 2 min T = 3 min

T = 4 min T = 5 min

Time Elapse 10 Min Charge, Constant Glow (2.5:1), Varying Water Content

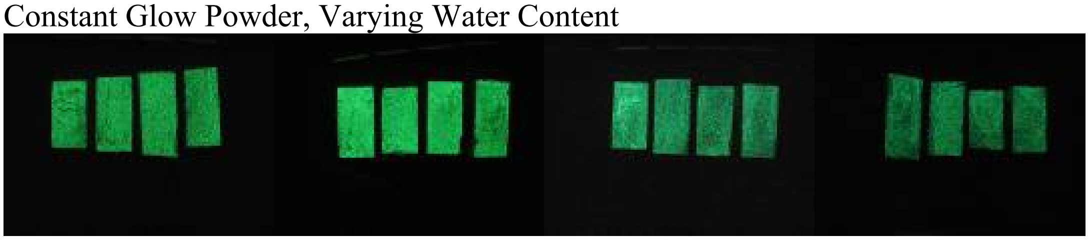
T = 0 min T = 1 min T = 2 min T = 3 min



T = 4 min T = 5 min

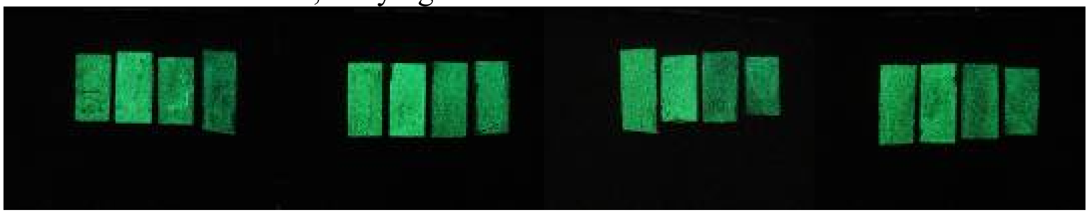
UV LIGHT

Constant Glow Powder, Varying Water Content



5:1 Glow 2.5:1 Glow 1.7:1 Glow 1.3:1 Glow

Constant Water Content, Varying Glow Powder



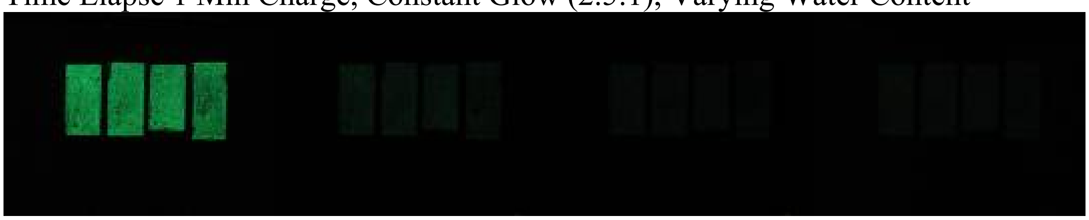
2.4:1 Water 2.1:1 Water 1.9:1 Water 1.7:1 Water

Controls

Pure Cement and 5:1 Glow Throughout 2:1 Water

Cross Section of 2.5:1 Glow, 2.4:1 Water

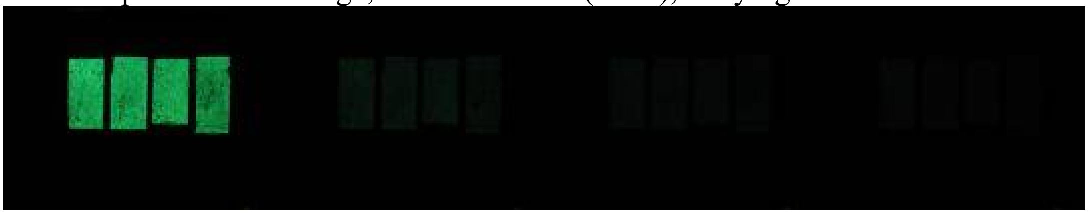
Time Elapse 1 Min Charge, Constant Glow (2.5:1), Varying Water Content



T = 0 min T = 1 min T = 2 min T = 3 min

T = 4 min T = 5 min

Time Elapse 10 Min Charge, Constant Glow (2.5:1), Varying Water Content



T = 0 min T = 1 min T = 2 min T = 3 min

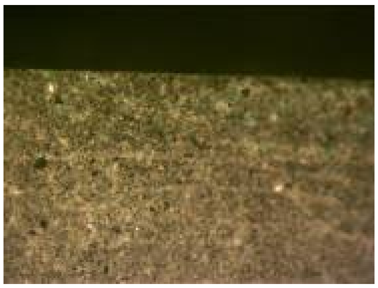
T = 4 min T = 5 min

Appendix M: Three Point Bend Test Results

This appendix contains the cross section pictures after the three point bend test of samples containing 5:1 and 1.3:1 glow powder ratios. 2.5:1 and 1.7:1 are not included because the test was removed from procedures before they were tested due to the limited timeframe for the project.


5:1 Glow Powder, 2.4:1 Water


5:1 Glow Powder, 2.1:1 Water


5:1 Glow Powder, 1.9:1 Water


5:1 Glow Powder, 1.7:1 Water


1.3:1 Glow Powder, 2.4:1 Water


1.3:1 Glow Powder, 2.1:1 Water


1.3:1 Glow Powder, 1.9:1 Water


1.3:1 Glow Powder, 1.7:1 Water

Pure Cement

5:1 Glow Powder Throughout, 2.1:1 Water

Appendix N: Compression Test Adhesion Results

This appendix contains the pictures taken after the compression test. Water and powder ratios are found below. All pictures were taken by Andy Long.

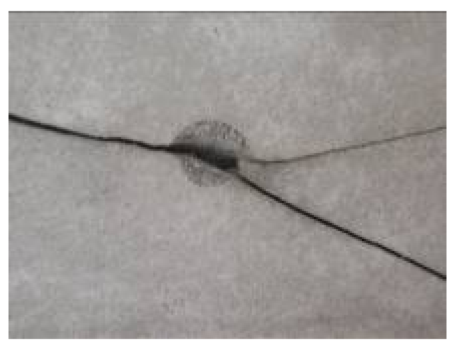
Pure Cement

5:1 Glow Powder Throughout, 2.1:1 Water

5:1 Glow Powder, 2.4:1 Water

5:1 Glow Powder, 2.1:1 Water

5:1 Glow Powder, 1.9:1 Water



5:1 Glow Powder, 1.7:1 Water

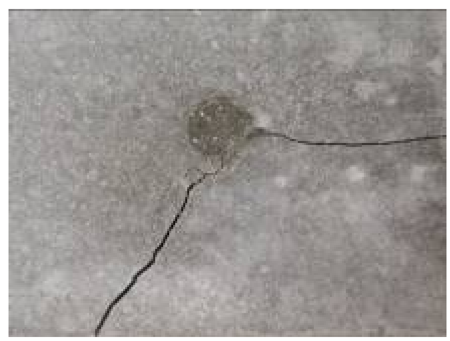

2.5:1 Glow Powder, 2.4:1 Water


2.5:1 Glow Powder, 2.1:1 Water


2.5:1 Glow Powder, 1.9:1 Water


2.5:1 Glow Powder, 1.7:1 Water


1.7:1 Glow Powder, 2.4:1 Water


1.7:1 Glow Powder, 2.1:1 Water


1.7:1 Glow Powder, 1.9:1 Water


1.7:1 Glow Powder, 1.7:1 Water


1.3:1 Glow Powder, 2.4:1 Water


1.3:1 Glow Powder, 2.1:1 Water


1.3:1 Glow Powder, 1.9:1 Water


1.3:1 Glow Powder, 1.7:1 Water

Appendix O: Qualitative Procedure Used to Determine Adhesion form Compression Tests

This appendix contains the methods and results for determining the adhesive properties from pictures taken after the compression test. All water and powder ratios are found below.

Methods: The pictures were observed qualitatively, along the following guidelines: 1-10 very poor adhesion, 11-24 poor adhesion, 25-30 good adhesion (Table 5)

Table 5: Criteria Used for Evaluating the Results from the Compression Test

Caused by Poor Adhesion	Ranking
Creator Shape	1-3: Triangular, extremely misshapen 4-6: Moderately misshapen, but still round 7-10: Very round, size of indenter
Flaking Off	1-3: Layer is flaking off 4-6: Layer is cracked and can be forced to flake off 7-10: Layer is not flaking
Crack Propagation	1-3: Relatively large 4-6: Medium 7-10: Relatively small

The percentage of distortion around the creator caused by the indenter was also measured. The percentage increase from the original indenter creator was measured and included in the qualitative analysis (Table 6).

Table 6: Measurements of Distortion around Indenter for Compression Test

Glow Powder Ratio	Water Ratio	Percentage Increase Due to Cracking/Flaking
5:1	2.4:1	50%
5:1	2.1:1	0%
5:1	1.9:1	0%
5:1	1.7:1	0%
2.5:1	2.4:1	0%
2.5:1	2.1:1	0%
2.5:1	1.9:1	0%
2.5:1	1.7:1	0%
1.7:1	2.4:1	0%
1.7:1	2.1:1	56%
1.7:1	1.9:1	71%
1.7:1	1.7:1	100%
1.3:1	2.4:1	0%
1.3:1	2.1:1	20%
1.3:1	1.9:1	108%
1.3:1	1.7:1	275%
Pure Cement	2.1:1	0%
Glow Powder Throughout	2.1:1	0%

Appendix P: Failure Modes and Effect Analysis

This appendix explains some errors in testing and failure modes about the Glowcrete design. Future testing would be required to determine the frequency at which many of these failures may occur.

Failure Modes of the Testing Procedures

Errors During Testing of Thin Layer

- Glow powder not evenly dispersed throughout sample
    - Cause: cement and glow powder may not have been mixed thoroughly
    - Effect: phosphorescence would not be consistent across thin layer
    - Detection: if there is uneven light emission, the cement and glow powder were probably not mixed thoroughly
    - Solution: when making samples, mix cement and glow powder thoroughly until mixture is homogenous
- Bulk cement may have seeped into layer
    - Cause: if the phosphorescent thin layer had a low viscosity, the bulk cement material may have seeped into layer
    - Effect: adhesion properties would be incorrect and the bulk cement may reach bottom, blocking phosphorescent powder
    - Detection: no visible layer when UV light is shined on it
    - Solution: test wide range of water amounts, in order to find optimum water content
- Measuring errors
    - Cause: weighing scale may have calibrated incorrectly
    - Effect: adhesion and phosphorescent properties may be incorrect
    - Detection: results appear to be inconsistent when variables held constant
    - Solution: use more than one scale to ensure correct measurements
- Bubbles
    - Cause: air pockets in cement when setting
    - Effect: sample has weaker strength
    - Detection: when testing, bubbles can be seen after sample is broken
    - Solution: vibrate sample when cement is wet to force air bubbles out
- Waiting too long between layer and bulk
    - Cause: delays in smoothing layer or laying bulk cement
    - Effect: thin layer may start hardening and have weaker adhesion with bulk cement
    - Detection: unable to detect
    - Solution: work quickly and with more than one person when laying samples

Possible Failure Modes of Glowcrete when Used on a Large Scale

Failure Mode	**Failure Cause**	**Failure Effect**	**Failure Detection**	**Severity***	**Action**
Chips off	Poor adhesion	Thin layer falls off	No glowing on surface	3	More tests for better adhesion
Structurally unsound	Poor cement	Weak samples	Test various types of cement	4	Use strongest cement
Temporary no glow	No light to layer	No glow	No glow	2	Additional lighting should be provided
Glowing of layer gradually wears off	Weak phospho rescent property	No glow	Determine light intensity as function of time	2	Research for better glow powder; recharge layer with external lighting

*Severity
1 = mild annoyance, but does not compromise the function of material (glowing or structure)
2 = minimal detrimental effects on phosphorescent properties
3 = serious failure; compromises phosphorescent properties
4 = serious failure; compromises structural integrity possibly leading to human injury