DEVELOPMENT OF A LOW-COST CONDUCTIVE MEASUREMENT TECHNIQUE TO AUGMENT OBJECTIVE METHODS FOR DAMAGE DETECTION IN CONCRETE PAVEMENTS

FINAL PROJECT REPORT

by

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Detection of degradation has the potential to improve the long-term performance and integrity of concrete pavements and structures. Conductive surface sensors have been shown to be effective and adaptable when used as part of crack detection systems. This paper mainly concerns the use of conductive paints as conductive surface sensors, but the capabilities of other conductive materials used as conductive surface sensors are discussed. The impact of environmental effects on conductive surface sensors must be known if these sensors will be used on pavements or structures exposed to environmental changes. This paper presents two experiments used to evaluate the effects of temperature and relative humidity on the behavior of a silver-based conductive paint and a more economical nickel-based conductive paint. Environmental effects on sensitivity to cracking and resistance are evaluated. A third experiment is presented that considers different patterns of conductive paint for use in crack localization applications. The results show that the nickel-based and silver-based conductive paints perform comparably at detecting cracking and can be used over a range of temperature and relative humidity conditions. The patterns evaluated were shown to be effective at localizing cracking over an area, which is promising for application of this technology.</td></tr>
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List of Abbreviations

CHPP: Center of Highway Pavement Preservation
EIT: Electrical Impedence Tomography
LVDT: Linear Differential Variable Transformer
MnDOT: Minnesota Department of Transportation
RFID: Radio Frequency Identification

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Executive Summary

Concrete cracking due to routine deterioration from age or significant loading has the potential to accelerate degradation and shorten the service life. Surface cracking allows water and other undesirable agents to more easily permeate the concrete. Detection of concrete cracking can localize areas of concern and allow for more focused inspection and repair. Concrete pavements are typically susceptible to small surface cracks, cover a large region, and are subjected to variable environmental conditions, which can make monitoring challenging.

Of numerous concrete detection strategies, conductive surface sensors have been shown to reliably detect the formation of smaller cracks. Conductive surface sensors leverage conductive materials applied to the concrete surface to detect cracking by relating their resistance to the presence of a crack. Many existing studies have investigated conductive surface sensors as linear strips or sensing skins. Linear strips provide a simple and effective method of crack detection. The binary nature of the large increase of resistance at cracking leads to a sensor output that is easy to interpret and makes it easy to identify the presence of cracking. On the other hand, two-dimensional sensing skins allow for detailed spatial evaluation of damage to the concrete pavement. However, increased complexity of the sensor and post-processing of the measurements coincides with this increase in resolution.

If conductive surface sensors will be used on large pavements or structures exposed to environmental changes, a robust approach to crack localization and understanding of the impacts of environmental effects on these sensors is required. The lack of research on environmental effects on conductive surface sensors leave several open questions regarding their application. This study aims to identify the impact of environmental conditions, particularly temperature and relative humidity changes, on the sensitivity and effectiveness of conductive surface sensors.

Additionally, to make the surface sensors more robust to changes and viable over large-scale areas, a conductive surface sensor that is both simple and able to localize cracks for further inspection is investigated.

Three experiments are conducted to examine the use of patterned linear conductive strips under variable environmental conditions. Experiments #1 and #2 are used to evaluate the effects of temperature, relative humidity, paint strip width, and paint type on the behavior of conductive paints used as conductive surface sensors. Experiment #3 evaluates the crack localization abilities of various patterns of linear strips of conductive paint. This experiment tests four larger reinforced concrete beams loaded in four-point bending to evaluate how well different patterns of linear strips of conductive surface sensors can localize concrete cracking.

The patterns of linear strips of conductive paint used in this paper can localize cracking to a given area of concrete. Patterns of linear strips maintain the simplicity of taking only resistance measurements to detect cracking, while introducing the potential for crack localization reminiscent of two-dimensional sensing skins. The binary nature of the patterns avoided the noise and variability in sensitivity introduced by humidity and temperature change, respectively. As seen with the four patterns in this study, a more tightly spaced pattern provides greater potential for crack localization, but with the cost of more instrumentation being required to monitor the pattern.

The crack identification technique developed in this study could allow for the identification of areas of interest over a large region, which could enable more focused inspection work. The crack localization capabilities and simplicity of the patterns used in this study, along with the potential for integration with RFID technology, are promising for concrete pavement crack detection applications.

CHAPTER 1 - INTRODUCTION

Surface sensors have potential in the evaluation of concrete elements to augment visual inspections and structural health monitoring. When paired with wireless technology, concealed structural members can be evaluated for damage after seismic events or deterioration due to age. In addition to detecting significant structural cracking, such as spalling, surface sensors can be used to reliably detect the formation of smaller cracks. Smaller cracking, which is also known as surface cracking, in concrete allows water and salts to more easily permeate and potentially accelerate deterioration of the concrete structure.

Conductive materials applied to the surface of concrete pavements or structures, commonly referred to as conductive surface sensors, can be used to detect surface cracking by relating their resistance to the presence of a crack. When a crack forms in the concrete substrate, the conductive surface sensor is strained and eventually cracks as well, resulting in a permanent increase in the sensor's resistance by several orders of magnitude. Detecting and localizing concrete surface cracking using conductive surface sensors can potentially extend the service life of concrete by allowing for more focused inspection and repair work.

The experimental research presented in this study focuses on the use of conductive paints as conductive surface sensors. Many existing studies using conductive paints as conductive surface sensors apply the paint as linear strips. Linear strips of paint provide a simple and effective method of crack detection, as the formation of a crack can be related to an increase of several orders of magnitude in the resistance of the sensor. This characteristic large resistance increase essentially reduces resistance measurement to either a continuous or non-continuous circuit. This binary state of sensor resistance leads to sensor output that is easy to interpret and consequently makes it easy to identify the presence of cracking. In contrast to linear strips of conductive surface sensors, more sophisticated two-dimensional sensing skins have been used for crack detection in concrete. The skins allow for detailed spatial evaluation of damage of concrete. However, increased complexity of the sensor and post-processing of the measurements coincide with this increase in resolution.

If conductive surface sensors will be used on large pavements or structures exposed to environmental changes, a simple approach to crack localization and an understanding of the impacts of environmental effects on these sensors is required. There is presently no research addressing environmental effects on conductive paints used as conductive surface sensors. Three experiments are conducted to examine the use of patterned linear conductive strips under variable environmental conditions. Experiments #1 and #2 are used to evaluate the effects of temperature, relative humidity, paint strip width and paint type on the behavior of conductive paints used as conductive surface sensors. In addition to frequently researched silver-based conductive paint, a more economical nickel-based conductive paint is examined in experiments #1 and #2 to determine how it performs compared to silver-based conductive paint. Experiment #1 tests reinforced concrete beams instrumented with strips of conductive paint of different widths. The beams are loaded in three-point bending at temperatures ranging from -10°C to +20°C to evaluate the crack width sensitivity of the various strips of paint. Experiment #2 evaluates the effects of temperature and relative humidity on the resistance of conductive paints applied to concrete, when the concrete substrate is not experiencing cracking. Changes to the resistance of a conductive surface sensor can potentially indicate the presence of a crack, so it is important to determine environmental effects on resistance to avoid false positive indications of cracking. Experiment #3 evaluates the crack localization abilities of various patterns of linear strips of conductive paint. This experiment tests four larger reinforced concrete beams loaded in four-point bending to evaluate how well different patterns of linear strips of conductive surface sensors can localize concrete cracking. Using patterns consisting of linear strips of conductive surface sensors maintains the simplicity of linear strips, while introducing the potential for crack localization that is reminiscent of more sophisticated two-dimensional sensing skins. While these patterns likely do not have the potential for as detailed damage evaluation as two-dimensional sensing skins, the simplicity of the characteristic binary resistance output and easier instrumentation makes them appealing for large-scale applications.

1.1 OUTLINE OF REPORT

The report is structured as follows:

- Chapter 2 presents the relevant literature on conductive surface sensors. Different materials, surface sensor types, and interrogation methods are addressed.
- Chapter 3 details the three experimental setups. The conductive paints, concrete mixes, and specimen designs are outlined. The testing setup and protocol for each experiment is provided.
- Chapter 4 provides the results of the three experiments and presents an initial discussion of the findings.
- Chapter 5 discusses the implications of the results from the experiments, in particular (1) conductive strip width and material, (2) environmental effects on the resistance measurements, and (3) crack localization.
- Chapter 6 summarizes the conclusions of the work and outlines recommendations for future technology transfer.

CHAPTER 2 - LITERATURE REVIEW

The detection of concrete cracking can be used to identify safety hazards and potentially extend the service life of concrete systems by allowing for focused repair work. Surface cracking of the scale of millimeters or smaller is of particular interest. Small surface cracking in concrete allows water and other undesirable agents to more easily permeate the concrete and potentially accelerate deterioration of the concrete structure (Akhavan et al. 2012; Pour-Ghaz et al. 2009; Pourasee et al. 2011; Reinhardt and Jooss 2003; Wang et al. 1997). This chapter outlines relevant research on the application of conductive sensing skins to identify concrete cracking, particularly small surface cracks.

2.1 EFFECTIVENESS OF CONDUCTIVE SENSING SKINS

Conductive surface sensors have the potential to capture both larger scale cracking and small surface cracks. When paired with wireless technology, conductive surface sensors can be used to evaluate concrete structural elements even when they are concealed by other materials (Kõrbe Kaare et al. 2012; Morita and Noguchi 2008; Pour-Ghaz et al. 2014). This wireless interrogation of sensors on concealed concrete structural elements could allow for damage evaluation after seismic or other severe events (Kim et al. 2010; Morita and Noguchi 2008; Pour-Ghaz et al. 2011a). In addition to detecting significant structural cracking, conductive surface sensors can be used to reliably detect the formation of smaller cracks, less than 0.2 mm (0.008 in.) in width (Pour-Ghaz et al. 2014; Pour-Ghaz et al. 2011c; Raoufi et al. 2011).

The research in this study focuses on the use of conductive paints as surface sensors. The crack detection abilities of linear strips of conductive paints have been shown by several researchers and compare favorably to other crack detection techniques. Pour-Ghaz and Weiss (2011a) applied silver-based conductive paint to restrained ring and restrained base specimens and identified the time and location of shrinkage cracking; they additionally introduced a frequency bifurcation model for detecting the formation of multiple cracks. Pour-Ghaz et al. (2011b; c) instrumented restrained ring specimens with silver-based conductive paint, strain gauges and acoustic emission sensors, with the three techniques detecting the formation of visible cracking comparably. Raoufi et al. (2011) analyzed restrained base concrete specimens with silver-based conductive paint, image analysis, and acoustic emission sensors, concluding that the conductive paint detected visible cracking comparably to the image analysis, but acoustic emission sensors could identify damage before it became visible.

2.2 STYLE OF SENSING SKINS

Many existing studies using conductive paints as conductive surface sensors apply the paint as linear strips. Linear strips of paint provide a simple and effective method of crack detection, as the formation of a crack can be related to an increase of several orders of magnitude in the resistance of the sensor (Morita and Noguchi 2008; Pour-Ghaz and Weiss 2011a; Pour-Ghaz et al. 2011b,c). The binary state of the sensor output makes it easy to interpret but can limit the resolution of the identified surface cracking.

In contrast to linear strips of conductive surface sensors, more sophisticated two-dimensional sensing skins have been used for crack detection in concrete. Hallaji et al. (2014) used copper-based conductive paints in electrical impedence tomography (EIT)-based sensing skins for detailed two-dimensional spatial evaluation of damage in concrete. EIT-based sensing skins made of carbon nanotubes have also been used effectively for two-dimensional evaluation of damage when applied to the surface of cementitious materials (Hou et al. 2007; Loh et al. 2007, 2008, 2009). Schumacher and Thostenson (2014) used a sensing skin made of carbon nanotubes and related the changes in areal resistance of the sensing skin to the strain, displacement and cracking of a concrete beam under loading.

Existing studies of conductive sensing skins have leveraged many conductive materials, including copper, silver, carbon nanotubes, and carbon black. Of the conductive paints, silver-based conductive paints have been shown to be particularly effective at detecting surface cracking in concrete (Pour-ghaz et al. 2014; Pour-Ghaz et al. 2011b; c; Pour-Ghaz and Weiss 2011a; Raoufi et al. 2011). Morita and Noguchi (2008) showed that silver-based conductive paint applied directly to concrete is more sensitive to cracking compared to conductive paint applied on printed adhesive sheets, they also showed that wider strips of conductive paint on adhesive sheets likely result in less crack sensitivity. Therefore, silver conductive paint is one of the main focuses for this study.

2.3 SURFACE SENSOR INTERROGATION

Beyond traditional resistance measures, techniques have been proposed for wireless and simultaneous interrogation of numerous conductive surface sensors, with promising results for application of these sensors. Pour-Ghaz and Weiss (2011b) developed a frequency selective circuit that allows for rapid and simultaneous interrogation of multiple conductive surface sensors. Pour-Ghaz et al. (2014) used radio frequency identification (RFID) technology to monitor restrained ring specimens instrumented with silver-based conductive paint, concluding that RFID technology is capable of wirelessly detecting time of cracking and could potentially be used to monitor crack width as well.

2.4 KNOWLEDGE GAPS

Despite the quantity of existing research on conductive surface sensors, several key questions remain. First, how will the environment, particularly temperature and relative humidity, impact the sensitivity and effectiveness of conductive surface sensors? Second, is there a conductive paint that might be more effective under varying environmental conditions? There is presently no research addressing environmental effects on conductive paints used as conductive surface sensors. The environmental impacts will likely make two-dimensional skins less effective. As a result, a conductive surface sensor based on a simpler binary approach is desirable. So, third, can conductive paint strips be patterned to combine crack localization with the simplicity of linear strips?

CHAPTER 3 - MATERIALS, INSTRUMENTATION, AND EXPERIMENTS

This section outlines the conductive paints and their implementation as surface sensors. Three experiments are conducted to address sensitivity, environmental hardening, and crack localization. The setups and instrumentation are presented for each experiment.

3.1 MATERIALS AND SPECIMENS

3.1.1 Conductive Surface Sensors

Silver-based and nickel-based conductive paints are used as conductive surface sensors for the experiments performed. Appendix A provides commentary on other conductive materials that were considered as conductive surface sensors. The silver-based and nickel-based conductive paints have a similar composition, both being approximately 50% metal flakes by weight. However, the resistivity of the silver-based paint is approximately five percent that of the nickel-based paint. The nickel-based conductive paint is more economical than the silver-based conductive paint. The paints are applied in linear strips directly to the surface of concrete specimens, with strip widths of 2 mm (0.079 in.), 4 mm (0.16 in.), or 6 mm (0.24 in.). The paints are applied in a single layer with a thin paint brush by the same operator for every specimen, leading to relatively consistent layer thickness between all strips of paint. Multimeters are used to measure the resistances of individual paint strips during experiments. Wires are attached to the strips of conductive paint using conductive epoxy to ensure consistent and reliable connections to the multimeters. When cracking occurs and a paint strip fractures, the resistance of the individual strip increases by several orders of magnitude, essentially reducing the measurement of resistance to a measurement of circuit continuity. The stark contrast between resistances leads to easy interpretation of data, with the high and low resistance states directly corresponding to the presence or absence of a crack. It has been shown that there is an increase in resistance just prior to cracking (Morita and Noguchi 2008; Raoufi et al. 2011), but this small resistance increase is more difficult to measure and less definitive compared to the large resistance increase due to cracking.

3.1.2 Concrete Beam and Slab Specimens

Eighteen reinforced concrete beams, one unreinforced concrete slab, and four larger reinforced concrete beams are used in the three experiments presented in this paper. The eighteen reinforced concrete beams used in Experiment #1 each measure 40.6 cm (16 in.) long, 7.6 cm (3 in.) wide, and 10.2 cm (4 in.) deep. A single piece of no. 3 rebar is placed in each beam at a depth of 6.35 cm (2.5 in.) from the top surface. The reinforcement allows for the formation of flexural cracks in the beams. The unreinforced concrete slab used in Experiment #2 measures 33 cm (13 in.) long, 22.9 cm (9 in.) wide, and 8.9 cm (3.5 in.) deep. An identical concrete mix design is used for all specimens in Experiments #1 and #2, with a maximum aggregate size of 1.27 cm (0.5 in.) and an average 28-day compressive strength of 31 MPa (4500 psi). The four reinforced concrete beams used in experiment #3 measure 76.2 cm (30 in.) long, 25.4 cm (10 in.) wide, and 8.9 cm (3.5 in.) deep. Three pieces of no. 3 rebar are placed in each beam, with center-on-center spacing of 6.4 cm (2.5 in.) and depth of 5.7 cm (2.25 in.) from the top surface. The reinforcement allows for the formation of flexural cracks in the beams. The concrete mix design used for the beams in Experiment #3 is representative of a MnDOT, high-strength concrete pavement mix, with a maximum aggregate size of 2.5 cm (1 in.) and an average 28-day compressive strength of 46 MPa (6600 psi).

3.2 EXPERIMENT #1 – BEAM TESTS FOR CRACK WIDTH SENSITIVITY

Experiment #1 evaluates the effect of paint type, temperature, and paint strip width on the sensitivity of conductive paints to crack width when used as conductive surface sensors. The paint types considered are a nickel-based and silver-based conductive paint. These paints are applied in linear strips of 17.8 cm (7 in.) length to the bottom surface of the concrete beam specimens, using a small paintbrush. The strips are applied in widths of 2 mm (0.079 in.), 4 mm (0.16 in.), and 6 mm (0.24 in.). The average thickness of the 108 paint strips used in this experiment is estimated as 35 µm (0.0014 in.) with a standard deviation of 4 µm (0.00016 in.). Thickness is estimated using the resistances of the strips, the volume resistivity of the two paint types, and the geometry of the strips. Eighteen concrete beams are tested, each has six strips of conductive paint applied to its bottom surface. Of the six strips of paint, there are two strips for each paint strip width, one of which is nickel-based conductive paint and one of which is silver-based conductive paint. The six paint strips are applied in different location order for each specimen to avoid any bias related to a specific strip position; Figure 3-1 shows one of the concrete beam specimens with paint strips applied. Wires are attached to the ends of the strips of conductive paint using conductive epoxy, to allow the resistances of the paint strips to be measured consistently.

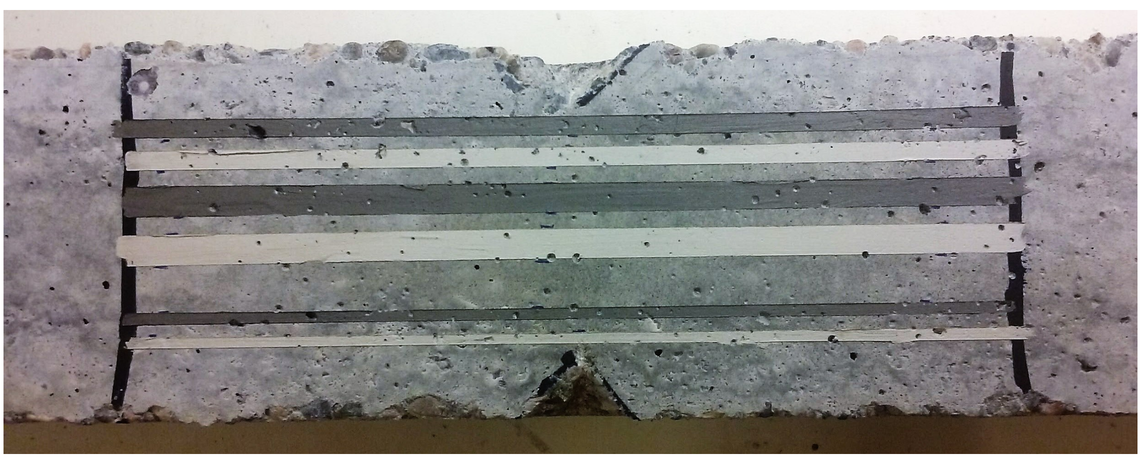

Figure 3-1 Experiment #1 concrete beam specimen with conductive paint strips applied

The concrete beam specimens are loaded in three-point bending to induce a flexural crack on the bottom surface of the beams, crossing the strips of conductive paint. Loading is applied at a rate of approximately 45 N (10 lbF) per second. The concrete beams are notched prior to loading to facilitate the formation of a single flexural crack at the beam midspan, these notches are visible in Figure 3-1. During loading, the extension of the bottom surface of the concrete beam is measured using a gage head linear variable differential transformer (LVDT) attached with nonconductive epoxy to the side surface of the beam. Figure 3-2 shows the geometry of the three-point bending test and the placement of the gage head LVDT. The resistances of the six strips of conductive paint are monitored individually during loading, using multimeters. When an individual strip of paint experiences a large resistance increase due to concrete cracking, it is related to the LVDT measurement to determine the extension when the paint strip cracked.

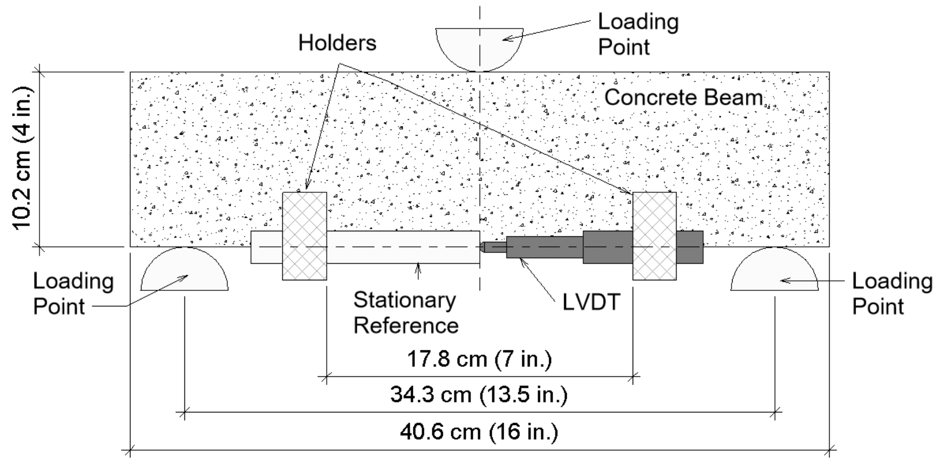

Figure 3-2 Experiment #1 three-point bending test and instrumentation

The 18 beam tests are performed at temperature levels of +20°C, +5°C, and -10°C, with six beams tested at each temperature level. To achieve these temperature levels, the concrete beams are stored in a temperature-controlled chamber for 24 hours prior to testing. While 24 hours is typically not enough time for concrete to fully equilibrate to a temperature level (Andrade et al. 1999; Kallel et al. 2017), the duration is adequate for the conductive paint strips applied to the surface of the concrete beams to reach the desired temperature levels.

Regarding the extension measurements for this experiment, the gage head LVDT measures extension across 17.8 cm (7 in.) of the bottom surface, not just at the location of cracking. The extension measurements include both the crack width and any elongation of the bottom concrete surface over the length monitored. While the extension measurements are not equal to crack width, the consistency of the instrumentation and concrete across all 18 tests allows for crack width sensitivity trends relating to paint type, temperature and paint strip width to be identified.

3.3 EXPERIMENT #2 – ENVIRONMENTAL EFFECTS ON THE RESISTANCE OF CONDUCTIVE PAINTS

Experiment #2 is used to evaluate how temperature and relative humidity affect the resistance of conductive paints applied directly to concrete, when no cracking is present in the concrete substrate. The same nickel-based and silver-based conductive paints used in Experiment #1 are applied to an unreinforced concrete slab that is exposed to various temperature and relative humidity conditions. The environmental conditions are achieved by placing the slab in a temperature controlled and relative-humidity controlled chamber. Six strips of conductive paint are applied to the slab, each measuring 50 cm (19.7 in.) in length. Three strips each of nickel-based and silver-based conductive paint are applied, with both sets of three strips having widths of 2 mm (0.079 in.), 4 mm (0.16 in.), and 6 mm (0.24 in.). Wires are attached to the ends of the strips of conductive paint using conductive epoxy, to allow the resistances of the paint strips to be measured consistently using a multimeter.

For the first phase of this experiment, the slab is exposed to a constant temperature of 20°C while the relative humidity is set to values between 25% and 85%. Resistance measurements for each strip of conductive paint are taken at each relative humidity level, after the slab has been exposed to the environmental conditions for 72 hours. For the second phase of this experiment, the slab is exposed to a constant relative humidity of 50% while the temperature is set to values between 5°C and 30°C. Resistance measurements for each strip of conductive paint are taken at each temperature level, after the slab has been exposed to the environmental conditions for 72 hours. Similar to Experiment #1, the concrete may take longer than 72 hours to fully equilibrate to a given relative humidity or temperature level (Andrade et al. 1999; Kallel et al. 2017). However, the duration is adequate for the conductive paint strips applied to the surface of the concrete beams to reach the desired temperature and relative humidity levels.

3.4 EXPERIMENT #3 – CRACK LOCALIZATION USING CONDUCTIVE SURFACE SENSOR PATTERNS

Experiment #3 is used to evaluate the crack localization capabilities of four different patterns of linear strips of conductive surface sensors. The four patterns are shown in Figure 3-3. The patterns are applied using the same silver-based conductive paint as used in Experiments #1 and #2, with paint strip width of 2 mm (0.079 in.). Sections of the patterns form closed circuits over which resistances are measured. The points where resistance measurements are taken for each pattern are labeled with numbers in Figure 3-3. Patterns A, B, and C work under the principle that when a section of the pattern experiences a large resistance increase, a crack has formed in the area covered by that section of the pattern. This provides a simple method to localize a crack to a given section of a pattern. Pattern D is a more sophisticated grid pattern that could potentially localize cracks more precisely, by taking advantage of intersecting lines of the pattern that have both experienced large resistance increases. To facilitate intersecting lines in pattern D, non-conductive spacers are required between intersecting conductive paint lines. Each of the four patterns covers the same 25.4 cm (10 in.) by 20.3 cm (8 in.) rectangular area, but require different amounts of instrumentation, and have different gaps where a crack could potentially form undetected. The benefits and limitations of each pattern are discussed more thoroughly when analyzing the experimental results.

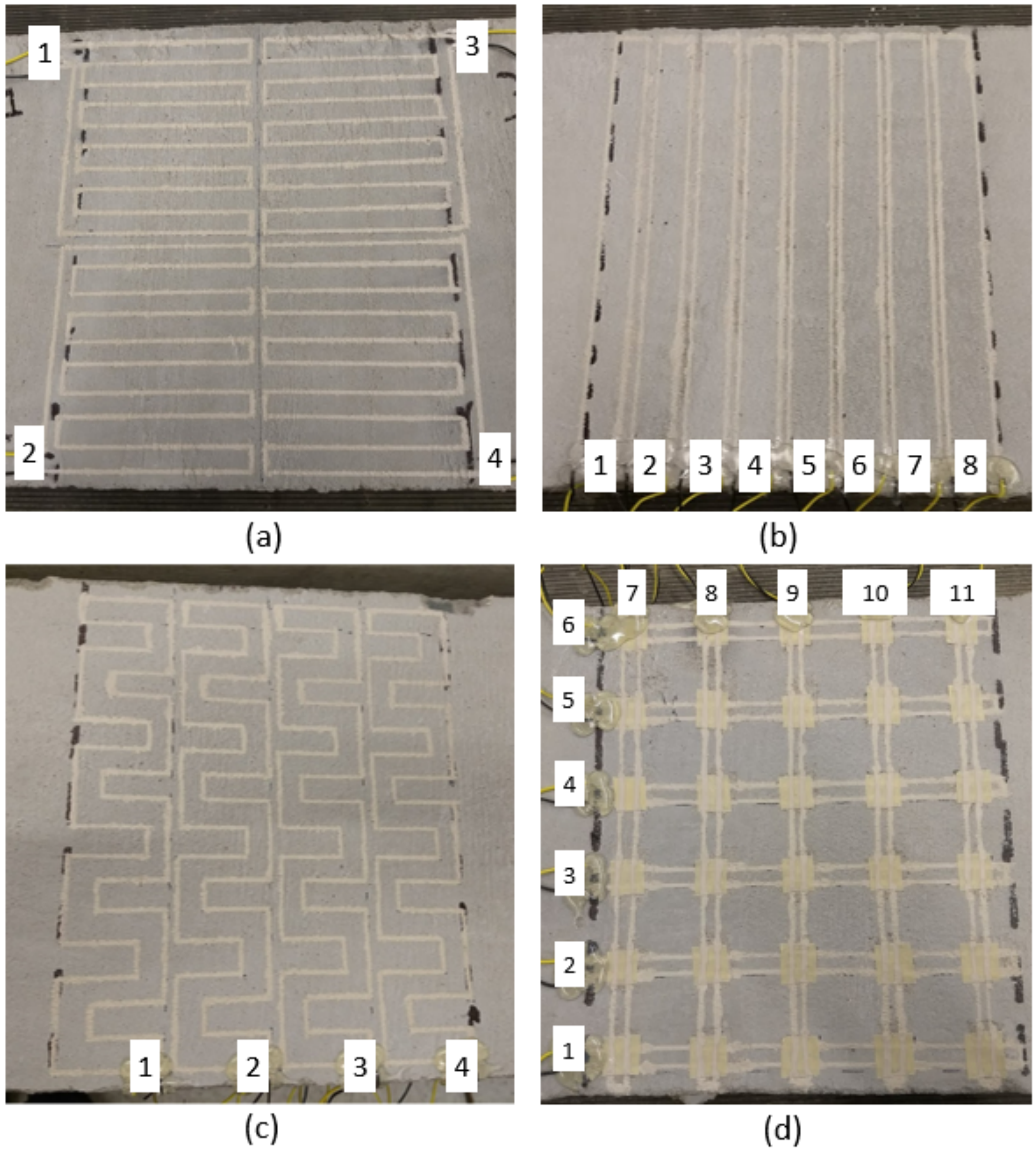

Figure 3-3 Experiment #3 patterns applied to concrete beam specimens: (a) pattern A, (b) pattern B, (c) pattern C, (d) pattern D.

Each of the four patterns is placed on the bottom surface of a concrete beam, the beams are loaded in four-point bending to induce flexural cracks in the areas where the patterns are applied. Total load is applied at a rate of approximately 45 N (10 lbF) per second. Figure 3-4 shows the loading geometry of the four-point bending tests. The beams used in this experiment have a width of 25.4 cm (10 in.), which creates a larger surface area for application of area patterns, compared to the smaller beams used in Experiment #1. The use of four-point bending allows for the formation of multiple flexural cracks in a beam, compared to the individual flexural cracks seen in Experiment #1 under three-point bending. Wires are attached to the conductive paint strips at the points labeled in Figure 3-3, using conductive epoxy to allow for reliable connections to multimeters for resistance measurements of sections of the patterns. During the four-point bending tests, the resistances of sections of the patterns are monitored and the times at which any sections of the patterns experience large resistance increases are recorded. Additionally, the bottom surfaces of the beams are visually recorded during testing using a small camera taking still images every two seconds. The times at which sections of the pattern experience large resistance increases can be compared to the times at which visible cracking becomes visible on the camera images, to determine how well a pattern detects and localizes visible cracking. While the geometry of the crack itself cannot be captured using the resistance measurements of the pattern, knowledge of the geometry of the pattern allows for the localization of cracking using only resistance measurements.

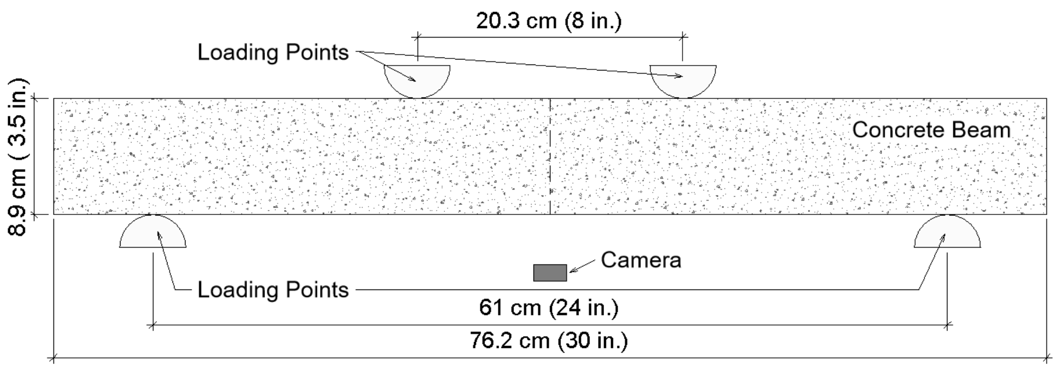

Figure 3-4 Experiment #3 four-point bending test.

To allow for clearer identification of visible cracking using the camera images, the bottom surfaces of the beams are coated with a thin layer of lime-water mixture prior to loading and illuminated with lights during loading. The layer of lime-water mixture is applied to the beams after the conductive paint so as not to interfere with the interface between the conductive paint pattern and the concrete substrate. In practice, the layer of lime-water mixture would not be necessary for crack detection using these conductive paint patterns, it only assists in the visual detection of cracking.

CHAPTER 4 - RESULTS

This section presents the results from each of the three experiments and an initial discussion of the findings.

4.1 EXPERIMENT #1 – BEAM TESTS FOR CRACK WIDTH SENSITIVITY

For both the nickel-based and silver-based conductive paints, at the three temperature levels tested, the average extension at crack detection increases with paint strip width. Figure 4-1 plots the average extension values at crack detection versus paint strip width to visually summarize the relationship between paint strip width and crack width sensitivity. Table 4-1 shows a complete summary of the data collected from the 18 tests performed for Experiment #1. These results agree with other researchers, which have noted that crack sensitivity is dependent not only on paint strip width, but also on paint layer thickness and the quality of the paint layer at the crack location (Pour-Ghaz et al. 2014; Pour-Ghaz et al. 2011c; Pour-Ghaz and Weiss 2011a). The variability in strip thickness and paint quality across all paint strips very likely contributes to the distribution of values of the extensions at crack detection, among paint strips of the same width and paint type. However, the consistent application of all paint strips and the relatively small standard deviation of the paint thickness estimates neutralize these sources of variability to some degree. The main source of variation in the extension at crack detection data is likely the variation between the 18 concrete beams tested. Any surface imperfections of the individual concrete beams at the location of cracking could affect the sensitivity of the paint strips to crack width. Despite the presence of variability in the data, the increase in average extension at crack width detection as paint strip width increases supports the assertion that the cross-sectional area of a paint strip is proportional to the crack width it can detect.

Table 4-1 Summary of Experiment #1 Data

Paint Type	Temperature (C)	Paint Strip Width (mm)	Extension at Crack Detection (mm)						Average (mm)	Standard Deviation (mm)
			Test #1	Test #2	Test #3	Test #4	Test #5	Test #6		
Nickel	-10	2	0.076	0.095	0.152	0.086	0.177	0.094	0.113	0.0374
		4	0.124	0.217	0.189	0.130	0.208	0.101	0.162	0.0449
		6	0.155	0.142	0.163	0.183	0.256	0.122	0.170	0.0427
	+5	2	0.095	0.106	0.107	0.116	0.067	0.114	0.101	0.0167
		4	0.128	0.116	0.102	0.186	0.088	0.116	0.123	0.0308
		6	0.223	0.157	0.226	0.211	0.200	0.073	0.182	0.0537
	+20	2	0.161	0.189	0.140	0.082	0.093	0.219	0.147	0.0451
		4	0.103	0.112	0.246	0.100	0.183	0.246	0.165	0.0587
		6	0.126	0.162	0.444	0.221	0.189	0.221	0.227	0.0950
Silver	-10	2	0.080	0.112	0.147	0.088	0.188	0.092	0.118	0.0383
		4	0.109	0.105	0.212	0.104	0.199	0.109	0.140	0.0467
		6	0.151	0.159	0.160	0.224	0.250	0.118	0.177	0.0451
	+5	2	0.091	0.110	0.098	0.114	0.071	0.100	0.098	0.0141
		4	0.126	0.121	0.123	0.169	0.050	0.108	0.116	0.0353
		6	0.110	0.129	0.150	0.148	0.181	0.126	0.141	0.0226
	+20	2	0.242	0.129	0.086	0.244	0.097	0.087	0.148	0.0637
		4	0.198	0.401	0.121	0.193	0.130	0.144	0.198	0.0884
		6	0.432	0.405	0.201	0.143	0.247	0.127	0.259	0.111

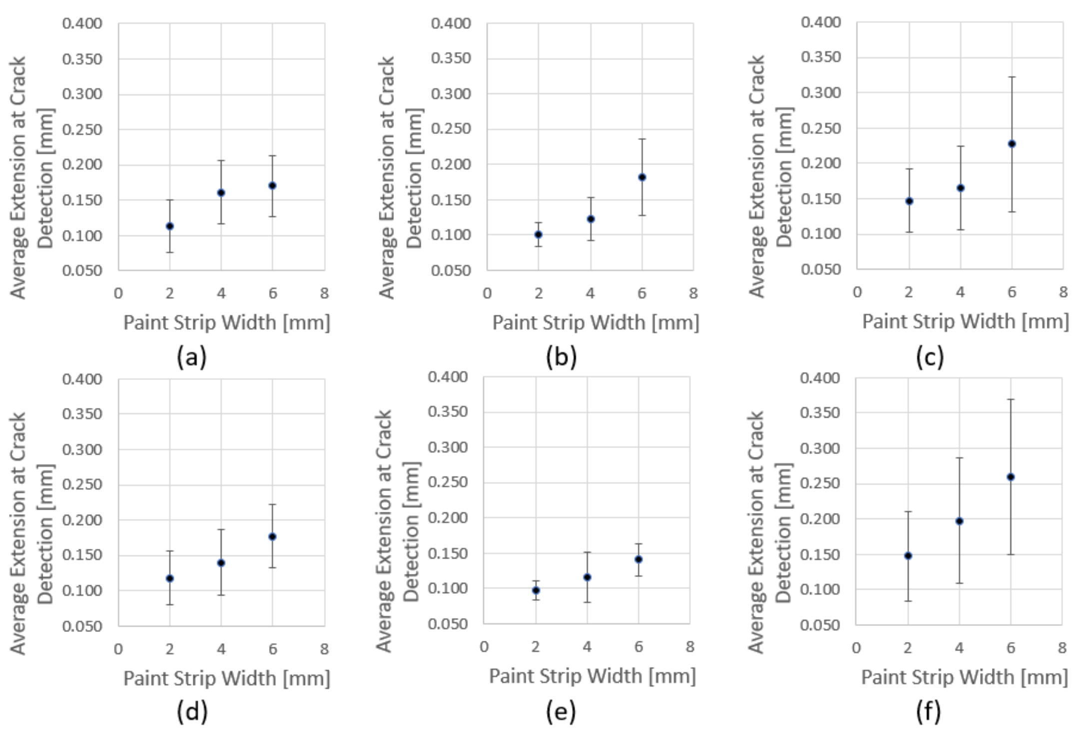

Figure 4-1 Average extension at crack detection compared to paint strip width for all experiment #1 temperatures and paint types, the error bars represent the standard deviation of the data (a) nickel paint at -10°C (b) nickel paint at +5°C (c) nickel paint at +20°C (d) silver paint at -10°C (e) silver paint at +5°C (f) silver paint at +20°C

4.2 EXPERIMENT #2 – ENVIRONMENTAL EFFECTS ON THE RESISTANCE OF CONDUCTIVE PAINTS

The relative resistance changes under varying temperature and humidity are plotted in Figure 4-2. In the first phase, where temperature is held constant at +20°C, the resistances for each strip of paint at each relative humidity level are divided by the resistance of that paint strip at 25% relative humidity to create a unitless ratio. In the second phase, where relative humidity is held constant at 50%, the resistances for each strip of paint at each temperature level are divided by the resistance of that paint strip at +5°C to create a unitless ratio. The unitless ratios allow for a comparison of relative resistance change between all strips of paint, despite the different magnitudes of resistance for each paint strip.

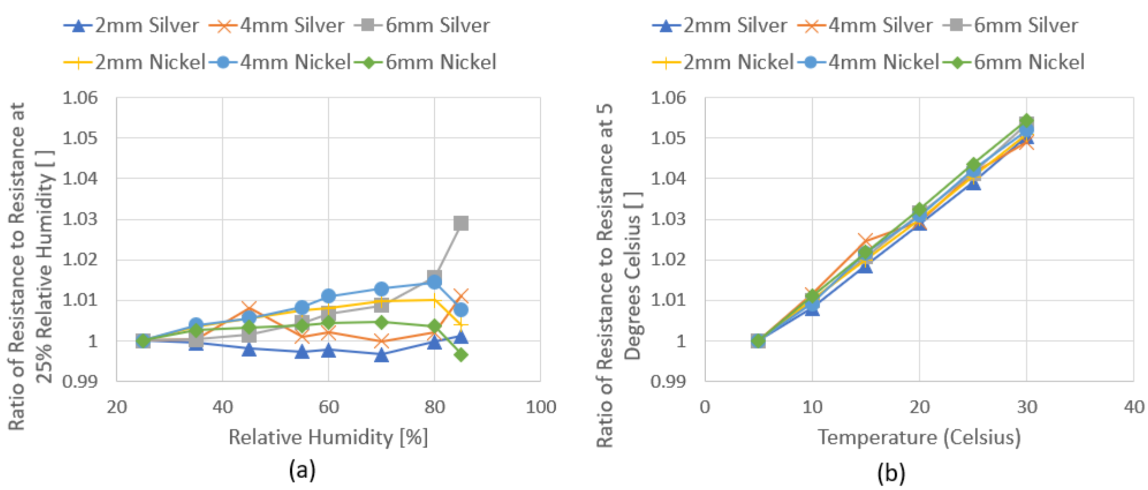

Figure 4-2 Relative resistance changes for experiment #2 data (a) ratio of resistance to resistance at 25% relative humidity when temperature is held constant at 20°C (b) ratio of resistance to resistance at 5°C when relative humidity is held constant at 50%

From the results shown in Figure 4-2a, there is no general trend for change in paint strip resistance as relative humidity increases. While many of the paint strips show a slight resistance increase as relative humidity increases, the 2 mm (0.079 in.) and 4 mm (0.16 in.) wide silver-based paint strips are mainly constant in their resistance values. The 2 mm (0.079 in.) wide silver-based paint strip even shows slight decreases in resistance at some of the relative humidity levels. Figure 4-2a suggests that changes in relative humidity over the range tested will likely add environmental noise to conductive paint resistance values, without any apparent trend.

On the other hand, as temperature increases, the resistances of all six strips of conductive paint increase as well (see Figure 4-2b). For each 5°C temperature increase, the resistance of each strip of paint increases by approximately one percent. The 4 mm (0.16 in.) wide silver-based paint strip shows some deviation from this trend, but still demonstrates an increase in resistance with increase in temperature. The collected data suggests a linear relationship between temperature and conductive paint resistance between +5°C and +30°C.

4.3 EXPERIMENT #3 – CRACK LOCALIZATION

Figure 4-3 through Figure 4-6 show the crack progressions during Experiment #3 for the concrete beams instrumented with patterns A, B, C and D, respectively. The images are taken from the camera used to record the bottom surfaces of the beams during the four-point loading tests. For clarity, cracking is highlighted in the camera images. Number labels for the sections of the patterns are shown in the figures, using the same numbering scheme as in Figure 3-3. Section numbers are highlighted in images where a section has experienced a large resistance increase, indicating that the section has detected cracking.

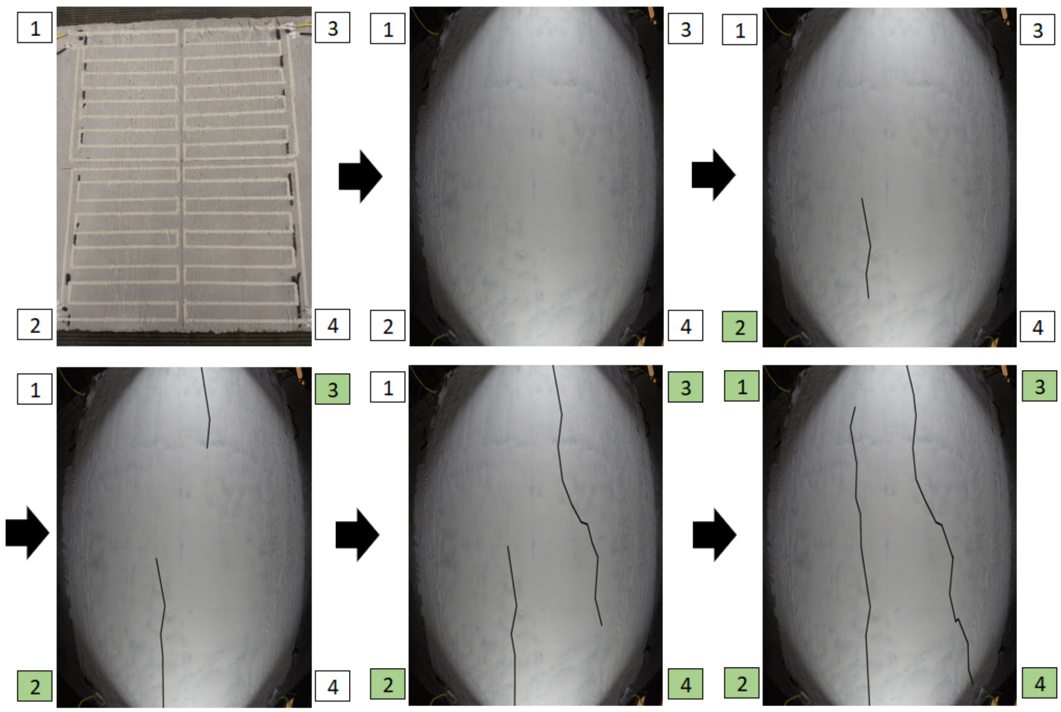

Figure 4-3 Crack progression during Experiment #4 for Pattern A.

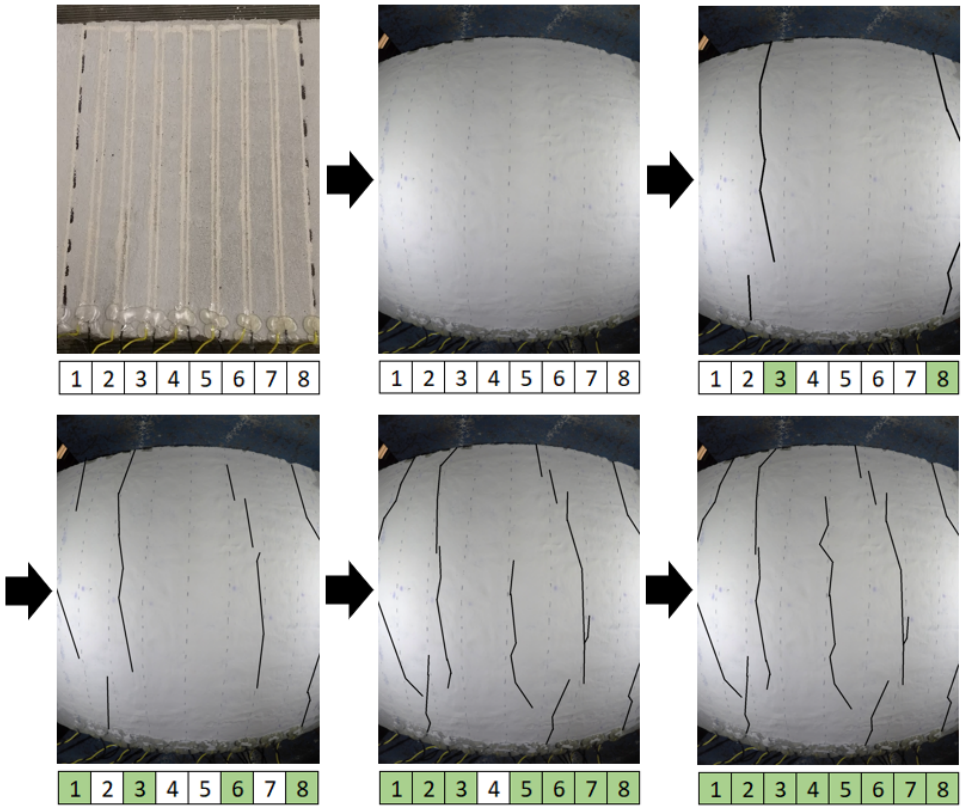

Figure 4-4 Crack progression during Experiment #4 for Pattern B.

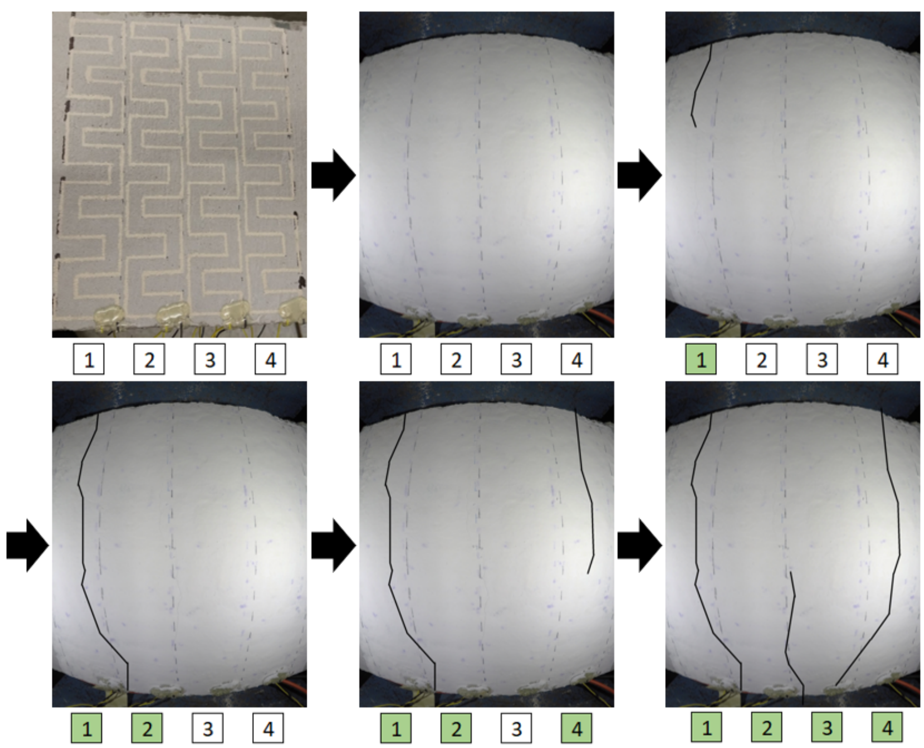

Figure 4-5 Crack progression during Experiment #4 for Pattern C.

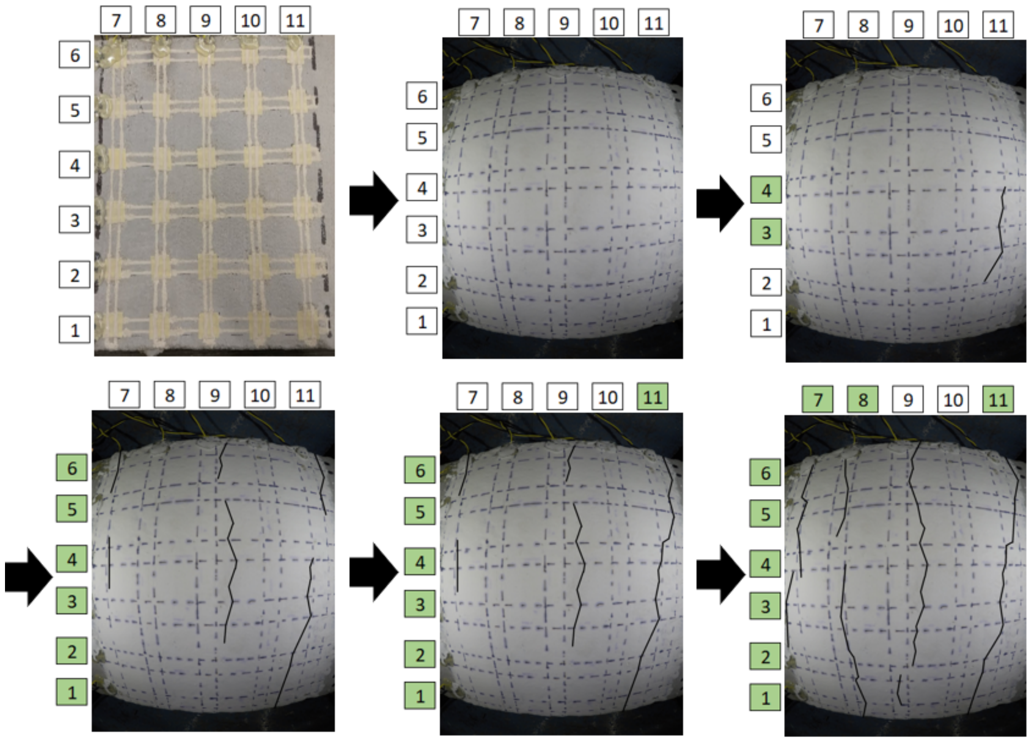

Figure 4-6 Crack progression during Experiment #4 for Pattern D.

The beam instrumented with pattern B experiences the most extensive cracking of the four beams tested (see Figure 4-4), which allows for a detailed discussion of its performance at localizing the cracking. All eight sections of pattern B experienced large resistance increases during testing, and therefore detected cracking during testing. Each of the eight sections detected visible cracking in the area covered by the section, at the time when the cracking intersected a paint strip in the pattern. For this experiment, visible cracking was defined as cracking that was visible to the eye in the camera images recorded. Of interest is the crack that formed in the bottom left of the camera images, first visible in the top right image of Figure 4-4. This crack remained undetected until further crack formation because it formed in an area between conductive paint strips. The areas between paint strips were a main consideration when designing the patterns, because they create areas where cracks can form undetected. Aside from the crack that formed between paint strips, each section of the pattern successfully detected visible cracking when it formed. The sections of the pattern detected cracking in the sequence the cracks formed, indicating that pattern B was able to successfully localize cracking to given sections of the pattern.

The patterns A and C perform similarly to pattern B, detecting cracks at the time they became visible and localizing the cracks to the correct sections of the pattern (see Figure 4-3 and Figure 4-5, respectively). The areas between paint strips in patterns A and C were generally smaller than the areas in pattern B. No cracks formed in the empty areas of patterns A and C during testing, so no visible cracks went undetected as they did with pattern B. The smaller empty areas in patterns A and C could contribute to fewer undetected cracks. However, the patterns were also oriented such that the cracking in the tests was typically perpendicular to many of the paint strips in the patterns, leading to a greater chance of cracks intersecting the paint strips in the patterns. This differs from the pattern B test, where the cracking was essentially parallel to many of the paint strips in the pattern.

Figure 4-6 shows the crack progression during the four-point loading of the concrete beam specimen instrumented with pattern D. The cracking initially forms intersecting only the horizontal sections of the pattern, which correctly detect the cracking as it crosses each section. After each horizontal section of the pattern has experienced cracking, a vertical section of the pattern experiences cracking as well, as shown in the bottom middle image of Figure 4-6. At this point in the crack progression, the resistance measurements from the pattern suggest that a crack has formed across all horizontal sections and one vertical section, accurately localizing the largest crack shown by the camera. This shows that pattern D most accurately localizes cracking when compared to the other three patterns. This accuracy at localizing cracking comes at the expense of pattern D requiring the most instrumentation for measuring resistance of any of the four patterns. Another consideration is that pattern D requires non-conductive spacers between the horizontal and vertical sections of the pattern. Ideally, the non-conductive spacers would be brittle enough to allow cracks to fracture a spacer and fracture any conductive paint on top of a spacer as well. This would allow complete detection of a crack that forms under a spacer. A non-conductive tape was used for the spacers in this experiment. While the tape performed well as a nonconductive barrier, it lacked the ideal brittle quality for transferring cracks. Acrylic paint, insulating varnish, and liquid rubber were tested for use as nonconductive spacers, but none of the tested materials provided a sufficient nonconductive barrier between strips of conductive paint.

CHAPTER 5 - DISCUSSION

This chapter discusses the implications of the experimental results presented in Chapter 4. Any experimental limitations are identified, and the corresponding impacts are addressed.

5.1 CONDUCTIVE STRIP DIMENSIONS AND MATERIAL

The average extensions at crack detection show that the nickel-based and silver-based conductive paints perform comparably across all paint strip widths and all temperature levels tested. The average extensions at crack detection agree within the standard deviation error bounds for the nickel-based and silver-based paint strips of the same width that were tested at the same temperature level. The average extensions at crack detection are particularly similar for the paint strips with widths of 2 mm (0.079 in.) and 4 mm (0.16 in.). Figure 4-1 illustrates that the standard deviation errors are generally smaller for the paint strips with smaller widths. The strips with smaller widths likely have greater consistency in paint layer thickness and paint quality due to their smaller size, leading to reduced variability in the crack widths they detect. This suggests that the nickel-based and silver-based conductive paint strips perform comparably at detecting cracks of the same width when the paint strips have similar cross-sectional area and paint application quality.

Strips of conductive paint, both nickel-based and silver-based, detected cracks with widths on the order of magnitude of 0.1 mm. Paint strip width has an impact on crack width sensitivity, as shown in Experiment #1, but strips between two and six millimeters in width have comparable crack detection capabilities. The paint strips tested in Experiment #1 detected crack widths between 0.1 mm and 0.3 mm on average. Temperature was shown to have an impact on crack width sensitivity, but like paint strip width, the impact was not overly significant and did not impede the crack detection abilities of the paint strips. If larger structural cracks were desired for detection, conductive paints could be applied to adhesive sheets and then applied to concrete. The adhesive sheet reduces the crack width sensitivity of the conductive paint by introducing a medium between the paint and the concrete.

5.2 ENVIRONMENTAL EFFECTS ON CONDUCTIVE SURFACE SENSORS

Both conductive paint types used, silver and nickel, have comparable crack width sensitivity across the three temperature levels tested. Figure 4-1 shows that the average extensions at crack detection agree within the standard deviation error bounds across the three temperature levels tested, for paints strips of the same paint type and same strip width. There is no distinct trend showing a decrease or increase in crack sensitivity with temperature level. This indicates that more temperature levels may be required to fully characterize the effect of temperature on conductive paint crack sensitivity. Additionally, a more sophisticated extension or crack width measurement system may be beneficial for experiments of this type to capture any trends, although it would have to be reliable over a range of temperature levels. Regardless of any apparent trend, both conductive paint types are able to reliably detect similar cracking at the three temperature levels tested and the temperature does not adversely impact crack detection.

The results from Experiment #2 (see Figure 4-2) show that while relative humidity and temperature can affect the resistance values of conductive paints, the resistance changes are small enough that they would not interfere with identifying the large resistance increases associated with crack detection. The resistance changes due to relative humidity are all less than 3%, while the resistance changes due to temperature are all less than 6%. However, the relative changes in resistance as a function of temperature could impact techniques more sensitive to the resistance measurements for localization. Resistance values could be affected further outside the temperature and relative humidity ranges tested in Experiment #2, but the results suggest that any resistance changes due to these environmental effects would not be of the same magnitude as the resistance increases associated with crack detection using a strip technique.

5.3 PATTERN IMPACT ON CRACK LOCALIZATION

The variability in the crack detection between all four patterns suggests that while empty areas in a pattern are critical to avoiding undetected cracking, what direction cracks are likely to form is also an important consideration. The fewer number of sections in patterns A and C, compared to patterns B and D, mean that the patterns can cover the same area with less resistance measurement instrumentation, at the expense of localizing cracking to larger areas within the patterns.

For this experiment, patterns A, B, C, and D were created to cover an area of 25.4 cm (10 in.) by 20.3 cm (8 in.). However, these patterns could be scaled in size to cover larger or smaller areas. The repetitious nature of patterns A, B, and C would allow them to very easily be placed over any desired area. As seen with the four patterns in this study, a more tightly spaced pattern provides greater potential for crack localization, but with the cost of more instrumentation being required to monitor the pattern.

CHAPTER 6 - CONCLUSIONS AND RECOMMENDATIONS

In the present work, nickel-based and silver-based conductive paints are used as conductive surface sensors for crack detection in concrete specimens. When a concrete substrate experiences cracking, the conductive surface sensors experience cracking as well, resulting in a permanent resistance increase of several orders of magnitude. This stark contrast between resistances allows for simple detection of cracking.

While several researchers have shown that linear strips of conductive surface sensors can detect concrete surface cracking (Morita and Noguchi 2008; Pour-Ghaz et al. 2014; Pour-Ghaz et al. 2011a; b; Pour-Ghaz and Weiss 2011a; Raoufi et al. 2011), research has been lacking on how to localize cracking over an area using linear strips of conductive surface sensors. The patterns of linear strips of conductive paint used in this paper can localize cracking to a given area of concrete. This is done by taking advantage of known pattern geometry and taking resistance measurements over separate sections of a pattern. Patterns of linear strips maintain the simplicity of taking only resistance measurements to detect cracking, while introducing the potential for crack localization that was previously only possible with much more sophisticated two-dimensional sensing skins (Hallaji et al. 2014; Hou et al. 2007; Loh et al. 2007, 2008, 2009). The crack localization abilities of the linear strip patterns are more rudimentary than those of two-dimensional sensing skins but offer the advantage of much easier interpretation of collected resistance measurements.

The environmental effects of temperature and relative humidity on conductive paints used as conductive surface sensors have never been evaluated prior to this research. Over the temperature range and relative humidity range tested in Experiment #2, it was shown that these environmental factors have a limited impact on the resistances of the nickel-based and silver-based conductive paints used for this study. The environmental impacts on resistance would not interfere with identifying the large resistance increases associated with the detection of cracking. Additionally, the results from Experiment #1 show that the nickel-based and silver-based conductive paints used were able to reliably detect cracking between -10°C and +20°C. These results are promising for the use of conductive paint conductive surface sensors in locations exposed to environmental change.

Silver-based conductive paints have been shown to be effect at detecting cracking, but research on more economical conductive paints has been lacking. In this study, a nickel-based conductive paint was compared to a silver-based conductive paint and was shown to have comparable reactions to environmental effects and demonstrated similar crack detection capabilities. The larger resistivity of the nickel-based conductive paint did not interfere with identifying the large resistance increases associated with crack detection. The nickel-based conductive paint results are promising for applications of conductive paints as conductive surface sensors because they provide a more economical alternative to silver-based conductive paints.

A direct relationship between conductive paint strip width and crack width sensitivity was observed over the relatively large sample size of Experiment #1. While this relationship was expected, it has never been demonstrated over a sample size this large, or with conductive paint strips applied directly to the surface of concrete specimens. The factors of paint layer thickness and paint layer quality also affect crack width sensitivity, but the results shown in Experiment #1 strongly support that if paint layer thickness and quality are held relatively constant, the width of a paint strip affects its crack width sensitivity. This property can be more broadly stated as indicating the cross-sectional area of a paint strip affects the crack width sensitivity of the paint strip.

The crack widths detected in this study were on the order of magnitude of 0.1 mm (0.004 in.). A known method to reduce crack width sensitivity is to apply conductive paint strips to an adhesive sheet applied to concrete, rather than directly to the surface of the concrete (Morita and Noguchi 2008). If detecting larger cracks is desired, adhesive sheets are a viable option. Additionally, the use of adhesive sheets could potentially enable easier production and application of the patterns discussed in this study.

6.1 TECHNOLOGY TRANSFER

The simple crack localization technique developed in this study could allow for the identification of areas of interest over a large region, which could enable more focused inspection work. The patterns could possibly be implemented over this large region with aerosol paints and stencils. The four patterns used in this study have the potential to be paired with RFID technology to allow for wireless and rapid interrogation of multiple patterns (Morita and Noguchi 2008; Pour-Ghaz et al. 2014). The crack localization capabilities and simplicity of the patterns used in this study, along with the potential for integration with RFID technology, are promising for concrete pavement crack detection applications.

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Appendix A - Comments on Different Types of Conductive Materials

Conductive paints are used as the conductive material in the conductive surface sensors for the experiments performed for this study, but other conductive materials can be used as well. Conductive paints, copper tape, and thin wires (24 AWG) were subjected to preliminary tests to determine the benefits and disadvantages of each material prior to the experiments described in this paper. The preliminary tests consisted of general observations about the application process for each material, methods for measuring resistance, and crack sensitivity tests identical to those performed in Experiment #1.

APPLICATION OF CONDUCTIVE MATERIALS

The silver-based and nickel-based conductive paints used require nearly identical application processes. The paints were applied using a thin paint brush in this study, but the paints would be suitable for aerosol application as well. With either application method there is the potential for inconsistent paint layer thickness, which can potentially affect the crack sensitivity of a conductive surface sensor. Aerosol application could potentially reduce variability in paint layer thickness compared to brush application and could potentially result in quicker application of paint over a larger area. However, as shown in Experiment #1, consistent application using a brush can lead to relatively consistent paint layer thickness. Painter's tape was used to create the patterns seen in this study, aerosol application would work well with pattern stencils for more consistent and faster application of patterns.

The use of copper tape as a conductive material addresses the issue of inconsistent thickness associated with conductive paint but has the drawback of being more difficult to apply. Copper tape has a constant thickness and width, enabling consistent lines of conductive material. Copper tape can be easily applied to a surface in straight lines, but curves or corners in a pattern are more difficult to facilitate. Additionally, there are issues with adhesion between copper tape and concrete. The built-in adhesive on the tape is insufficient for consistent adhesion to concrete, particularly if any dust or particles are present on the surface of the concrete. To address the adhesion issue, a high strength spray adhesive was applied to the concrete prior to the application of the copper tape. The involved procedure of applying the tape manually in a pattern would need to be addressed for copper tape to be practical for large-scale applications.

Like copper tape, thin wires have a consistent cross section, but there are some issues with application. Adhesive is necessary to enable the wires to adhere to the surface of concrete. The same high strength spray adhesive used with the copper tape was used to allow the wires to adhere to concrete. Figure A - 1 shows three wires applied to a concrete specimen using the spray adhesive, conductive paint strips are also visible in the image. Despite the high strength spray adhesive used, the wires did not consistently achieve adequate adhesion to the concrete, likely due to the thin wires lacking a large area of contact with the concrete. Wires of size 24 AWG were used in this study, but the same adhesion issues would likely apply to other sizes of thin wires. Patterns are easier to apply with wire compared to copper tape, but still require manual placement. The issues of manual placement and inconsistent adhesion would need to be addressed for small gauge wires to be used as conductive surface sensors on a large scale.

Figure A - 1 Thin wires applied to concrete using spray adhesive.

A high strength spray adhesive was used in this study to apply copper tape and thin wires to concrete, but other adhesives may provide better results. A more in-depth analysis of adhesives could identify an adhesive more suitable for use with conductive surface sensors made with copper tape or thin wires. An ideal adhesive for conductive surface sensor application would be easy to apply, provide reliable adhesion, and not overtly interfere with the crack detection capabilities of the conductive materials.

RESISTANCE MEASUREMENT METHODS FOR CONDUCTIVE MATERIALS

All resistance measurements made in this study were made using multimeters connected to wires affixed to the conductive materials. RFID tags or more sophisticated equipment could be used to make resistance or continuity measurements, but connections to the conductive materials would still require techniques similar to those used for this study.

In this study, wires were affixed to the conductive paints using a conductive epoxy. Most conductive epoxies require curing time but provide reliably conductive and moderately durable connections to conductive paint applied to concrete. Another connection option from wires to conductive paints is the use of conductive gel. Conductive gel provides a conductive medium between wires and conductive paint, but an external force is required to maintain contact between the wires, gel, and conductive paint because the gel itself provides very little cohesive force. Both thin wires and copper tape can be connected to wires using soldering for a very reliable conductive connection.

CRACK WIDTH SENSITIVITY OF CONDUCTIVE MATERIALS

The type of conductive material used in a conductive surface sensor has a large impact on the crack width sensitivity of the sensor. The variability in crack width sensitivity between conductive paint, copper tape and the thin wires tested was significant in the preliminary tests performed. The cross-sectional area of a strip of conductive material also impacts the crack width sensitivity of a conductive surface sensor, but this impact is overshadowed by the differences among different materials. The preliminary tests for crack width sensitivity were identical to the tests performed in Experiment #1 described in this report.

Copper tape detected larger width cracks than the conductive paint strips. Copper tape with a width of one millimeter detected crack widths of approximately 0.5 mm on average. Wider strips of copper tape, with widths of two and three millimeters, were significantly less sensitive to cracking, detecting cracks with widths wider than 1 mm. The reduced crack sensitivity of wider strips of copper tape also came with less consistency in the crack widths detected, in some tests the wider strips did not break at all, even when crack widths exceeded 2 mm. The greater cross-sectional area of the wider tape strips was expected to result in less crack width sensitivity. The larger extensions necessary to produce wider cracks had the unforeseen effect of separating the copper tape from the concrete when the adhesive could not stand the larger strains. Figure A - 2 shows a concrete specimen with copper tape strips after a crack width sensitivity test. The top strip of tape in the figure fractured during the test, but the second from the top strip of tape did not fracture and shows separation from the concrete surface. The separation of the copper tape from the concrete specimens, in addition to the larger cross-section of the wider tape strips, was likely the cause of the strips not detecting some cracks.

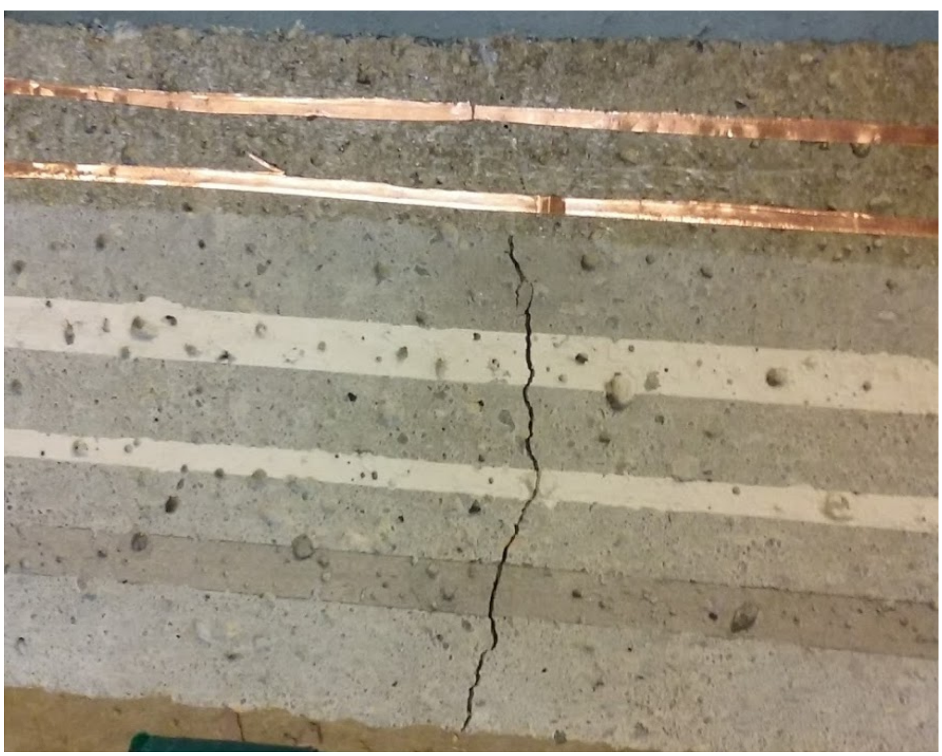

Figure A - 2 Copper tape strips after a crack width sensitivity test.

The 24 AWG thin wires tested were inconsistent in detecting cracking. Similar to the wider strips of copper tape, there were tests performed where the thin wires were unable to detect cracks even when the cracks had widths exceeding 2 mm. When cracks were not detected it was due to a separation of the wires from the concrete, at the location of cracking. When the thin wires did detect cracking, the crack widths were in the range of 1 mm to 2 mm. The crack widths detected were very inconsistent, making it difficult to definitively say how sensitive 24 AWG wires are to crack width. The results of the preliminary tests suggest that a thinner wire would be necessary to more consistently detect concrete cracking. However, the use of thinner wires could lead to further issues with adhesion between the wires and concrete.

GENERAL COMMENTS ON CONDUCTIVE MATERIALS

Based on the experience of the researchers, and the results of the experiments, it is not unreasonable to suggest that any type of conductive paint could be used effectively as a conductive surface sensor. The main differences between types of conductive paints are the different resistivities due to different metal bases, different percentages of metal, and cost. Resistivity was shown to have a negligible impact on the performance of the conductive surface sensors in this study. Only paints with approximately 50% metal by weight were used in this study, so further research would be required to quantify the consequences of different percentages of metal in conductive paints used as conductive surface sensors. However, based on the results in this study, so long as paint is reliably conductive, it should function as a conductive surface sensor. The results of this study show that a less expensive nickel-based conductive paint can perform comparably to a more expensive silver-based conductive paint. The findings suggest that any conductive paint, so long as it is reliably conductive, could be used as a conductive surface sensor. Environmental effects on conductive paints other than the nickel-based and silver-based paints used in this study would be necessary to fully evaluate if a conductive paint was suitable for use as a conductive surface sensor.

Copper tape is commonly available in the width of 6 mm, but given the results of the preliminary tests, smaller widths of tape are necessary to detect cracks with widths less than 1 mm. This created the issue of having to cut down 6 mm wide copper tape into smaller widths. This process was tedious and would present a major obstacle if copper tape with width less than 6 mm was ever to be used on a large scale with conductive surface sensors. Manufacture of less wide copper tape would be necessary to make the detection of cracks with less than 1 mm wide feasible with copper tape. Commercially available copper tapes are suitable for the detection of larger width structural cracking.

Thin wires present an appealing option for conductive surface sensors due to their consistent cross section, wide range of sizes readily available, and inexpensive cost. The main obstacle for the use of thin wires as conductive surface sensors is getting the wires to consistently and reliably adhere to a surface. The high strength spray adhesive used in this study proved to be only somewhat effective. Research into the suitability of other readily available adhesives would be a worthwhile project to further the use of thin wires as conductive surface sensors.