Detection of Infrastructure Damage in Concrete Piles Using Smart Aggregates

Jonathan Kastner – Undergraduate
Mentor: Dr. Haichang Gu
Advisor: Dr. Gangbing Song

University of Houston REU summer research program 2009
Table of Contents:

Abstract 2

Introduction 2

Experimental Setup 4

Data/Results 8

Conclusion 14

Future Work 15

Acknowledgments 16

References 16
Abstract

This paper shows the usefulness of smart aggregates in the buildings and infrastructure of today. Smart aggregates can take in a signal such as a vibration and return a voltage to a sensor, and similarly it can be given a voltage and will send of a signal. This means that these smart aggregates can be used as actuators or sensors after they are cast into concrete structures, meaning they can give off signals as well as pick up signals. To help monitor health of different structures, one of these aggregates can send off a signal and the others will pick up that very same signal, and if there are any cracks or imperfections in the concrete as it passes through, this will affect the signal and we will be able to see this in the sensors. Smart aggregates are primarily used for three different things, monitoring early-age strength of structures, impact detection on structures, and monitoring structural health. This project dealt with a combination of the impact detection as well as the monitoring of structural health. Two concrete piles were cast with these smart aggregates inside of them, one completely normal and healthy, but the other with a tube in the center to mimic a crack in the concrete. Both piles were then hit with an object to send vibration signals through the piles. In some of the testing, the sensors of the health pile returned very similar voltages with only slight differences in the values while the pile with the crack in the middle sometimes had the voltages returned differ by over 50%. Signals are dampened as they go through these cavities mimicking holes that will give us a smaller voltage value in return once it hits the smart aggregate.

Introduction

Concrete is the most popular and widely used resource for structures. Since this is the case, it is very important to monitor the health of concrete during its life to insure that these structures remain stable and sound while they are still being used. One of the older is to cast a few samples with the same concrete mix used to make the structures and test these samples as the age of the structure wears on. A problem with this form of testing is that there will be different forces acting on the structure and the samples as well as different conditions that the two pieces are in throughout the life of the structure. Another way of testing would be to take an actual sample from the structure itself and test that piece for its health. Problems that arise with this form is that by taking the sample you are actually weakening the structure by taking the sample out, also you will only be viewing a tiny area of the structure, meaning that these tests might miss major problems in different areas of the structure. Currently there are a few different ways of using sensors to assess the health of these structures so as to not damage the structure as well as to test the actual structure itself, and these are ultrasonic scanning, transient pulse and infrared thermography, and ground radar [1]. Some other more current ways of monitoring the health is by using optic sensors with a device known as the fiber Bragg grating (FBG) sensors [1,2]. They use these sensors almost as mirrors in these concrete piles, they send an incidence wavelength and the sensors reflect these wavelengths back, where they will be picked up and evaluated. Different problems in the pile will cause changes to the wavelength and the returned values will show how serious of a problem there is. One of the advantages of smart aggregates over these optic sensors is that the
aggregates will also be able to detect impulse forces as well as be able to monitor the health.

This paper focuses on the health monitoring of concrete by using the above-mentioned smart aggregates. These smart aggregates are sensors surrounded by a small cube of concrete. These sensors are small patches made out of the piezoelectric material lead zirconate titanate (PZT). These patches are quite interesting in the fact that if they are put under a stress or strain, they will produce an electric charge and similarly if they are given an electric charge from an electric field, these patches will produce a stress or strain. With this special property, these smart aggregates can be utilized as both an actuator as well as a sensor during the testing of these concrete piles [3]. With these given properties, these aggregates can be used to monitor different areas of structural health. Another added benefit to smart aggregates is that they are very lightweight, cheap, and easy to install. One of the bad aspects however is that these patches are very delicate and fragile and can break easily, and this is the reason that they are cast in small concrete blocks before casting them in the larger concrete piles, to protect them from any damage during casting of the larger structures.

These smart aggregates can be used for three major tests during the life of concrete structures. The tasks that these smart aggregates can due is to monitor the early-age strength of the structures [4,5], impact detection on the structures [6], and finally to monitor the structural health of the infrastructure [7]. To monitor the early-age strength, one of the aggregates will be used as an actuator and send high frequency harmonic signals and the other aggregates will be used as sensors to pick up this signal. This amplitude is directly related to Young’s modulus of the medium it is traveling through. As the concrete hardens, Young’s modulus is becoming a greater value, which will in turn affect the amplitude. Since Young’s modulus is the main value to help determine the strength of this concrete, the amplitude changes can be evaluated to help determine Young’s modulus that will in turn give us the strength of the concrete structure. The second function that these smart aggregates can do is to help us monitor impact detection, which is a very important because most damage to structures is by a sudden force hitting the concrete, and these smart aggregates will allow us to sense the severity of the force that was applied. The last thing that smart aggregates are used for is health monitoring of concrete structures. This is done by one of the aggregates acting as an actuator and sending out a signal and the other aggregates acting as sensors. This form of testing will allow us to find out if there are any imperfections such as cracks as well as tell us where they are located in the structure. The signal going through the structure will be dampened if there are any cracks that the wave is heading through. By knowing the position of the sensors, if there is a significant drop in the amplitude as the returning voltage between two different sensors, the crack must be in between the two sensors.
Experimental Setup

The testing for this project was to help test the aspect of smart aggregates that returns the signals from the impact on the structures. This test had two different specimens that would allow us to compare the two concrete piles. Both of the piles had a diameter of 3” and were 6’ in length. Each of the test specimens had four smart aggregates evenly spread out throughout the piles, and these aggregates were attached to a 3/8” rebar down the center of the piles as shown in Figure 1. In one of the piles however, we attached a small 2” diameter and 2” height tube in the middle of the pile, and this is to mimic a crack that the signals will need to pass through. The first thing to do is to make 8 different smart aggregates to put into these piles, and there are quite a few different steps to make these.

For our experiment, we had to make 8 smart aggregates for the concrete piles. As described above, the main component of these is a small piezoelectric patch that will be able to pick up signals and return a small voltage in return. The first step therefore is to make all of these patches. For our aggregates, the patches we used as shown in Figure 2 were cut into small 10 mm x 10 mm squares. After these are cut, they must be checked to make sure that there are no imperfections in the square, because if there is even a small crack will cause problems in the sensing of these patches. The next step to make the smart aggregates is to solder the PZT patches to our wires as shown in Figure 3. After soldering the patches to our wires, the other end of the wire is soldered to a BNC connector, and this is for the wire to be connected to other things. If the aggregate is used as a sensor, the wire will be attached to an oscilloscope with will be able to pick up the voltage that the sensor is giving off because of the signal it is picking up. If the aggregate is instead being used as an actuator, then this wire will be connected to a function generator, which will be giving the aggregate normally a sine wave of voltage, and the PZT patch will be sending off signals in relation to the voltage it is picking up. Now that we have the PZT patches attached to the wires, we need to make sure that they are correctly working before we try to cast them in our small concrete blocks. This is done by taking the wire and attaching it to an oscilloscope, so therefore if...
the patch picks up a signal it will return a voltage that the oscilloscope will pick up. After the wire is attached, we take the other side and flick the wire very close to the sensor, if we get a flicker of voltage on the scope then we know that the patch is correctly working. After we see that the patch is working, we are about ready to cast it in the concrete to make the smart aggregate. There is just one small step to help protect from the concrete while it is being cast. Since there is water in the concrete mix, this could damage the PZT patch as well as the exposed wires right next to the part that has been soldered. To protect the patch from this, we take liquid tape as shown in Figure 4 and coat the patch, exposed wires, and the solder that is attaching the wires to the PZT patch. Now that the wire is successfully attached to the patch and the patch and any exposed wires are safely protected, the next and final step is to cast them in the small concrete blocks to make the smart aggregates.

The final step to making the smart aggregates is to cast it into our concrete mixture. For this mixture we used a ratio of 3:2 in pouring our sand and cement mix. When mixing this, we only poured enough water in to make it able to be mixed, using less water here allowed it to dry quicker and be stronger than the concrete mixture we will later cast the concrete piles with. After we have the mix, we put the patches into the small 1.9 cm x 1.9 cm x 1.9 cm (0.75 in x 0.75 in x 0.75 in) blocks and filled it with our mixture as shown in Figure 5. An important aspect to pouring these is to make sure that all the patches are pointing in the same direction, this will be important when we are placing them in the piles. If we do not know the direction that the patches are facing, an aggregate that we use as an actuator might actually be facing outward instead of down the pile towards the other sensors. This will cause the signal to either not reach those sensors or to be very weak by the time it reaches it, and when analyzing this it could be mistaken as a major imperfection in the concrete. The same goes if the sensor is not facing the same direction that the signal if coming in, once again this will influence the signal it receives which will cause the analysis of the sensor to be incorrect.

Now that the smart aggregates are all made, they are ready to be attached to the rebar and cast into the concrete piles. The smart aggregates are 0.75 in cubes, and Figure 6 gives us a picture of the smart aggregate and the sensor that we
started with. Figure 7 shows one of the smart aggregates attached to the rebar and about ready to be cast. The tape is to assure that the aggregate does not move or change direction when the concrete is hitting the aggregate while being poured into the tubes. The aggregates were spaced evenly throughout the piles, but the more important aspect that the tape is protecting is the direction that the PZT patch inside the aggregate is facing. As talked about earlier, if the direction of the patch is not facing directly down the pile, then this will throw off both of the sensing of the signals that are going through the pile as well as the direction that the signal is being sent through the pile by a patch being used as an actuator.

After we have all of our aggregates, we once again need to test them to make sure they can still pick up a signal and return a voltage in return. Sometimes the patch can be damaged in the casting process, so therefore we need this to make sure that we do not have a useless sensor in either of the piles to throw off our data. We do this once again by flicking the wire close to the patch and seeing if we get a return signal on the oscilloscope. After all the aggregates have been checked, they are attached to the two 3/8" rebars as shown in Figure 8. They are all attached so that the face of the patches are facing parallel to the bar so that if one sends a signal through the concrete the others will be able to pick up the signal on the face of the other patches. The bar on the right has the tube mentioned before to mimic our crack, and the size of this is shown in Figure 9. It is a cylinder with approximately a 2" diameter and a height of 2". This is put over the rebar right in the middle of the four sensors, after it is put over the bar it is taped securely to fasten it in place as well as to stop concrete from filling it in which would completely destroy the point of trying to put a crack in the pile. After this, the rebars are put into the cardboard cylinders with our concrete mixture that we had mixed up. The concrete was a mixture of cement mix, sand, coarse aggregate, and water given by the following chart.

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>8.7</td>
</tr>
<tr>
<td>Cement</td>
<td>20.0</td>
</tr>
<tr>
<td>Sand</td>
<td>24.5</td>
</tr>
<tr>
<td>Coarse Aggregate</td>
<td>56.9</td>
</tr>
</tbody>
</table>
All of this was needed to fill our tubes that were a total of 0.6 ft³, and now the tubes were filled. One 6’ tube was built by first completely covering two individual 3’ packing tubes with enough duct tape to make sure that the moisture stayed inside while the concrete was curing. If air bubbles would appear in these piles while they were being cast, this would throw off our data because these would also affect the signal going through the concrete and appear as cracks. The only thing we wanted to influence the signal was the crack that we manually made in one of the tubes, so to try to prevent this from happening, there were some extra precautions that needed to be taken. It was more of a problem in these tubes compared to other piles that have been tested because these two tubes that we filled were so narrow. They were only 3” wide compared to other piles that are a few feet wide, and because of this some of the coarse aggregate might not be able to fit through the narrow spaces in between the smart aggregate and the wall or an even thinner path being between the small tube and the wall on the one pile. This tube only left ½” room to get through on any side. Trying to stop these air bubbles, we at first only filled one of the 3’ tubes while using a vibrator on the side to try and let the mix settle down and remove the air pockets. The reason only doing one tube at a time here is that we could try to manually pack it down and not just trust that the vibrator was getting rid of the problems. After this one tube was filled, the other 3’ tube was attached to it with duct tape to make sure its stable and water proof once again. After this was attached it was filled again to end with the final 6’ concrete pile. During this whole process the wires attached to the smart aggregates were kept up so that at the top of the pile all of the wires are together and organized. All of the wires are labeled so that when the piles are ready the smart aggregates can be attached to an oscilloscope or a generator and the position is known for the collection of data.
Data/Results

For the testing of these two concrete piles, there was a form of impact testing done by hitting one of the piles with a rebar and all of the smart aggregates used as sensors. The rebar was hit with approximately the same force each time, so the results should be very similar between the two piles as far as the amplitude of the voltage returned when the signal reached the sensor. The only difference that should appear is the voltage returned by the pile with the crack in the middle, the amplitude was decreased because the signal was dampened. The signals on the oscilloscope attached to the pile with no imperfections were almost the same amplitude, but the pile with the crack through the center had major differences between the sensors on the same side of the crack. The two different piles were struck in similar positions and the data collected and compared. The sensors were in the same position so the distance from the point of impact to the sensor position does not matter; the only object that should cause a difference is the crack. The first place that the piles were hit were on the end of the smallest numbered sensors, followed by the other end of the piles, the last place to hit the piles were in the middle of the piles. The pile with the crack was hit on either side of it in the middle because it will cause a major impact of the data depending on just a few inches. Since there was no way of knowing the true force of impact that the piles were being hit with, this data is used for proving that the smart aggregates will be able to show where cracks or imperfections may be in the concrete piles. Unfortunately due to time, we were only able to test the reactions that the sensors picked up by hitting the piles to test the health, if there were more time the rest of the testing would have included using some of the smart aggregates as actuators and some as sensors.

![Figure 11: Picture of the two piles with their sensors numbered](image)

![Figure 12: Pile one with no imperfections, as can be seen the amplitudes are similar at their peaks right after the smart aggregates pick up the vibration through the pile](image)
Figure 13: Pile two with crack in center hit on same side as graph from Figure 12 was, sensor 7 and sensor 8 both have significant decreases in total amplitude.

Figures 12 and 13 are the graphs of the two different piles, and comparing them we see that there are definitely changes in amplitudes for sensors on the other side of the crack. Although it is slightly hard to distinguish from the graph, sensors 7 and 8 have smaller peak-to-peak voltages. It is slightly harder to distinguish because the base point is not exactly at the point of zero voltage; it is more noticeable if there is only one sensor being graphed at a time. The rest of the graphs will be shown just as one sensor at a time to make the amplitude of the voltage easier to read. As shown by the graphs above, the graphs of pile 1 should be similar and the graphs of pile 2 should have two of the sensors with a smaller voltage.
Piles hit on side of Sensor 4 and Sensor 8
Pile 1 hit in the middle and Pile 2 hit in between Sensor 6 and crack
Pile 1 hit in the middle and Pile 2 hit in between Sensor 7 and crack

Pile 1 Sensor 1

Pile 1 Sensor 2

Pile 1 Sensor 3

Pile 1 Sensor 4

Pile 2 Sensor 5

Pile 2 Sensor 6

Pile 2 Sensor 7

Pile 2 Sensor 8
These graphs show positive results for what we were trying to probe with this project. For the most part, the return voltages on pile 1 were similar values in between all the different sensors while there would be a significant change in the voltages of the sensors in pile 2. Oftentimes in pile 1 the sensor 4 will give back a smaller voltage than the others, but it is consistent with its value that it returns with a force that sends a signal through it. An important thing to do with this sensor is to test it more and see if it always lower or if changes the values it returns, due to lack of time I was not able to fully test all of these sensors in this way after they were cast. The first set of data shown on page 9 shows the data that we got from hitting pile 1 on the side that holds sensor 4 and hitting pile 2 on the side with sensor 8. Pile 1 had an average peak-to-peak voltage return of a little more than 0.4 V, with no drastic changes between two different sensors. Pile 2 had more drastic changes between some of the sensors as the signal was moving down the pile. Sensors 7 and 8 were on the same side of the crack as that of the impact spot, and both of these returned $V_{pp}$ values of approximately 0.55 V. Sensor 6 which is right on the other side of the crack had a return signal of about 0.45 V which is a noticeable loss, but the most substantial loss was in sensor 5 that was on the complete other side of the pile from the impact. Sensor 5 had a $V_{pp}$ value of about 0.27 V, which is cutting the return voltage of the sensor closest to the impact in half. This is the result that we had wanted, because this loss in amplitude shows that signal gets dampened much more in the pile with the artificial crack compared to the pile with no imperfections.

The next graphs on page 10 show the data collected by hitting pile one directly in the center and by hitting pile two in between the crack and sensor 6. The voltages we got returned on pile 1 were all consistent except for once again sensor 4 gave a smaller value. The values for all of these sensors are approximately $V_{pp}$ 0.55 V. Pile 2 once again gave us the results that we wanted to get. The sensors of the pile on the same side as the impact this time were sensors 5 and 6, and both of these sensors gave us a $V_{pp}$ value of approximately 0.58 V. Sensor 7 gave us a value of approximately 0.54 V, which is not too much less of a value but this might also be because the sensor was only a few inches away from the impact spot. The whole area around the impact zone on the pile might have been vibrating right after it was hit so this might have influenced the voltage returned more than the vibration heading down the length of the pile. Sensor 8 was over two feet away from the impact spot, so the main influence on this sensor was the vibration heading down the length of the pile from the spot it was hit, meaning that the artificial crack will have an influence over the signal heading towards the sensor. The values we got confirmed this thought since our value was not even over 0.4 V, it was approximately 0.37 V which is a loss of value from the sensors without the crack affecting the signal.

Page 11 shows the last test that was run, and this test was hitting pile 1 in the middle and hitting pile 2 in between the crack and sensor 7. We just used the data points we had from the previous test on pile 1 because there should be no difference, unlike pile 2 where just the few inches over causes the impact place to be on the other side of the crack. The new points that we got from pile 2 are also similar to what the graphs showed us on the last test. Both sensors on the same side as the impact spot returned values approximately 0.5 V. The sensor directly on the other side of the crack had once again a
similar value to the sensors on the same side of the crack. In this instance, sensor 6 actually had a larger value than that of sensor 8, and once again I believe this is just due to the fact that the entire area was vibrating enough so that the crack did not matter. As expected however, the furthest sensor away that has to go through the crack gave us the weakest signal in a value of approximately 0.4 V.

**Conclusions**

There was definitely a drop in the values returned by the sensors when the signal had to travel through the length of the pile as well as pass through the artificial crack that was inserted into pile 2. While analyzing pile 1, it appeared that there was oftentimes a decrease in voltage returned the further away the sensor was from the point of impact. Both of these facts prove that the signal is affected by distance needed to be traveled as well as any imperfections passed along the way. This is what was expected and hoped for when setting up this procedure, and with this being proved by the project it can start to be used to help monitor health of different structures. Something needed to help with this project more is to better individually test the sensors so that a returned signal might not be mistakenly taken as a problem in the concrete. As shown in sensor 4 in pile 1, this can happen to some of the sensors and must be known before the testing for the actual health can be commenced. If not known beforehand, analysis of data returned by different sensors in a building will be completely thrown off; one might mistake a crack in a part of concrete that is completely healthy. A crack might also be missed if it is right after the sensor with the problem and a different sensor picks up a weaker signal because of the crack, this might be overlooked because these two voltages might be similar even if only one is being affected by the crack. When the tests did seem to go well however, pile 2 often showed similar results to those expected. When the pile was hit on one of the ends, the two closest to the impact had similar values while those of the sensors where the signal had to pass through the crack had their values diminished. When pile 2 was hit in the center, the sensor on the other side of the crack but still close to the impact had similar values to those where there were no cracks the signal had to pass through. The fact that these piles were hit on a concrete floor had an impact on the signal being sent out after initial hit. This might be the reason that the sensors on the other side of the crack did not return a signal that appeared to be dampened too much. Comparison of the two concrete piles is also hard to do because there was no definite way of knowing if the piles were being hit with the same force each time. The force was simply by swinging a rebar and hitting the concrete piles in different spots. Because we do not know the force that the piles were hit with, we also cannot correctly analyze the relation between force of impact and the voltage that the smart aggregates will return.
Future Work

There are quite a few new plans that must be taken now that we are seeing that these smart aggregates work and are very useful for helping to detect damage in our infrastructure nowadays. Continuing with the impact detection, there are a few new steps now to better analyze the results we get. One of these steps would be to take the impact tests on a surface that will better dampen the pile after it has been hit. This will be to make sure that the only vibration signals sent through the piles are from the object that is making the initial impact on the concrete. Another step to follow with this is to get a better controlled form of hitting the concrete piles with a force, a consistent one that will give us the force that it hits the pile with. If we know the actual force we can compare the voltages we get in return with the force that it is hit with, and from this hopefully an equation can be formulated to help find the relation. After we have a better way of taking the impact tests, there needs to be found a way to check whether one of the smart aggregates is well enough for testing or not. Either this or some way of knowing whether a sensor will return a weaker signal similar to how sensor 4 did in pile 1.

The next big thing to try in these concrete piles is to test the structural health by using one of the smart aggregates as an actuator to send the signal through rather than just hitting the pile with an object. This will be a better way of testing for cracks or other problems with the pile because we know that the waves being sent out are solely in the direction that the smart aggregates are facing. The way we were testing was sending vibration waves in all directions when the pile was hit even though we were only interested in the longitudinal direction of the pile. The way these piles were tested would be better used to test the force that these piles are being hit with.

After the smart aggregates have been tested with these two piles, the next step to help us understand these situations would be to add more holes to mimic cracks into our piles. There should once again be a healthy pile for comparison and then a pile with cracks in between every single sensor. These cracks should be made of different sizes to help show how much of an impact the size of a crack has on the returned value of the sensor. This will be very important because knowing the severity of the condition is just as important as knowing that the crack is there. After this has been tested, they need to be put into much larger scale concrete piles or actual structures themselves. It needs to be known how many aggregates need to be placed into a structure to make them actual worthwhile. For instance, if two of the smart aggregates are placed so far apart that one would not be able to pick up a signal if the other were to be used as an actuator then they would be completely pointless. But if we find a good spacing to use these with, then smart aggregates in infrastructure today would be incredibly valuable. It would alert people of problems before they become so detrimental to the structure that it makes it unsafe for people to continue working there. These smart aggregates put into buildings today could save countless lives by making buildings better prepared for health monitoring.
Acknowledgements

The research study described herein was sponsored by the National Science Foundation under the Award No. EEC-0649163. The opinions expressed in this study are those of the authors and do not necessarily reflect the views of the sponsor. The research here was also conducted under the supervision and guidance of Dr. G. Song and Dr. H. Gu, both of the University of Houston.

References


