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CONDUCTIVE CONCRETE FOR ELECTROMAGNETIC SHIELDING – METHODS FOR DEVELOPMENT AND EVALUATION

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CONDUCTIVE CONCRETE FOR ELECTROMAGNETIC SHIELDING –

METHODS FOR DEVELOPMENT AND EVALUATION

by

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CONDUCTIVE CONCRETE FOR ELECTROMAGNETIC SHIELDING –

METHODS FOR DEVELOPMENT AND EVALUATION

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This research investigates the development and evaluation innovative methods for the use of conductive concrete as an electromagnetic shield. New testing methods are developed to determine the best conductive components to use in the design of a concrete mixture for shielding that shows the best promise. The conductive concrete mixture has the potential to provide electromagnetic shielding that is cost-effective in terms of construction, operation, and maintenance compared to conventional approaches. Two testing methods, Small Sample Testing and Large Slab Testing, are developed based on standardized testing methods that have been modified for the testing of conductive concrete mixtures. As a result of these innovative testing methods, a promising conductive concrete design has been chosen and the testing methods validated.

Acknowledgments

There are many people who deserve a great amount of thanks for their support through the pursuit of my Master's Degree and none more than Professor Lim Nguyen. Without his involvement and encouragement I would have never become involved in this project or come to appreciate the importance or realize my interest in electromagnetics. Through my college education he has guided me to learn and understand many things and constantly challenged me to better myself along the way.

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Most importantly, a great amount of thanks and adoration belongs with my family. Without their encouragement, love, and support I would not be where I am today, and could never have accomplished all that I have.

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CHAPTER 1 - Introduction

The subjects of conductive concrete and electromagnetic (EM) shielding, or even, the use of composite materials such as conductive concrete for EM shielding are not new [1] [2]. However, advancements in the latter have been few and far between in recent years. The need for adaptive shielding solutions is more and more important every day in the ever-changing electromagnetic world we live in. In this regard, evaluation of new technologies outside the norm of steel panels and fine meshes must be considered in order to provide alternative construction methods. This research investigates two methods of testing the shielding properties of conductive concrete mixtures. The first method, Small Sample Testing, provides a way to judge the effects of mixture components in a low-cost and timely manner. The second method, Large Slab Testing, gives a strong sense of the actual shielding effectiveness provided by concrete mixtures that have been determined to be desirable by Small Sample Testing. The results from these testing methods have been analyzed and proven their usefulness in evaluating the EM shielding properties of conductive concrete.

1.1 Purpose

The purpose of this research was to investigate simple and innovative approaches towards developing an effective conductive concrete mixture for EM shielding applications. Concrete as a material is often difficult to work with in small construction, especially with the addition of components such as steel fibers. To this end, it was desired to develop a method for evaluating the effect of conductive concrete ingredients on the shielding properties that they provide. As a rule, the only reasonable way to judge the shielding effectiveness of concrete is to build small structures that can be subjected to standardized tests involving large antenna systems. This presents many challenges for research efforts that are subject to restrictive budgets and other constraints. As a result, the critical considerations in this respect are the cost, manpower, and space available to complete the research. To address these issues, testing methods that employ relatively small samples, therefore requiring less time and materials, are extremely valuable.

1.2 Literature Review

Conductive concrete mixtures and even the use of conductive concrete for EM shielding are not new concepts. Research and development in this area, however, has been sporadic with inconclusive results. Previous efforts usually concluded with varying degrees of limitations and subsequently abandoned as the shielding performance was deemed inadequate. A very early look into this concept was presented by Gunasekaran after his extensive work into developing polymer concretes [2]. Using polymers, he was able to make concrete mixtures either conductive or insular. He discusses that the affordability of the components, such as carbon fibers, used in making concrete conductive and suggests that the mixture should include other ferromagnetic materials to help increase the absorption of the material. This thinking is definitely in the right direction for shielding against EM energy; however it does not take into consideration that as frequency decreases, the effect of absorption decreases as well. Other solutions that have been investigated do not consider frequencies lower than 500 MHz. For many applications such as electronic eavesdropping on computer systems, which normally run in the gigahertz frequency range, do not require protection in the lower frequencies. However, this should be a priority, in order to provide an overall protection against multiple threats all at once.

A review of conductive concrete products revealed that there are several solutions that have been patented for the purpose of EM shielding. However, most of these solutions do not address the idea of shielding requirement at low frequencies that are less than a few hundred megahertz at best [3]. One such patent is from a group in Japan for "Electromagnetic wave shielding building material" [4]. The building material here is a conductive concrete mixture that incorporates carbon fibers to increase the conductivity. The mixture is studied from 30 MHz to 1 GHz and shows a decent amount of shielding, between 26 and 54 dB across the frequency range. One issue that arises with this product however is that the data presented shows no discernible difference when the concrete thickness increases from 5 mm to 10 mm. This lack of change suggests that the majority of EM wave attenuation is due to reflection rather than absorption. Though this product shows a decent amount of shielding, it is still far from meeting the High-Altitude Electromagnetic Pulse (HEMP) standard that was set as a goal for this project. Another patent, developed under the support of the National Research Council of Canada, shows that conductive concrete can be made to achieve a very low resistivity and also describes its use for shielding, but does not specify how well the mixture actually works [5]. This concrete mixture utilizes coke breeze - a byproduct of steel making, as well as carbon fibers, to increase the conductivity of the concrete. In much the same way, this research develops a conductive concrete mixture that also employs carbon powder, which is a more refined carbon product with a higher conductivity than coke breeze. Nevertheless, the inventors in this patent were able to attain an average conductivity of less than 10 Ω-cm in resistivity with coke breeze, which is the limit set in the patent as being acceptable for conductive concrete. The lack of shielding analysis for this mixture is indicative of another issue with researching conductive concrete as an EM shield: the lack publicly accessible SE data. Another product named Electro Conductive Concrete was developed into individual blocks that could be used to build structures using a conductive mortar [6]. This study shows promising results over a large frequency range, 30 MHz to 5 GHz. The concrete block structure provides a good deal of SE in the higher frequencies, measuring about 65 dB at 500 MHz, 75 dB at 1 GHz, and rising quickly to 95 dB at about 1.5 GHz.

Very few SE data are available on concrete mixtures in structure applications such as rooms or buildings. This is partly due to the desire to keep the data from third parties or foreign powers, since there is a strong possibility of military applications. Providing others with the capabilities of conductive concrete shielding could empower them to devise way to circumvent the protection provided by the shield or allow them to use the materials to protect their own assets, putting the developer at a disadvantage. Many initiatives into measuring the SE of conductive mixtures focus on using smaller samples of concrete poured into a coaxial structure. One such investigation into various mixtures of concrete utilizing steel and carbon fibers as well as different grades of carbon powder, reached the same conclusion as our research on a conductive mixture that could provide around 52 dB of SE at 1 GHz [7]. They find that the most promising conductive mixture would contain steel fibers and carbon powder to achieve the desirable low resistivity. Another pair of studies provide a more in-depth look at using carbon fibers to produce a conductive mixture for shielding, but attains an SE of only around 20 dB to 30 dB between the frequencies of 1 GHz and 2 GHz [8] [9]. This supports the decision of to use steel fibers over carbon fibers due to the effect on resistivity of the concrete versus cost of the fibers. Further testing of steel fiber mixes produced a cement paste that was able to reach 70 dB of SE at 1.5 GHz. However, this paste did not include any of the main components used in the concrete mixtures, such as sand or aggregates, which are typically insulating factors that reduce the conductivity of the final product [10].

Several research efforts seek to analyze and simulate the SE of concrete structures rather than actual implementation [11] [12]. Most of the simulations employ utilize the finite-difference time domain (FDTD) method. This computational method numerically solves Maxwell equations to estimate the interaction of EM waves with the material surfaces. FDTD method requires prior knowledge of the electrical properties of the material, such as conductivity, permittivity, and permeability. Since these material properties are measurable with most conductive concrete mixtures, FDTD can model and analyze how EM waves propagation through the concrete structure, and evaluates the use of conductive concrete as an EM shield. One good example of this approach was reported by the Nanjing Engineering Institute outlining the effect of conductive concrete mixtures on a HEMP pulse [13]. HEMP research, focuses on the effect of conductive concrete on an intense EM pulse (modeled mathematically as a double exponential waveform) that can be analyzed using FDTD. In this case, the authors studied the amount of shielding that can be estimated for differing conductivities as well as thicknesses of concrete. To test this idea, the authors constructed rooms of conductive concrete with the desired conductivities. Using a pulse source, they determined the amount of attenuation provided by the room. The experimental results showed a higher amount of attenuation than was predicted by FDTD, but within a discrepancy of around 10% - 20% of the expected value. This shows that the use of FDTD is valid for estimating the attenuation provided by conductive concrete mixtures to EM waves. The discrepancy could be attributed to the possibility of the electrical properties of the concrete mixtures being frequency dependent. Since a HEMP event would produce energy across a wide frequency range, this would affect the concrete attenuation level of the EM energy by the concrete.

Other attributes of concrete structures as well as other conductive additives have been thoroughly examined in the scope of conductivity and shielding. Several reports detail the effect of rebar structures in reinforced concrete on RF waves [14] [15]. In these cases, the authors were investigating the effect of rebar in concrete structures and how they affected communications such as wireless internet, but this same data can be applied to shielding applications. The majority of the interactions caused by rebar being embedded in concrete are of a reflective nature in regards to EM waves. Due to the grid-like structure produced, the rebar effectively creates a Faraday cage. The research presented is for wire mesh cages with rather large apertures, about 4 to 6 inches square, in comparison with the wavelengths of the frequencies studied. The results show that there is a decent amount of reflective shielding. The amount of EM shielding is at a high enough level to hamper low-power communications in the gigahertz range, but not enough to satisfy the HEMP requirements. This effect should become more pronounced as the frequency decreases and the wavelength increases inversely. So even though the data produced by the authors may not be directly applicable for the given frequency range, it does show the advantage of using a conductive mesh structure in concrete to provide reflective attenuation. This reinforces the idea of using fibers of steel to create a mesh network in conductive concrete.

1.3 Methods

Two methods of evaluation are used in to determine the effectiveness of conductive concrete in attenuating EM energy. These methods are directly derived from; though do not necessarily hold to, well-established standards used in their respective fields. The Small Sample Testing method uses the EM-2107A test fixture from Electro-Metrics, which is designed to conform to the ATSM test method D4935-1 [16]. This standard outlines a test method for determining the SE of planar materials. These materials are expected to be electrically thin, described in the standard as a material thickness less than one one-hundredth of the electrical wavelength inside the specimen [16]. This requirement is relaxed to allow for the testing of concrete specimens since they must be thicker than outlined by the ASTM test method. A second consideration for Small Sample Testing is the frequency range to be investigated. According to both the ASTM method as well as the EM-2107A datasheet [17], the applicable frequency range is between 30 MHz and 1.5 GHz. Interest in high-altitude electromagnetic pulse shielding spans a range of 10 kHz to 1 GHz. Because of these differences, the Small Sample Testing method must be considered in terms of “relative attenuation” when comparing material components, but will be proven to be accurate in predicting the effect of the components.

The second method presented here is Large Slab Testing to more accurately gauge the ability of conductive concrete to shield against EM energy. Much like the Small Sample Testing setup, the large slabs are tested in a hybrid method. This experimental method is a combination of testing outlined by MIL-STD-125-188-1 and the use of an RF shelter. Normally HEMP testing is performed on room-sized structures when testing building components. This concept is not feasible when trying to develop a new product based on conductive concrete. Building structures large enough to contain the test equipment and antennas are labor-intensive and high monetary cost if a good number of different mixtures are to be tested. To alleviate these issues, an RF shelter is modified with a test port to allow for EM waves to penetrate from the outside of the shelter to the inside. Concrete slabs are then cast in an appropriate configuration to cover this port. By blocking the port with the conductive concrete, an estimate of the shielding provided by the different mixtures can be determined. This allows for timely and accurate development of a final conductive concrete mixture to be used for EM shielding.

CHAPTER 2 - Shielding Effectiveness Theory

2.1 Introduction

The most important concept in electromagnetic (EM) shielding is the shielding effectiveness (SE) of a material. For most shielding applications, the highest possible SE level is without a doubt the most preferable solution. The details of SE lie in two main concepts, the reflection and absorption of EM waves. Because the EM waves of a HEMP event are comprised of both magnetic and electric fields over a broad frequency range, a broad-spectrum solution is necessary to attenuate the EM energy over a large range of frequencies. Unfortunately, when dealing with a heterogeneous mixture like concrete it is much more difficult to appropriately estimate the possible reflection or absorption provided. This becomes an issue due to the reactions occurring inside the conductive concrete components. Because of the interactions between conductive components and the normal structure of concrete, the conductivity, permittivity, and permeability of the conductive mixture are expected to be frequency dependent. Although the electrical properties of the concrete change with frequency, the basic SE concepts remain unchanged and are applicable to the final conductive mixture.

Shielding effectiveness is defined as a measure of how well a given material attenuates EM energy in the form of magnetic and electric fields [18]. This basic concept is typically broken down into three components: reflection, absorption, and multiple reflections. Multiple reflections can be ignored when considering the bulk of SE provided by an EM shield. Over the course of reflection and propagation through the material the amount of SE due to each succeeding reflection becomes successively small and hence may be of little interest. The two concepts of reflection and absorption are envisioned as mathematical terms that make up the SE equation: $SE_{dB} = S_r + S_a$, where S_a is the attenuation due to absorption and S_r is attenuation due to reflection in dB [19]. These two terms add directly to result in the overall SE provided by a material. Both of these methods for attenuating signals are extremely important in creating an effective shield. Overall, both reflection and absorption apply to the EM spectrum of a HEMP event, but achieving significant levels of shielding can be difficult due to size and material restrictions. The basic solution for most EM shielding needs is by means of steel plates. The high conductivity and continuous surface provide excellent shielding all across the frequency spectrum defined in MIL-STD-188-125-1. To reach the goal of this standard, illustrated in Figure 2-1, it is almost necessary to use either steel plates entirely or a combination of other materials. The goal of this research in conductive concrete is to develop a mixture that will provide shielding to meet or exceed this military standard.

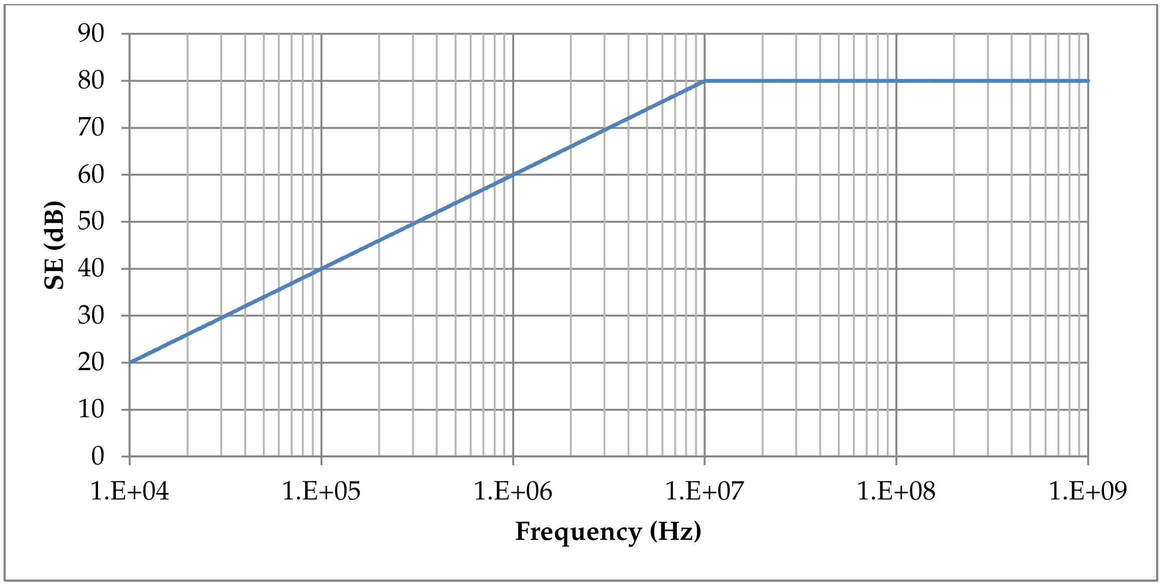

Figure 2-1: MIL-STD-188-125-1 shielding requirements

2.2 Reflection

Reflection is one key concept to shielding effectiveness. The reflection of EM energy depends on what basically amounts to impedance mismatching. EM reflection occurs at the border between any two media with large discrepancies in their electrical or magnetic impedances. The amount of reflection due to a shield is determined by the refection coefficient for that surface [20]. For the electric field, this depends highly on the conductivity of the media, while for the magnetic field it depends on the.

For the example case of a highly conductive sphere with an electric field incident to the surface, an electric field will be induced in the opposite direction on the. This effect is illustrated in Figure 2-2. Because the surface is high conductive, the field will not penetrate towards the interior and instead will re-radiate from the surface, creating a reflected field. This reflection is largely dependent on the wavelength of the energy being reflected. Any aperture on the surface will reduce the reflection compared to a solid, complete surface, hence the preference for using steel plates when constructing EM shielding structures.

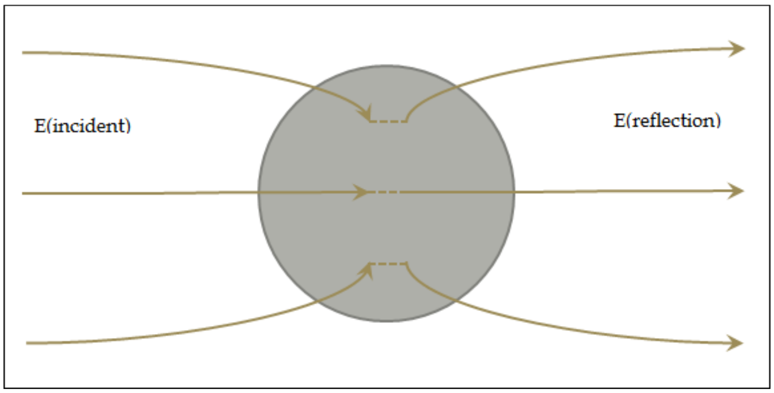

Figure 2-2: Electric field interaction with highly conductive surface

Since the steel plate solution is rather expensive, wire meshes are extensively used for shielding when a certain frequency range is specified. The SE of a metallic wire mesh will decrease with higher frequency due to the aperture effects. In the same respect, as the frequency decreases and SE increases, the amount of SE reaches an upper limit that is equivalent to ratio of the resistance of the screen to the inductance of the screen [21]. The aperture size of the wire mesh is most often determined by the frequencies which are desirable for attenuation. The amount of attenuation provided by the aperture is determined by its size relative to the wavelength. It follows that the smaller the aperture, the more attenuation that will be provided by the surface as a whole, due to the fact that it will start to act more and more like a perfect sheet. One advantage to this type of shielding is that the effect of the aperture size translates to all frequencies of electric fields below the cutoff frequency desired. This means that if a mesh is designed to work at 1 GHz for example, then it will also attenuate frequencies lower than 1 GHz to a larger degree as the frequency decreases. This effect however will eventually give way to the skin-depth property needed for absorption and thus results in the noticeable differences in SE between wire meshes of exceedingly small aperture size and metal plating. One example cited by Björklöf, is that a wire mesh room designed with aperture size of 0.5 mm will only attain SE of about 40 dB for frequencies up to 1 GHz while an aluminum-plated room of 6 mm thickness can achieve around 100 dB across the same spectrum.

In regards to magnetic fields, reflection acts much differently. Magnetic reflection depends on the magnetic field inducing a current on the conductive surface, as seen in Figure 2-3. This induced electrical current will be in a plane perpendicular to the incident magnetic field. This induced current then acts to establish another magnetic field that will directly oppose the incident magnetic field according to Lenz law. This creates a region where the incident magnetic field will be at least reduced in strength due to the induced and opposing field.

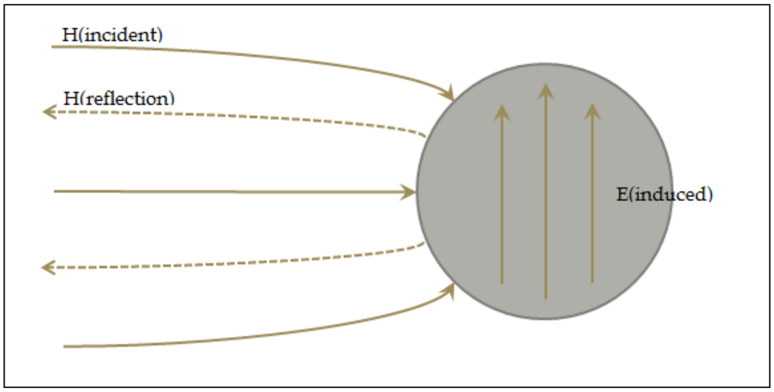

Figure 2-3: Magnetic field inducing a current on conductive surface

Much in the same manner as electric reflection, apertures on the conductive surface will produce problems due to interfering with the natural flow of the current. This disturbs the uniformity of the induced current on the surface, which in turn leads to a less uniform reflected magnetic field. Due to this disruption, the effect of the reflection will be much reduced. To alleviate this disruption while preserving the use of a mesh over steel plates, the spacing between apertures should be as large as possible. This gives the impression of a large sheet with very small perforations instead of just a sheet of woven wire. The larger the surface area in between apertures, the more uniform the current will be allowed to flow over the entirety of the surface.

2.3 Absorption

Absorption is the second component of shielding effectiveness. The main idea is to provide a material that is highly absorbing of EM energy across the selected range. This effect is referred to as the skin-depth of the material. This can be defined as "the penetration depth at which the strength of the field will have decayed to 1/e" of the surface current density [19]. Skin depth (δ) is computed as follows: $\delta = \frac{1}{\sqrt{\pi f \mu \sigma}}$; where f is the frequency, μ is the permeability of the material, and σ is the conductivity. The amount of absorption provided by a given material is approximated by the factor, $e^{-t/\delta}$, where t is the thickness of the material [20]. This shows that the amount of absorptive attenuation provided by a shield is largely dependent on the thickness of the material as well as the conductive properties of said material, sharply in contrast with reflective attenuation which depends almost entirely on the conductive properties of said material. The EM fields penetrating the materials decay exponentially. For higher frequencies, around the megahertz and gigahertz range, the skin-depth begins to get very small. For this reason, thin metal plating is a good solution for EM shielding. Improving the conductivity and permeability of a given material can greatly increase the amount of EM absorption.

2.4 Summary

The shielding property of a given material depends on reflection and absorption. Both of these properties are heavily dependent on conductivity and permeability of the material in question. The reflective property depends on creating an impedance mismatch between the incident EM field and the conductive surface. The absorptive property is determined by the amount of absorption of EM energy penetrating the given. Efficient shielding over a broad frequency spectrum depends on finding a good combination of these properties.

CHAPTER 3 - Testing

3.1 Introduction

Testing methods for conductive concrete have been developed to gain an understanding of how different mixtures and thicknesses will affect the shielding effectiveness (SE) of the final product. Thus far, two stages of testing have resulted in finding a viable mixture of components that can now be used for larger scale, more expansive testing. The two testing methods are referred to as Small Sample Testing and Large Slab Testing. These two testing methods allow for a reduction in the cost in terms of labor, time, and money associated with developing an effective concrete mixture.

3.2 Small Sample Testing

Small Sample Testing is the first step used in determining what ingredients can be added to the concrete mixture to increase the overall shielding properties. This test uses relatively small samples that require minimal amounts of concrete to be produced. Making small samples allows for the production of a large number of sample sets with a sweeping variety of mixtures. This provides the option of making almost every combination of ingredients to effectively see how each element behaves and what significance it has in the final mixture. Using this method, we can quickly narrow down the most effective combination of elements that warrant future testing.

The simplicity of the system is also a very important aspect of this testing method. To test the small samples, we utilized the EM-2107A from Electro-Metrics. This test fixture is specifically designed to measure the shielding effectiveness materials with various conductive, as well as dielectric properties. Normally these samples are very thin, less than 0.25” in thickness, however, it is very difficult to make a concrete sample thin enough to match the standard size used. Because of this inaccuracy, the test fixture is not used for its traditional function to measure SE, but instead provides a comparative analysis of different mixtures and how varying the ingredients can effect electromagnetic energies passing through the concrete. The test fixture is connected to a network analyzer, as seen in Figure 3-1 below.

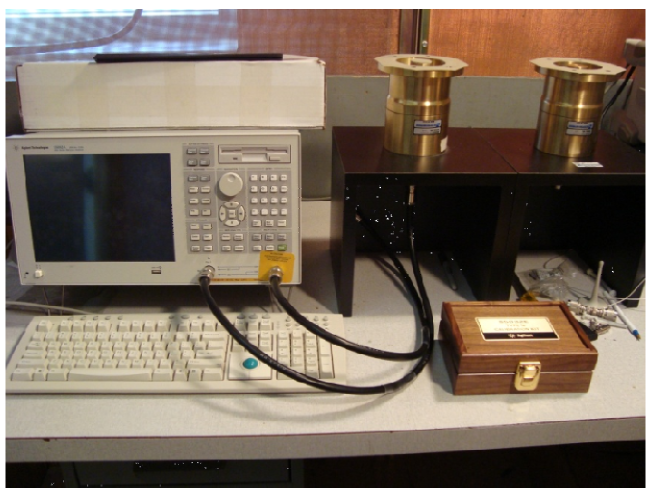

Figure 3-1: EM-2107A test fixture attached to network analyzer

The network analyzer is adept at producing the measurements need to compare these sample sets. The most important measurement needed is to see how much energy passes through the concrete. This gives us an idea of how it will work for shielding purposes. By measuring the S21 of the test fixture, we can observe how much energy is passed from port 1 to port 2 of the network analyzer and thus judge the relative attenuation seen in the concrete. By comparing the S21 measurements of various samples, we can get a clear picture of how each additive element affects the EM attenuation over the frequency ranges. Using an Agilent E5062A Network Analyzer, we are able to take measurements from 300 kHz to 2 GHz. In addition to measuring the attenuation, the network analyzer also allows for a measurement of the reflection due to transmission from a port, or the S11. Utilizing this measurement gives us a basic understanding of the reflective nature of a mixture. Since reflection is necessary in the lower frequencies, especially below 100 MHz, it is extremely useful to know the impact of the various on the EM reflection with the concrete. Using the given measurements of S21 and S11, we can gain insight on how well the concrete mixture absorbs and reflects EM energy. It is simply of matter subtracting the reflective effect from the total loss through the material. An example of this can be found in Figure 3-2.

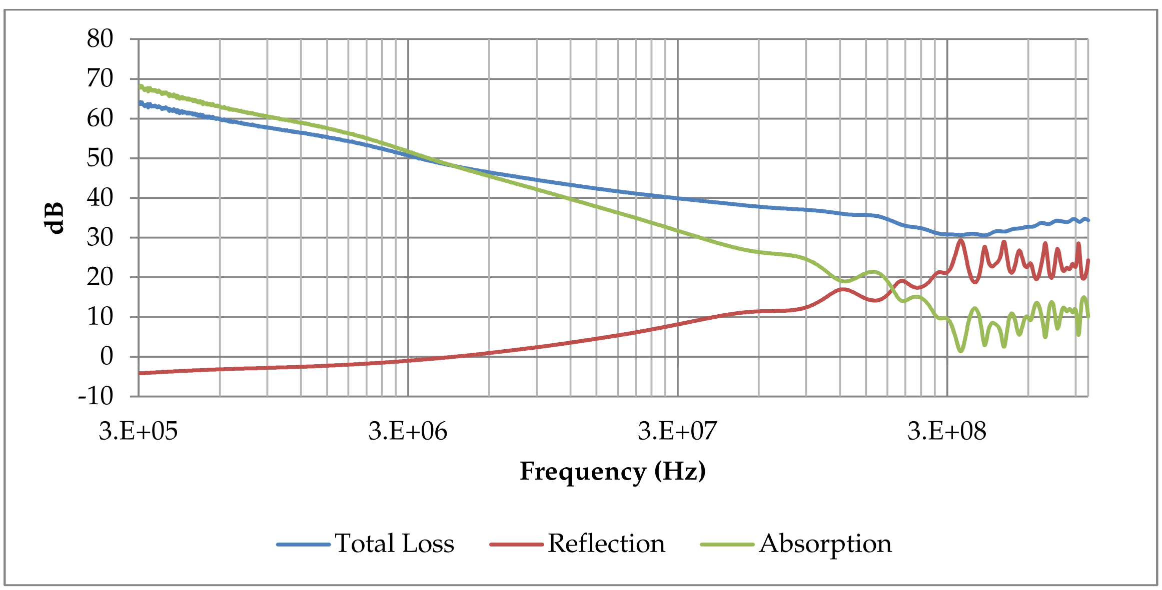

Figure 3-2: Example plot of total loss, reflection, and absorption measurements

Through this testing we can gain significant knowledge of the effects differing ingredients have on the EM attenuation provided by conductive concrete. The results for this round of testing are found in Section 4.1. For this testing method, a wide variety of sample sets were produced using varying amounts and qualities of ingredients. Throughout the testing the main components remained the same: cement powder, carbon powder, conductive fibers, and taconite. To gauge effectiveness of carbon powder, the amount was varied between different sample sets. Different conductive fibers were tested including short and long steel fibers, fine and coarse steel fibers, as well as copper filings. Taconite was prepared in forms that included a fine powder, small pieces, and high purity. The great multitude of possible combinations provides a large amount of guidance when proceeding with larger scale testing.

3.2.1 Test Fixture

The test fixture used for Small Sample Testing, as previously stated, is the EM-2107A. This device is made to conform to the standard ASTM test method D4935-1, used to determine the amount of SE provided by a sample material. The fixture is essentially an enlarged section of a coaxial cable. To this end, it is built with an inner conductor that is insulated from the outer conductor by an air gap, as seen in Figure 3-3. The inner conductor acts as a guide for the EM energy produced by the network analyzer while the outside conductor connects to the grounded shield. This fixture is then split into two halves to allow the inclusion of the test samples as shown by Figure 3-4.

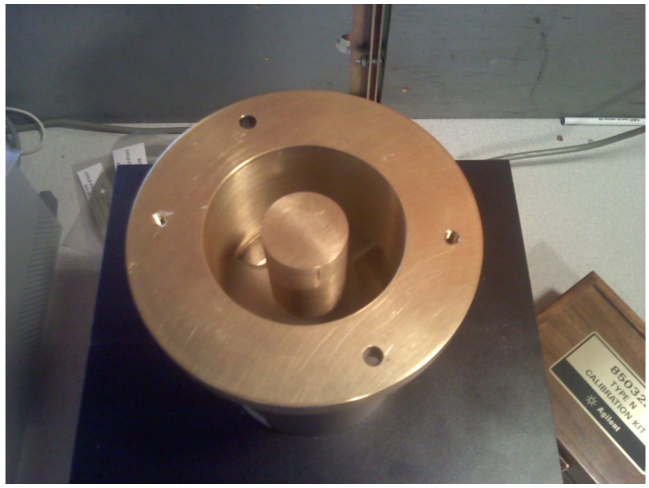

Figure 3-3: Inside structure of EM-2107A

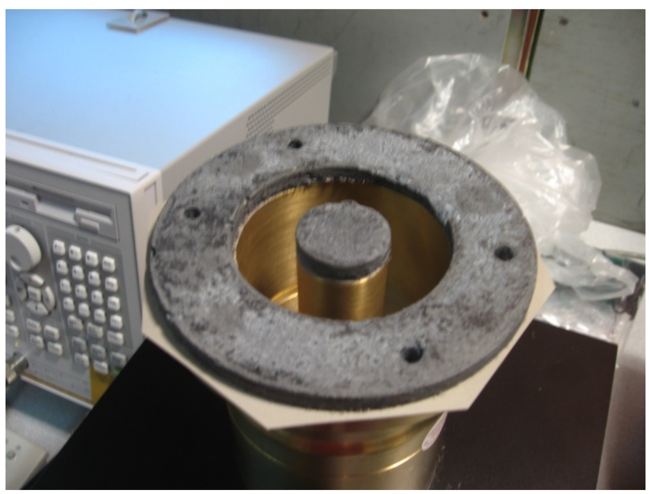

Figure 3-4: Test fixture with test sample in place

One important consideration for the use of the test fixture is its frequency range. Even though the network analyzer has the ability to scan frequencies ranging from 300 kHz to 2 GHz, the test fixture is designed to measure SE between only 30 MHz and 1.5 GHz. This means that sweeping the entire range possible is outside the scope that the fixture is intended to be used. To this end, we needed to verify that the measurements could still be considered useful below 30 MHz since the standard we wish to meet requires attenuation measured as low as 10 kHz. The dynamic range (DR) of the test fixture can be seen in Figure 3-5. The dynamic range presented here is calculated using measurements collected from two standard test specimens that came with the fixture and constitute a set that act as an electrical open and an electrical short. It is clear from Figure 3-5 that the fixture is designed for the range of 30 MHz to 1.5 GHz. Below 30 MHz, there is a steady decrease in DR, and above 1.5 GHz the fixture becomes much less reliable. The goal of Small Sample Testing is not to get an accurate SE reading of the conductive concrete, so the limit on low frequency DR is not important and the test fixture can still be of use to compare the contribution of different mixtures.

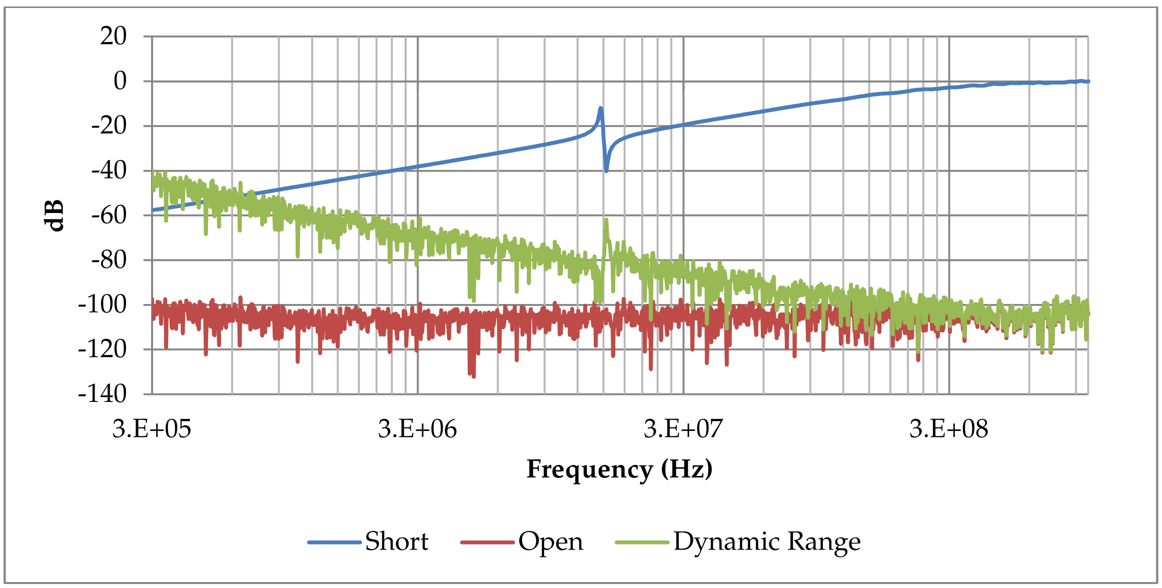

Figure 3-5: Dynamic Range vs. Frequency of EM-2107A

3.2.2 Sample Sets

Samples to be tested using the fixture are produced in sets of two specimens. One specimen is considered a reference load, or collar. The reference load is made of two pieces, one that matches the inner conductor, resembling a small disk, and one that matches the outer conductor, resembling a collar. The second specimen is considered the experimental load, or disk. This piece is a solid disk with the same diameter as that of the outer conductor of the test fixture. Figure 3-6 shows an example of a reference load on the left and an experimental load on the right. The measurement of EM energy passing through the disk load with that of the collar load subtracted gives the attenuation to the energy passing through due to the material being tested. In this way, the only energy that matters in the measurement is what is able to pass completely through the thickness of the material.

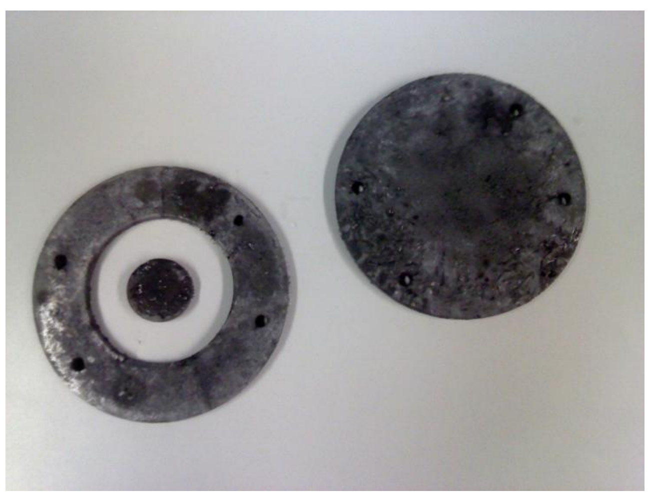

Figure 3-6: Example reference (left) and experimental (right) sample loads

3.2.3 Sample Preparation and Sealing

It is natural for concrete surfaces to have a certain amount of roughness and inconsistency. The test fixture is designed to test samples that have perfectly smooth surfaces and consistent thickness throughout. This situation proves to be problematic for producing reliable and accurate measurements. Because of this, the sample specimens must first be prepared after the concrete has set. The first step to this process is to use an angle grinder with a masonry disk to get rid of large imperfections and better level out the surface. The second step is to use a lapping table to get the surface as smooth and level as possible. Even after using the lapping table, the surface of the specimen is still somewhat rough and pitted. Further smoothing is possible but much too labor intensive for the final result. In the end, the surface of the concrete will still not be smooth enough to accurately match the surface of the test fixture. Because of this, the use of gaskets was investigated. Two choices of gaskets were considered to meet the specimen and fixture surfaces, dielectric and conductive. Either type of gasket would be a viable candidate, though ultimately the dielectric option was eliminated. Dielectric gaskets tend to be harder and less pliable than conductive materials. In this configuration, the gasket would be considered to be extending the surface of the specimen to mate with the fixture. Instead the conductive gaskets seen in Figure 3-7 were chosen. These elastomer gaskets are highly conductive and made of silicone impregnated with silver, nickel, and other conductive materials. The gasket material was cut in such a way that it will only make contact with the inner and outer conductors of the fixture. This alleviates any possibility that the gaskets will interfere with sample measurements. The softness of the gaskets allows them to conform to the surface of the concrete samples and greatly increases the surface area in contact with the test fixture surfaces, as seen in Figure 3-8.

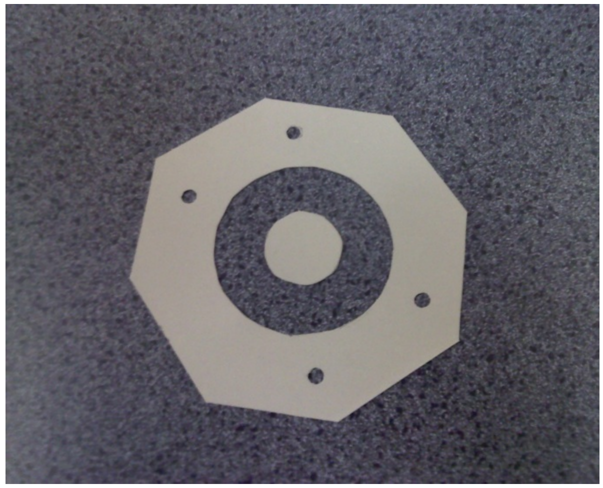

Figure 3-7: Elastomer gaskets cut to fit test fixture surfaces

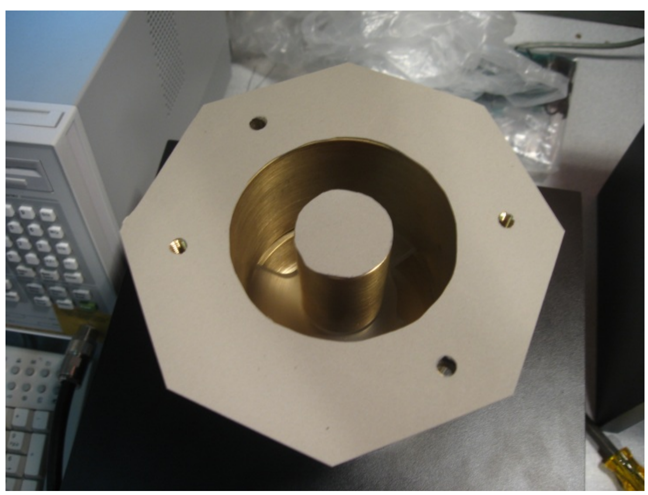

Figure 3-8: Test fixture with gaskets placed to mate samples

3.3 Large Slab Testing

Large Slab Testing is the second step in determining a viable mixture of conductive concrete for EM shielding. This test gives a better idea of how the concrete will react to EM energy and how effective it can be at attenuating it. Much like the Small Sample Testing, the slab testing method provides important data at what can be considered a low cost of materials and labor. One large advantage to using slabs over the small samples is that we can adhere more closely to the testing methods outlined by MIL-STD-188-125-1.

This method of testing allows the use of larger slabs whose properties will act much more like those of a structure made with conductive concrete. To test these slabs, a new system for testing had to be considered. Under normal circumstances, a conductive material to be tested can be placed over an aperture created in a RF (radio-frequency) shelter. However, in the case of conductive concrete, it is not as easy to mate with a conductive surface as a metal plate or something of similar construction. The thickness of the concrete also creates an issue with the most common setups, because they rely on thin, highly conductive samples much like what is used with the EM-2107A for Small Sample Testing. To cover an aperture large enough to be useful and allow the passing of a wide range of frequencies, the concrete slab must be thick enough to stay together. This requires then that the slab be of significant thickness as well as length and width. Because of the density of concrete, the weight of the test slabs presents another impediment to building a testing method. A wire mesh shelter cannot support the extra weight without a large amount of reinforcement.

For this round of testing we were fortunate enough to be allowed the use of a mobile RF shelter. This shelter is built of steel plating and is about 8' wide by 8' tall by 16' long (Figure 3-9.) To prepare the shelter for use, the first step was to verify that it had enough SE at the military standard frequency range to easily gauge how much SE is provided by the concrete slabs. This was accomplished by using a system called PAMS (Portable Attenuation Measurement System) to determine where weak points were present in the shield. PAMS consists of a transmitter and receiver pair of handheld devices, seen in Figure 3-10 [22]. PAMS measurements yield the path loss between the two devices at a wide range of power levels from +30 dBm transmitting to -120 dBm on the receiving end, giving the total dynamic range of 150 dB.

The measurement procedure beings with a free-space calibration performed at a distance of 10 feet between the transmitter and receiver. This calibration allows for a zero point to be set on the receiver, showing the difference readout from the nominal value. Once this has been performed, the transmitter is setup outside the shelter and the receiver is taken inside the shield. Once the shield is sealed, the receiver can be used to "sniff" around the seams and other areas of concern within the shelter. Areas that show a lack of shielding can be reinforced using copper tape to seal along seams or possible cracks in the steel shielding as shown by Figure 3-11.

Figure 3-9: RF shelter used in Large Slab Testing

Figure 3-10: PAMS setup used for detecting RF leaks

Figure 3-11: Copper tape used to seal RF leaks in shelter

Once the structure has been checked for RF leaks, it must then be tested to ensure that it provides an appropriate level of SE above what is expected to be seen from the conductive concrete slabs. In this case, the shelter must show a level above that of the desired SE curve produced for MIL-STD-188-125-1 shown in Figure 2-1. After the shelter's initial SE was verified, it could then be modified for use in Large Slab Testing. The size of slabs was set to be about 2 feet by 2 feet, due to weight and ease of use considerations, a square of that size was removed from the shelter's outer skin. This size was also deemed appropriate due to the spacing of wall studs at approximately 12 inches. A larger slab size would require cutting through multiple supports, which would reduce the strength of the structure and is not desirable due to the heavy weight of the test slabs. With the outer skin removed, two L-shaped shelves were welded to the bottom as well as the top of the square hole. These two shelves support the mounting of test slabs, as seen in Figure 3-12. The two shelves are then drilled with holes to allow for the placement of mounting connectors. In this case we used 3/8” all-thread with appropriately sized washers and bolts to hold standard wood 2”x4” boards in place across the slabs as shown by Figure 3-13.

Figure 3-12: Square hole cut in shelter skin with mounting shelves installed and test port

Figure 3-13: Concrete slab mounted to outside of shelter

The final step in preparing the RF shelter for use in Large Slab Testing was to cut a 4-inch circular test port in the exposed area of the shield, seen in Figure 3-12. This port was appropriately cut in the center of the exposed area allowing about 10 inches of shield for the concrete slabs to make contact with the structure. The desired thicknesses for tests slabs were 3, 6, and 12 inches. A ten-inch allowance on either side of the test port is considered adequate to disallow leakage through the sides of the concrete which would have greatly reduced the attenuation observed. The desired path for the transmitted energy is through the face of the concrete slab at a perpendicular angle to the face. If the allowance to each side of the test port was significantly smaller than the thickness, EM energy would be able to pass through the concrete with much less attenuation than would be afforded through the thicker parts of the slab. The setup used for testing in this case helps to alleviate this possibility.

The basic setup use for this testing method consists of a transmitting RF source placed on the outside of the shelter directed towards the test port and a receiver placed inside the shelter to measure the strength of the signal penetrating through the test port. By receiving on the inside of the shelter, we are able to better isolate the measurements from outside noise. This improves the dynamic range of this system by lowering the noise floor with the help of the RF shelter. By placing the transmitting source outside the test port, we can take measurements that describe the amount of attenuation due to placing materials over the test port. By comparing the received power with a test material in place to that of an open test port, we are able to calculate a rough estimate of the SE, or relative attenuation in this case. Much like the measurements taken in Small Sample Testing, these results are more of a comparable nature than true SE figures.

3.3.1 Test Setup

The test setup used for Large Slab Testing consists of three main systems: RF shelter, transmitter, and receiver.

The transmitter side of the test setup is placed on the outside of the shelter. This system consists of four main parts: signal generator, switch bank, amplifiers, and antennas. The signal generator provides a sine wave at the desired testing. To satisfy the requirements of the HEMP standard, the selected signal generator must have a range of at least 10 kHz to 1 GHz. For this testing, the SMB100A RF signal generator from Rohde & Shwarz was used. This signal generator has a range of 9 kHz to 6 GHz. The output signal from the generator is sent into a bank of RF coaxial switches, in this case the SC1000M1 RF Controller from Amplifier Research (AR). These switches are used to determine which amplifier is used as well as which antenna is active. A diagram of the coaxial switches and their connections can be found in Figure 3-15.

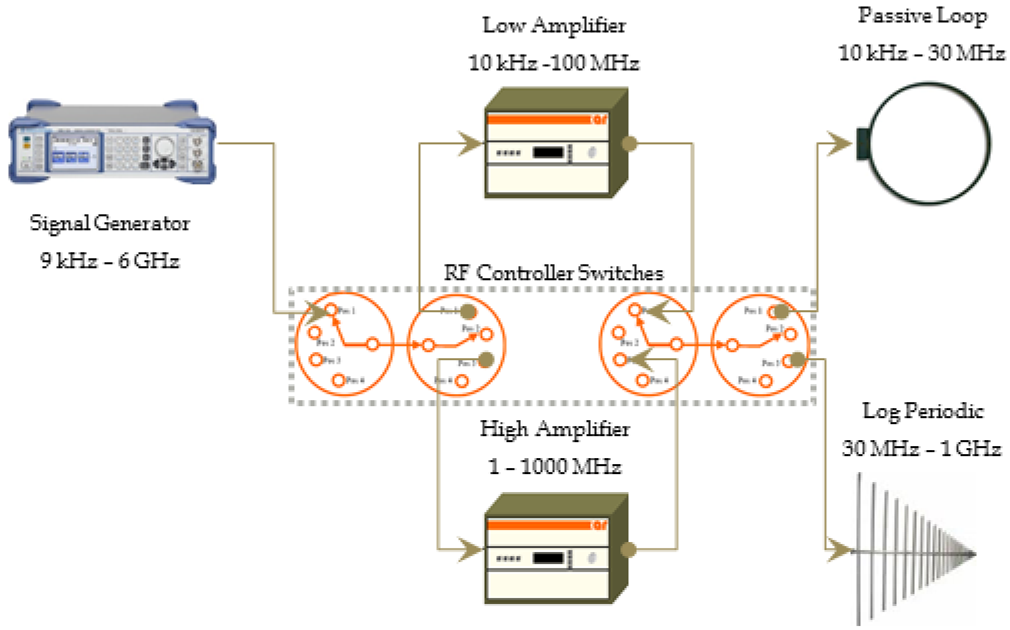

Figure 3-14: Switch connections for transmitter system

Figure 3-14 shows that for this transmitter system, two amplifiers and two antennas are utilized. Both the amplifiers and antennas are used to span different frequency ranges of the measurement spectrum. The signal in the lower frequency range is amplified using a 150A100B power amplifier from AR. This amplifier is rated at 150W across the frequency range of 10 kHz to 100 MHz. Referring to the switch configuration above, it can be seen that this amplifier is then connected through to the passive loop antenna for transmission. Per MIL-STD-188-125, the passive loop antenna is used to transmit signals in the frequency range of 10 kHz to 30 MHz. The passive loop establishes a magnetic field at these lower frequencies, while the higher frequency signals are transmitted as electric fields using a log periodic antenna between 30 MHz and 1 GHz (Figure 3-15). For this frequency range, a second amplifier is needed better matched to the entire range. The 30W1000B amplifier from Amplifier Research, with a range of 1 MHz to 1 GHz, was used. This amplifier has a lower power rating at 30W.

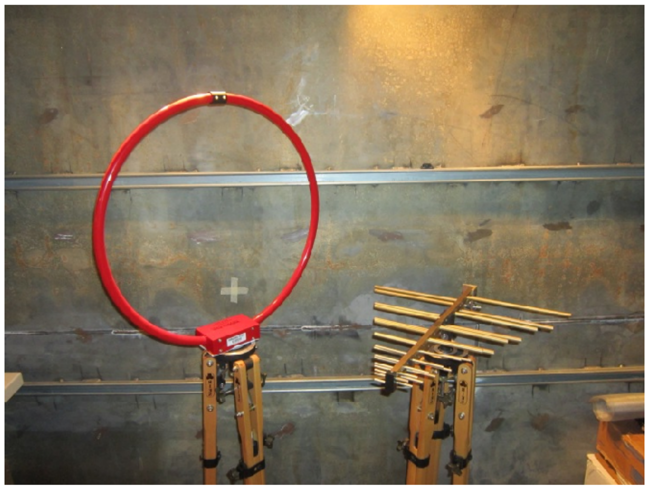

Figure 3-15: Passive loop, left, and log periodic, right, antennas

The receiver side of the testing system is very similar to the transmission side. Matching antennas are used on both sides of the system. In much the same way as the transmission side, the antennas are connected to an identical set of switches to enable the selection of signal to be received. These switches are then connected to a spectrum analyzer to take a reading of the power level received. For this test setup, the N9010A spectrum analyzer from Agilent was used in the measurements. Since this side of the test system is independent of the transmission side, the spectrum analyzer must be tuned to the desired frequency for each of the individual test frequencies. This creates a very timeconsuming process that could be expedited by computer control of the entire test system. A diagram of the entire test system is seen below in Figure 3-16.

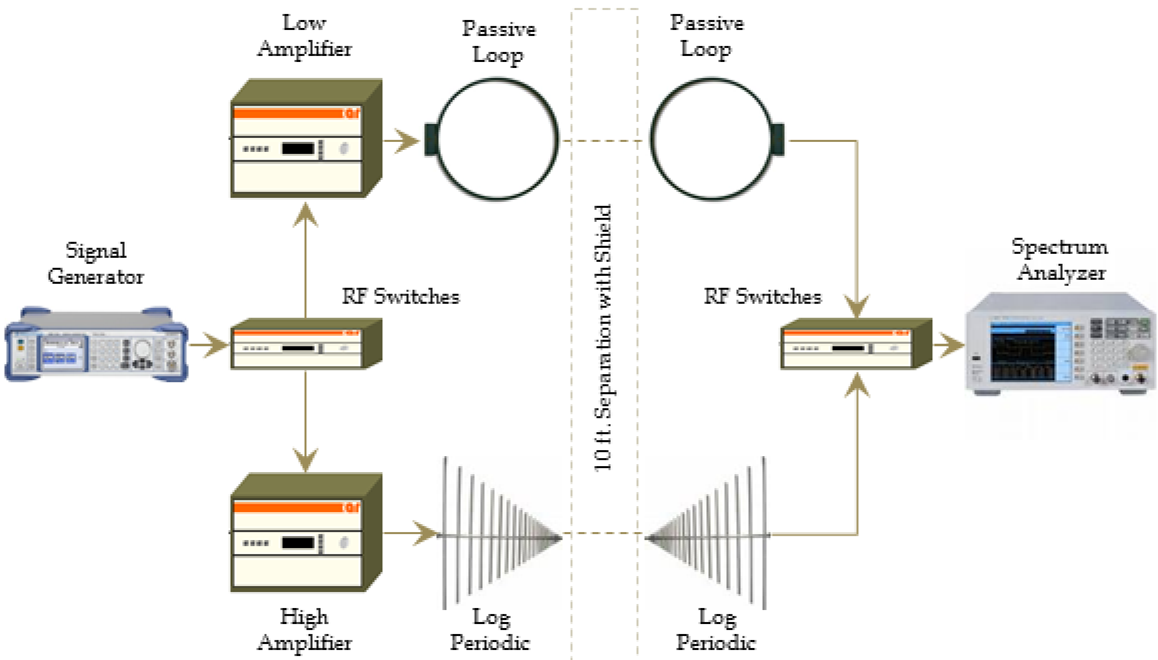

Figure 3-16: Large slab test system

3.3.2 Sample Slabs

Over the course of large slab testing, several thicknesses of various combinations of the desired materials were produced to judge the effect different mixtures would have on attenuating EM energy. The first test slab, seen below as Figure 3-17, was a simple slab of 3in. thick using steel fibers and carbon powder in the normal concrete mixture. This was cast to keep in line with the first set made for small sample testing. This slab presented issues almost immediately. Mating the straight concrete surface with that of the steel shelter proved problematic. There were variations in the relief of the concrete surface that could not be accommodated by any force that could be applied. To combat this issue, conductive gaskets were affixed to the RF shelter test port in the manner seen in Figure 3-18. However, due to the large difference in conductivity between conductive concrete and steel, a better method of mating the surfaces was deemed necessary.

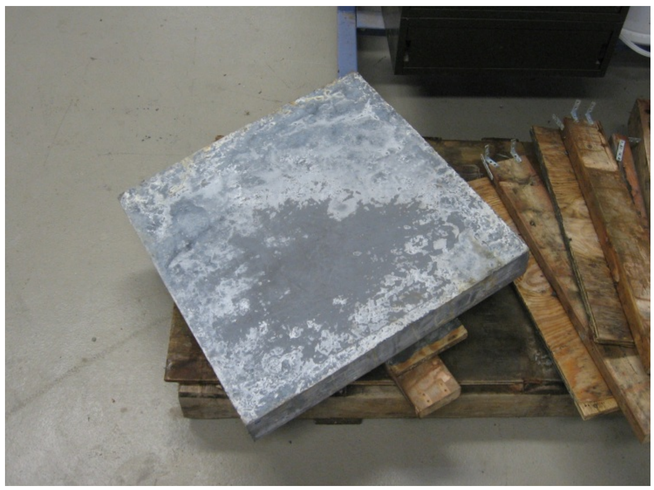

Figure 3-17: First slab of steel fibers and carbon powder

Figure 3-18: Gaskets on RF shelter test port

In order to achieve a better seal between the conductive concrete and RF shelter, the new slabs of conductive concrete were poured directly on a steel plate made to match the dimensions of the slab. Each steel plate was cut with a 4-inch hole in the center to match the test port of the RF shelter. In this configuration, the plate provides a good contact between the concrete and shelter by ensuring a flat surface with good conductivity to match the shelter. Figure 3-19 shows the tight bond between the conductive concrete and steel plate. To calibrate the test system with this configuration, a steel plate with a 4-inch hole was placed over the shelter test port and sealed using conductive gaskets. This provided the baseline reading for signal strength that could pass into the shelter. The ability of the conductive gaskets to seal properly was tested by placing a full steel plate over the test port while making contact with all the gaskets. This test showed that with the steel plate in place, the shielding effectiveness of the shelter was the same as it was before the test port was cut.

Figure 3-19: Slab with steel plate

After several rounds of testing, using the 4-inch test port proved to be an issue in terms of the dynamic range of the test system. Because of the signal attenuation that was attributed to the test port, a new design for test slabs was created. The succeeding slabs were produced in the same manner with the steel plate for sealing, but they also included a domed cavity as seen in Figure 3-20. The cavity allows for a small antenna to be inserted directly into the conductive concrete slab as seen in Figure 3-20. Using this smaller antenna, a more accurate measurement of the relative attenuation can be taken while not losing the desired EM seal between the shelter and concrete slab. One drawback to this method of construction, however, is that the test configuration no longer meets MIL-STD-188-125-1.

Figure 3-20: Slab with steel plate and domed cavity

3.3.3 Issues with Port

The size of the test port proved to be a large impediment in taking measurements over the frequency range required by MIL-STD-188-125-1. With the test port sized as it is, there is a large amount of attenuation already present in the frequencies below 100 MHz. This is due to the wavelength of the RF signal being too large for the port. Because the test frequency range reaches as low as 10 kHz, cutting a test port large enough to accommodate the wavelength is not feasible. Increasing the size of the test port above four inches would require the area of the test slabs to be increased as well. This presents problems to the test system as well, due to the increase in weight that accompanies the size of the slabs. One alternative to meet the weight and size requirements for a larger test port would be to cut it in the ceiling of the structure rather than a wall. This would allow for a much larger port to be cut since the slab would no longer have to be supported on the side of the structure. Doing this would create an issue with antenna placement on the outside of the shelter though, seeing as how the antennas would need to be suspended above the shelter. With the difficulties presented in altering the test port seeming insurmountable, the original size was deemed adequate for comparative testing. If measurements were desired to be taken over the entire range with great accuracy another system would need to be devised, however for the purpose of comparing slab composition it is within reasonable ranges. The dynamic range of the test port is seen in Figure 3-21. It is easy to see that the DR below 100 MHz is limited by the size of the test port.

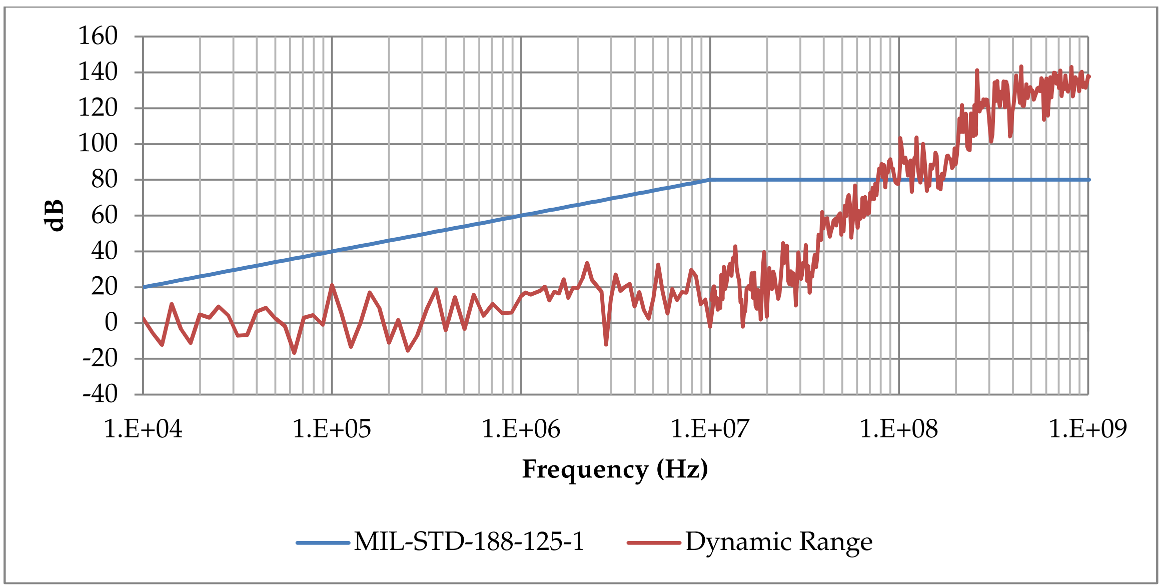

Figure 3-21: Dynamic Range vs. Frequency of 4-inch test port

3.4 Summary

Testing of conductive concrete can be conducted in two stages to facilitate the determination of a useful mixture: Small Sample Testing and Large Slab Testing. Small

Sample Testing yields useful comparative information of how the individual components in the mixture will affect the overall shielding. Large Slab Testing gives a more accurate measurement of how the conductive concrete will attenuate EM energy. Combining these two methods enables the development of a conductive concrete mixture that will yield promising results for EM shielding.

CHAPTER 4 - Results

4.1 Introduction

Thus far the results of Small Sample Testing and Large Slab Testing with conductive concrete have been very promising. The results of the Large Slab Testing validated the method used with the small concrete samples. Observing the EM attenuation of conductive concrete under actual testing has demonstrated the experimental process that was developed for gauging the effect of different components on the final concrete mixture. Much in the same way, the Large Slab Testing is an experimental method at its core, but further testing on a larger scale will allow for proper standards to be used and should prove the validity of this testing method. The following results demonstrate that the mixture derived from Small Sample Testing is on the right track further standardized testing is warranted.

4.2 Small Sample Testing Results

The results obtained from Small Sample Testing validate the expected attributes of several different components used in the conductive concrete mixture. The reflective nature of the steel fibers as well as the absorptive properties of the taconite aggregates seem to show rather prominently in the tests that were undertaken. Several sets of samples were created using various combinations of the desired components to determine a mixture that performed well at attenuating EM energy. Multiple mixtures were used to determine not only the nature of the components used but also what effect attributes such as quality and quantity of the selected additives had on the conductive concrete. With respect to the steel fibers, the amount of fibers used was one way to vary their effect, as well as fibers that were larger, longer, and processed differently. For the taconite, the concentration of taconite aggregates was varied greatly as well as a foray into how much the purity of the taconite affected its contribution to the concrete mix. In addition to varying the components of the concrete, several thicknesses were tested as well. This was in an effort to extrapolate the difference thickness would make on the effects of different concrete components. To this end, samples were produced in thicknesses of 0.25 in, 0.5 in, and 0.75 in. These wide-ranging variations gave plenty of possible combinations to be considered for further testing. After exhaustive Small Sample Testing a promising mixture was determined and was then used in Large Slab Testing.

It is very important to note that the results reported in this section cannot be taken as actual SE measurements even though that is the intent of the EM-2107A. It is noticeable in the data recorded that the limits of the test fixture are stretched to accommodate testing of concrete samples. The test fixture is normally used to judge the shielding effectiveness of very thin material samples. The thicknesses of concrete used are much greater than what would normally be used for testing. To this end, the results of Small Sample Testing must be regarded as comparison between the various mixtures and not as a measure of how effective the concrete would be.

It is easily observed in Figure 4-1, that traditional concrete with no added conductive components creates little to no attenuation in reaction to EM energy. This gives a good baseline for comparison of the results obtained from conductive mixtures. Any change in the amount of energy passing through the concrete or even in the general shape of the frequency spectrum can be attributed to the components introduced in the concrete mixtures.

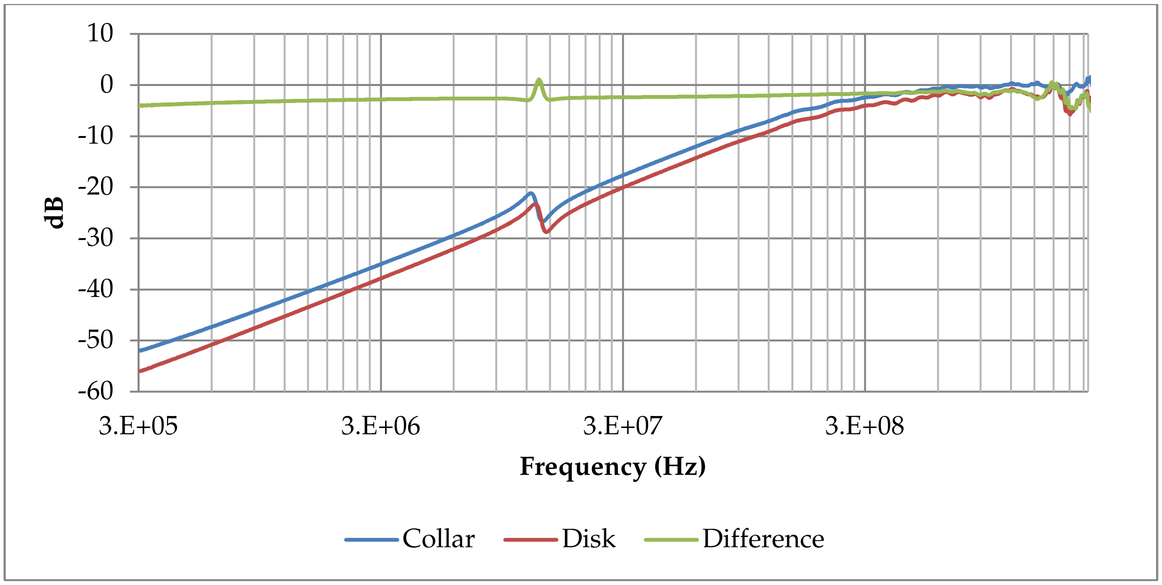

Figure 4-1: S21 vs. frequency of 0.25 in. concrete with no conductive components

The first conductive mixture investigated in testing was the traditional conductive concrete mixture developed for use in deicing roadways and other surfaces. This mixture consists of normal concrete but incorporates steel fibers and carbon powder to greatly increase its conductivity. The conductive mixture was further enforced by the inclusion of a greater quantity of steel. From Figure 4-2, it is easy to see that the effect of steel fibers in the lower frequencies below 100 MHz is very noticeable. This effect is very evident in the creation of the sloping line, which can be compared to the relatively straight line in the same region of the regular concrete mixture.

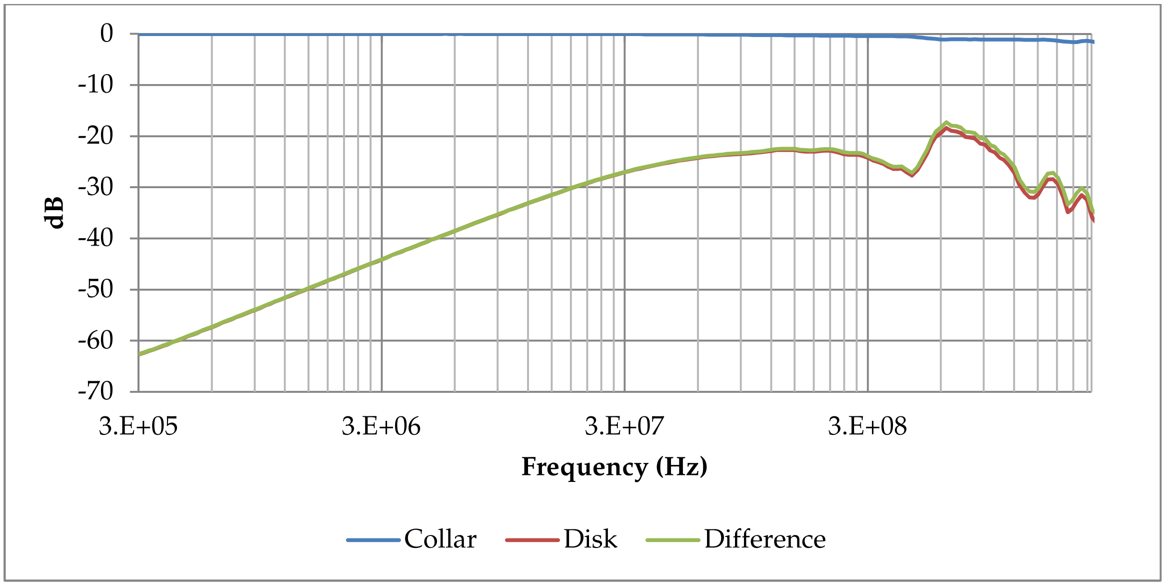

Figure 4-2: S21 vs. frequency of 0.25 in. concrete with steel fibers and carbon powder

The results presented in Figure 4-3 are of great interest. Prior to this testing little was known as to the effects of taconite in the concrete mixture. From previous research, it was known that taconite has good absorptive properties at high frequencies but it was not known how this would improve the ability of the concrete to absorb EM . The effect of the taconite is seen in the frequencies above 30MHz and shows a steady drop as the frequency increases. This attribute would be very advantageous in a conductive concrete mixture used for shielding. For Figure 4-3, a 0.5 in sample was used to increase the absorption with a larger. By comparing the results in Figure 4-2 and those of Figure 4-3, it can be concluded that the positive effects caused by steel fibers and taconite should enhance the shielding properties of conductive.

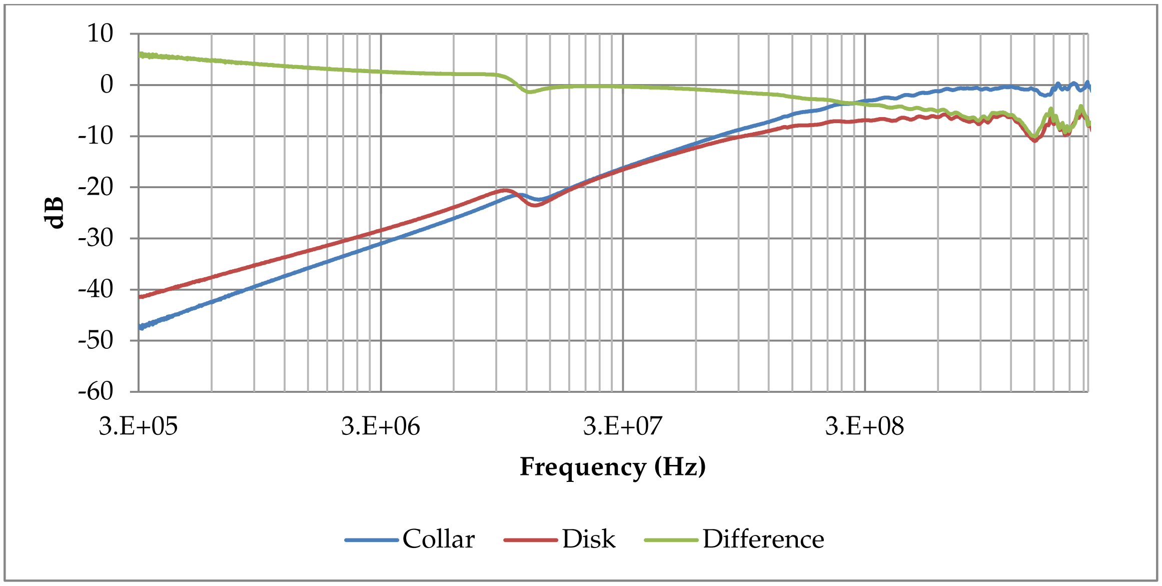

Figure 4-3: S21 vs. frequency of 0.5 in. concrete with taconite aggregates

After obtaining the very promising results of the steel fiber mixture as well as the taconite mixture, it was natural to investigate the total affect created by including both components in one conductive mix. The results of this combination are found in Figure 4-4. In this graph, the effects of the components are seen to create a plot where the component attributes of reflection and absorption do work together across the frequency range. The telltale slope of the plot from the low end of the spectrum to around 20 MHz displays the reflective area quite well, while the drop off above 100 MHz is indicative of the absorption area that was observed independently. This shows that the combination of the conductive components performs just in the way that was expected. Since this mixture shows great promise, it is the one to be used in further testing in the method described as Large Slab Testing.

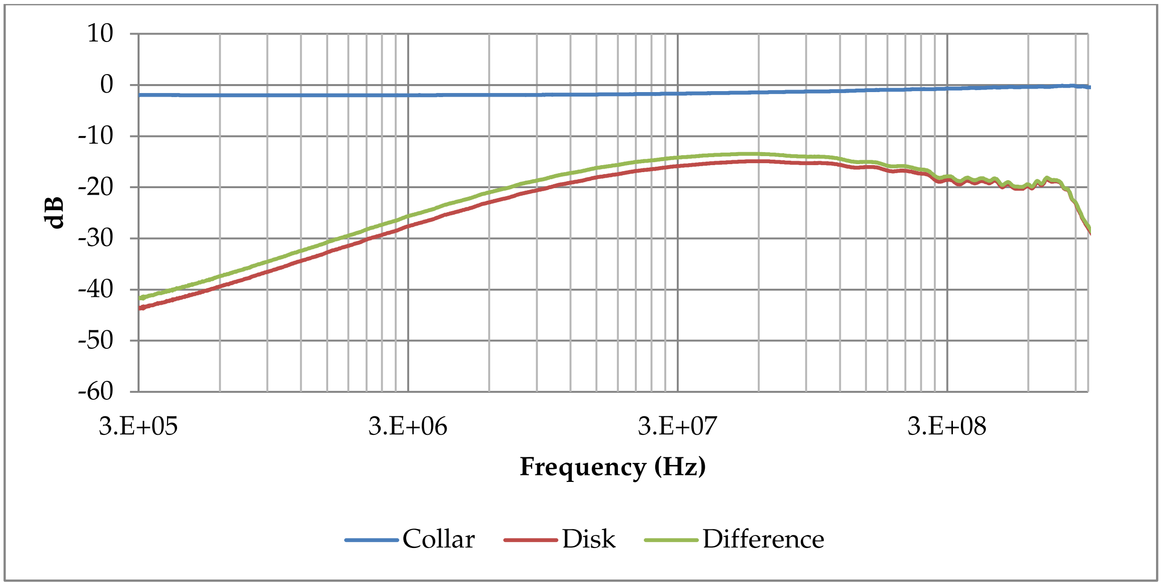

Figure 4-4: S21 vs. frequency of 0.25 in. concrete with steel fibers and taconite

Another important result from Small Sample Testing was the indication that thickness of the concrete should make a large difference in how well it can attenuate EM energy. Figure 4-5 displays the difference that can be seen between samples with different thicknesses containing carbon powder, steel fibers, and taconite. This data was recorded for each set of small samples cast, but was most important in regards to the mixture deemed most promising. The effect of the thickness is very noticeable across the entirety of the frequency spectrum. The increase in the reflective area can most likely be attributed to a greater amount of fibers being connected inside the concrete, creating more reflections and a larger aperture depth to the fiber mesh. The amount of attenuation also increases due to a higher amount of taconite being used to create absorption in the higher frequency range. Another important attribute to notice is that the amount of absorption seems to reach a maximum as the thickness of the sample increases. As the amount of steel fiber grows denser in the sample, the amount of reflection increases as well, showing that a more dense mesh of steel fibers enhances this attribute of the conductive concrete.

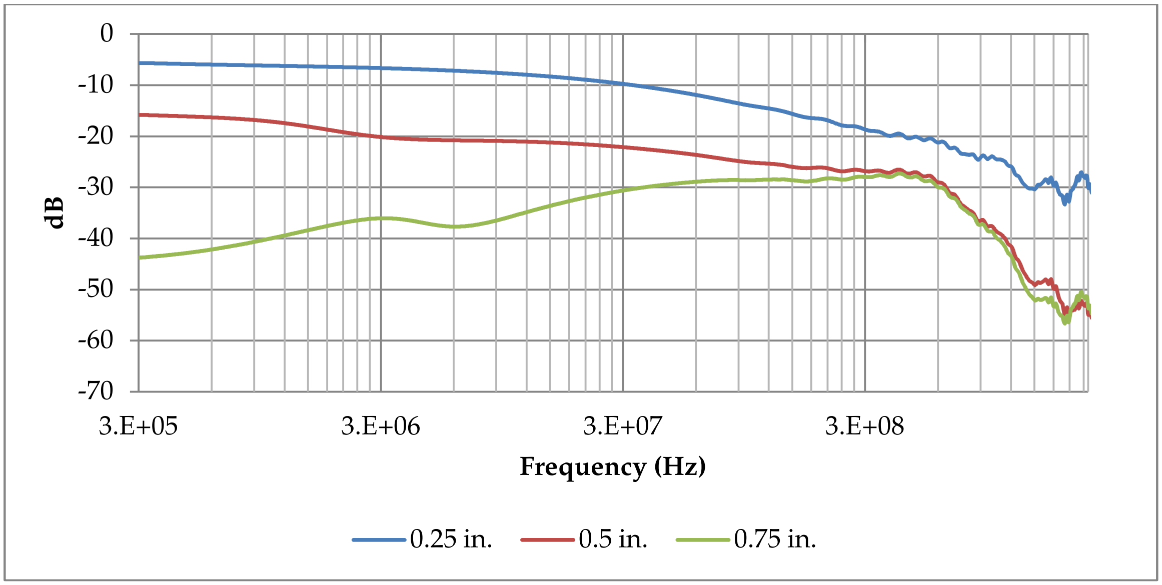

Figure 4-5: S21 vs. frequency of several thicknesses of small samples

4.3 Large Slab Testing Results

The objective of Large Slab Testing is to get a more realistic look at how well a particular conductive concrete mixture will work to shield against EM energy. This testing is done in a manner that is much in line with traditional testing methods outlined in MIL-STD-188-125-1. Because this type of testing utilizes much thicker samples that are more like a concrete wall that would be used in full-scale testing, the results can be used to make a strong argument for further research into certain conductive concrete mixtures. Due to the constraints of the test port and the effect this has on the dynamic range of the system used, the data recorded here should be considered as a measure of the relative attenuation, and not SE under standardized tests. The most important aspect of this testing was to show a connection between the data taken in Small Sample Testing and how the conductive concrete performs in a real-world environment. Throughout the previous testing with small disks samples there was an obvious effect due to taconite and it will be shown that this positive data is reinforced through the second round of testing with larger specimens.

Several slab thicknesses were investigated for the chosen concrete mixtures. Because of the higher complexity offered by manufacturing the large slabs and the much higher cost incurred, fewer mixtures were tested using this method. The thicknesses chosen for Large Slab Testing were decided to be 3 in, 6 in, and 12 in. Larger samples become much heavier and thus harder to mount in the manner needed for this testing. Due to this issue, data for the lighter, thinner slabs is more commonly used for comparison between mixtures.

Two main mixtures were chosen for this round of testing: concrete with steel fibers and carbon powder, and concrete with steel fibers, carbon powder, and taconite. The first is once again the starting point for this testing based on the fact that it is the mixture already chosen for deicing purposes and was the first mix tested in the small sample manner. This first slab was produced at the 3 in and 6 in thicknesses. Though it has little bearing on the effectiveness of the desired mixture, this test shows that the data taken in Small Sample Testing does seem to extrapolate to how the concrete would perform on a larger scale across the desired frequency spectrum. Figure 4-6 shows the results from this test and demonstrates that Small Sample Testing does in fact give a good idea of how the concrete will perform in a real free-space environment. As expected, the frequency response shows a decent amount of attenuation above 100 MHz, about 50 dB or so, but it falls well below the standard line.

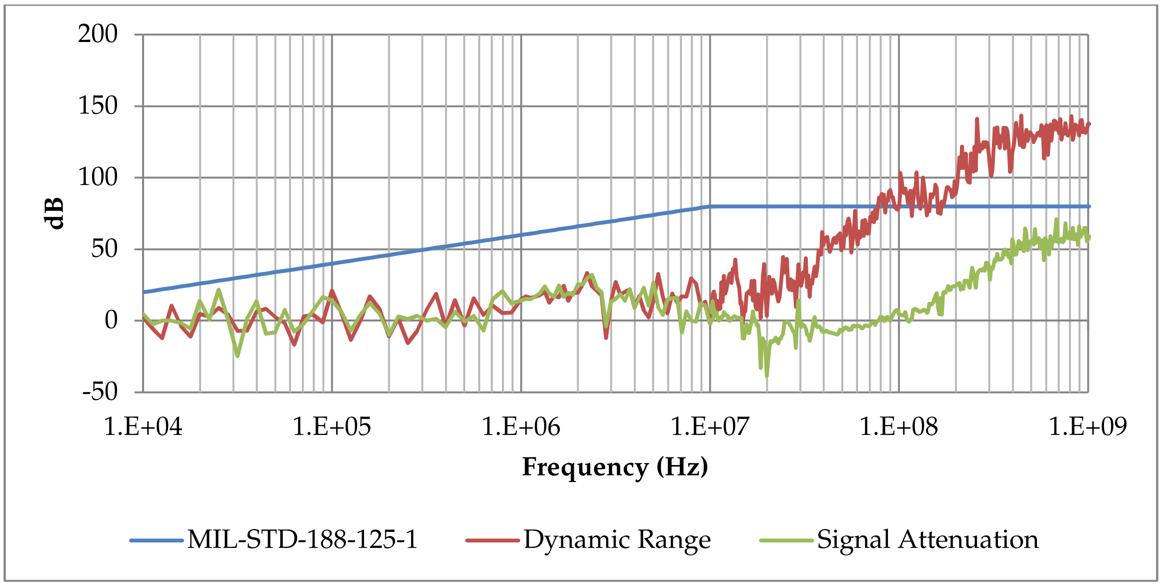

Figure 4-6: Relative attenuation vs. frequency of initial conductive concrete

The second mixture tested was the combination of steel fibers, carbon powder, and taconite determined to be interesting by Small Sample Testing. This was more or less the make or break point for using taconite as a component in conductive concrete for EM shielding. The results of testing the first slab were inconclusive for the entire frequency range due to the limited dynamic range of the test port. This is evident in Figure 4-6 by observing how the relative attenuation is buried in the dynamic range of the test configuration. Without a higher dynamic range for the system, nothing can be said about the effects of the conductive concrete components on EM shielding.

To counter the issue of test port dynamic range, a new method of pouring the concrete slabs was devised. The addition of the domed cavity in the concrete slabs, as described in section 3.2.3, proved to help alleviate this issue. This again modified the testing method in a way that does not correspond with the standardized testing outlined in MIL-STD-188-125-1, but the data recorded supported the use of smaller antennas inserted into the domed cavity. As it is seen in Figure 4-7, the small antennas, specifically the loop and rubber duck, provide a much higher dynamic range that either exceeds or holds very near the desired range. This plot also shows that the data collected in the higher frequency range, above 100 MHz, stays much the same as it was before.

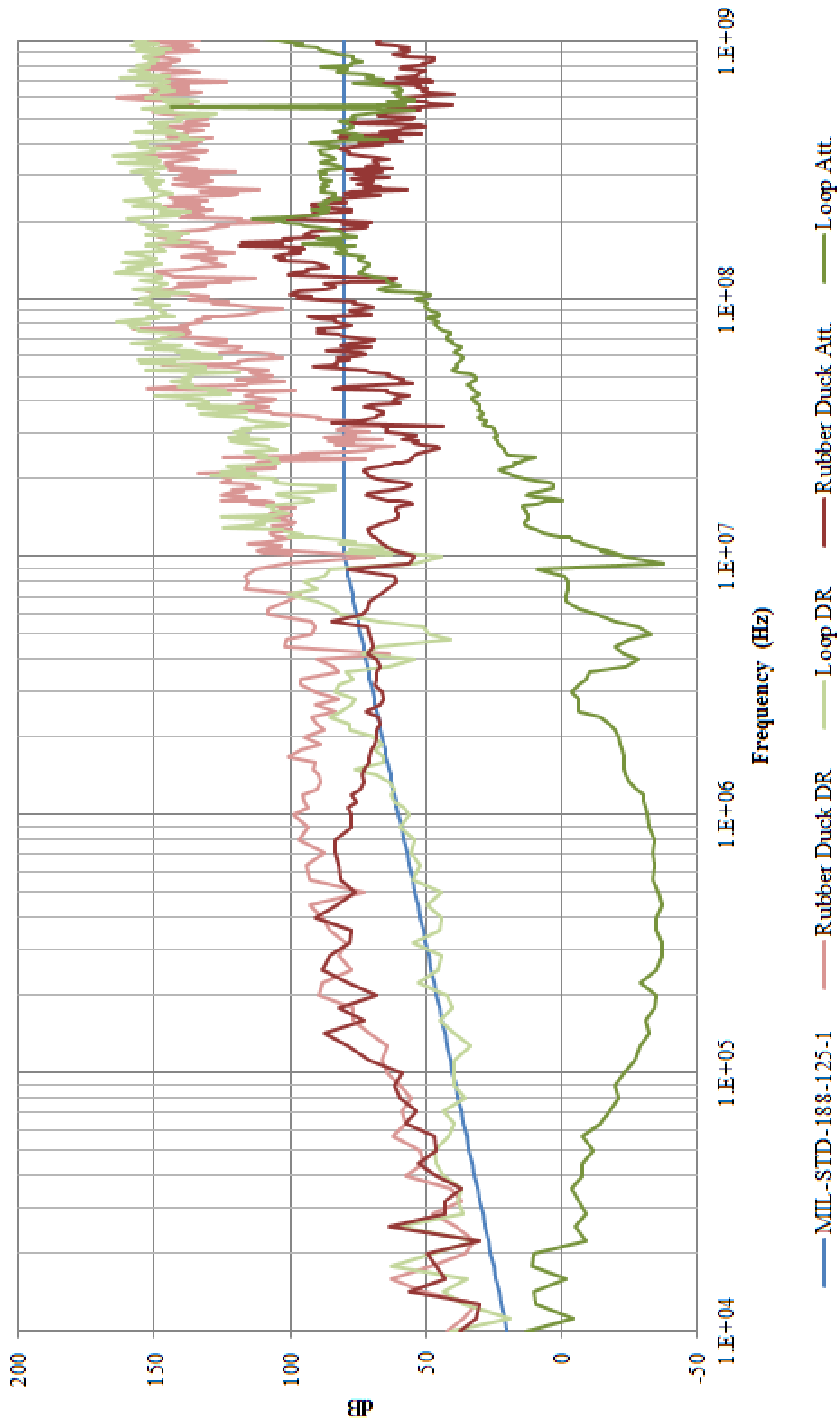

Figure 4-4-7: Relative attenuation vs. frequency of 3 in. conductive concrete slab with domed cavity

Slab of 6 in and 12 in thicknesses were produced in the same manner using the domed cavity. These results are presented in Figures 4-8 and 4-9. Comparing these two sets of data with that of Figure 4-8, it can be concluded that the increase in thickness does affect how much attenuation is produced, especially in the higher frequencies. In comparing Figures 4-8 and 4-9 however, it can be expected that at some thickness the effectiveness of the concrete plateaus. The attenuation provided at this point can be seen to exceed the military standard by as much as 20 to 30 dB above 100 MHz. The discrepancy between the results recorded using the loop and rubber duck antennas is most likely attributed to a resonance effect between the loop and RF shelter.

In order to counter the possible leakage effects between the test slab and the RF shelter, a coating of conductive paint was added to the outside edge surfaces of the 3in. concrete slab with the domed cavity. This paint coat was then connected to the steel plate on the shelter side of the slab using conductive tape. In essence, this made all but the front surface of the slab grounded to the RF shelter. The results are presented in Figure 4-10. It can be seen that isolating the front surface of the slab does indeed affect the relative attenuation. This modification helps to reduce leakage signal penetration through the side surfaces of the test slab.

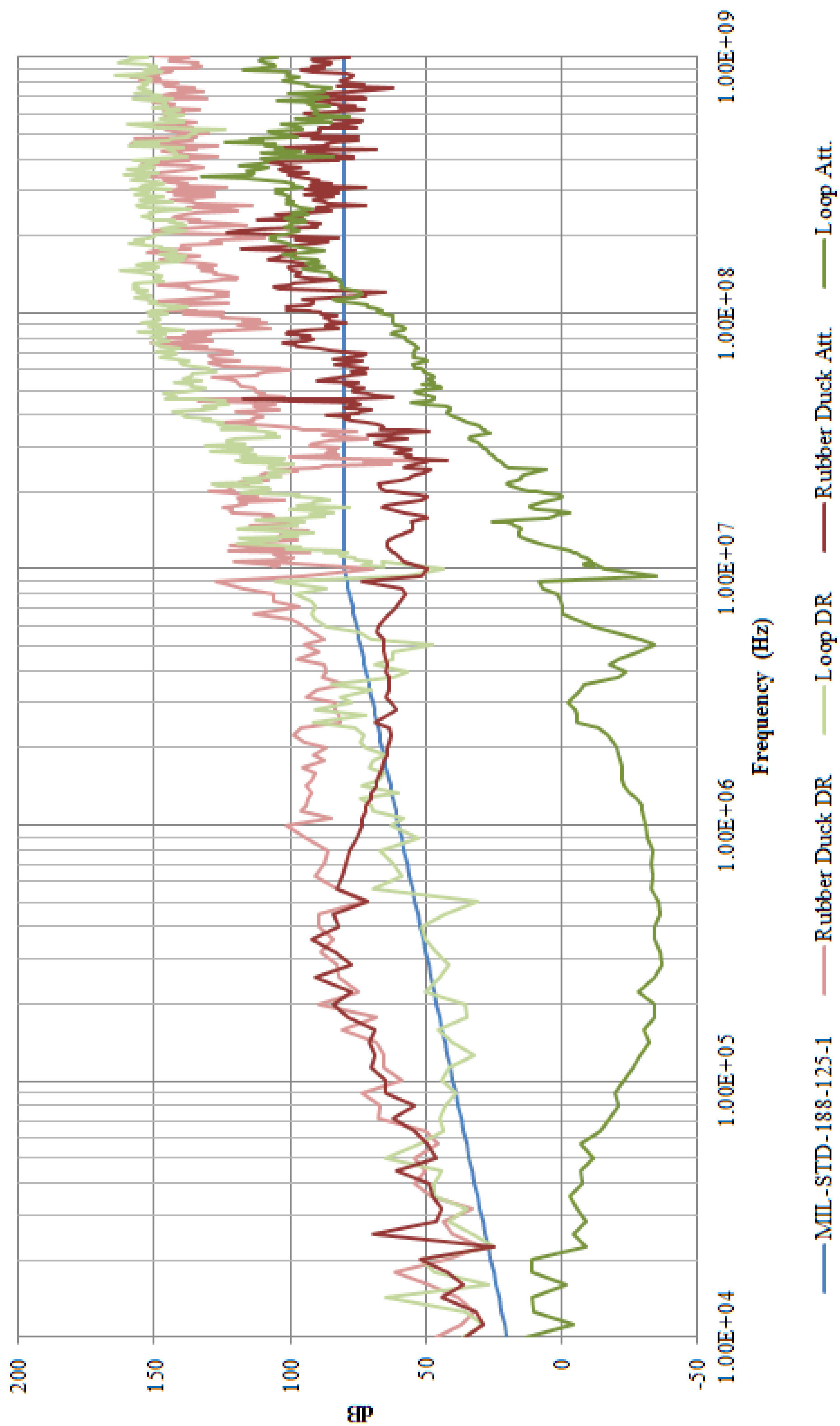

Figure 4-4-8: Relative attenuation vs. frequency of 6 in. conductive concrete slab with domed cavity

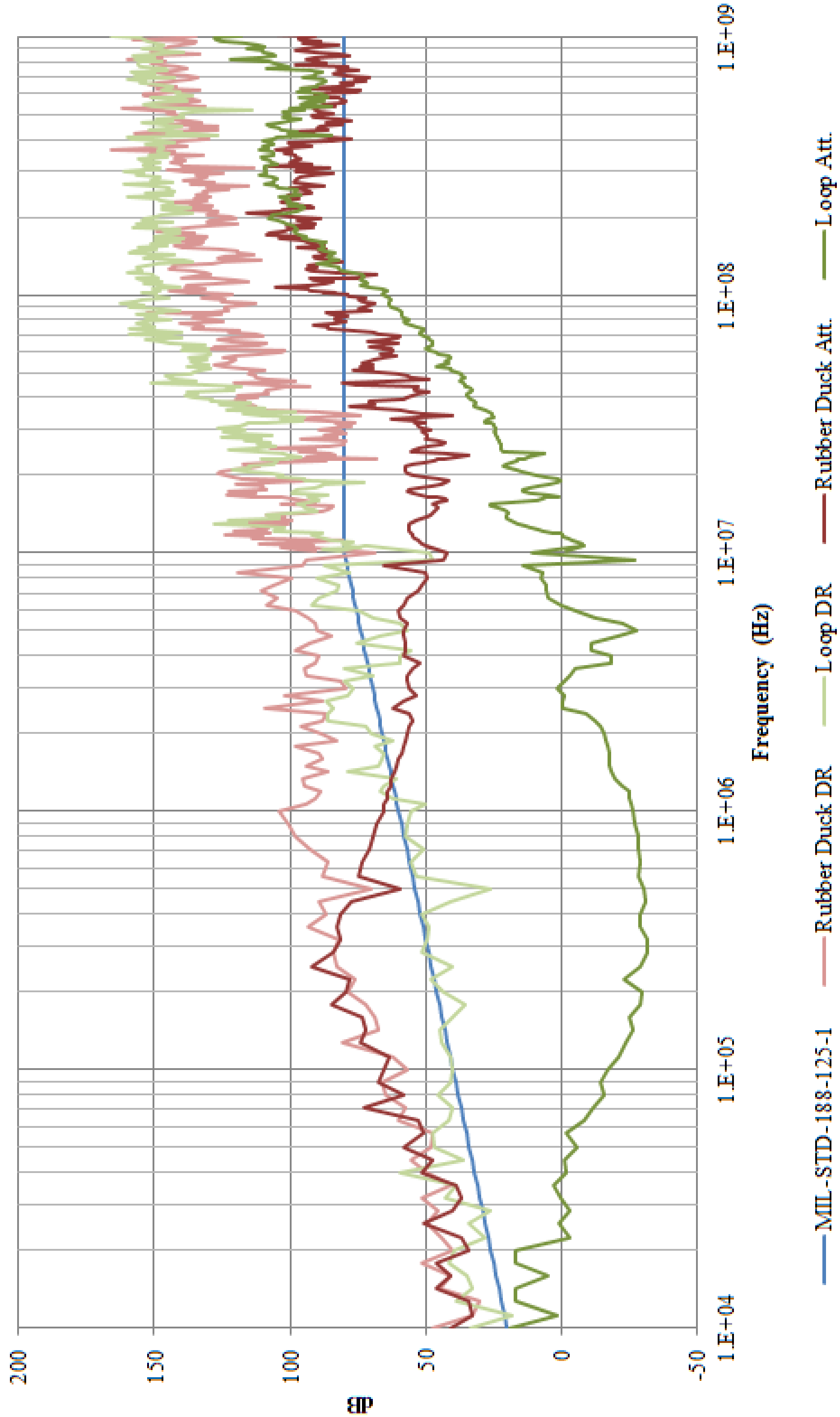

Figure 4-4-9: Relative attenuation vs. frequency of 12 in. conductive concrete slab with domed cavity

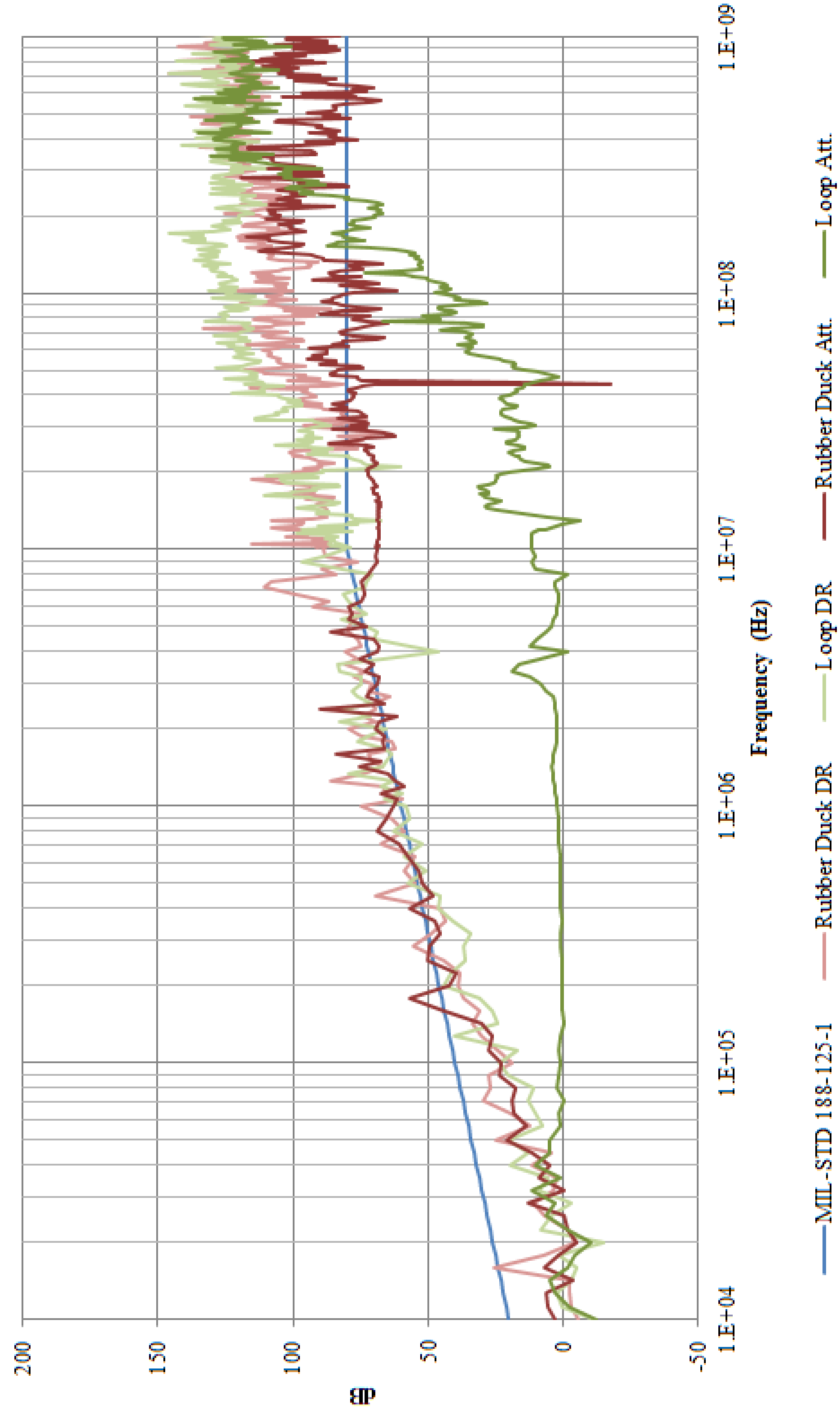

Figure 4-10: Relative attenuation vs. frequency of 3 in. conductive concrete slab with painted sides

The overall results of Large Slab Testing are very promising as to the future of conductive concrete, composed of steel fibers, carbon powder, and taconite, being used for EM shielding. They also act to validate the use of Small Sample Testing for determining the possible effect of concrete components at a smaller, more cost-effective level of testing. From the results produced here, it can be expected that conductive concrete should work effectively as a shielding.

4.4 Summary

The results provided by Small Sample Testing and Large Slab Testing help to validate the use of conductive concrete as an EM shield. Through Small Sample Testing, the effects of individual components were proven and the inclusion of taconite showed a marked improvement in frequencies higher than 100MHz. Further experiments in Large Slab Testing helped to reinforce the results of Small Sample Testing as well as demonstrating how well conductive concrete can attenuate EM energy. The result of shielding at a level of 80 dB above 100 MHz show that conductive concrete has the potential to be a promising EM shield material.

CHAPTER 5 - Conclusions

The objective for this research was to develop a cost-saving method for evaluating conductive concrete mixtures for the purpose of EM shielding along the lines of MIL-STD-188-125-1. Through Small Sample Testing, it has been shown that the effects of conductive concrete components can be observed. Using this method, it can also be determined what mixture of these components and their derivatives would make a conductive concrete that is worthy of investigation. In this case, the final mixture that was most promising was comprised of cement powder, carbon powder, steel fibers, and taconite. Previously, taconite had not been included in conductive concrete mixtures. With the most interesting mixture decided, Large Slab Testing was developed to verify the results of Small Sample Testing and to demonstrate how well the concrete would perform in more typical testing conditions. Through this testing method, it was verified that the addition of taconite aggregates did enhance the relative attenuation in the high frequency range very well, resulting in over 80 dB above 100 MHz. The absorption provided by the taconite was of greater value than previously anticipated. This testing method experienced the problem with the degradation of the dynamic range of the test setup due to the limited size of the RF shelter test port. Adding the domed cavity to the test slabs alleviated this problem and the testing results were able to demonstrate the relative attenuation of conductive concrete. By using the small test samples and large test slabs, a great deal of money and effort was saved in relation to the amount of test data collected for various mixtures and thicknesses. Investigating the concrete as thoroughly as it was, would cost a great deal more if conductive concrete rooms had been constructed in the same quantity as the test samples and slabs. These methods also saved much time in the development process as the time needed to produce the samples and slab used is much less than what is needed to build even a small structure. Overall, this research verifies the test methods that have been developed. The results encourage future research effort to develop conductive concrete as an electromagnetic shielding material with a great deal of potential in a world so concerned with electronic privacy and safety.

REFERENCES

[1] K. Casey, "Electromagnetic Shielding by Advanced Composite Materials," Kansas State University, Manhattan, KS, 1977.

[2] M. Gunasekaran, "A Simplified Low-cost Materials Approach to Shielding in EMC Applications," in *Seventh International Conference on Electromagnetic Compability*, 1990.

[3] L. Huang and S. Ding, "Experimental and Numerical Analyses of Electromagnetic Attenuation Properties of an L-Shaped Channel Constructed by Electromagnetic Absorbing Concrete," in *Third International Joint Conference on Computational Science and Optimization*, 2010.

[4] T. Shintani and M. Nakamura, "Electromagnetic Wave Shielding Building Material". United States of America Patent 5422174, 13 August 1993.

[5] G. B. Pye, R. E. Myers, M. R. Arnott, J. J. Beaudoin and P. J. Tumidajski, "Conductive Concrete Composition". United States of America Patent 6503318, 28 March 2001.

[6] Tarmac, "Electro Conductive Concrete," in *IET Seminar on Electromagnetic Propagation in Structures and Buildings*, 2008.

[7] D. D. L. Chung, "Electrically Conductive Cement-Based Materials," *Advances in*

Cement Research, vol. 16, no. 4, pp. 167-176, 2004.

[8] S. Muthusamy and D. D. L. Chung, "Carbon-Fiber Cement-Based Materials for Electromagnetic Shielding," *ACI Materials Journal,* vol. 107, no. 6, pp. 602-610, 2010.

[9] J.-M. Chiou, Q. Zheng and D. D. L. Chung, "Electromagnetic Interference Shielding by Carbon Fibre Reinforced Cement," *Composites,* vol. 20, no. 4, pp. 379-380, 1989.

[10] S. Wen and D. D. L. Chung, "Electromagnetic Interference Shielding Reaching 70 dB in Steel Fiber Cement," *Cement and Concrete Research,* vol. 34, no. 2, pp. 329-332, 2004.

[11] Z. Zhao, X. Cui, L. Li and C. Gao, "Analysis of the Shielding Effectiveness of Rectangular Concrete Enclosure," in *International Symposium on Electromagnetic Compatibility. EMC 2007*, 2007.

[12] A. Ogunsola, U. Reggiani and L. Sandrolini, "Shielding properties of conductive concrete against transient electromagnetic disturbances," in *IEEE International Conference on Microwaves, Communications, Antennas and Electronics Systems, 2009*, 2009.

[13] G. Fei, Z. Bihua, G. Cheng and C. Hailin, "Analysis of Shielding Effectiveness of Conductive Cement-based Materials in HEMP Environment," in *International Conference on Microwave and Millimeter Wave Technology*, 2008.

[14] L. Ping, Y. Qi-tao and L. Yun-liang, "Analysis of electromagnetic propagation into reinforced concrete walls by FEM-PML methods," in *International Conference on Microwave and Millimeter Wave Technology, 2008*, 2008.

[15] R. A. Dalke, C. L. Holloway, P. McKenna, M. Johansson and A. S. Ali, "Effects of Reinforced Concrete Structures on RF Communications," *IEEE Transactions on Electromagnetic Compatibility,* vol. 42, no. 4, pp. 486-496, 2000.

[16] ASTM Standard 4935-10, *Standard Test Method for Measuring the Electromagnetic Shielding Effectiveness of Planar Materials,* West Conshohocken, Pennsylvania: www.astm.org.

[17] Electro-Metrics, "2107A-New-Version," [Online]. Available: www.electro-metrics.com. [Accessed 8 July 2012].

[18] Department of Defense, "MIL-STD-188-125-1," 7 April 2005. [Online]. Available: http://www.wbdg.org/ccb/FEDMIL/std188_125_1.pdf. [Accessed 5 July 2012].

[19] D. Björklöf, "Shielding for EMC," 1999. [Online]. Available: http://www.ce-mag.com/99ARG/Bjorklof137.html. [Accessed 5 July 2012].

[20] C. R. Paul, "Shielding Effectiveness," in *Introduction to Electromagnetic Compatibility*, Hoboken, New Jersey, John Wiley & Sons, Inc., 2006, pp. 718-721.

[21] K. F. Casey, "Electromagnetic Shielding Behavior of Wire-Mesh Screens," *IEEE*

Transactions on Electromagnetic Compatibility, vol. 30, no. 3, pp. 298-306, 1988.

[22] Practical Systems Engineering: Praxsym, "PAMS-C Datasheet," 2012. [Online]. Available: http://www.praxsym.com/documents/PAMS-Cdatasheet.pdf. [Accessed 22 July 2012].