Increasing the Sound Absorption Coefficient in Concrete

Andrew S. Cheyne '22 and Hugh O. Thurman III

Department of Physics and Astronomy, Hampden-Sydney College, Hampden-Sydney, VA 23943

Abstract

Sound absorption and strength measurements were made on concrete samples with varying percentages of fly ash and rubber additives that were mixed using a 2:1:1 ratio and a water-to-cement ratio of 0.45. Absorption coefficients were measured through the standing wave ratio technique in a constructed impedance tube. Strength measurements were made through the resonant frequency and pulse velocity technique using ultrasonic transducers. Concrete samples with some of the fine aggregate replaced with either crumb rubber or 1.0-5.0mm rubber pieces had higher sound absorption coefficients across the spectrum of interest; however, neither of these samples were able to achieve the strength of the control concrete sample. In the samples with mixtures of fly ash and rubber additives, it was observed that higher percentages of fly ash increased the elastic modulus of the sample, but it did not always correspond to higher absorption coefficient except in one particular case. In our sample of concrete that contained 25% fly ash and 25% crumb rubber, the sound absorption was higher than the control and the strength values were higher than the other fly ash and rubber combination samples. From this research, it is possible to create concrete that does have a higher sound absorption coefficient through various additives. Future research will be focused on testing various other percentages of fly ash and rubber as well as other additives such as metal fibers and plant-based debris such as saw dust.

Introduction

Concrete barriers along highways in urban areas are popular because, they maintain privacy in the neighborhoods surrounding the highway and reduce the highway noise. Concrete has a sound absorption coefficient between 0.1 and 0.2 over the range of the frequencies generated by highway traffic. This low absorption coefficient protects the neighborhoods surrounding the highway but exposes the motorists on the highway to higher levels of noise. This exposure to increased noise level is a world health concern because it is leading to early hearing loss and other adverse health effects related to noise exposure [1]. Concrete has an elastic modulus that ranges between 14 and 40 GPa and a Poisson's ratio that varies between 0.11 and 0.21. These ranges are due to the variety of mixtures and curing processes that can be used to make concrete.

In this experiment we are trying to increase the sound absorption coefficient while maintaining the strength by adding additional components to the standard concrete mixture. In standard concrete there are four main components: coarse aggregate (rocks), fine aggregate (sand), Portland cement and water. Ratios are used to divide these components, some common ratios are 4:2:1, 3:1:1, 2:1:1 [2]. For every ratio, the order goes coarse aggregate: fine aggregate: cement. The amount of water added to the mixture is determined by the ratio of water to cement. This ratio varies from 0.4 to 0.6 with a smaller ratio corresponding to a stronger blend of concrete [3].

For this experiment we chose a 2:1:1 ratio for strength purposes [4] with a water-to-cement ratio of 0.45 for all samples. To change the sound absorption coefficient of the standard concrete, we must change the material composition in the concrete. So, we are added rubber and coal fly ash. The rubber was added to increase the concrete's sound absorptivity and the fly ash was added to maintain or increase the strength for safety purposes. We divided both the rubber and the coal fly ash with the fine aggregate component in the concrete ratios since it is roughly the same size. For the rubber additives, we are using 4 different sized grains ranging from rubber mulch to a crumb rubber. We are using around 20-40% rubber based on research [5]. The different size rubber additives are seen in Figure 1 with the largest being on the left and the smallest being on the right.

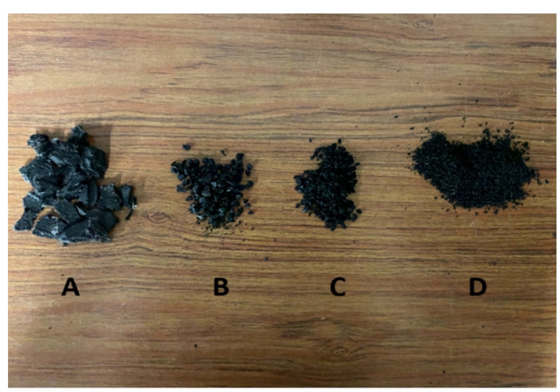


Figure 1: Various rubber additives. A – rubber mulch; B - 1.3 - 5.0 mm; C - 1.0 - 5.0 mm; D – crumb rubber.

In this experiment, we are measuring two components of the concrete, the strength, and the sound absorption coefficient. For both, we are measuring them every 7 days until 28 days because that is when concrete fully strengthening. In this experiment, we are measuring the sound absorption coefficient with an impedance tube using the standing wave ratio method over the range of 700 – 1300 Hz which corresponds to highway noise [6]. The strength of concrete samples will be measured using ultrasound transducers and the strength will be assessed through three important values: elastic modulus, p-wave velocity, and Poisson ratio.

Theory

Sound is defined as a longitudinal wave propagating in a medium. A longitudinal wave is different from a transverse wave in that its oscillation direction is the same as its propagation direction. A classic example of a transverse wave is light. The audible range of sound ranges from 20 Hz to 20,000 Hz. Frequencies above 20,000 Hz are called ultrasound and frequencies below 20 Hz are called infrasound. An application of ultrasound and infrasound are medical imaging of soft tissue and study of earthquakes respectively.

When sound is incident onto the surface of a material or a fluid, there are three processes that can occur: reflection, transmission, and absorption. Reflection is the process of returning the sound wave into the incident medium. Transmission is the process of the sound wave passing through the material or fluid. Absorption is the process of the sound wave being converted into another form of energy such as thermal energy in the material or fluid.

The goal of the research is to increase the sound absorption coefficient of concrete by using various compounds as substitutes for the regular components of concrete. Standard concrete has a sound absorption coefficient between 0.1 and 0.2 over the frequency range from 125 Hz to 5000 Hz. There are two main techniques for measuring sound absorption of materials: reverberation room and impedance tube. The reverberation room technique requires the use of a chamber or room that is filled with diffuse sound and the reverberation time is measured from the material placed in the chamber or room. This time value is used in the Sabine equation to calculate the absorption coefficient. The impedance tube technique utilizes either the standing wave ratio or the transfer function to determine the absorption coefficient of the material placed in the tube. The standing wave ratio technique requires the use of a speaker and the insertion of the material to be tested into a pipe that is either circular or rectangular. A microphone measures the pressure of the sound generated at locations in front of the material under study.

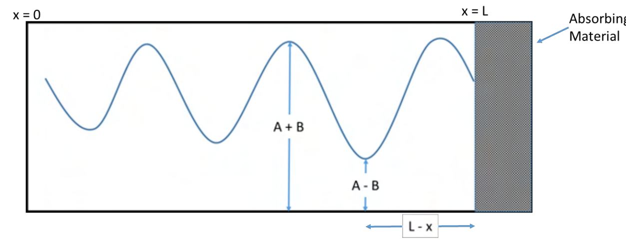


Figure 2: Standing Wave Ratio Impedance Tube Technique

To determine the absorption coefficient, the first pressure minimum from the material's surface and the successive pressure maximum are measured to determine the standing wave ratio.

$$SWR = \frac{p_{max}}{p_{min}} \qquad \text{(Eq. 1)}$$

The magnitude of the reflection coefficient from the surface of the material is given by:

$$|r| = \frac{SWR-1}{SWR+1} \qquad \text{(Eq. 2)}$$

The absorption coefficient of the material is given by:

$$\alpha = 1 - |r|^2 \qquad \text{(Eq. 3)}$$

Inserting the definition of the magnitude of the reflection coefficient into the absorption coefficient and performing a few algebraic manipulations the following expression for the absorption coefficient in terms of the standing wave ratio can be derived:

$$\alpha = \frac{4\,SWR}{(SWR+1)^2} \qquad \text{(Eq. 4)}$$

The strength of materials used in structures is typically quantified by the elastic modulus and the Poisson ratio. The elastic modulus is a ratio of the tensile stress to the tensile strain. Stress is defined as the force applied per unit area and therefore it is measured in the units of pressure, Pascals. Strain is the ratio of the change in length to the original length and as such is a unitless quantity. Standard concrete used in structures has an elastic modulus greater than 30 GPa. A standard technique for determining the elastic modulus of a solid is through the resonant longitudinal frequency. If the solid is impacted by another object such as a steel ball bearing, the solid will generate a resonant standing wave which can be measured. This resonant frequency is directly related to the elastic modulus:

$$E = 4\rho L^2 f^2 \quad \text{(Eq. 5)}$$

Poisson's ratio is defined as the ratio between the lateral strain and the axial strain. When a material is loaded with a stress that either compresses or stretches the material, there is a change in the axial length along the direction of the applied force and there is also a change in the length perpendicular to the applied force which is typically called the lateral direction. The mathematical definition of Poisson's ratio is given by the following equation:

$$\nu = -\frac{\varepsilon_l}{\varepsilon_a} \quad \text{(Eq. 6)}$$

Poisson's ratio is defined as a negative quantity to keep the ratio positive because as the axial strain increases the lateral strain decreases and vice versa. Poisson's ratio varies between 0.0 and 0.5 with the lower theoretical bound describing compressible materials where the lateral and axial directions are completely independent of each other and the upper theoretical limit describing materials that do not change in volume when a load is applied to them. As stated earlier, the Poisson ratio for concrete varies between 0.11 and 0.21 and lower values correspond to concrete samples that show less elastic behavior even when exposed to high levels of strain. For a building or structural material this is exactly what is required. Poisson's ratio can be measured directly through the use of strain gauges and a Tinius Olsen machine. As the load is applied to the concrete sample in the Tinius Olsen machine, the strain gauges attached to the sample axially and laterally measure the strain in the respective directions. This can be done until the sample actually fractures which will provide the compressive strength of the concrete sample and can be related to the elastic modulus. This type of testing is typically known as destructive testing in that the sample is destroyed in the collection of the data. As we were interested in studying how the concrete samples evolved over the 28 day curing cycle, a non-destructive technique was required to assess the Poisson ratio of the samples.

The Poisson ratio is related to the elastic modulus through the longitudinal velocity of sound through the material given by the following equation:

$$v_p^2 = \frac{E(1-\nu)}{\rho(1+\nu)(1-2\nu)} \quad \text{(Eq. 7)}$$

Ultrasound transducers were used to measure the longitudinal velocity by measuring the time for a pulse to travel between the transmitter and the receiver which is given by the following equation:

$$v_p = \frac{L}{\Delta t} \quad \text{(Eq. 8)}$$

The pulse velocity can be used to gauge how strong the concrete is at the time of the measurement. Note that the velocity will change over the 28-day period of the concrete curing process. Table 1 provides a quick reference to assess the strength of the concrete samples.

Table 1: Concrete Classification based on ultrasonic pulse velocity

Pulse Velocity (m/s)	Concrete Classification
Above 4500	Excellent
3500-4500	Good
3000-3500	Medium
Below 3000	Poor

With the longitudinal velocity and the elastic modulus value, Equation 7 can be solved using the quadratic equation for the Poisson ratio of the concrete sample.

Experimental Methods

The first step in our experimental process is making the concrete samples. We use the molds seen in Figure 3 to conform to the resonant frequency test requirement of a Length:Diameter ratio equal to 2:1 and to create concrete samples that will fit into our impedance tube.

Figure 3: Concrete Mold, Were the drying phase occurs for 1-6 days

To determine how much concrete to put in the mold, we measure the volume of the mold. Then calculate the mass using the desired density of concrete. Next, a ratio is chosen to use for the concrete samples. For our samples, the ratio tested included 2:1:1, 3:1:1 and 4:2:1. All ratios follow the order, coarse Aggregate: fine aggregate: cement. The amount of water added to the mixture is determined by the ratio of water to cement. This ratio varies from 0.4 to 0.6 with a smaller ratio corresponding to a stronger blend of concrete. For our experiment we chose the 2:1:1 ratio for strength purposes [4] and a 0.45 w/c ratio. To better understand how concrete ratios work here are some ratios we tested during the experiment,

Mass (lb-oz)	Ratio	Coarse Agg (lb-oz)	Fine Agg (lb-oz)	Cement (lb-oz)	w/c (ml)
8.8	2-1-1	4lb 4oz	2lb 2oz	2lb 2oz	0.45
8.8	3-1-1	5lb 1.6 oz	1 lb 11.2 oz	1lb 11.2 oz	0.45
8.8	4-2-1	4 lb 13.72 oz	2 lb 6.8571 oz	1 lb 3.43 oz	0.45

Table 2: Ratio chart used for concrete samples

There are two parts we use when measuring the concrete samples, Strength and Sound Absorption. The strength measurement uses two different methods to obtain the strength of the concrete sample. The first strength measurement method is the Elastic Modulus. To acquire the Elastic Modulus we need three components, ρ(Density) = mass/volume, L (length of concrete sample), and f (Resonance Frequency).

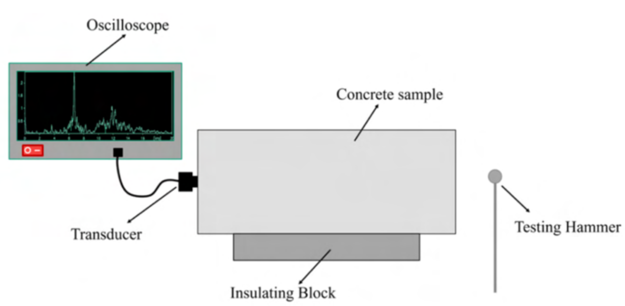


Figure 4: Elastic Modulus Experimental Setup

To acquire the Resonant Frequency, we use the equipment in the diagram above. We hit one side of the concrete sample with the impact hammer which creates a resonance in the sample. This resonance is detected by the transducer on the other side which we can then read off the oscilloscope. On the oscilloscope we put it into the frequency mode through the Math function and then the cursor is used on the oscilloscope to measure the resonant frequency as seen in Figure 5.

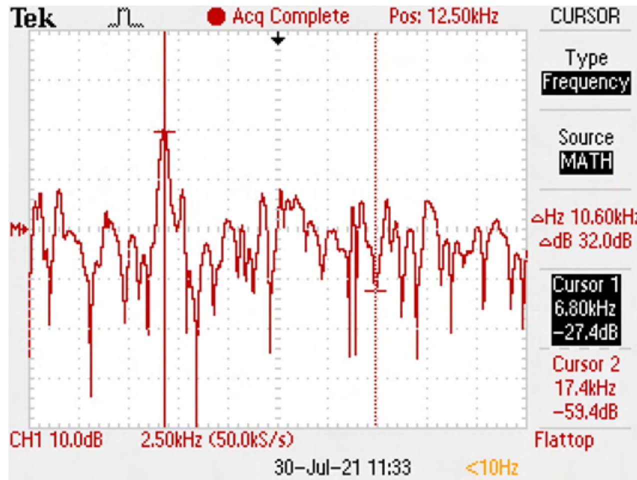


Figure 5: Cursors on oscilloscope measuring the Resonant Frequency

The Second Strength Measurement Method is the Poisson Ratio. The Poisson Ratio measures how much the concrete sample will deform under stress (such as Stretching or Compression). We measure it by measuring the strain in two different directions the x and y axis. We have all the values except for the V_p which is the Pulse Velocity of the Concrete Sample. The Pulse velocity is obtained by this method of measurement in the diagram below,

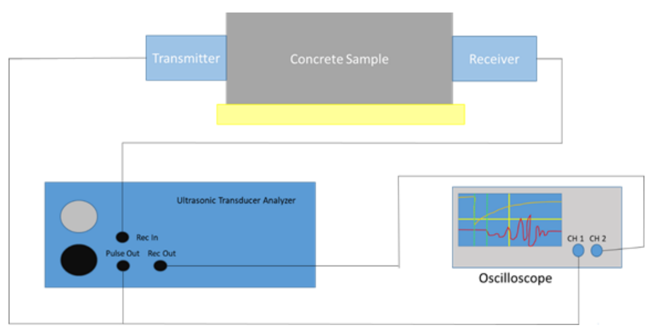


Figure 6: P-wave Velocity Experimental Setup

Using two Transducers, One Transmitting and one receiving. The transmitting transducer is connected to the Ultrasonic Transducer Analyzer which is where the pulse is generated. The transmitted transducer sends the pulse across the concrete sample and the receiving transducer picks up the pulse on the opposite side of the sample. The pulse eventually makes its way back to the oscilloscope which measures the Δt (time pulse takes to get from the transmitting to receiving transducer. In order to make all this work we put ultrasonic gel on the transducers and a table clamp to improve the transmission and reception of the signal.

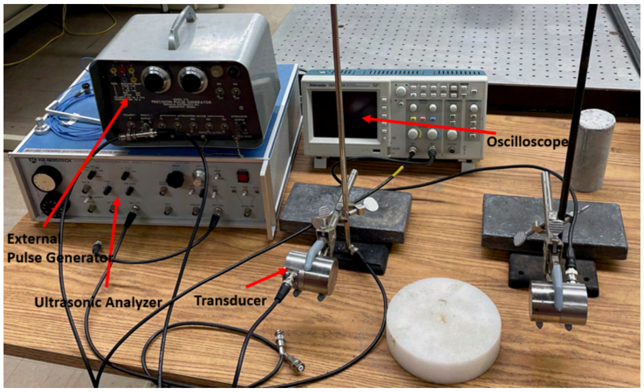


Figure 7: P-wave Velocity Experimental Setup (In person)

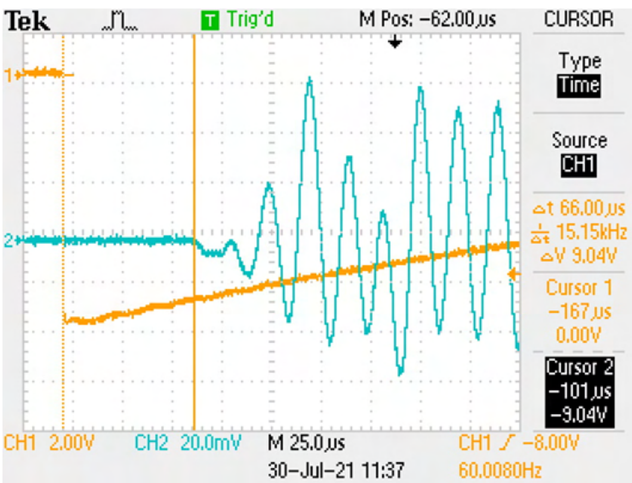


Figure 8: On the oscilloscope measuring the Δt with the cursors

Next is the sound absorption measurement, for this experiment we are using the standing wave ratio method. In this method we are using three main pieces of equipment, Impedance Tube, Function Generator, and the Oscilloscope shown in Figure 4 below.

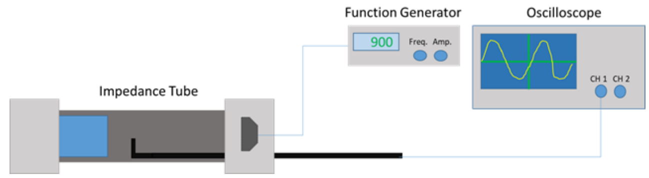


Figure 9: Standing Wave Ratio Experimental Setup

The first value we must find is the SWR (Standing Wave Ratio) [7]. To acquire this value, the concrete sample is loaded into the impedance tube and an air gap of roughly 10 cm is used behind the sample. The maximum and minimum pressures are measured using the peak-to-peak voltage of the microphone that is displayed on the oscilloscope. Once we acquire the SWR, we can find the Absorption coefficient easily by using the formula in the "Theory" section. The function generator in this experiment changes the frequencies that are being measured. In this experiment, we are doing 700-1300hz and we are doing it in increments of 100, so that is seven measurements for each sample every 7 days. *Source about SWR Articles we used at the beginning*

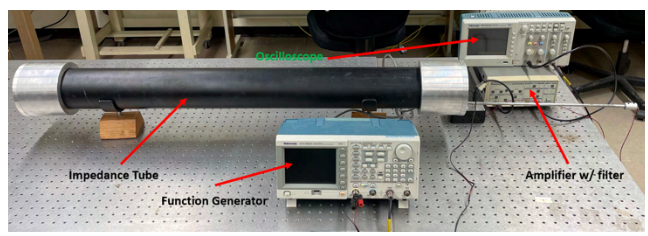


Figure 10: Standing Wave Ratio Experimental Setup (In person)

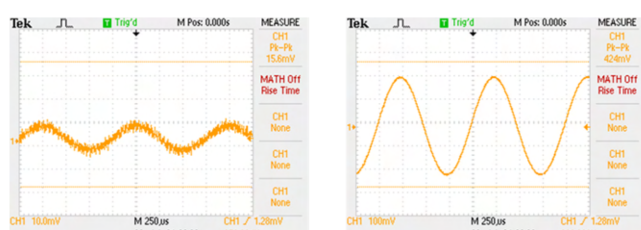
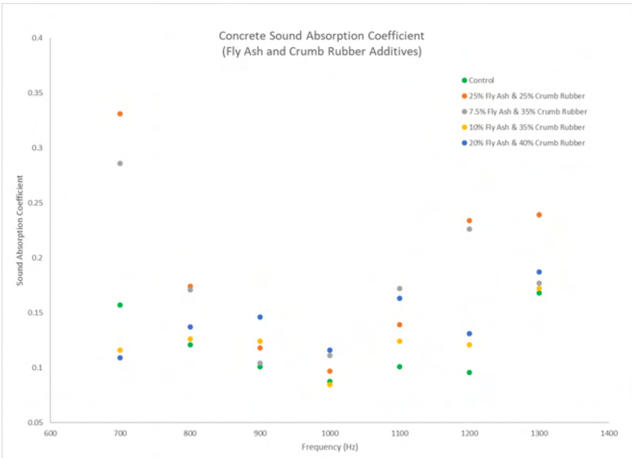


Figure 11: Measuring the Pmin and Pmax for the SWR

Data & Analysis



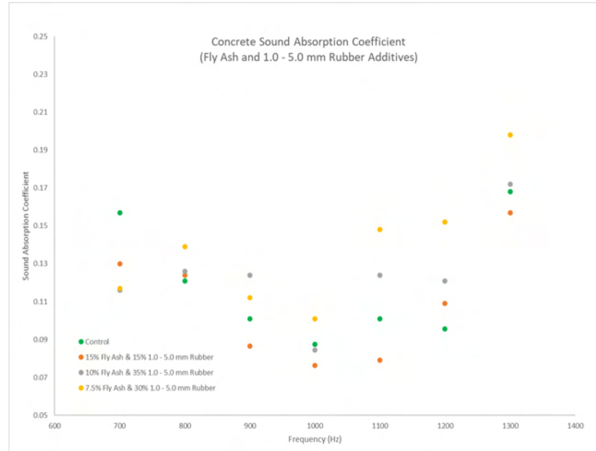
Graph 1: Results for the Fly Ash and Crumb Rubber Mixture

Sample	E (GPa)	V_p (m/s)	v
Control	37.8	3980	0.153
25% Fly Ash and 25% Crumb Rubber	24.4	3620	0.228
7.5% Fly Ash and 35% Crumb Rubber	21.7	3500	0.247
10% Fly Ash and 35% Crumb Rubber	20.1	3290	0.212
20% Fly Ash and 40% Crumb Rubber	17.9	3190	0.235

Table 3: Strength Values for Concrete Mixtures using Fly Ash and Crumb Rubber

Analysis

As seen in the plot of the sound absorption coefficient for the various samples using different proportions of fly ash and crumb rubber, it is clear that the best sample had 25% fly ash and 25% crumb rubber when compared to the control sample of standard concrete whose sound absorption coefficient lies between 0.1 and 0.2 for the frequencies sampled. The 25% fly ash and 25% crumb rubber sample also had the highest elastic modulus and longitudinal velocity after the control sample.



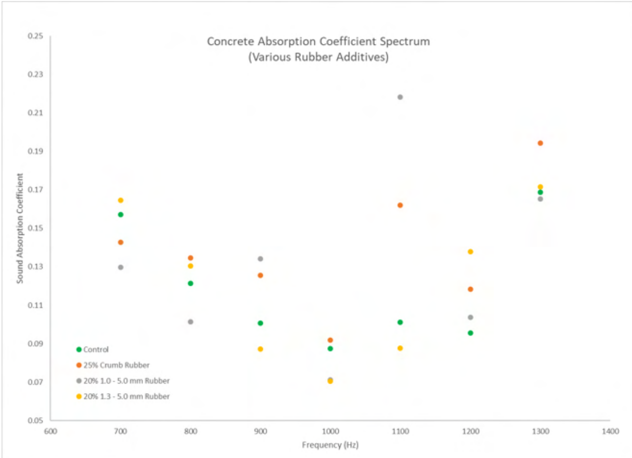
Graph 2: Results for the Fly Ash and 1.0-5.0mm Rubber Mixture

Sample	E (GPa)	V_p (m/s)	v
Control	37.8	3980	0.153
15% Fly Ash and 15% 1.0 – 5.0 mm Rubber	28.7	4380	0.327
10% Fly Ash and 35% 1.0 – 5.0 mm Rubber	19.3	3250	0.223
7.5% Fly Ash and 30% 1.0 – 5.0 mm Rubber	22.2	3610	0.259

Table 4: Strength Values for Concrete Mixtures using Fly Ash and 1.0 – 5.0 mm Rubber

Analysis

As seen in the plot of the sound absorption coefficient for the various samples using different proportions of fly ash and 1.0 – 5.0 mm rubber, it is clear that the best sample had 7.5% fly ash and 30% 1.0 – 5.0 mm rubber when compared to the control sample of standard concrete whose sound absorption coefficient lies between 0.1 and 0.2 for the frequencies sampled. The 7.5% fly ash and 30% 1.0 – 5.0 mm rubber sample also had the second highest elastic modulus and longitudinal velocity after the sample with equal percentages of fly ash and 1.0 – 5.0 mm rubber. While the strength of this sample was high, the sound absorption coefficient was at or below that measured for the control across the spectrum analyzed.



Graph 3: Results for different proportions of rubber mixtures

Sample	E (GPa)	V_p (m/s)	v
Control	37.8	3980	0.153
25% Crumb Rubber	24.5	4290	0.353
20% 1.0 – 5.0 mm Rubber	27.8	3710	0.170
20% 1.3 – 5.0 mm Rubber	29.1	3980	0.251

Table 5: Strength Values for Concrete Mixtures using Various Rubber Additives

Analysis

As seen in the plot of the Concrete Absorption Coefficient for the various proportions of rubber samples only, it is clear that the best sample is 25% Crumb Rubber when compared to the control sample of standard concrete whose sound absorption coefficient lies between 0.1 and 0.2 for the frequencies sampled. 25% Crumb Rubber also had the highest longitudinal velocity.

Conclusion

In this experiment, we are trying to increase the sound absorption coefficient of concrete while also maintaining the strength for safety purposes. Our real-life application are concrete barriers on highways. We are replacing the fine aggregate in concrete with Crumb rubber and Fly Ash to try and complete this goal.

For our results, starting with the mixtures between Fly Ash and Crumb Rubber. We found that the mixture of 25% FA and 25% CR had the highest sound absorption coefficient elastic modulus and longitudinal velocity after the control sample. The longitudinal velocity is 3620 m/s which according to the UPV concrete classification chart it is classified as good strength. The absorption coefficient is much higher compared to every other sample, reaching almost 0.25. Elastic Modulus is 24.4 GPa which is not in the 30-50 GPa range but out of all the samples it is highest excluding the control sample.

For our 2nd set of results, which is the Fly Ash and Rubber 1.0-5.0mm mix. We found that 7.5% fly ash and 30% 1.0 – 5.0 mm rubber when compared to the control sample had the best results. Having a 3610 m/s longitudinal velocity indicating it has good strength. It was the only sample that got up to 0.20 in sound absorption. The elastic modulus is 22.2 GPa which is close to the range 30-50 GPa we are aiming for. The Poisson ratio is 0.259 which is a little high but is reasonable.

For our 3rd set of results, which is the various proportions of rubber samples only. We found that the 25% Crumb rubber when compared to the control sample was the best. It had the highest Longitudinal velocity categorizing it as excellent concrete strength. It had the best sound absorption coefficient at around 0.20.

Overall, we found that replacing crumb rubber or 1.0-5.0mm rubber increases the sound absorption coefficient in all the samples. We cannot however definitively state any conclusion about adding fly ash along with rubber to concrete as having a benefit toward increasing absorption or strengthening the concrete.

Acknowledgement

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