Experimental Characterisation of Polyethylene Terephthalate (PET) Bottle Eco-Bricks

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Abstract

This paper addresses the issue of recycling waste plastic by considering the feasibility of use of Eco-bricks for constructional purposes. The Eco-bricks are formed by packing plastic within Polyethylene Terephtalate (PET) bottles. Guidelines were provided for the construction of Eco-bricks. Experiments were carried out to characterise some of the properties of these bricks. Compression test, sound insulation assessment and light transmission were considered in this regard and compared with traditional construction materials and conditions. Possible applications of Eco-bricks were discussed. The paper presents the first attempt to characterise these bricks and the results encourage future use of them to a significantly wider extent and for various purposes.

Keywords: Plastic waste, Compressive Test, Sound Insulation, Light Transmission, Eco-brick

1. Introduction

Waste management problems related to high production of plastic is an extremely important global challenge [1-4] and recycling or recovery [5] routes of plastic solid waste have been highlighted by a number of researchers [6]. The mineralisation rate from long-term biodegradation experiments of both Ultra-Violet (UV)-irradiated samples, non-pre-treated, and additive-free low density polyethylene samples, in natural soils indicate it is likely to take more than 100 years [7]. In the last 20 years both diminishing landfill capacity and concern of general environmental issues have resulted in the United

States and the European Union (EU) introducing new legislations to promote waste reduction [2, 9]. The impact of plastics on primary and secondary carbon footprint is also a very important factor that has been highlighted by researchers [3]. High Density Polyethylene (HDPE), Low Density Polyethylene (LDPE) and Linear Low Density Polyethylene (LLDPE) are widely used for the manufacture of plastic bags [10]. Supermarkets shopping bags, the most prevalent type of plastic bag, are ideally produced out of LLDPE to obtain the desired thickness and glossy finish. LDPE is usually used if the producer is looking for a very thin and gauzy bag [11]. Life Cycle Analysis can provide important insights to the effects of such plastic products [12-14]. Consumer behaviour and governmental policies have an important role in the disposal stage. For example in Ireland a plastic bag levy was first introduced on 4th March 2002 at the rate of 15 cent per disposable plastic bag. It had an immediate effect on consumer behaviour with a decrease in plastic bag usage from an estimated 328 bags per capita to 21 bags per capita overnight. The current levy of 22 cent was introduced on 1 July, 2007. It was increased as the bags per capita had increased to 31 during 2006. The aim of the increase is to reduce the plastic bag per capita usage to 21 or lower [15]. This number may be compared to the equivalents in China and India as 1095 and 150 respectively [3].

Re-use of plastic bottles have been considered for the construction industry and there exists studies on concrete [16], on mortars containing Polyethylene Terephtalate (PET) waste aggregates [17], use of rice husk and plastics [18], application as a composite in concrete [19], aggregate replacement in concrete [20-22], investigation in water-cement ratios of such concrete with PET bottles [23] and even as soil reinforcement [24].

Although significant work is present in the use of plastic bottles as additive to traditional construction materials, there exists a significant gap in studying if the bottles themselves can be used for potential applications in construction and very little study exists attempting to characterize such solutions to any extent. Recently POLLI-Bricks have considered the usage of plastic bricks [25]. There are some examples, especially in Latin American countries where a concept similar to eco-brick has been used as a part of a volunteering campaign and for detailing eco-parks or certain structural features.

This paper presents a first characterization study on eco-bricks, which are essentially empty PET beverage bottles filled with waste plastic bags or other discarded plastic. Manufacturing aspects, consistency in weight and mechanical strength aspects are investigated as well as noise insulation and light insulation aspects. Experimental investigation is carried out on eco-bricks this regard and potential applications are discussed.

2. Background to Characterisation

2.1 Compressive Strength

Compressive strength is a typical value quoted for units of construction but may have different interpretations based on the brittleness, ductility and the load-displacement characteristics of a material. Independent of a true failure or rupture of the material, a yield in compression is always representative of a characteristic strength of a unit of construction. Uncertainties in production within or between batches are acknowledged in construction design, but within batch variations are expected to be relatively lower for a manufacturing unit under appropriate control. However, it is difficult to assess such uncertainties with confidence for small and medium sized jobs by observing the number of defectives in a batch.

2.2 Sound Insulation

In building acoustics, the main frequency range used to assess sound insulation lays between the 100 and 3150 Hz one-third-octave-bands and an optional extended frequency range is defined between the 50 and 5000 Hz one-third-octave-bands. The range between 50 and 5000 Hz is referred to as the building acoustics frequency range. It is possible to define frequency ranges using one-third-octave-band centre frequencies low frequency range (50–200 Hz), mid-frequency range (250–1000 Hz) and high-frequency range (1250–5000 Hz) [26]. For this paper it is assumed that ‘typical rooms’ have volumes between 20 and 200 m^3 and this covers the majority of practical situations. Measurements of sound insulation may be laboratory measurements that provide information at the design stage, field measurements that demonstrate whether the required sound insulation has been achieved in a building, and field measurements that help an engineer solve sound insulation problems in existing buildings. For many buildings the acoustic requirements are described in building regulations; hence repeatability, reproducibility, and relevance (i.e. the link between the measured sound insulation and the satisfaction of the building occupants) are particularly important for airborne and impact sound insulation. Laboratory measurements of the acoustic properties of materials and building elements (e.g. walls, floors, windows, doors) are primarily used for comparing products and calculating the sound insulation in situ. Measurements of material properties are particularly useful in assessing whether one material in the construction could be substituted for a different one, and for use in prediction models. Testing may also be carried out in-situ with limited number of samples. Sound insulation is heavily dependent on the quality of construction and workmanship. The test room should ideally be empty and unfurnished. It is common to express sound intensity on a logarithmic scale, called decibel SPL (Sound Power Level). On this scale, 0 dB SPL is a sound wave power of 10-16 watts/cm2, roughly the weakest sound detectable by the human ear. Normal speech is at around 60 dB SPL, while painful damage to the ear occurs at around 140 dB SPL [27].

2.3 Light Transmission

Transmission is the property of a substance to permit the passage of light, with some or none of the incident light being absorbed in the process. If some light is absorbed by the substance, then the transmitted light will be a combination of the wavelengths of the light that was transmitted and not absorbed [28]. The transmission coefficient is a measure of how much light (electromagnetic wave) passes through an optical element or a surface. Transmission coefficients can be calculated for either the intensity of the wave or the amplitude. Different instruments are required to assess light transmission. A spectrometer is an instrument used to measure properties of light over a specific portion of the electromagnetic spectrum. The variable measured is most often the intensity of light. The independent variable is usually the wavelength of the light or a unit directly proportional to the photon energy, such as wave number or electron volts, which has a reciprocal relationship to wavelength. An amplified photomultiplier tube (PMT) is designed for detection of light signals from DC to typically 20 kHz. The light to voltage conversion can be estimated by factoring the wavelength-dependent responsivity of the PMT with the transimpedance gain.

3. Manufacture and Control of Specimens

Eco-bricks are formed by compacting waste plastic bags within pet bottles. An example of such bottles is presented in Figure 1. The manufacture and control of the various specimens are presented next.

3.1 Manufacturing of Specimens

3.1.1. Selection of Bottle Size

There are many alternative sizes of plastic bottle to choose from including 500ml, 750ml, 1l, 1.25l and 2l bottles. The most appropriate bottle to use was found to be of size 500ml. There are a number of reasons behind this choice. It is quite difficult to manually pack a bottle of larger size. The force required from the stick to compact the plastic into bigger bottles is difficult to reach when packing the bottle by hand. Also, generally larger bottles can come in a variety of sizes due to their larger volume to manipulate the shape of the bottle. Using the 500ml bottle ensures that the geometry of the bottles are usually consistent.

3.1.2. Packing Material

It is preferred that the waste that goes in as a packing material is of a plastic form. There are some suggestions of using any household waste but most non-plastic household waste do not have as long a decomposition rate as plastic. The decomposition of any material can alter the compaction of the waste within the bottle and as a result compromise the structural integrity of the brick. Any forms of plastic can be used including cling film and food wrapper. The plastic that enters the bottle has to be relatively clean and always dry. This is important because particles of food can cause mould and other unpredictable bacteria to form. However, the majority of food packaging/garbage just needs a quick shake to remove most of the food from the garbage. It is important that the bottle is dried out before the packing process begins.

3.1.3. Tapping Test

From experiences of making Eco-bricks it is advised to keep a set number of taps to compress the plastic into the bottle, needing between 4-6 taps for every piece of plastic. At the beginning of manufacturing a brick it takes less effort to compress the plastic but as more is entered it can be noted that the waste needs more force to compress the waste. The 4-6 taps is only a guideline as when one begins the process they will notice that sometimes mope taps will be needed to compress the plastic properly as indicated in the next subsections.

3.1.4. The Packing Process

Before the packing process begins it is vital to ensure that a proper 'stick' is used to pack with. It must be able to reach the bottom of the bottle and be able to avoid the possibility of breaking. It must also be of a diameter which will fit into the bottle and have the leverage to reach the inner edges of the bottle. It is required that the stick is of sufficient length to ensure that one can have a firm grip on the stick so that it reaches the bottom of the bottle. Considering the alternative lengths of 500ml bottles available the recommendation is a metal rod of diameter 12-16mm and 350-500mm length. A wooden stick could also be used, but the weight of the metal reduces the physical effort needed in packing the garbage. This increases the force applied into the bottle hence increasing the ease of creation. The best method is to start packing the waste in little by little and alternating between adding the plastic and compacting it with the stick. While compacting with the stick the bottle needs to be rotated while pressing down to ensure that the waste will be evenly compacted throughout the bottle. This helps ensure that the bottle will not have any voids and will have the solid properties similar to a concrete block.

3.2. Control of Specimen

There are a number of aspects to the manufacturing to the brick that need to be kept to a high standard as one makes the bricks.

3.2.1. Manual Checks

From the experience of making Eco-bricks, it is advised that the bottle eco brick should weigh no less than 220g after the packing process. If it is less that this weight it implies that the compression ratio of the brick is insufficient to be considered for structural purposes. The mass per unit volume plays an important role in the strength of Eco-bricks. The relationship is investigated in the next section experimentally. A weight below 220g is acceptable for use as an insulator but lower than this indicates that it might not be strong enough to withstand large pressures. Significant qualitative information can be retrieved about the specimen after construction by touch. When the brick is manufactured if a person can feel the surface area of the bottle to ensure there is not any major voids in the packing. Due to human error in the manufacturing it has been acknowledged in tests that there can be small gaps in the packing but as long as they are not featuring frequently throughout the bottle and that they are so large that they are pose a risk to the structural integrity of the bottle.

3.2.2. Void Detection

There are many different options that exist for finding and quantifying voids within the bottle eco brick. These include sophisticated methods like elastic and electromagnetic wave propagation [29]. With knowledge of sound wave propagation and the use of appropriate reference standards along with generally accepted test procedures, a trained operator can identify specific patterns corresponding to the echo response from good parts and from representative flaws. The echo pattern from a test piece may then be compared to the patterns from these calibration standards to determine its condition [30].

3.2.3. Sample Checks

It is acknowledged that sampling checks are required when the bricks are manufactured in large quantities. As a guideline, the check for concretes in site may be referred to. As an initial recommendation, one in every ten bricks made by an experienced manufacturer could be tested, as testing every single brick would be very costly and time consuming. Figure 2 presents a flowchart related to the making of Eco-bricks.

4. Experimental Considerations

4.1 Compression Test

A Denison compressive testing machine was used for compression test. An extra platen had to be added to the machine to allow for the smaller specimens in the test as 150 x 150 x 150 cubes would be the norm for concrete cubes. The brick is first placed into the centre of the machine, with the bottle cap facing away from the front in case the pressure build up forced it to pop off. The initially preload is 5 kN. The full load is applied till there is a sudden drop in force, which results in the machine stopping. The failure is not complete since the specimen is substantially deformed but that no fracture occurs.

4.2 Sound Insulation Assessment

It is not possible to test the sound insulation of the bottle "eco-brick" unless an entire room is made out of it. Therefore, to assess the sound insulation of the brick a viable option was to calculate the sound reduction index of the bottle "eco-brick" and undertake a comparable analysis to other bricks used in construction. Sound Reduction Index (R) is a quantity, measured in a laboratory which characterises the sound insulating properties of a material or building element in a stated frequency band [31]. It is possible to estimate the sound reduction index of a solid construction such as a brick wall by using the Mass Law, and this can be used to estimate the sound reduction index of a brick if the mass per unit area is known. To obtain the mass per unit area of the brick, a bottle was split in half with a saw. The half bottle is placed onto a piece of paper, and the outline is traced. The bottle is split up into very small trapezoids and the area of each trapezoid is calculated. Figure 3 presents the method of this conversion for different sections.

4.3 Light Transmission Assessment

An amplified photomultiplier tube is used. A buffered output device drives a 50Ω impedance to 5V. The PMM01 housing includes SM1 (1.0352 x 40) threads that are compatible with any number of Thorlabs' SM1-threaded accessories. The housing also includes tapped holes that are compatible with Thorlabs' 30mm cage system.

The PMM01 has three 8-32 (M4 on –EC version) tapped mounting holes with a 0.2 mounting depth and includes a switchable line voltage power supply. The desired tube control voltage has to be kept in the range of 0 to 1.25V. The anode current should not 100µA. The anode current is dependent on both the sensitivity of the PMT at a given wavelength and the applied voltage. The maximum output of the PMM01 is 10V for high impedance loads (5V for 50Ω loads). The output signal should be below the maximum output voltage to avoid saturation. If necessary, use external neutral density filters to reduce the input light level. A class 3B laser was used for this experiment. To have the laser at a fixed point on the rotating arm of the spectrometer a laser arm was pre-designed and constructed. An optical chopper was placed in front of the laser and before the Eco-brick being tested. This was held in place by a retort stand and used to modulate the laser beam at a frequency of approximately1kHz. Once the set-up was turned on, a laser beam is emitted towards the test subject, the PMT then detects any beams that have passed through the brick and the results can be taken from a multimeter. The results should be considered for a number of angles. These angles can be made by rotating the arm with the PMT attached to it and the angle can be read from the vernier scale on the spectrometer. While undertaking the experiment it is pivotal to ensure that the experiment is done in dark surroundings. Any form of daylight entering the room where the tests are carried out can hinder the results received by the apparatus. The protective black boards that are put up around the apparatus are to prevent any deflected beams that might refract away. This prevents any rays that might refract towards a person within the vicinity of the experiment.

5. Results

5.1 Compression Testing

The bottle weights, brick weights and compressive loads at failure as defined in the previous section, are presented in Table 1 for 10 Eco-bricks tested.

All of the initial bottle weights are very similar, within a range of 24 to 27 grams. As the bottles are all the same size, the similar weights of each give an indication that that all bottles are made from a similar standard of plastic, and that this would have equal on the compressive force. All final manufactured Eco-bricks have a similar weight, the lowest being 245 grams up to 260 grams. The bricks themselves showed good resistance to the compressive force applied; displaying values of up to 40 kN, these values are similar to that of basic concrete cubes that are tested using the same machine and process. There appears a linear relationship between the weight of a brick and the compressive force it can bear, though they are not directly related. This is shown in Figure 4. Since all bottles are made from a similar grade of plastic, this means that the packing ratio is the main variable that affects the strength of the brick.

To obtain an estimated stress at failure, the area of the squashed specimen is found by tracing the outline of the bottle onto a piece of paper and drawing a series of rectangles and trapezoids, calculating the area of each and adding them all together. The stress at failure, indicative of its compressive strength, was assessed by dividing the force at failure divided by this area. Table 2 presents the computed results in this regard. The manufacturing of the PET bottles and the failures are consistent to the resolution to which the results have been reported.

The specific strength of a material may be represented through the strength/weight ratio. It is computed by dividing estimated strength with bulk mass per unit volume. For calculating bulk mass per unit volume, the mass of the bottle is divided by the volume. It can be assumed that the volume of each brick is the same as they are all 500 ml bottles. Their volume, in reality, may slightly vary but this s negligible when a first estimate of strength of Eco-bricks is being made. Table 3 presents the specific strengths of the Eco-bricks.

The linear relationship between specific strength and weight is presented in Figure 5.

When the specimen is squashed to a contraction in the direction of the applied load, there is a corresponding extension in a direction perpendicular to the applied load. The ratio between these two quantities is estimated as the Poisson's ratio. The Poisson’s ratio was calculated by comparing the axial and transverse stain at failure. The brick displays slight elastic rebound as it regains some of its shape when loading is removed. To measure axial strain the distance between the two platens is measured upon failure, and then divided by its original length. The extension and contraction is measured about the centre of the brick. The Poisson’s ratios for the Eco-bricks were estimated within a range of 0.27-0.35.

1

5.2 Sound Insulation

Sound reduction index (R) of Eco-bricks were estimated using the Mass Law, The reduction in dB at normal incidence,

$$R_o = 20\log\left(\frac{\omega m}{2\rho c}\right) \tag{1}$$

where $\omega = 2\pi f$ is the angular velocity of the sound in radians/s, m is the mass of the partition per unit area in kg/m^2 and ρc is the characteristic acoustic impedance of air in Rayls ($\frac{Pa.s}{m}$), which is about 420 $\frac{Pa.s}{m}$ at room temperature.

Reduction in dB for all angles of incidence is expressed as

$$\mathrm{R} = \mathrm{R_o} - 10\log(0.23\mathrm{R_o}) \tag{2}$$

A comparison of sound reduction index with Eco-bricks and other traditional construction materials are presented in Figure 6.

Eco-bricks do not have as good a sound reduction index as a concrete block. However, the lack of performance is not too significant. Additionally, with the addition of mortar to the walls made from bottle “eco-bricks” this would increase the sound reduction index of the walls thus increasing the overall sound insulation of the structure being constructed. An alternative option of the bottle Eco-brick filled with sand was also assessed for sound reduction index. This is better than the plastic version but still not as good as the concrete block and the use of sand defeats the purpose of removing waste plastic from the system. A 110 dB sound between 1000 and 5000Hz, centred at around 3500Hz, is a value that is close to the threshold of pain to the ear [32]. With a sound reduction index of roughly 44 dB, the bottle eco brick alone can reduce the figure of this sound down to around 70dB which is the same value as a normal conversation would be at. This would be even further reduced by mortar, if it is used. Sound insulation is heavily dependent on the quality of construction and workmanship.

5.3 Light Transmission

The range was turned down on the lock-in amplifier to 300nV, without seeing any signal from the PMT. It can thus be said that the signal out from the lock-in is < 300nV.

The PMT produces a current, rather than a voltage as its output. It is converted to voltage by a factor of 10^6VA^{-1} passing through a1MΩ resistor. The current from the PMT (I_{PMT}) is

$$I_{PMT} < \frac{300x10^{-9}V}{10^{6}V/A} = 300\text{x}10^{-15}A \qquad (3)$$

The PMT has a sensitivity of 86 V/W. Consequently, the optical power incident on the PMT is

$$P_{opt} < \frac{300x10^{-15}A}{86A/W} = 3.5\text{x}10^{-15}W \qquad (4)$$

The transmission (*T*) of the sample is the proportion of the incident light that would pass through the specimen. This is obtained by

$$T < \frac{3.5x10^{-15}W}{4.5x10^{-1}W} = 8\text{x}10^{-13} \qquad (5)$$

As the above result is a ratio, it can also be expressed as < 120dB. This means that there is minimal transmission of light passing through the brick. The amount of light is so minimal that it is not visible to the human eye but it is picked up by the apparatus.

6. Discussion

A major motivation behind carrying out the work was the immediate applicability of Eco-bricks in various situations. The lead author has already been a part of a volunteering project in Costa Rica introducing Eco-bricks as a building resource. There was an existing problem with plastic waste related to protective covering for berry farming that was addressed through Eco-bricks.

Using concrete blocks instead of Eco-bricks has its advantages and disadvantages. The cost of Eco-bricks is zero whereas the cost of a block in Central America for example averages out at roughly 75c per block. Considering a small, three room Eco-brick house for four people, made of 8000 Eco-bricks, there is a potential saving around €1500. On the other hand, the use of concrete blocks requires significantly less labour. The issue with the cost of the Eco-bricks is deciding to hire labour. Usually, it takes 30 to 60 minutes to make one brick and the main deciding factor for practical implementation will be labour.

There are potential applications of Eco-bricks in basic constructions. They can also be used for decorative purposes for community areas such as parks. Other possible potential applications may include assessing the efficacy of Eco-bricks in stabilising soil, slopes or being used as barriers.

Ecological approaches towards the development of units of construction is gaining increasing popularity for cleaner production processes in geographical regions where which are already experiencing or are expected to experience significant anthropogenic pollution levels due to rapid industrialisation [33]. The use of PET bottles as an additive for construction units have been considered before [34-36]. On the other hand, novel ideas of producing ecological bricks is also known to researchers [37-39]. This first approach of creating a structural unit entirely from PET bottles filled with plastic bags, which is expected to a unique and interesting way of recycling these materials with potential applications in construction.

7. Conclusions

It can be concluded that Eco-brick is a viable resource for construction purposes with a number of possible applications. The bricks are relatively easily manufactured with controlled weight and packing. Eco-bricks have relatively good compressive strength, with values matching that of basic concrete cubes. The weight of Eco-brick was observed to hold a nearly relationship with load at failure and with specific strength. Eco-bricks have a relatively good specific strength. They are lightweight but strong for the weight they bear. The lightweight properties of the brick would reduce the cost of transportation if necessary. The calculated Poisson's ratio was observed to be within the range of 0.27 to 0.35. Eco-bricks have a relatively high sound reduction index, even when compared to that of a normal concrete block, which is a far more dense material. It has been shown that light visible to the naaked eye does not appear to travel through Eco-bricks. Lightweight Eco-bricks also reduce the chances of injury due to lifting heavy materials. The bricks are non-brittle, unlike concrete blocks. They are a simple recycling advancement, reaping significant environmental benefits. They save on trash travel allowance and landfill space. There is one inconvenient negative aspect of the brick and that is their fire resistance. Plastic can be set alight quite easily but considering that they are covered by a cement/sand mix or mud this will aid in the lack of fire resistance from the bricks themselves.

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Figure 1.

Figure 2.

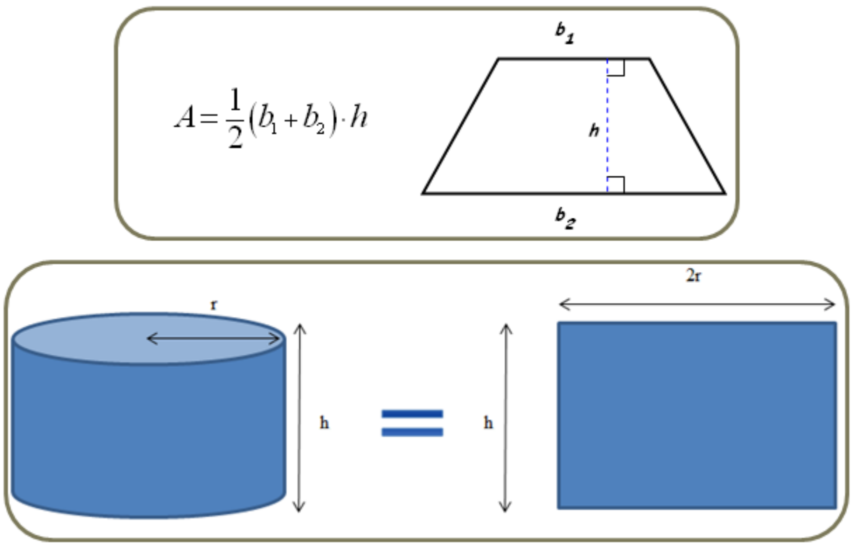

Figure 3.

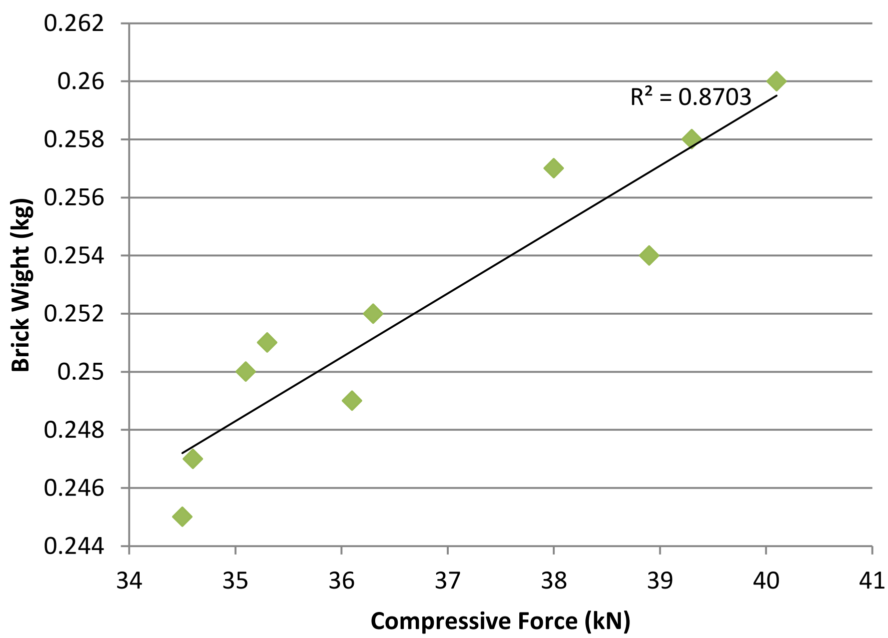

Figure 4.

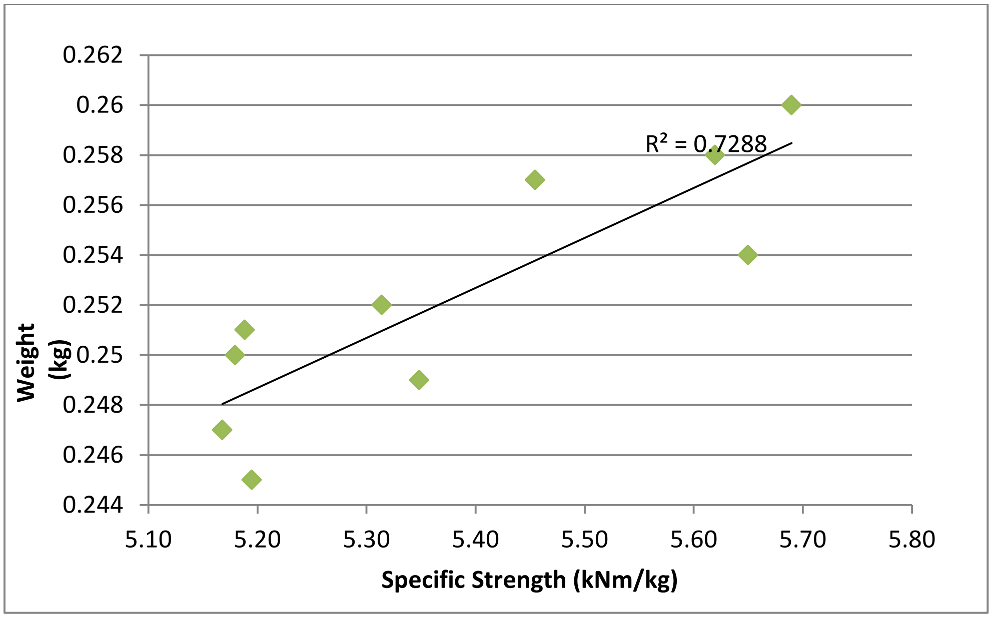

Figure 5.

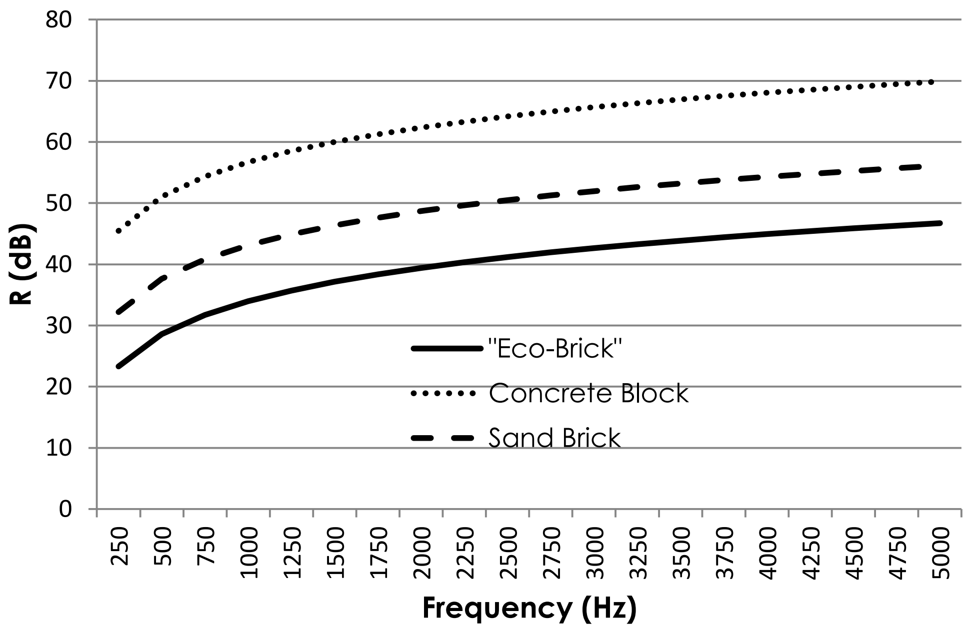

Figure 6.

List of Tables

	Bottle Weight (g)	Brick Weight (g)	Compressive Force (kN)
Specimen 1	26	250	35.1
Specimen 2	25	247	34.6
Specimen 3	26	258	39.3
Specimen 4	27	260	40.1
Specimen 5	25	251	35.3
Specimen 6	27	254	38.9
Specimen 7	24	245	34.5
Specimen 8	26	249	36.1
Specimen 9	25	252	36.3
Specimen 10	25	257	38.0

Table 1.

	Compressive Force (kN)	Area (m^2)	Strength (MPa)
Specimen 1	35.1	0.0136	2.59
Specimen 2	34.6	0.0136	2.55
Specimen 3	39.3	0.0136	2.90
Specimen 4	40.1	0.0136	2.96
Specimen 5	35.3	0.0136	2.60
Specimen 6	38.9	0.0136	2.87
Specimen 7	34.5	0.0136	2.55
Specimen 8	36.1	0.0136	2.66
Specimen 9	36.3	0.0136	2.68
Specimen 10	38.0	0.0136	2.80

Table 2.

	Pressure (MPa)	Bulk Mass per Unit Volume (kg/m^3)	Specific Strength (kNm/kg)
Specimen 1	2.59	500	5.18
Specimen 2	2.55	494	5.17
Specimen 3	2.90	516	5.62
Specimen 4	2.96	520	5.69
Specimen 5	2.60	502	5.19
Specimen 6	2.87	508	5.65
Specimen 7	2.55	490	5.20
Specimen 8	2.66	498	5.35
Specimen 9	2.68	504	5.31
Specimen 10	2.80	514	5.45

Table 3.