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'Rock Guitar' - Optimising concrete properties for the manufacture of a concrete guitar

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ABSTRACT

There is potential for cement-based materials to be used in making high-value customised musical instruments. This paper considers the properties (modulus, density, strength, and damping ratio) that a cement-based material requires to replicate traditional materials currently used in instrument production. Results are presented which demonstrate sound interaction with cementitious materials. A selection of mixes incorporating PVA, Lytag lightweight aggregate and normal sand mix with PVA were produced and tested with an impact hammer using the roving hammer technique and modal analysis in order to obtain the natural frequencies and damping ratio of the specimens. Lytag based mortars with PVA was determined as the optimum mix from the tests which was subsequently used to cast a workable full-size solid-bodied electric guitar, due to its lower elastic modulus and lower density compared to the normal compared mix, and its damping ratio in the region of wood (pine).

1. INTRODUCTION

Many instruments conventionally incorporate wood in their construction such as violins, pianos, guitars etc. However, the high quality timber, which is suitable for manufacturing the resonance board of musical instruments is expensive and sourcing materials sustainably has been increasingly difficult. As a consequence there are significant benefits in identifying other suitable materials which are economic, can be easily sourced and still have good acoustic properties. This paper considers the use of concrete mixes to meet this goal.

Plywood, bamboo, fibreboard have already been widely used for making the guitar soundboard, as the principal sound-generating component of the instrument. Guitars made from these materials are claimed to perform musically as well as the more expensive traditional wood ones (Besnainou, 1998) (Wegst, 2008). Nowadays, many researchers have focused on other materials, such as carbon fibre composite material, foamed polycarbonate and wood plastic composite (WPC) used for creating soundboards (FECC, 2010). There should be potential for the cement-based material to perform acoustically in a similar manner, due to its material properties which can be engineered to a certain degree by adding the numerous additives, admixtures, binders and aggregates. Other advantages include its abundance, ease of production in complex shapes, precise volume control (no wastage) and cost effectiveness. This change in material could make it possible to shift some instrument production from hand crafting to mass production for a significant drop in price.

Over recent years several researchers have considered the use of cementitious materials for musical instruments. One example is the concrete flute created by the National Chiayi University in Taiwan. This concrete flute is only slightly heavier than a plastic flute, but the tonal quality is even more steady and rich than a normal flute (Su, 2009), thus demonstrating the potential for the concrete to be used as a wind musical instrument.

Ritsumeiken University in Japan constructed a concrete harp and alphorn using ultra high strength fiber reinforced concrete (UFRC). Their research however only focuses upon the manufacturing ability to cast concrete into such shapes, rather than to explore the acoustic properties of cement based materials. Whilst they found out that concrete does have potential acoustics due to the sound box of harp made from UFRC can easily resonate notes within a frequency range of 300-400Hz and also proves that UFRC have the potential for manufacturing thin yet strong concrete. This find helps us to know that choosing the right mix, a portable instrument made from cementitious material is feasible (Takeda et al., 2009).

An electric concrete guitar was created by Parker Sloan of Western Kentucky University (Anon, 2007). This is also a workable instrument although no technical publications have been produced.

Concrete however are very variable material and there is a gap in knowledge about the acoustical properties of each. This paper presents measurements of fundamental acoustic/mechanical properties of various materials and mixes and demonstrates a viable instrument constructed from an optimum material, chosen from those tested.

2. METHODOLOGY

The measurements conducted follow the methods suggested by Fujiso (2009), which considers the influence of a normal electric guitar's material on its tone.

Fujiso investigated different variables of the electric guitar and determined how each affects the tone. To analyse the effect the material of the body has on the guitar, three different woods material of electric guitars were chosen, Ash, Mahogany (both of which are widely used in guitar construction), and also Medium, whose structure is isotropic, unlike natural wood and is therefore more similar to cement based materials. Through using a technique known as Experimental Modal Analysis to investigate dynamic damping ratios of the guitars, and also generate modal shapes and natural frequencies to help compare how the materials differ from each other. It was concluded that the three guitars dynamically behave in a similar way, with almost the same modal frequencies, modal damping and modal shapes, but this maybe due to the nature of the guitars having identical shapes, components and construction. However, this analysis provides a promising platform for cement based materials to be used as bodies for a guitar and also can be compared to the wood guitar.

The present study investigates the modal parameters (damping ratio and natural frequency) of sand and Lytag based mortars with the polymer additive polyvinyl acetate (PVA) used for making an electric guitar in order to determine whether they can be engineered to match the modal properties of wooden materials used in electric guitar construction. The modal parameters of materials are investigated before analysing them applied to an electric guitar. Nominal tests such as compressive and flexural strength are conducted in order to judge the mix's durability; however the elastic modulus and modal analysis experiments are the focal points.

In the model analysis, Guillaume (2002) described modes as inherent properties of a structure that are determined by material properties such as mass, damping, stiffness, and also boundary conditions (damping constants). Each mode is defined by a natural (modal or resonant) frequency, and a mode shape.' Therefore values generated are unique for every specimen and changes to mass, stiffness or shape would change the modal parameters. This can be expressed mathematically (Rao, 2005):

$$\omega_n = \sqrt{\frac{k}{m}}$$

$$\zeta_{eq} = \frac{c}{2m\omega_n} = \frac{c}{2\sqrt{mk}}$$

-ω_n= natural frequency
- k = stiffness - m = mass
-ζ_{eq}= damping ratio - c = damping coefficient
- r = frequency ratio = ω/ω_n

The stiffness of the material (k) is related to the size (Area A and Length L) and elastic modulus (E):

$$k = \frac{AE}{L}$$

The stiffness is therefore proportional to the elastic modulus.

In the Modal Analysis, Frequency Response Functions (FRF) is the easiest way to determine the modal parameters, such as natural frequencies, the damping ratios and modal shapes. Through collating the data of individual responses from multiple points along the surface of a specimen, an FRF representative of the whole sample can be collected. This process creates a modal model from which the modal parameters can be distinguished.

Table1. Material properties

	Guitar woods	Cementitious materials	Water	Fly ash
Density (kgm^{-3})	400-800	2000-2500	1000	<1000
Elastic Modulus (GPa)	8-12	20-35	-	-

In order to match the material properties of guitar woods, an initial problem that can be identified is the variable, mass. From the table 1, the density of guitar woods averages between 400-800 kgm^{-3} (Jahnel, 2000). While cement based materials have a density between 2000-2500kgm^{-3}, where water is the lightest ingredient at 1000kgm^{-3}. There are numerous admixtures available such as fly ash which can have a density of <1000kgm^{-3} (Cangialosi et al, 2000), and can replace a percentage of cement to help reduce weight, while it is still hard to have it in the same region of wood. Possible option such as casting air voids may be able to reduce the density. However, the behaviour of such a material could be unpredictable and will increase the variables. Therefore, stiffness will be the primary variable investigated rather than reducing the mass.

The analysis above referred to the equation of stiffness, which as explained earlier is proportional to the modulus of elasticity. From Table 1, for cement based materials with compressive strengths between 20-60MPa, the elastic modulus can range between 20-35GPa (Neville, 1995). However, the young's modulus of wood is only between 8-12GPa (Jahnel, 2000). This suggests that the elastic modulus for typical cement based materials needs to be at least halved if they are to be used in the same way as wood, Ohama (1995) investigated a wide variety of polymer substitutions and showed that there is potential for reducing the elastic modulus by adding PVA and thus seems a potential method for lowering the elastic modulus and thus achieving a stiffness similar to wood. Due to the size specific nature of modal analysis however, there is no literature with similar experimentations that the specimens in this project can be compared to. Comparative analysis is therefore conducted, and compared to a control piece of wood (pine).

3. MIX DESIGN

6 mixes have been investigated upon. They consist of 3 standard mortar mixes of sand and cement with varying polymer contents of 0, 10 and 25%. The remaining 3 are Lytag mortar mixes with the same polymer modifications. The codes N0, N10, N25, L0, L10 and L25 etc denote the mix, normal or Lytag aggregate and PVA content. They will be used to refer the mixes for the remainder of this paper. 40mm polymer fibre reinforcement is also included into all the mixes.

The mix design was based on a simple 2:1 sand / cement ratio with a water cement ratio of 0.45. The total amount of mortar required is $0.0085m^3$. Therefore $0.01m^3$ was manufactured to account for losses and wastage. Then the whole volume of contents was calculated according to the requirement of material supplier per $1m^3$.

4. TEST

Compressive strengths of the samples were tested in compliance with BS EN 12390-3:2009 using a Dennison compressive machine with a loading rate of $0.6Nmm^{-2}s^{-1}$. Flexural strengths of the samples were tested in compliance with BS EN 12390-5:2009 using a Dennison tensile machine with a loading rate of $0.005Nmm^{-2}s^{-1}$.

The testing for reducing the modulus of elasticity was conducted in compliance to BS1881:part121:1983. The strain needs to be measured on all 4 sides using single element PFL-30-11 electric strain gauge. DMEC pips were adhered to all 4 sides to enable strain to be calculated mechanically using a Mercer strain gauge. All of the gauges were placed centrally and parallel to the axis of loading. The samples were tested using an Instron 5500R 6025 machine, with each of them tested 3 times at loading increments of 0.25 or 0.5 Nmm^{-2}.

The 'Roving Hammer' technique is chosen to perform the modal analysis test. It is quite simpler method that the user can hit the specimens at various points along a single surface and the response is measured using an accelerometer. Through the computer software, the data can be interpreted and provide the user with the modal parameters. The shortcoming through such testing is that only the fundamental modal parameters can be found.

5. RESULTS AND DISCUSSION

Table 2 below shows the result of key material properties.

Table2. Key results of material properties

Mix	Density (kgm^{-3})	28 day Comp. Strength (Nmm^{-2})	28day Flex. Strength (Nmm^{-2})	Elastic Modulus GPa
N0	2108	39.7	18.5	17.5
N10	2050	14.6	11.5	9.41
N25	1986	3.9	4.3	1.76
L0	1785	33.4	15.1	8.28
L10	1675	17.8	10.6	4.18
L25	1562	4.8	5.4	1.38

Although mass is not the key variable to this research, a lower density is still desirable in terms of influencing the modal parameters and potential manufacture of a guitar. With the above mix design and resources, the density of the L25 mix was the lightest result possible. This result will be taken into consideration upon manufacture of the guitar as well as the modal parameters and strength. The samples under standard compressive strength testing at intervals of 7 and 28 days, flexural strength testing at 28 days are actually not a key issue for the potential of making a cement based guitar. But it will again prove the influence of increased contents of PVA on both the normal and Lytag mortar mixes and both compressive and flexural strengths, figure 1.

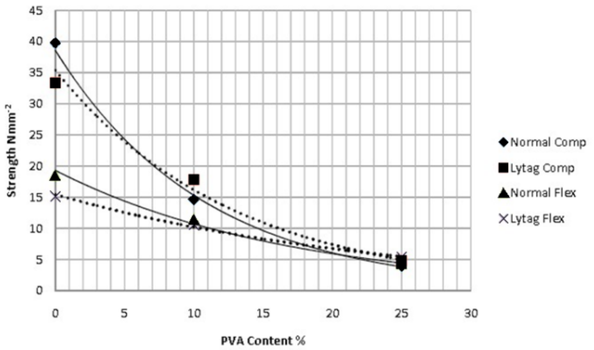

Figure1. Decrease of Compressive and Flexural Strength with PVA at 28 Days

This result indicates that the strength difference between Lytag and normal mixes are not too dissimilar. But N0 and L0 show that N0 has greater value on both strengths, yet L10 and L25 have greater strengths than their counterparts, which may illustrate that Lytag is able to cope with the addition of PVA better. It also highlights the good properties of Lytag, being lightweight yet strong and shows its potential as a possible aggregate for an electric guitar.

Elastic modulus can be seen as a key variable to understand the modal parameters of the specimens. From the Figure 2, the addition of PVA greatly lowers the values of the elastic modulus. According to the equation $\zeta_{eq} = \frac{c}{\sqrt{mk}}$, therefore a very low stiffness will counter the fact that the mortar samples have a higher mass can also achieve modal parameters that are closer to wood.

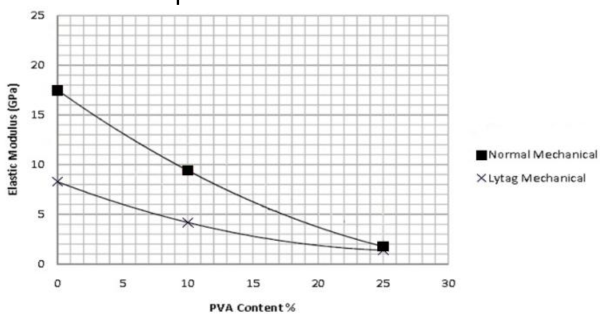

Figure2. PVA's effects of the Elastic Modulus

The errors caused in the test are inevitable, such as calibration error etc. Due to the poor casting workability of the mixes containing PVA, especially N25 and L25, it was impossible to gain a smooth surface for the exposed face in the mould by using a hand float. Consequently, the strain readings from this side were consistently higher strains than the other sides. The compaction of the specimens is also an issue which will result in different strain values from the bottom and the top floated side.

If the results show that the specimens are only able to match the elastic modulus of wood (8-12 GPa), then the modal parameters of such a specimen would still differ from woods due to its higher mass. However these results show that the reduced elastic modulus could now be low enough to possibly compensate for the extra mass of the specimens.

During the modal analysis experimentations, the natural frequencies/FRF's has been tested, from which the damping ratio's can be determined (Table 3). It clear shows that the natural frequencies reduce with the higher PVA content, which correlates with a lower elastic modulus and there stiffness will achieve lower modal frequencies, as explained by the formula: $\omega_n = \sqrt{\frac{k}{m}}$.

Table3. The Modal Parameters

	1st mode		2nd Mode		
Mix	**Nat. Freq.**	**Damp. Ratio%**	**Nat. Freq.**	**Damp. Ratio%**	**Ave.Damp. %**
N0	4192	0.57	8797	0.54	0.555
N10	3534	1.44	7283	1.46	1.45
N25	2388	3.51	4898	2.67	3.09
L0	3173	1.41	6680	0.99	1.2
L10	2923	1.25	6004	1.23	1.24
L25	2145	2.88	4507	2.97	2.925
Wood (Pine)	3548	2.14	6120	2.33	2.235

Table 3 shows that a wide range of damping ratios were achieved from the specimens and almost all show good correlation between the lowered stiffness and the damping ratio. It highlights the effects which increased PVA content has on the damping ratio, but has less on Lytags than the normal mix.

From the point of view on making the cement based material guitar, these above modal parameters results again show potential of it. If they are compared to modal parameters of wood pine as seen in table 3, then it can be observed that there is an overlap, and that somewhere between N10 and N25 the damping ratio cross, this is also the case for the L10 and L25 samples. This suggests that there is an optimum mix which will have the same modal parameters as wooden materials, from which the body of an electric guitar can be made. These data highlight the PVA content and elastic modulus of a normal or Lytag mix that would have the same damping ratio as pine.

At last, balance all of the above parameters determined, due to Lytag's ability to be less affected by PVA, having lower density compared to N25, According to the damping ratio effects contrast with wood pine, 20% PVA content will be used. The corresponding elastic modulus is 2.5GPa from figure 2, compressive strength is 7.5 Nmm^{-2} yet the flexural is slightly lower at 6 Nmm^{-2} from figure 1. Considering the strength isn't a key variable of making an instrument, the body is durable enough to use. Therefore, Lytag mortar mix will be used to manufacture the body of the electric guitar.

6. MANUFACTURING A MORTAR GUITAR

The shape similar to a Fender Telecaster was chosen to enable comparison with Fujiso (2009).An AutoCAD model of the outline was cut out of 12mm pieces of plywood using a 2D water jet router.

The chosen mix was 20% PVA. The mass of the guitar is 6.97kg (Figure 3)Through the impact hammer modal test, the range of damping ratio is 1.91% to 2.56%, compared to the wooden guitars with the same shape mentioned from Fujiso's, of 0.6%-2.3%. Since the Lytag mortar guitar is not fully isotropic through casting in the items (e.g. reinforcement and bolt anchors etc), it doesn't perfectly correlate to the previous data of the tested samples.

Figure 3: Concrete electric guitar

7. CONCLUSION

This study has explored the versatility of cement based materials and shown their potential for engineering the mix designs in an attempt to match material properties of wood material.

The PVA shows its great influence on the compressive and flexural strength of the sample, which also affects the elastic modulus.

After modal analysis, good correlation between lower natural frequencies and stiffness were present. The damping ratios increased with lower stiffness and mass which was also predicted by the mechanical vibration theory shown in the methodology.

Lytag based mortar shows that it is able to achieve similar compressive and flexural strengths as sand based mortar. It has an elastic modulus of approximately 50% of its sand based peer, and is also half the density. This suggests that for the purpose of this experiment, Lytag was the more suitable aggregate.

The modal analysis provided consistent data, however, doesn't directly correlate to previous literature, suggesting that the mix used was not stiff enough. This does not make the guitar a failed model. After all, it is still a workable guitar. It just indicates that there is a further potential to progress this research and the modal parameters of wood could be matched.

Following this study, there are still more acoustic parameters of cementitious material available to be investigated, such as the velocity of sound transmitted in the cementitious material, and acoustic impedance. When combined with the physical properties of the material itself, like porosity, surface finish and also density, modulus which have been tested in this study, more relationships can be still researched.

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