Investigation of acoustical and structural parameters of recycled glass bead composite panels

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Abstract

An investigation is conducted on the acoustical and structural properties of sandwich composite beams comprising polyurethane glass beads set in a matrix of epoxy resin core between two fibreglass sheets in order to assess their suitability for engineering applications, especially in urban, built-up or noisy environments. Transmission Loss (TL) and absorption coefficient of composite samples were determined using transfer function method. Experiments are conducted in order to determine the modulus of elasticity of the fibreglass sheets, the compressive strength of the bead core.

1. Introduction

The design of effective acoustic insulation and noise barriers is of great importance in ensuring that the ever-expanding residential and commercial infrastructure associated with increasing development, industry and population do not impact negatively on the normal everyday use of the built environment. In addition, there is an increased need to produce practical designs that also incorporate benefits to the environment and to reduce the impact on the health and lifestyles of people [1, 2]. Meeting the combined demands of increased population density and limited resource availability has become a key challenge which the structural and infrastructural designers of this century are facing.

It has been suggested [3] that the current demand for housing stock within the United Kingdom necessitates the construction of 260,000 new residential units each year until 2023. Meeting this demand within such a short period of time can be approached by i) developing faster methods of construction, and ii) developing additional sites suitable for construction. Modular and offsite construction methods, whereby structural units or subunits are fabricated offsite and then assembled onsite, are becoming increasingly popular in the construction industry owing to their potential to reduce construction time [4], reduce overall costs of manufacture [4] and increase safety and reliability during construction and operation [5]; thus, increased research and development has focussed on the use of various construction materials and fabrication techniques in offsite construction, which have been summarised in a number of review studies [6–10]. The need to develop residential sites within urban centres is continuously increasing due to growing global urbanisation. With construction space already at a premium within most urban centres, the need to construct residential units in noisy or vibration-prone environments such as in proximity to highways and rail corridors is increasing [11,12]. When considering these particular challenges that face the construction industry, structural solutions that can combine speed and reliability of construction with the ability to provide a built environment free from excessive noise or uncomfortable vibrations offer considerable advantages to structural designers.

Recycled glass bead composite panels (RGCPs) comprise two fibreglass facing sheets surrounding an inner core of recycled glass beads bonded in a matrix of polyurethane (PU) resin. Recycled glass has previously been employed in construction as both fine and coarse aggregates in concrete [13,14], as an additive in asphalt for highways [15] and lightweight residential units and emergency shelters. Their low weight and portability make them ideally suited to modular construction, where whole units can be fabricated offsite and transported to their final location; alternatively, the panels can be easily manipulated onsite. Given that they are composed of recycled material, the sustainability of structures incorporating RGCPs is enhanced [16] and the composition of the core, which contains a number of voids, aids acoustic insulation [17]. However, although the mechanical behaviour of structural glass is relatively well understood and data exists for properties such as tensile strength, compressive strength and modulus of elasticity, to the best of the authors' understanding, there is little to no literature available concerning the structural and mechanical properties of polyurethane-bound recycled glass bead core as a load-transferring mechanism in itself.

Previous studies on the impact of noise from highway networks found that the frequency spectrum of A-weighted road traffic noise is typically between 125 Hz and 4000 Hz [18]. Acoustic noise barriers are required to ensure good performance in the mid frequency range between 500 Hz and 1500 Hz and to guarantee they relate to road traffic noise [2]. The effectiveness of a noise barrier is related to the characteristics and mechanics of the materials that they are made of. The critical elements are the absorption coefficient of the material and the surface impedance [19]. There are other characteristics that collaborate towards the overall effectiveness of the material as an acoustic absorber, these are: characteristic impedance, porosity, density, flow resistivity and tortuosity. Highway noise barriers are made of porous materials to increase the sound absorption, leading to a lower sound level being reflected and transmitted. The flow resistivity and insertion loss generally increase as the density of the fibrous material increases. Fibrous materials are generally assumed anisotropic, meaning the fibres within the material lie in planes parallel to the surface. The subsequent flow resistivity changes depending on direction; along the panel in a planar direction has a lower flow resistivity, and at a normal incidence, the flow resistivity increases. Fibrous materials such as mineral wool are used for panel absorbers because of their anisotropic characteristic and cellular structure [20]. The effectiveness of a simple noise barrier is typically limited to a reduction of sound approximately 15 dBA due to diffraction, and barriers are most efficient at mitigating middle and high frequencies [21].

The noise contribution from road traffic vehicles differs dependent on the type, size, weight and speed of the vehicle, effects of the road surface materials and meteorological effects such as temperature, humidity and wind direction [22–24]. As the acoustic properties of traffic noise reducing devices such as highway noise barriers is frequency dependent, there is a need to define a generic noise spectrum for test purposes [25]. For noise control application, any solid structure may be used for noise barrier between sound source and receptor point as long as the barrier has a sound transmission loss of at least 10 dB greater than the desired noise reduction.

The aim of the present study is to determine the acoustical and structural properties of recycled glass bead composite panels in order to assess their suitability for civil engineering applications, especially in noisy urban environments, both as a construction material and as dedicated noise barriers. The sound absorption coefficient and transmission loss of noise barriers made of recycled glass bead composite panels were determined from the data obtained using transfer function method in an impedance tube system designed for the testing materials. Structural and mechanical tests were conducted in order to determine the modes of failure, the ultimate resistances, the initial linear stiffness and the ductility of the recycled glass bead panels. A simple design equation for the cross-sectional moment resistance of the panels is proposed and compared against the experimental results.

2. Acoustical investigation of composite panels' performance

In this section, experiments conducted on RGCP specimens to measure acoustic reflection, sound absorption and sound transmission loss are described. In the present study, the impedance tube method, which is performed via the transfer function method in accordance with BS EN ISO 10543-2:2001 [26], was employed to determine the acoustic properties. Three cylindrical specimens cut from full RGCPs, as shown in Figure 1, were tested: Specimens C01-4-L and C02-1-L were 130 mm thick with a nominal glass bead diameter of 4–8 mm and 1–2 mm, respectively, while specimen C03-1-S was 50 mm thick with a nominal glass bead diameter of 1–2 mm. The same specimens were tested in compression, as described in Section 3.2.

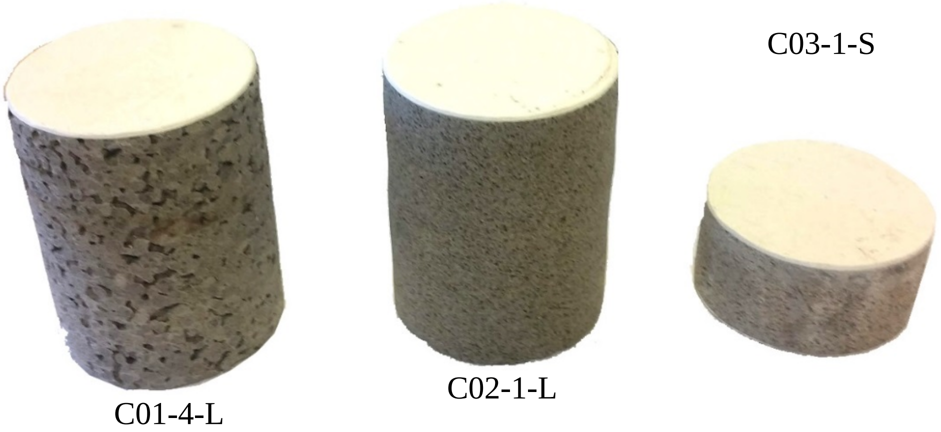

Figure 1: Acoustic and compression test samples.

2.1 Absorption coefficient of RGCP specimens

Sound attenuating barriers are solid structures that intercept the direct noise transmission path from a sound source to a receiver. They reduce the noise level within the shadow zone on receptor side. Measurements of sound absorption were taken in a circular impedance tube with an internal diameter of 100 mm (see Figure 2). In keeping with a previous study of clamped poro-elastic plates [26], the experiments were conducted in accordance with the procedure outlined in BS EN ISO 10543-2:2001 [27].

2.2.1 Methodology

A sample of test material with a movable rigid backing is placed at one end of a tube and a loudspeaker is placed at opposite end of the tube. Two ¼ inch microphones were mounted into a microphone grid at positions along the length of the impedance tube (as indicated in Figure 2), with each microphone grid being sealed tight to its housing. The microphones were fed to a four-channel data acquisition card (type MC3242, BSWA Tech.) which was connected to a computer for logging and further analysis. The acoustic sound field, an incident plane sinusoidal wave, P_i was created by a loudspeaker with a built-in amplifier. The transfer function method is used to determine the acoustical properties of the sample whereby the sound pressure at two fixed microphone locations within the tube is measured and then used as input for the acoustic transfer function to calculate the absorption coefficients.

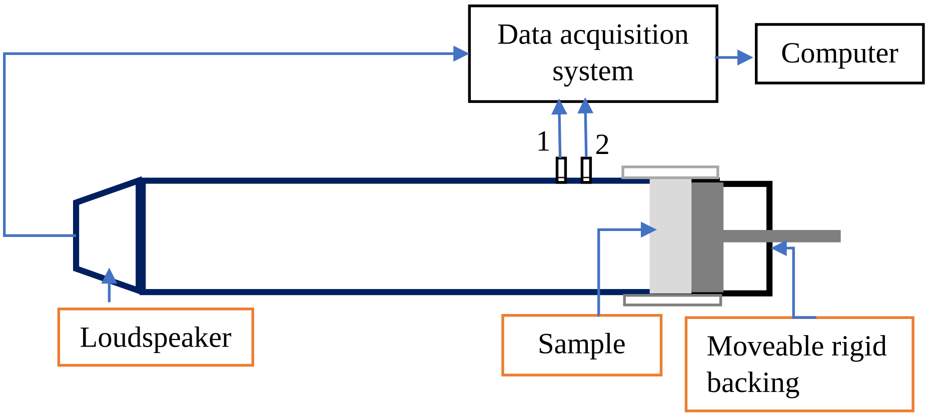

Figure 2: Impedance tube system for absorption measurement

2.2.2 Results

The measured absorption coefficient spectra for the three samples are shown in Figure 3. Specimen C01 has an initial absorption peak of 0.58 at 251 Hz and a secondary absorption peak of 0.55 at 630 Hz while specimen C02 has an absorption peak of 0.62 at 250 Hz and a secondary absorption peak of 0.45 at 800 Hz. Specimens C01 and C02 are effective at low and mid-frequency ranges and behave like porous panels. Specimen C03 has only one absorption peak of 0.84 at 501 Hz. The absorption mechanism of specimen C03 is effective around the resonance frequency, thus it is behaving like a resonator. Specimen C03 attenuates 84% of acoustical energy impinging on its surface at its resonance frequency. Specimens C02 and C03 have the same nominal glass bead diameter (1–2 mm) but they have different thicknesses. Increasing the thickness of the materials enhanced the low frequency performance of the material while reducing mid-frequency absorption and shifting the resonance peak to a lower frequency. The resulting absorption performances of these samples are close to the peak sound pressure levels in the typical spectrum of road traffic noise.

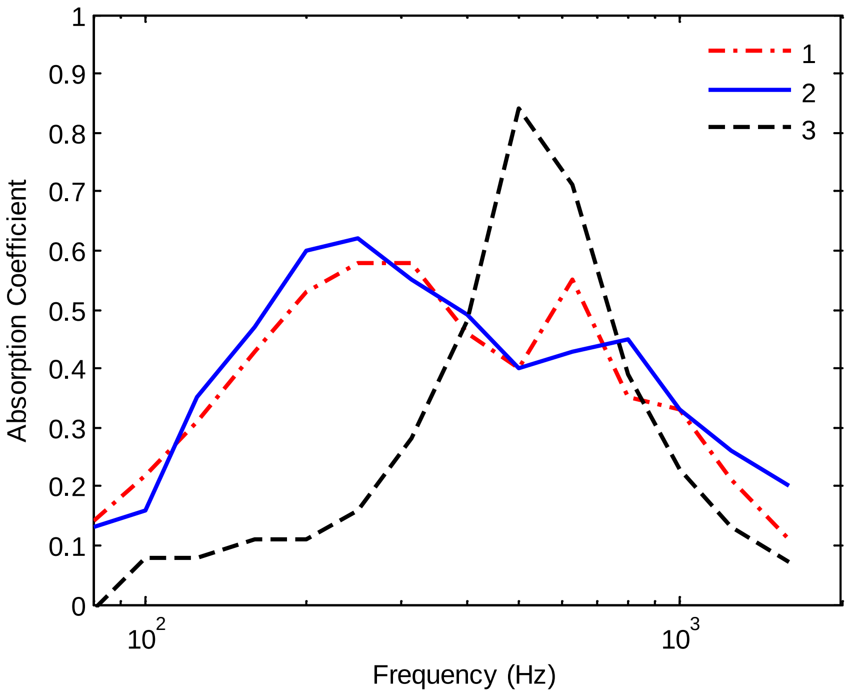

Figure 3: Absorption coefficient of glass bead samples.

2.3 The sound transmission loss (TL)

The sound transmission loss of acoustic materials is important in building acoustics and environmental noise attenuation panels. There is not any established international standard for measuring the sound transmission loss of acoustic materials. Bolton et al [28] has modified the impedance tube and the procedure given in [26] for the transmission loss measurements. A measurement procedure given in [28,29] is followed for the transmission loss of RGCPs specimens.

2.3.1 Measurement methodology

Measurements have been carried out in a circular impedance tube with an internal diameter of 100 mm (see Figure 4). A sample of test material is placed at the middle of a tube. A loudspeaker is placed at one end of the tube and a rigid plate is placed at the opposite end of the tube. Six ¼ inch microphones (three microphones on each side of the test sample) were mounted into microphone grid at positions along the length of the impedance tube. Each microphone grid was sealed tight to its housing. The microphones were fed to a four-channel data acquisition card (type MC3242, BSWA Tech.) which was connected to a computer for data analysis. The acoustic sound field, an incident plane sinusoidal wave, P_i was created by a loudspeaker that was fed with a power amplifier with build-in pink noise generator (type PA50, BSWA Tech.). The sound signals at four fixed microphone locations within the tube were simultaneously measured. Microphones 1 and 3 for upstream tube and 4 and 6 for downstream tube are used to measure the transmission loss between 63 Hz and 500 Hz while microphones 2 and 3 for upstream tube, and 4 and 5 for downstream tube are used to measure the TL of noise barriers between 250 Hz and 1600 Hz. The VA_LAB using Transfer Function Method separates the incident and reflected energy from the measured transfer function, and then estimates the acoustic properties of the tested sample installed in the tube.

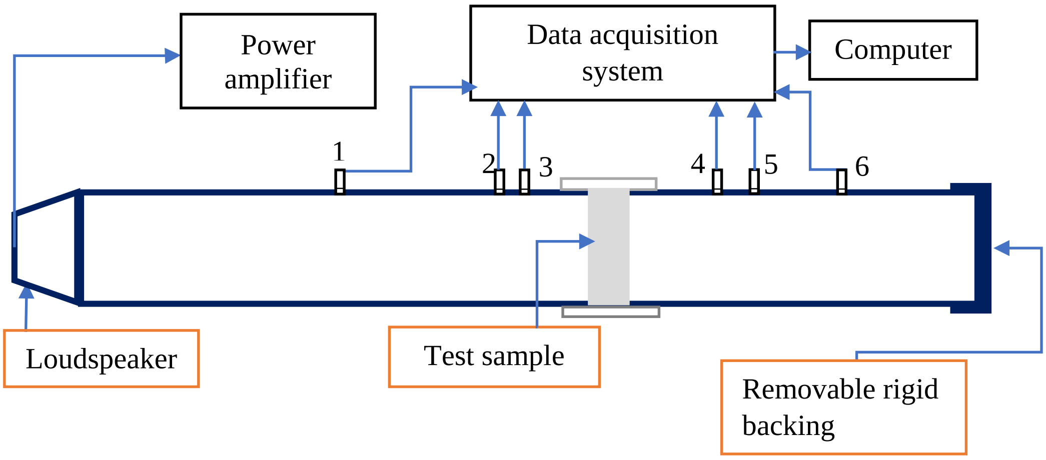

Figure 4: Impedance tube system for transmission loss measurement

2.3.2 Determination of the transmission loss

The sound transmission loss (TL) of a noise barrier is defined [29] thus:

$$TL = 20\log\left|\frac{e^{jks}-H_{13}}{e^{jks}-H_{64}}\right| - 20\log|H_t| \qquad \textit{for TL between 63-500 Hz} \qquad (1\,a)$$

$$TL = 20\log\left|\frac{e^{jks} - H_{23}}{e^{jks} - H_{54}}\right| - 20\log|H_t| \qquad \textit{for TL between 250-1600 Hz} \qquad (2\,b)$$

where s is the distance between the centre of microphones, and k is the complex propagation constant, $H_{13} = \frac{P_3}{P_1}$ and , $H_{23} = \frac{P_3}{P_2}$ are the transfer function which is the ratio of the Fourier transform component between the sound pressures at microphones 1 and 3, and at microphones 2 and 3 respectively, and $H_{54} = \frac{P_4}{P_5}$, and $H_{64} = \frac{P_4}{P_6}$ are the transfer function which is the ratio of the Fourier transform component between the sound pressures at microphones 4 and 5, and at microphones 4 and 6. $H_t = \sqrt{|S_d/S_u|}$ is the ratio between the auto-spectrum in the upstream tube S_u and the auto-spectrum in the downstream tube S_d, respectively.

The transmission loss of three composite samples tested in the experiments are shown in Figure 5. The transmission losses of three samples increase throughout 1/3 octave band frequency range from 14.5 dB at 63 Hz up to 33 dB at 1600 Hz. At lower frequencies (63 Hz - 300 Hz) specimen C01 has a higher TL than specimens C02 and C03, while specimen C03 attenuates more noise than the other specimens at frequencies above 300 Hz. Specimens C01 and C02 have different nominal glass bead diameter but their transmission loss performance above 400 Hz is similar. The sound transmission losses of the specimens C01, C02 and C03 are 17.3 dB, 16.5 dB and 21.8 dB at 500 Hz, respectively. These results are in the range of maximum transmission losses obtained with a practical noise barrier which is used for attenuating road traffic noise. The maximum noise transmission loss for noise barrier is approximately around 15 to 20 dB at 500 Hz for the barriers very close to either source side or receiver side. Using masses for a barrier in excess of around 15 kg/m^2 is a waste of recourses because the performance of noise barriers is limited by the diffraction over the top of the barrier and around the ends of the barriers [30].

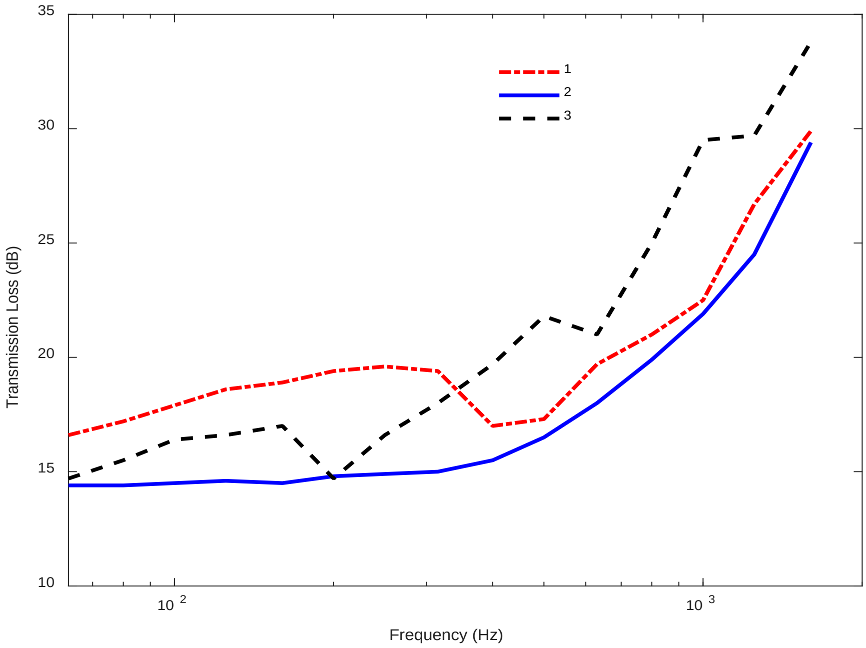

Figure 5: Transmission loss of glass bead samples.

3. Structural and mechanical testing

In order to determine the structural and mechanical properties of the composite panels, a series of tensile tests, compression tests and bending tests were conducted on various specimens in the Strengths of Materials laboratory at London South Bank University. In this section, the experiments are described, and the observed behaviour and the mechanical properties determined from the results are discussed. RCGPs have been used previously as floor panels bearing directly onto prepared soil surfaces, and also as roof panels. The current investigation aims to ascertain whether the panels are suitable as short-spanning floor panels.

3.1 Determination of modulus of elasticity of fibreglass sheeting

Two tensile coupons were cut from full RGCP specimens in order to examine the behaviour of the facing material in situ. After determining the average breadth and thickness (23.1 mm, and 2.26 mm, respectively) across the central portion of the coupons, the ends were clamped in a Tinius Olsen H25KS tensile testing machine (see Figure 6), a clip gauge with a gauge length of 25 mm was attached to its central portion, and the specimen was then loaded in tension in the elastic range in order to determine the modulus of elasticity E_{fg}. Based on the four experiments conducted, an average value of E_{fg} = 7489 N/mm^2 was obtained.

Figure 6: Fibreglass specimen clamped in preparation for determination of modulus of elasticity.

3.2 Compression tests of recycled glass bead cores

Compression tests of cylinders cut from the panels were conducted at the Strengths of Materials laboratory at London South Bank University. In this section, the experiments are described and the load – deflection behaviour, the observed modes of failure, the ultimate resistances and the compressive strength of the cores are discussed.

After the acoustic experiments described in Section 2 and density measurements were conducted, the specimens shown in Figure 1 were positioned between the loading platens of a Zwick/Roell 250 kN Universal testing machine (see Figure 7) and then loaded in compression via displacement control at a rate of 5 mm/min.

Figure 7: Specimen C02-1-L positioned in preparation for compression testing.

As can be seen in the graphs of machine load *P* against end shortening *Δ* shown in Figure 8, an initial regime of elastic deformation was observed in each test specimen prior to the onset of crushing of the bead core. There then followed a regime of successive crushing, cracking and compaction of the bead core. The failure modes observed are shown in Figure 9. It can be seen that the compressive resistances of the specimens are quite similar, indicating that the compressive strength $\sigma_{c,c}$ of both types of bead core are similar; these values are shown in Table 1, respectively. Measurements of the compressive modulus of elasticity of the material were less reliable owing to the variable strain distribution being transferred through the bead core. It can be seen in the case of specimen C03-1-S that after a certain amount of crushing of the bead core, the load increases again, which can be attributed to densification and compaction of the core after voids are removed. This indicates that an additional reserve of strength and resistance can be developed within recycled glass bead cores if the thickness of the core is optimised. This might be one of the reasons for C03-1-S behaving like a Helmholtz resonator and attenuating maximum absorption around its natural frequency.

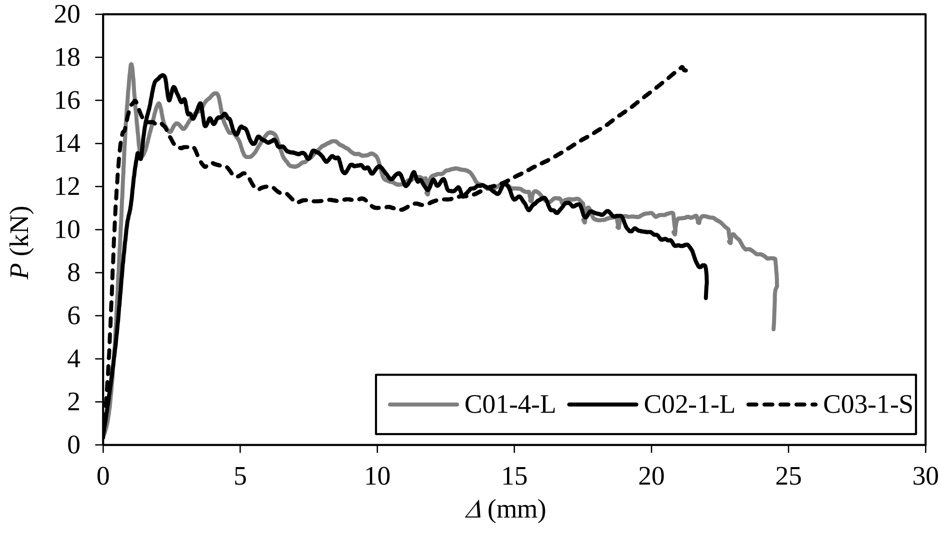

Figure 8: Load–end shortening relationships of recycled glass bead cores in compression.

Table 1: Compressive strengths of glass bead core specimens.

Specimen	*h* (mm)	Bead diameter (mm)	$\sigma_{c,c}$ (N/mm^2)
C01-4-L	130	4 - 8	2.29

C02-1-L	130	1 - 2	2.20
C03-1-S	50	1 - 2	2.08

Figure 9: Failure modes of glass bead core specimens in compression: (left to right: specimens C01-4-L, C02-1-L, C03-1-S).

4. Conclusions and further work

A state of art investigation is carried out to determine the acoustical and structural parameters of recycled glass bead composite panels comprising two fibreglass facing sheets surrounding an inner core of recycled glass beads bonded in a matrix of polyurethane resin. The acoustical experiments were conducted on cylindrical samples cut from full composite panel specimens in an impedance tube using the transfer function method in order to determine the sound absorption coefficient and transmission loss of them. The results show that C01 and C02 samples are good at attenuating noise at lower frequency while C03 sample is good at absorbing sound at mid frequency, around its natural frequency. The absorption performances of composite panels are close to the peak sound pressure levels in the typical spectrum of road traffic noise. The sound transmission loss of the samples measured at 500 Hz are in the range of maximum transmission loss obtained with a practical noise barrier, hence demonstrating the efficacy of the panels in providing acoustical insulation both as highway noise barriers and also in a residential application.

A range of structural and mechanical tests have been conducted in the Strengths of Materials laboratory at London South Bank University. Tensile tests were performed on coupons cut from the fibreglass outer sheets of full recycled glass bead composite panels in order to determine the elastic modulus of the sheeting material after the fabrication process. Compressive testing was conducted on the cylindrical samples used in the acoustical testing in order to determine the compressive strengths of the two different bead core compositions under investigation. It was found that the compressive strengths of cores containing 1–2 mm diameter bead and those containing 4–8 mm diameter bead are very similar. It was also found that, after complete compaction of the 50 mm thick bead core, the overall load increased again, indicating that there exists an additional reserve of strength within recycled glass bead cores, which makes C03 sample to behave like a resonator and making the sample to be effective at around its natural frequency.

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References

1. Department for Communities and Local Government, 2012. National Planning Policy Framework. Department for Communities and Local Government.
2. Highways England, 2017. Design manual for roads and bridges. Highways England Available from: http://data.theeuropeanlibrary.org/BibliographicResource/3000075494711.
3. Ministry of Housing, Communities and Local Government. 2017. Fixing our broken housing market. London: HM Government, 2017.
4. J. Hong, G.Q. Shen, Z. Li, B. Zhang, W. Zhang. 2018. Barriers to promoting prefabricated construction in China: a cost–benefit analysis, J. Clean. Prod., 172 (2018), pp. 649-660.
5. M.M. Fard, S.A. Terouhid, C.J. Kibert, H. Hakim. 2017. Safety concerns related to modular/prefabricated building construction, Int. J. Inj. Contr. Saf. Promot., 24 (1) (2017), pp. 10–23.
6. R. Jin, S. Gao, A. Cheshmehzangi, E. Aboagye-Nimod. 2018. A holistic review of off-site construction literature published between 2008 and 2018, Journal of Cleaner Production, Volume 202, 20 November 2018, Pages 1202–1219.
7. W. Pan, R. Sidwell. 2011. Demystifying the cost barriers to offsite construction in the UK, Construct. Manag. Econ., 29 (11) (2011), pp. 1081-1099.
8. Z. Li, G.Q. Shen, X. Xue. 2014. Critical review of the research on the management of prefabricated construction. Habitat Int., 43 (2014), pp. 240-249.
9. V.W.Y. Tam, I.W.H. Fung, M.C.P. Sing, S.O. Ogunlana. 2015. Best practice of prefabrication implementation in the Hong Kong public and private sectors, J. Clean. Prod., 109 (2015), pp. 216-231.
10. M.R. Hosseini, I. Martek, E.K. Zavadskas, A.A. Aibinu, M. Arashpour, N. Chileshe. 2018. Critical evaluation of off-site construction research: a Scientometric analysis, Autom. ConStruct., 87 (2018), pp. 235-247.
11. Department for Environment Food and Rural Affairs (DEFRA) (2013). Draft Noise Action Plan: Railways (Including Major Railways) Environmental Noise (England) Regulations 2006, as amended.
12. Department for Communities and Local Government (DCLG) (2006). Planning policy guidance 24: planning and Noise.
13. T. S. Serniabat, M. N. N. Khan, M. F. M. Zain. 2014. Use of Waste Glass as Coarse Aggregate in Concrete: A Possibility towards Sustainable Building Construction, International Journal of Civil and Environmental Engineering Vol:8, No:10, 2014.
14. A. Mohajerani, J. Vajna, T. Ho, H. Cheung, H. Kurmus, A. Arulrajah, S. Horpibulsuk. 2017. Practical recycling applications of crushed waste glass in construction materials: A review, Construction and Building Materials, Volume 156, 2017, Pages 443-467,
15. J. Tao. 2017. Use of Crushed Recycled Glass in the Construction of Local Roadways. Ohio’s Research Initiative for Locals, The Ohio Department of Transportation Office of Statewide Planning and Research, Technical Report 135329.
16. H. Heriyanto, F. Pahlevani, V. Sahajwalla, 2018. From waste glass to building materials – An innovative sustainable solution for waste glass, Journal of Cleaner Production, Volume 191, 2018, Pages 192–206.

17. M. Tascan, K. Lyon Gaffney. 2012. Effect of Glass-Beads on Sound Insulation Properties of Nonwoven Fabrics Journal of engineered fibres and fabrics 7(1):101-105
18. Sandberg, U., 2003. The Multi-Coincidence Peak around 1000 Hz in Tyre/Road Noise Spectra. Euronoise Naples.
19. Allard, J. and Atalla, N., 2009. Propagation of Sound in Porous Media: modelling sound absorbing materials. 2nd edition. Wiley: Chichester.
20. Lord, H. W., W. Gatley and H. Evenson, 1980. *Noise Control for Engineers.* London: McGraw Hill
21. Rossing, T. D., 2007. Springer Handbook of Acoustics, p.127.
22. Kotzen, B., and C. English. 2009. *Environmental noise barriers: a guide to their acoustic and visual design.*2nd Edition. Oxon: Taylor and Francis.
23. Dravitzki, V., Walton, D. K., and Wood, W. B., “Determining the influence of New Zealand road surfaces on noise levels and community annoyance,” Land Transport New Zealand, Wellington Report 292, 2006.
24. Boullosa, R. R., and Lopez, A. P., Technical Note: traffic noise spectra in dry and wet street conditions, Noise Control Engineering Journal, 1987, 29(2), 45-54.
25. BS EN 1793-3: 1998 *Acoustics – Road traffic noise reducing devices – Test method for determining the acoustic performance. Part 3: Normalised traffic noise spectrum.*
26. BS EN ISO 10543-2:2001. *Acoustics – determination of sound absorption coefficient and impedance in impedance tubes. Part 2: Transfer-function method.* London: British Standards Institute
27. Aygun, H., and Attenborough, K., 2008. Sound absorption by clamped poro-elastic plates. *The Journal of the Acoustical Society of America*, 124, 1550-1556.
28. Bolton, J. S., Yun, R. J. Pope, J., and Apfel, D., 1997. Development of a new sound transmission test for automotive sealant materials. Proceedings of ASE, Paper 971896.
29. Chung, J. Y., and Blaser, D. A., 1980. Transfer function methods of measuring in-duct acoustic properties. II Experiment. *The Journal of the Acoustical Society of America* 68, 914.
30. Peters, R. S., Smith, B. J., and Hollins, M. Acoustics and Noise Control. 3rd edition. Pearson.
31. Comité Européen de Normalisation. *EN 1990:2002 Eurocode – Basis of structural design*, CEN, 2002.