Vibration exposure of polydimethylsiloxane (PDMS) reinforced silica (SiO₂): comparison of different source of silica (SiO₂) as filler

M. Azham Azmi¹, S. Mahzan¹, S. Ahmad¹, S.M. Salleh¹, H.A. Rahman¹, M.A. Choiron², A. Ismail¹, H. Taib¹

¹Faculty of Mechanical and Manufacturing Engineering, Universiti Tun Hussein Onn Malaysia, 86400 Parit Raja, Batu Pahat, Johor, Malaysia.
²Mechanical Engineering Department, Brawijaya University, Malang Indonesia

E-mail: hariati@uthm.edu.my

Abstract. Application of vibration absorber in devices yields protection to the device and the operator from unpleasant and disturbing vibration. The study aims to highlight the characteristics of polydimethylsiloxane (PDMS) reinforced with Silica (SiO₂) and the capability of the polymer composites as vibration absorber. Two different sources of SiO₂ were investigated i.e commercially available SiO₂ (CS) and SiO₂ as-derived from rice husk ash (RHS), which were included as the filler in form of particulate to PDMS matrices. PDMS filled SiO₂ (CS and RHS) of 2 to 6 wt% SiO₂ panels were fabricated via the compression technique. The panels were characterized through elemental analyses as to confirm the compositions of SiO₂, morphological analyses, volume and density analyses as well as vibration properties analyses. It was confirmed that the addition of SiO₂ (both CS and RHS) at 2 to 6 wt% improved the vibration reduction and provided good vibration exposure time of grinder applications. Moreover, PDMS-RHS composite panel was proven to adopt better vibrational reduction properties than PDMS-CS composite panel.

Keywords: polydimethylsiloxanes (PDMS); silica (SiO₂); rice husk; filled polymer composite; hand arm vibration;

1. Introduction
Particulate polymer composites are also known as filled polymers due to the incorporation of filler material in form of particle. Particulate composites consist of heterogeneous systems which imply that, the filler and polymers flow and disperse together during processing [1].

Particulate polymer composites offer interesting mechanical, physical and rheological properties resulting from polymer matrix and filler dispersed phase interaction. Polymer matrix and filler would have to be prepared through mixing process which is requires specific equipment in order to achieve uniform dispersion of fillers in the polymer matrix[2] [3].

The importance of filler addition in polymer matrices is to modify properties, either mechanical properties in example stiffness, modulus, or physical properties for conductivity or density or rheological properties such as viscoelasticity or viscosity[4] [1].

Polydimethylsiloxane (PDMS) or PDMS or so called as silicone rubber is categorized as an elastomer
which is in the polymeric material family. Generally, PDMS are known for their biocompatibility, high thermal stability, hydrophobic nature, electrical and release properties [5]. PDMS also offer rubber-like properties due to the outstanding elasticity properties. Elasticity of rubber like material is definitely the most important parameter in reducing vibration source of machine to avoid hand arm vibration syndrome that may affect neurological and vascular disorders [6], [7]. However, the properties of PDMS which are soft and high in elasticity and thus is not attractive for applications in rigid structure. Studies have shown that filling PDMS with reinforced filler will enhanced PDMS especially in terms of its physical and mechanical properties [2], [8], [9][10].

Silica (SiO2) may act as a reinforcing filler in PDMS matrix, which would improve the mechanical properties of the composite. However the suitable filler-matrix ratio have to be identify, since the contribution of filler addition in enhanced material properties are limited. Once filler composition exceeds the filler maximum ratio, agglomeration or weak filler-matrix bonding of the composites will occur and lead to decrement of mechanical properties [11], [12]. Thus, various parameter such weight percentage (wt%) of filler, curing parameter and characteristics of filler during mixing were have to be considered.

Rice husk as one of the agricultural waste is indeed one of the step in controlling our environment sustainability. The usage of manufactured resources compared to natural resources may produce pollution and waste that may affect our environment. Control of sustainability will ensure humans for a better environment and ecological. The incinerated rice husk at 400°C-1000°C produced SiO2 and thus signifies rice husk as one of natural source for SiO2 [13], [9], [8].

The usage of engineering works and processes which involved the application of powered tool leads to exposure of hand arm vibration among operators. The vibration source may arise from rotating and percussive hand held power tool. Hand transmitted vibration also may occur from vibrating workpieces. Extreme hand arm vibration would affect hand arm neurological and motor functions and induce disturbances in finger blood flow [14]. Current practice, the most used material as a vibration damper were polymer and elastomer material including PDMS. High elastic of PDMS is the most suitable candidate in reducing vibration source. Thus, in order to elucidate the performance of PDMS and filled PDMS composites as a vibration damper, the contribution of SiO2 as a filler in reducing the hand arm vibration of portable hand grinder were revealed.

This study focuses on identifying characteristics of PDMS incorporated with two types of SiO2 filler i.e commercially available SiO2 (CS) and SiO2 as-derived from rice husk ash (RHS). The vibration properties of PDMS-CS and PDMS-RHS will also be highlighted.

2. Materials and methods

RHS Derivation

The derivation process of RHS started with cleaning the rice husk using tap water to remove impurities. Next, wet rice husk is dried at room temperature. The dried rice husk was then converted to RHS by burning process at 700°C using a muffle furnace (FL50, KF England, UK).

Composite Panel Fabrication

PDMS (Dow Jones Xiameter, USA) was applied as matrices and filler (CS and RHS) was added in the range of 2, 4 and 6 wt% as the reinforcement. Close mold compression technique at 100KPa was applied to fabricate the composite panel. The PDMS-SiO2 (CS and RHS) composite panels were cured at room temperature.

Surface Morphology

Scanning Electron Microscopy (SEM) (JSM-6380LA JEOL, Japan) to analyze surface characteristic of
Elemental Analysis

X-Ray Fluorescence (XRF) (Bruker S4 Pioneer, USA) was used to confirm the presence of filler (SiO2) in the composite and as to identify the purity and impurities of fillers.

Density of Fillers

ASTM C29 was applied as to determine the density of filler. Tapped method were chosen to analyze the density of filler.

Density of PDMS Composite Panel

Density was identified via buoyancy method as per ASTM D792 in which Mettler Toledo density determination kit XS64 were used to conduct the analysis with sample size at 0.02 x 0.02 x 0.003 m³.

Vibration Measurement

The vibration properties of PDMS-SiO2 (CS and RHS) composite panels were evaluated under BS ISO EN 8622 for testing procedure and BS ISO EN 5349 for Hand Arm Vibration (HAV) measurement. This test method used to determine the average sum frequency weighted acceleration of X, Y, and Z axis and measure the limit of daily vibration exposure of hand grinder (GWS 8-1 100CE, Bosch, Germany) to operator. Fig. 1 shows the PDMS-SiO2 (CS and RHS) composite panels and accelerometer attached to hand grinder grip. Human vibration meter (HVM100, Larson Davis, USA) was used to measure the hand arm vibration.

3. Result and discussion

Surface Morphology

CS was found to consist of clear coarse granular shape particles which is indeed a common shape for crystallized particles, due to their crystalline nature [15]. Fig. 2(a) showing the morphology of CS at 1000X magnification revealed the particle size range which is 5μm to 20μm.

On the other hand, RHS particles shape and structure differed from CS, in which the RHA SiO2 particles were observed to be of irregular shaped and ridged. The same findings were observed by [16].
[17] [18] as well as [19]. In most studies, the shape of rice husk ash particles represents its characteristics [11]. However, the RHS particles were also observed to adopt granular shape ranging from 150-200μm and have porous structure as circled in yellow morphology microphotographs. The wide granulometric characteristics and the porous structure morphology were also observed in rice husk ash as reported in previous studies [16], [17]. The porous cellular structure of RHS is indeed a natural significance due to its intrinsic structure of rice husk [20].

The increment of rice husk burning or incineration temperature affected the particles structure by promoting the occurrence of a more compact structure, specifically rice husk burnt at 600°C and above in which a more packed structure would be developed [18]. This is in line with the RHS which is observed to be compact and packed structure.

Elemental Analysis

Elemental analysis via XRF method identified presence of nine elements noted as impurities in CS. SiO2 was detected at 99.60% in CS (Table I) while total impurities detected were 0.4% which comprised of Calcium Oxide (CaO), Sodium Oxide (Na2O), Potassium Oxide (K2O), Manganese Oxide (MnO), Aluminium Oxide (Al2O3), (Fe2O3), Titanium Oxide (TiO2) and Chromium Oxide (Cr2O3).

The RHS (after firing at 700 °C) presented purity of SiO2 of 95.71% with 4.29% impurities (Table 1). The impurities consisted of six different elements which were SiO2, K2O, CaO, MgO, Sulphur trioxide (SO3) and Phosphorous oxide (P2O5).

| Filler | Element | Concentration (%) |
|--------|---------|-------------------|
| CS     | SiO2    | 99.6              |
|        | Impurities | 0.4          |
| RHS    | SiO2    | 95.71             |
|        | Impurities | 4.29           |

SiO2 as derived from rice husk ash in this study (RHS) produced is of high purity, as compared to previous study by Bie et al. (2015) (seven elements of impurities) Della et al. (2002) (nine elements) and Bakar et al. (2016) (10 elements of impurities) [21]–[23].

The variations of elemental composition, percentages of purity and impurity are known to be
affected by year of harvest, geographical factors, sample preparation and analysis methods [23].

**Density**

**Density of Filler**

Table 2 showed the average of CS (Unahan-Chem) bulk density was found to be 1.28g/cm$^3$ while the measured density of RHA SiO$_2$ was averaged at 0.59g/cm$^3$.

| Filler | Wt% | Density, (g/cm$^3$) | Volume, V (cm$^3$) |
|--------|-----|---------------------|-------------------|
| CS     | 2   | 1.28±0.03           | 6.62              |
|        | 4   | 12.95               |                   |
|        | 6   | 19.86               |                   |
| RHS    | 2   | 0.59±0.007          | 3.13              |
|        | 4   | 6.27                |                   |
|        | 6   | 9.39                |                   |

**Density of composite panel**

Table 3 compiled the average density values of both PDMS filled CS and RHS composite panels. Density of PDMS-CS panels were found to be only marginally affected by increment of filler loading (only up to 0.01g/cm$^3$). However, the increment of RHS filler loading decreased the density of the PDMS-RHS. The decrement in density was caused by the low density of RHS filler (0.59g/cm$^3$) compared to density of PDMS (1.29g/cm$^3$).

The decrement may be explained by the rules of mixtures by Chawla (2013). The low density filler (RHS) decreased the composites density since PDMS may be replaced with lower density RHS. This is as reported by Liu et al. (2009) in which the presence of filler would decrease the density of matrices and composites.[25].

| Composites | Wt% | Density, (g/cm$^3$) |
|------------|-----|---------------------|
| PDMS-CS    | 2   | 1.29                |
|            | 4   | 1.29                |
|            | 6   | 1.28                |
| PDMS-RHS   | 2   | 1.26                |
|            | 4   | 1.23                |
|            | 6   | 1.20                |

**Vibration Behavior**

Better vibration behaviors of both PDMS composites (CS and RHS filled) were observed at all percentages of filler addition.

The lowest vibration behaviors of PDMS-RHS- composites were shown at 6wt% filler addition and at 2wt% of filler addition as for PDMS-CS composites. Further addition (more than 2 wt% CS) caused the measured frequency weighted acceleration to increase as showed in Figure 3.

Comparison between PDMS-RHS composites and PDMS-CS composites showed that PDMS-RHS composites offered approximately 30% improvement for the vibration exposure through measured frequency weighted acceleration. Thus the addition of RHS into PDMS improved the vibration behaviors better than PDMS with CS addition.
As per described in standard by Malaysian Government Department of Safety and Health, the advised total daily exposure duration can be referred to the level of measured frequency weighted acceleration. The lower measured frequency weighted acceleration increased the total daily exposure duration. The measured frequency weighted acceleration of bare handle grip had allowed total daily exposure duration for one to two hours only. However, with addition of fillers (CS and RHS), total daily exposure duration were increased to the range of four to eight hours[26]. Thus, this increment would allow longer working hours and increase the productivity. Although both filled PDMS composites had the same total daily vibration hours, the lower measured frequency weighted acceleration in PDMS-RHS composite offered better comfort and safety to the the operator. In all, PDMS-RHS composites offered excellent performance as a vibration damper.

The filler surface characteristics was found to assist in distributing the vibration during exposure. As discussed before, RHS is capable to decrease the frequency weighted acceleration better than CS. This may be explained by the irregular shape, ridged and wide granular shape of RHS which are advantageous in providing better surface area with different and varied angles of surfaces [16], [17]. This characteristics helped in reflecting and distributing the magnitude of frequency weighted acceleration during vibration exposure. Besides, the porous structure found in RHS (Fig. 2) also helped in absorbing the vibration exposed better.

The filler volume effect were also analyzed in order to identify the effect of filler towards behavior of vibration. Table II has showed that the volume of RHS were almost always two times greater than the CS due to the low density of RHS. Moreover, the frequency weighted acceleration of PDMS-RHS composites were also lower than PDMS-CS composite. Thus, another basis of better decrement in frequency weighted acceleration in PDMS-RHS composites may be explained by the incorporation of larger volume of RHS which helped to absorb and dampen the vibration exposure better, ascribed to the surface characteristics of filler. The frequency weighted acceleration were found higher for RHS filled PDMS, as compared to CS filler.

Moreover, as found by previous studies, the materials with the least density would offer better vibration damping ability [6], [7]. As shown in Table III, the density of PDMS-RHS composite panels were consistently kept lower than PDMS-CS. Thus, it explained the reason of lower frequency weighted acceleration in PDMS-RHS composites compared to PDMS-CS composites. The lesser density material would dampped and absorbed the vibration magnitude better in order to decrease the vibration exposure via measured frequency weighted acceleration.
4. Conclusions
Both PDMS filled SiO$_2$ (CS and RHS) composites were found to be good candidates for vibration damping application. Both PDMS-CS and PDMS-RHS allowed daily exposure duration to vibration range of four to eight hours which is beyond the allowance of bare handle grip range of one to two hours. Nonetheless, RHS was found to surpass CS as filler in PDMS in terms of the vibration properties, as the frequency weighted acceleration of PDMS-RHS ranged only 4.33 to 4.22 ms$^{-2}$ compared to PDMS-CS (4.98 to 7.69 ms$^{-2}$). This significant finding is contributed by governing factors such as the unique surface morphology of RHS, as well as the density of RHS.

Acknowledgments
The authors gratefully acknowledge the financial support provided by Research and Innovation Fund of Research Management Centre (RMC) Universiti Tun Hussein Onn Malaysia (UTHM), UTHM Centre for Graduate Studies (CGS), Ministry of Higher Education Malaysia for grants including RAGS (R022), FRGS (1541 & 1593) and MyBrain15 Scholarship (MyPhD).

References
[1] Leblanc J L 2009 *Filled polymers: science and industrial applications*. CRC Press.
[2] Yahya S M, Azmi A, Ahmad S, and Taib H 2014 Characterisation of hand-cast polysiloxane-silica sheet composite *Advanced Materials Research* 893 pp 250–253.
[3] Pal R 2010 Rheology of Particulate Dispersions and Composites (Surfactant Science). London: Taylor and Francis.
[4] Yahya S M, Azmi A, Idris M I, Yunos M Z, Mahzan S, Ahmad S, and Taib H 2014 Short review: Role of metal oxides as filler in polysiloxane sheet composite *Applied Mechanics and Materials* 465–466 pp 27–31.
[5] Jerschow P 2001 *Silicone elastomers*, 137 Smart Publications.
[6] Singh J and Khan A A 2014 Effect of coating over the handle of a drill machine on vibration transmissibility *Appl. Ergon* 45 pp 239–46.
[7] Chaturvedi V, Kumar A and Singh J K 2012 Power tiller: Vibration magnitudes and intervention development for vibration reduction *Appl. Ergon.* 43 pp 891–901.
[8] Azmi, Marsayid M S M, Mahzan S, Ahmad S, and Taib H 2016 Vibration exposure analysis of polydimethylsiloxane reinforced silica derived rice husk ash *Malaysian J. Anal. Sci.* 20 pp 1138–1144.
[9] Mahzan S, Azmi M A, Taib H and Mohammad N E N A 2014 Vibration Exposure Analysis of the Polysiloxane Reinforced with Rice Husk Silica *Applied Mechanics and Materials* 660 pp 531–535.
[10] Ahmed K, Nizami S S and Riza N Z 2014 Reinforcement of natural rubber hybrid composites based on marble sludge/Silica and marble sludge/rice husk derived silica *J. Adv. Res.* 5 pp 165–173.
[11] Kozlov G V 2015 Structure and properties of particulate-filled polymer nanocomposites *Physics-Uspekhi*, 58 p 33.
[12] Kozlov G V, Yanovskii Y G and Zaikov G E 2010 *Structure and Properties of Particulate-filled Polymer Composites*. Nova Science Publishers.
[13] Azmi M A, Ismail N A A, Rizamahartaiz M, Taib H, Nazeri M F B M, Ying L B and Bin Idris M S 2016 Characterisation of silica derived from rice husk (Muar, Johor, Malaysia) decomposition at different temperatures AIP Conference Proceedings 1756 p 20005.

[14] BS EN ISO Measurement and Evaluation of Human Exposure to Hand-transmitted Vibration–Part 1: General Requirements Int. Organ. Stand., vol. Part 1, no. 5349, 2001.

[15] Guven O, Ozdemir O, Karaagacioglu I E and Celik M S 2015 Surface morphologies and floatability of sand-blasted quartz particles Miner. Eng. 70 pp 1–7.

[16] Fernandes I J, Calheiro D, Kieling A G, Moraes C A M, Rocha T L A C, Brehm F A and Modolo R C E 2016 Characterization of rice husk ash produced using different biomass combustion techniques for energy Fuel 165 pp 351–359.

[17] Van Tuan N, Ye G, Breugel K, Fraaij A L A, and Bui D D 2011 The study of using rice husk ash to produce ultra high performance concrete Constr. Build. Mater. 25 pp 2030–2035.

[18] Fernandes I J, Sanchez F A L, Jurado J R, Kieling A G, Rocha T L A C, Moraes C A M and Sousa V C 2017 Physical, chemical and electric characterization of thermally treated rice husk ash and its potential application as ceramic raw material Adv. Powder Technol. 28 pp 1228 – 36.

[19] Yalcin N and Sevinç V 2001 Studies on silica obtained from rice husk Ceram. Int. 27 pp 219–224.

[20] Ersöz G 2014 Fenton-like oxidation of Reactive Black 5 using rice husk ash based catalyst Appl. Catal. B Environ. 147 pp 353–358.

[21] Bakar R A, Yahya R and Gan S N 2016 Production of High Purity Amorphous Silica from Rice Husk Procedia Chem. 19 pp 189–195.

[22] Bie R S, Song X F, Liu Q Q, Ji X Y and Chen P 2015 Studies on effects of burning conditions and rice husk ash (RHA) blending amount on the mechanical behavior of cement Cem. Concr. Compos. 55 pp 162–168.

[23] Della V P, Kühn I and Hotza D 2002 Rice husk ash as an alternate source for active silica production Mater. Lett. 57 pp 818–821.

[24] Chawla K K 2013 Composite Materials: Science and Engineering, 2nd ed. Birmingham, USA: Springer New York.

[25] (Daniel) Liu J, Sue H J, Thompson Z J, Bates F S, Dettloff M, Jacob G, Verghese N and Pham H 2009 Effect of crosslink density on fracture behavior of model epoxies containing block copolymer nanoparticles Polymer (Guildf). 50 pp 4683–89.

[26] Department of Occupational Safety and Health 2003 Guidelines on Occupational Vibration pp 1–33.