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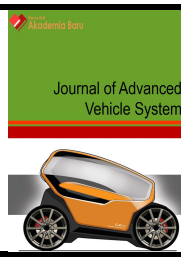


# Sedimentation Analysis for Uncured Magnetorheological Elastomer for Potential Additive Manufacturing using Vat Photopolymerization Technique

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**ABSTRACT**

Additive manufacturing using vat photopolymerization technique is one of the potential techniques to fabricate magnetorheological elastomer (MRE). However, due to the density mismatch between the elastic resin and magnetic particles for the preparation of the uncured MRE leads to sedimentation problem. Therefore, this study investigates the sedimentation behaviour between the photopolymer elastic resin and carbonyl iron particles (CIPs) in the uncured MRE. The uncured MREs were prepared in different weight percentage (wt.%) of 30, 40, 50 and 60 wt.% of CIPs. The result demonstrated that all wt.% of CIPs compositions has started to simultaneously sediment about 3 hours. The uncured MRE with 60 wt.% of CIPs has produced the lowest sedimentation ratio (50%), indicating the lowest sedimentation rate to settle at the base of the test tube after 24 hours. Therefore, the outcome of this study has deduced that sedimentation has occurred in the uncured MRE and this analysis provides prediction on the fabrication of MRE by vat photopolymerization technique.

***Keywords:***
Additive manufacturing; magnetorheological elastomer; Sedimentation; vat photopolymerization

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## 1. Introduction

Magnetorheological elastomer (MRE) is a smart material under magnetorheological (MR) family that able to change its rheological properties by controlling the strength of the magnetic field. MRE is introduced to overcome the problems occur in the MR fluid (MRF) due to sedimentation issue of magnetic particles within the carrier fluid. In general, MRE is produced by embedding soft magnetic particles such as carbonyl iron particles (CIPs) into a non-magnetic medium or elastomer material [1]. Natural rubber, silicone rubber, polybutadiene, polyurethane (PU), and polyisobutylene rubber are common elastomer matrices that can be utilized during MRE fabrication [2]. These materials are typically viscoelastic materials that can be homogeneously mixed with magnetic particles and then undergo solidification process to achieve the solid form. Hence, the production of MRE have become

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one of promising material for application that involves damping and stiffness such as engine mount of car and robotic gripper.

Additive manufacturing (AM) is one of the methods that able to print a polymer material with complex design and precise dimension. Various additive manufacturing techniques have been introduced such as material extrusion, vat photopolymerization, powder bed fusion, material jetting, binder jetting, and direct energy deposition [3,4]. One of the AM techniques that can produce a good quality and properties of polymer material is using vat photopolymerization method [5,6]. The material is in the form of liquid which the main components composed of monomer, oligomer and photoinitiator [6]. This method is cured using UV light to solidify the resin polymer under a certain duration of time. Thus, the addition of micron-sized magnetic particles into the liquid elastomer resin is possible to produce three dimensional (3D)-printed MRE products.

Sedimentation is a separation phenomenon of between mixtures hat occur due to difference in particles size and density [7].The distribution of fillers in an MR materials is often well-defined on producing a homogenous dispersion. However, according to Morillas *et al.,* [8], the sedimentation phenomenon is frequently observed in MR material as density mismatch on the mechanical properties. Also, the sedimentation can be related to the non-uniform structure has developed within the polymer composite [9]. Thus, the inhomogeneity of the filler distribution in the MR materials has disrupted the structure. Sedimentation issues in MR materials could probably affect the functionality of the MR material because the density mismatch among the magnetic particles [10]. Sedimentation in MR materials usually involved in the carrier medium which to be particular between the fluid and the magnetic particles. One of the MR materials that heavily affected by this issue is the MRF. Particularly, the sedimentation has affected the dispersion of MRF, decreased the MR effect and eventually affected the performance of MRF [11]. Based on Wei *et al.,* [12], the presence of magnetic particles in vat photopolymerization seems challenging as larger particles tends to sediment under the gravitational force and might reduce the printing reliability. Therefore, the sedimentation rate in an uncured of MRE composition need to be considered as it may affected on the fabrication of the 3D printing process.

During the fabrication of MRE by vat photopolymerization technique, it is possible to attain homogenous mixture of an uncured MRE because the mixing of elastomer matrix and magnetic particles can be achieved. Furthermore, according to Kourki *et al.,* [13], concentration of the materials also one of the factors that affect the sedimentation of uncured MRE in which high CIPs composition possible to result in slower the sediment of the magnetic particles. Hence, this study intends to investigate the sedimentation behaviour of uncured MRE prepared in different weight percentage (wt.%) of CIPs compositions. The sedimentation is measured based on the difference in the volume between elastomer resin and magnetic particles over times. In this study, the possibility outcome of fabricating MRE using vat photopolymerization technique from the sedimentation result was discussed.

## 2. Methodology

The elastomeric matrix material used to prepare the uncured MRE was Magma photopolymer elastic resin which contains methacrylate (density of 1.05 g/cm$^3$) as the monomer and supplied by Xtruwell Technology, Taiwan. Carbonyl iron particles of the OM type (BASF, Germany) were used as magnetic filler with median diameter of 3.9–5.2 µm and density of 7.8 g/cm$^3$. The uncured MRE was prepared with four various wt.% composition of CIPs in which 30, 40 50 and 60 wt.% of CIPs. The mixing of the photopolymer elastic resin with the CIPs was performed by using a mechanical stirrer (WiseStir HT-DX, PMI-Labortechnik) at the stirring speed of 200 rpm. The duration of the mixing

process was fixed to 15 minutes as a purpose to obtain a homogenous uncured MRE. A sedimentation test was conducted to observe the separation phenomenon in the solution mixture. Figure 1 shows a visual illustration of the sedimentation test, in which grey and blue colours represent sediment and elastic resin liquid respectively. The sedimentation ratio was calculated based on the according to Eq. (1) based on previous study [14].

$$\text{Sedimentation ratio, R\%} = [V_d/(V_d + V_s)] \text{ X } 100\ \% \quad (1)$$

where R represents the sedimentation ratio, volume dispersed phase ($V_d$) and volume of settled phase ($V_s$) in ml.

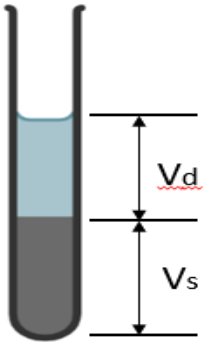
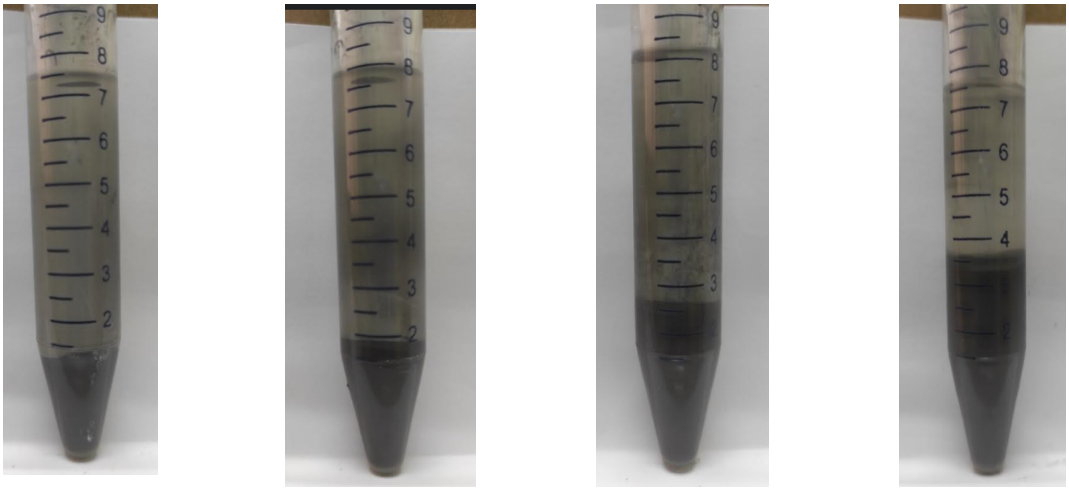



**Fig. 1.** Illustration of measuring the sedimentation in uncured MR

## 3. Results and Discussion

The sedimentation between the CIPs and elastic resin with different wt.% of CIPs compositions were visually measured through the height layers different between elastic resin and CIPs in certain duration of time. Figure 2 shows the sedimentation analysis based on visual observation taken for all CIP compositions ranging from 30, 40, 50 and 60 wt.% in 24 hours. It can be observed that the presence of sedimentation has occurred regardless the CIP composition. The CIPs was found to sediment at the base of the test tube after being left for 24 hours. The sedimentation was due to higher CIP density than the elastic resin which similar results have also been found in previous studies [11,15]. As a result of gravity, the CIP with greater density will settle at the bottom of the test tube, leading to the formation of a distinct separation layer between materials. This phenomenon known as sedimentation instability [8]. Therefore, the sedimentation between carrier fluid medium of resin and CIPs has occurred and an analysis was required as to predict the possibility duration of time to 3D print an uncured MRE.



(a) 30 wt.% (b) 40 wt.% (c) 50 wt.% (d) 60 wt.%

**Fig. 1.** Sedimentation of different wt.% of CIPs compositions: (a) 30 wt.%, (b) 40 wt.%, (c) 50 wt.% and (d) 60 wt.%. in uncured MRE

From the sedimentation test between the CIPs and elastic resin, several sedimentation studies were analysed with the duration of times. Figure 3 shows the volume difference of various wt.% of CIPs of uncured MRE. The volume difference in each composition have occurred simultaneously about 3 hours in the uncured MREs which indicates the initiation sedimentation of the mixture. However, there is a significant difference in sediment volume after 8 hours in all CIPs compositions. It is noteworthy that the CIPs of uncured MRE with 60 wt.% exhibited larger separation layer of magnetic particles which about 34% compared to 30 wt.% in 24 hours. The volume differences in the uncured MRE were related to the sedimentation and affected by the CIPs composition. Thus, based on this outcome, sedimentation of uncured MRE has time constraint in which less than 3 hours.

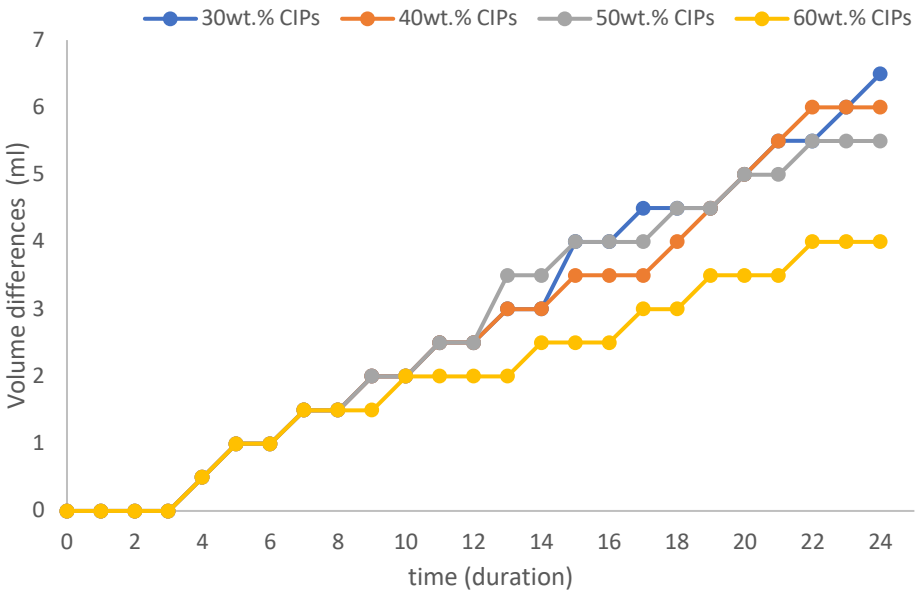



**Fig. 2.** The volume difference of various wt.% of CIPs of uncured MRE

From the result of volume difference, the sedimentation ratio can be obtained, as stated by Kariganaur *et al.,* [11], the sedimentation ratio refers to the proportion of the volume of clear carrier fluid to the total volume of liquid containing both materials in the test tube. Figure 4 depicts the graph of the sedimentation ratio of the uncured MRE in different wt.% composition of CIPs and the

sedimentation can be analysed from this figure. The uncured MRE with 60 wt.% of CIPs has produced the lowest sedimentation ratio which is 50% after 24 hours. This indicate that at the highest composition of CIPs (60 wt.%), the sedimentation rate tends to reduce the time to settle at the base of the test tube. It can be deduced that less movement is required for the magnetic particles to sediment under influence from gravitational force. This can be supported by previous work by Kourki *et al.,* [13] where the high concentration of particles has slowed the sedimentation rate due to stronger inter-particle attraction among the magnetic particles. Hence, the sedimentation ratio of the uncured MRE with the highest composition of CIPs has slowed down the settling of the CIPs. From this study, it can be deduced that the fabrication of MRE using vat photopolymerization 3D printing has time limitation within 3 hours as the sediment started to occur, whereas the performance of the MR effect of the 3D-printed MRE may reduce. Besides, the formation of inhomogeneous mixture of the uncured MRE may produce a separation layer between the elastic resin and CIPs.

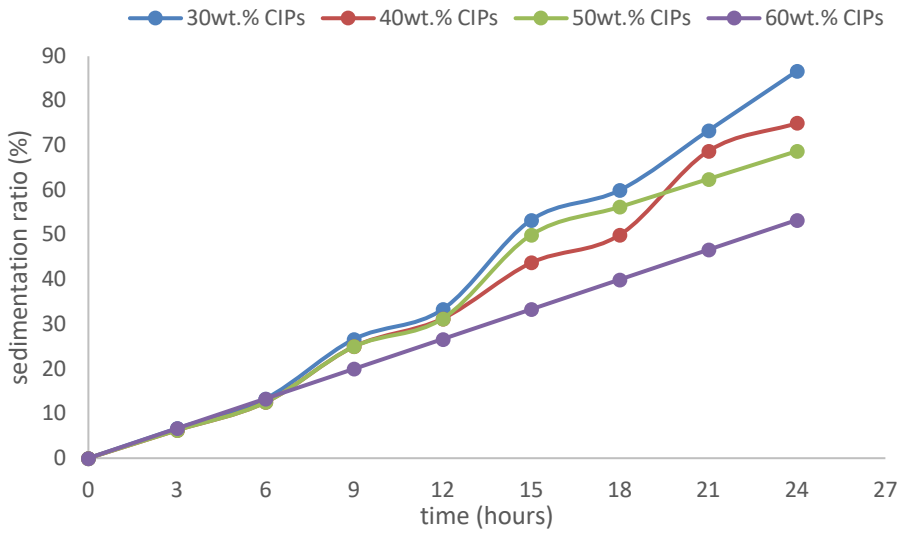



**Fig. 3.** Sedimentation ratio of uncured MRE in different wt.% compositions of CIPs over times

## 4. Conclusion

Sedimentation analysis for uncured magnetorheological elastomer for potential additive manufacturing using vat photopolymerization technique was studied. The sedimentation was conducted using the uncured MRE consist of elastic resin and CIPs with different wt.% of CIPs compositions. The volume differences and sedimentation ratio of uncured MRE as a function of time were analyzed. Based on the outcomes, CIPs in the uncured MRE started to settle at the base of the test tube about 3 hours, despite the differences in wt.% of the CIPs. Furthermore, the uncured MRE with the highest CIPs composition of 60 wt.% had produced the lowest sedimentation ratio after 24 hours compared to other compositions, as the less movement from magnetic particles to sediment. The sedimentation results have deduced some possibilities effects which can be taken towards 3D printing via vat photopolymerization techniques of MRE. Therefore, this study provides preliminary information on the possible effect on the fabrication of 3D printing MRE.

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