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An Overview of Durability Evaluations of Elastomer-Based Magnetorheological Materials

MOHD AIDY FAIZAL JOHARI[1], SAIFUL AMRI MAZLAN[1], UBAIDILLAH[2], (Member, IEEE), HARJANA[2], SITI AISHAH ABDUL AZIZ[1], NUR AZMAH NORDIN[1], NORHASNIDAWANI JOHARI[1], AND NURHAZIMAH NAZMI[1]

[1]Engineering Materials and Structures (EMaSt) ikhoza, Malaysia-Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur 54100, Malaysia
[2]Mechanical Engineering Department, Universitas Sebelas Maret, Surakarta 57126, Indonesia

Corresponding authors: Saiful Amri Mazlan (amri.kl@utm.my) and Ubaidillah (ubaidillah_ft@staff.uns.ac.id)

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ABSTRACT Most parts of the failures in structural elements in use were consequences of mechanical durability. Therefore, durability had been one of the critical factors to be considered in designing durable mechanical elements. In magnetorheological elastomer (MRE) materials, the durability process involves different damage mechanisms that result in the degradation of the materials. Increasingly used of outstanding performance of MRE was susceptible to failure under durability performance for various applications. In response to these problems, with limited sources of published articles on MRE durability, an overview of the durability of elastomer based MRE is presented. The study focuses on collecting and analyzing the works including experimental and modeling approaches that have been conducted on MRE durability up to date. Two bibliographic searched databases, Scopus and Web of Science were consulted to collect the final set of articles with the aims to identify current and future trends of MRE durability. Prominence works conducted on MRE durability were also encapsulated in this paper to provide a visual perspective and subsequently motivate researchers to heighten the need for MRE durability investigation.

INDEX TERMS Durability, magnetorheological, magnetorheological elastomer, rheology, smart materials.

NOMENCLATURE

LIST OF ABBREVIATIONS

BR	Butadiene Rubber
CIP	Carbonyl Iron Particle
CL	Chemiluminescence
CPVC	Critical Particle Volume Concentration
DMA	Dynamic Mechanical Analysis
DRS	Dielectric Relaxation Spectroscopy
ER	Electrorheological
ERE	Electrorheological Elastomer
FTIR	Fourier-Transform Infrared Spectroscopy
HV	Heat Vulcanization
HTV	High-Temperature Vulcanization
LVE	Linear Viscoelastic
MCR	Modular Compact Rheometer
MR	Magnetorheological
MRE	Magnetorheological Elastomer
MRF	Magnetorheological Fluid
MRP	Magnetorheological Plastomer
NR	Natural Rubber
PDMS	Polydimethylsiloxane
RV	Radiation Vulcanization
SEM	Scanning Electron Microscopy
SiC	Silicon Carbide
SIC	Strain-Induced Crystallization
SR	Synthetic Rubber
THEOS	Tetraethoxysilane
VSM	Vibrating -Sample Magnetometer

I. INTRODUCTION

Smart materials are a significant fragment of material engineering evolution. These materials regarded as smart since their property can be remarkably altered by external stimuli such as magnetorheological (MR) materials due to their

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responsiveness to external magnetic inducement [1]. The rheological properties of MR materials can be controlled rapidly and reversibly by the application of the magnetic field [2]. In a solid carrier matrix state, known as Magnetorheological elastomer (MRE) with its exceptional magnetic responsive feature, can be fabricated by merging magnetizable particles within an elastomeric polymer [1]. MRE introduces distinct characteristics the moment reacts to the external magnetic field. In MRE, magnetic fields can penetrate space and substances, thus results in incredible potentiality of MRE in prominent applications. The use of MRE in critical applications is growing in active vibration absorbers [3], automotive bushing [4], [5], propeller shaft absorber [6], variable spring rate [7], [8], tire pressure control [9], medical rehabilitation [10] and many other promising applications. Exhaustive progress on MRE was reported in previous innovational work of Ubaidillah *et al.* [1] encompassed functional behavior, arts of MRE, preparations technology, characterizations, applications, and potential prospects.

The condition under which some components operated are known to cause MRE to fail due to dynamic loading. Failure by dynamic cyclic load is catastrophic, therefore, it is very critical to identify their predicted life span under regular working conditions. Despite the tremendous performance characteristics, these materials are still not as widespread as conventional industrial materials. This is mainly due to important shortcomings in current experimental and theoretical research on these materials. Therefore, failure model prediction of durability in MRE material mainly under cyclic loading to develop and provide scientific and engineering know-how, research findings, fabrication practice, durability performance data, and other information related to MRE constituent materials and systems becomes a very important contribution to durability life model characteristics.

Durability is defined as resistance to any change in property levels due to the service environment [11]. It is commonly accepted that durability as a general term, is the harmful damage mode in materials. At the same time, fatigue as part of durability, is responsible for the majority of the structural failures. The combination of both factors must be the object of precise studies to gain a major insight into the behavior of this material. Along these lines, a better characterization of material properties and behavior can be achieved and structural MRE parts can be designed in efficient ways. Thus, this overview investigation and study are formed on these concepts. Indication from the industries on MRE progress and development for applications may vaguely promising, however as its potential and prospects, MRE offers a propitious future. On a par with similar materials such as rubber and elastomer, MRE has increasingly reached into new engineering applications and bound with irrefutable scientific procedure evaluation, particularly on its long-term performance ostensibly durability. The earliest works by Lewis [12] pleaded for the adoption of pertinent tests, which provided the engineer with data that enables to design a component for optimum performance by taking into account the limitations of the materials to be used.

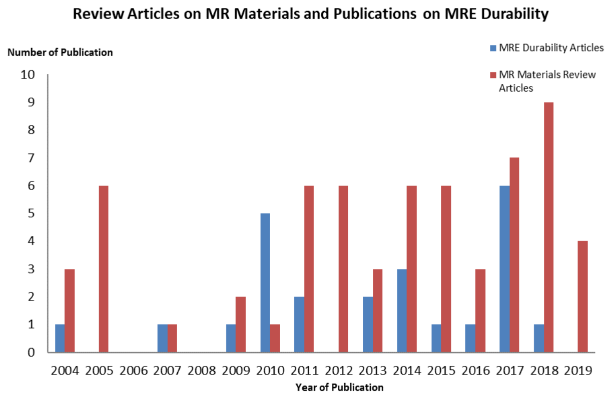


FIGURE 1. **MRE durability and MR materials review articles.**

Furthermore, assessment of durability was often in a qualitative way and derived from simply cataloging changes in standard test property values and comparing with earlier data [12]. Although this approach does give some guidance, with some information including in this paper, it is nevertheless usually inadequate for critical engineering components with demands for quantitative life assessment. Apart from mechanical loadings and chemical compositions, the environmental issue is another factor that contributes to the total life of the materials component. Exposure of materials in different environments may result in an alteration of mechanical properties, which eventually affect its service life. Assessment of the overall durability of an elastomeric component should take account of the mechanical effects of fatigue failure and strength, and also environmental durability associated with service temperatures, and pressures [12].

To get par with the similar materials, research on MRE durability has tremendously shows continual trend since the last decade. This encouraging development however requires progressive exploration, at least to catch up with the studies conducted in similar behavior materials such as rubbery materials. Rubber durability studies as remarkably reviewed by Tee *et al.* [13] have been significantly increased and till the present, nearly 200 papers were found, which highlighted the importance of durability studies in rubber industries. MRE however, still lingeringly waits for huge potential research activities to bring the gap closer. Concentrating on MRE durability studies since the literature around 2004, as can be discovered by the author, about 24 papers [14]–[37] have been published on various analyses of MRE durability. This statistical data can be consulted in Fig. 1.

According to Fig. 1, the data are obtained from two bibliographic searched databases were consulted to collect the final set of articles: Scopus and Web of Science. For publications of MRE durability, the keywords used were ‘durability’, ‘fatigue’, ‘MRE’, ‘magnetorheological elastomer’, and ‘total life’ as the main keywords in the searching tool. The finding indicates in great need of better understanding and prediction of the durability failure in MRE materials. Besides, for publications of review articles for MR materials, the publications consist of review articles on MRE, Magnetorheological fluid (MRF), and the latest type of MR materials such as Magnetorheological plastomer (MRP). As can be discovered and accessed, over 60 MR materials review articles have been published. However, since the focus of this review is on MRE durability, only MRE review articles were considered. In the same range of publication years and searched databases, review articles on MRE were identified at 16 exclusive informative articles [1], [29], [38]–[51], which four [39]–[43] were specifically reviewed on the MRE applications.

The comprehensive review of MR solids was reported by Ubaidillah *et al.* [52] consisted of MRE, MRP, and MR grease. Fundamental definitions and terminology described were very useful in constructing understanding and technical comprehension. Numerous available applications have been introduced to convey its potential as devices. The fabrication technique has also been elucidated including characterization that frequently conducted. MRE was greatly discussed by its physiochemical and viscoelastic properties. These characterization methods explained in accordance to specific investigation. In physicochemical examination, microstructural tests, thermal tests, and magnetic tests were reviewed. Nevertheless, it was agreed that no standardized testing method for the viscoelastic characterization of MRE. Yet, the procedures were reported based on the experiences and classified by its possible working modes. In the same review article, the rheological examination was emphatically discussed on the viscoelastic test and vibration test. Substantially, both characterization methods considered from the review interpreted the capabilities of MRE in adapting change in rheological properties.

In another study, the rheological performance of MRE was discussed by Lokander [48] specifically on the effect of particle size and its contribution to achieve substantial MR effect. Two different types and sizes of iron particles were used, irregular shaped pure iron particles and spherical carbonyl iron powder. The work has contributed to the significant findings that larger irregular particles reported to have large MR effect although the MRE is isotropic. As been concluded, the larger MR effect can be explained by the small distance between the particles. Then, Critical Particle Volume Concentration (CPVC) was introduced to explain the concentration relation within the particle and the matrix. Furthermore, enhancing the rheological properties of MRE was reviewed by Khairi *et al.* [44]. The influence of several additives on the MR effect of MRE was briefly discussed and presented. Different types of additive categories were reported to modify the properties of MRE in a dissimilar manner. In the addition of plasticizer, the rubber matrix was discovered soften, hence caused an increase in the MR effect. More than in anisotropic MRE, plasticizer has improved the dispersion of particles resulted in stiffer MRE with surpassing damping properties. Other additives namely carbon-based, chromium-based, and few incorporations of additives was reported to enhance the mechanical, electrical, agglomeration, stiffness, MR effect, and most importantly the rheological properties.

Extensively, the rheological and mechanical properties characteristic of MRE with a specific test procedure was briefly reviewed by Kwon *et al.* [46]. The main highlight was the dynamic oscillation test using a rheometer equipped with the magnetic field stimulant. The characteristics of MRE were examined using strain amplitude sweep and angular frequency sweep. The strain amplitude sweep defined the linear viscoelastic (LVE) region, which further been used in the frequency sweep test. LVE limit can be decided from the test and dynamic behavior of MRE can be analyzed both in linear and non-linear conditions. MRE as viscoelastic materials having an ability to store and dissipate some of the energy during deformation. Therefore, a dynamic test on MRE is useful to identify the elasticity (storage modulus) and viscous behavior (loss modulus), which fundamentally both describing the rheological properties of MRE. The review also discussed the phenomenon of creep. Creep test was conducted to analyze the dependency of strain on time in which then provides information on the materials recovery behavior. Both behaviors provide a guide to its engineering applications. Different from other available review articles, mechanical properties of MRE were discussed thoroughly on the Payne effect (softening stress at small strain), loss factor, and tensile strength. The work summarized that the mechanical and rheological properties of coated particles were greater than those uncoated particles due to its strengthened bonding energy between particles and elastomeric matrix. Moreover, the controllable, responsive, and ability of MRE to react with external stimuli renders MRE has huge potential to be applied to a variety of engineering devices.

Distinctive from previously discussed review articles, work done by Li *et al.* [47] reviewed the recent progress of MRE technology, prominently as a device and their applications. Inclusive discussion has been presented on the research and development of the MRE device encompassed of operation modes, coil placements, and principle fundamentals. Important issues, opportunities, challenges, and laborious matters on MRE potential have been intensively discussed. Entire knowledge and understanding of the MRE properties significantly discussed earlier have brought opportunities for the applications in the miscellaneous engineering field. In real application, MRE subjected to combined working modes and loadings, which should be further explored since present knowledge of MRE properties was only limited under tension, shear, and compression. In terms of MRE fabrication, the authors suggested that compromising between exceptional MR effect and other performances should be attentively considered. Therefore, better fraction and reliable durability of the MRE device can be produced to meet optimal performance and minimal power consumption. Exclusive part of the review, a summary of the research on modeling mechanical behavior for both materials and devices were presented.

An extensive review of the modeling of MRE has comprehensively presented by the study conducted by Cantera *et al.* [29]. Magneto-mechanical response of MRE and MRE-based system were reviewed. Models were brilliantly categorized into particle interaction-based, magnetoelastic response-based and magneto-viscoelastic response-based. The effects of environmental conditions and fatigue were also incorporated with the reviewed models. Deeper consideration was executed to the analytical, numerical, finite element, and phenomenological investigation, which then established at both micro and macro-mechanical levels. Models used in different applications of the MRE system were also examined. They reported about the concern on the unsuccessful commercialization of the MRE-based system, which mainly due to the inadequate data and modeling for long-term use of MRE. The data is desperately needed for the accurate prediction of long-term durability and performance. The importance of MRE durability performance studies was greatly acquired to provide data, which furtherly utilized towards the applications in actual engineering systems. These characteristics are crucial to bring MRE technology into the existing industrial system and achieve great success similar to the achievement of other conventional materials like metal, rubber, and composites. All aspects contributed to the long-term durability behavior of MRE brings the opportunity to be discussed. In that context, collections of previous works conducted on MRE durability performance are reviewed in this paper.

To date, to the best of authors' knowledge, there is most certainly no comprehensive review has been done or published on the MRE durability subject. The importance of this topic encouraged the presence of publications on similar materials such as rubber [13]. Therefore, review on MRE durability cannot be contradicted. This gap existed both in the MR materials and MRE materials. Motivated by this finding, the present work focuses on analyzing the entire amount of works on the durability of MRE since 2004 with the main objective to identify the current and future needs and trends in the MRE durability researches. Durability studies on MRE materials will provide data collections of the MRE degradation mechanism and its limitation to durability. Thus, it allows engineers to design MRE components for more critical applications and with increased reliability. This present review is anticipated to drive and stimulate more researches on MRE durability, following the establishment of MRE as a smart and credible materials system.

For this purpose, the discussion on MRE durability in this paper is organized as follows. Factors affecting durability are discussed in general inclusive similar materials to MRE (Electrorheological elastomer (ERE), elastomer, and rubber) in section II. These factors then summarized in a mapped chart to identify gaps in the establishment of MRE durability. In Section III, different collections of specimen designs used for durability analysis in MRE are discussed. Simultaneously, chemical parameters of the specimen and compositions are also updated in this section. Evaluations on the durability test conducted by reviewed researchers are discussed and reported in section IV. The current assessment conducted experimentally and modeling for durability evaluation is also included. Section V highlights the future trend of this study. Finally, Section VI ends the paper with concluding remarks.

II. FACTORS INFLUENCE DURABILITY

The durability of MRE materials is affected by several environmental factors in combination with the mechanical stresses caused by the use of the product itself. The basic factors that influenced durability are weathering, incompatibility, usage, biological attack, and stresses. However, these factors contributed from several types of durability, which consist of rot proofing, radiation hardening, toughness, resistance to fatigue, aging, thermal resistance, fire-resistant, and waterproofing. These types of durability can be further sub-categorized into numerous specific areas. Details mapping of these types and factors of MRE durability analysis is shown in Fig. 2. Comprehensive understanding from the mapping includes comparable materials to MRE, mainly due to the limited durability research so far been conducted on MRE itself. Established materials like rubber and elastomer were compared to MRE as well as less well-known material such as ERE. The comparison was made at least, to motivate for more new research to be undertaken for MRE durability.

Fig. 2 has clearly shown that MRE durability studies feature huge potential to be explored and investigated. To this point, MRE durability studies were only conducted in the minor section of weathering and stresses. On the other hand, rubber and elastomer tremendously covered in almost every aspect of the section. Meanwhile, ERE materials indicate the most few progressed [53]–[56]. Durability under dynamic mechanical behavior of ERE material was conducted by Hao *et al.* [57] with two types of electric elastomers were prepared and the elastic modulus were tested with dynamic mechanical analysis (DMA) with the round disk compression clamp. The study was looked into variation of storage modulus and loss modulus affected by frequency. Though, with increasing frequency, there is no noticeable change in the values. The introduction of particles, however, has astonishingly improved to the mechanical properties. MRE had complemented to ERE for numerous reasons, for example, MRE featured less power consumption to produce ER/MR effect and large change of mechanical properties needed. At higher voltage supplied, ERE is easy to overheat and this has caused changes in property, especially the modulus.

Among the earliest and recent investigations on the durability of elastomer were performed by many researchers [58]–[63] on cyclic loading, fatigue molecular orientation under stress, elevated temperature, chemical aging, heat build-up and chlorinated water effect respectively. All these affecting factors to the durability were reported governed, decreased, shorten, and demonstrated large reduction to the total life of the elastomers. Since elastomer commonly tested with rubber, these sections focused more on the rubber durability. Durability of rubber as shown in the mapping, has

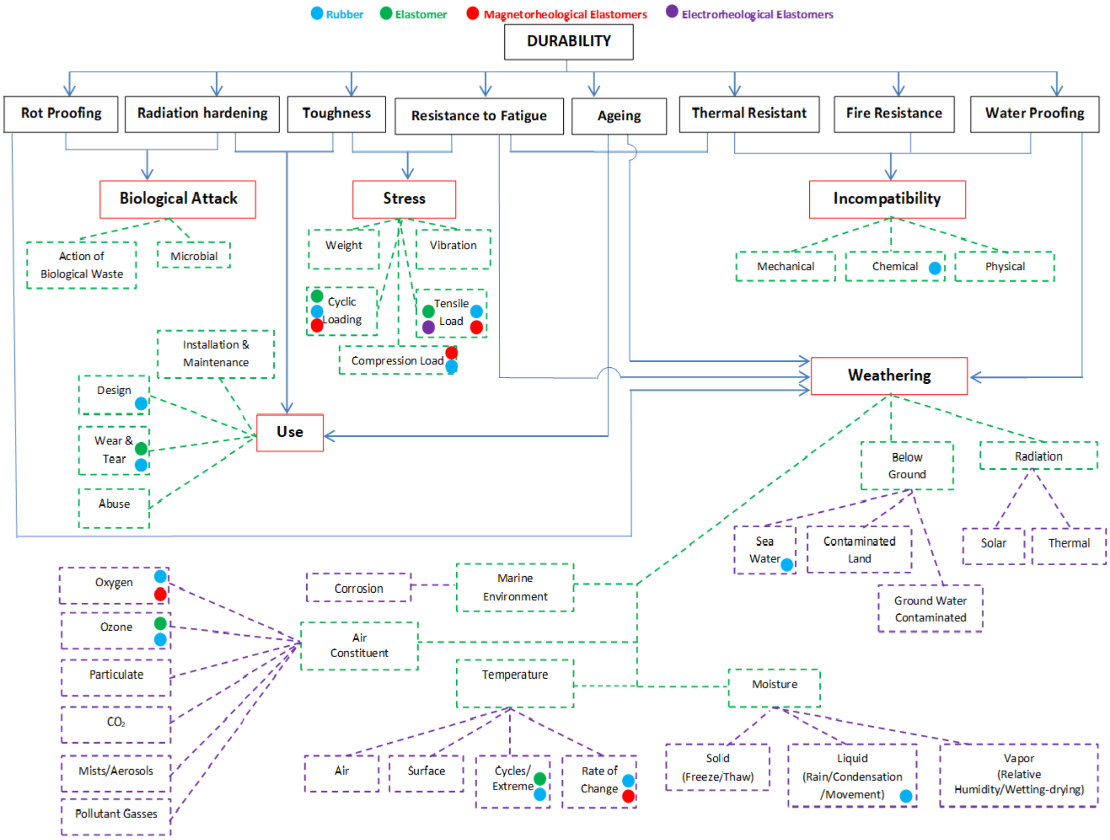


FIGURE 2. Mapping of types and factors affect durability on MRE, ERE, elastomer, and rubber.

established in numerous aspects. Recent development on rubber durability studies were focused on the fatigue failure and this has agreed by the reviewed studies of Tee *et al.* [13]. It was reported that works focusing on the durability of rubber has been significantly increased in the past few decades due to the importance of preventing the failure of rubber component in service. One of the earliest studies on rubber durability was conducted by Stevenson [64] in seawater effect. Results were presented on the effect of water absorption by rubber on the elastic modulus and fatigue crack growth rate. The durability in the saltwater of rubber is very dependent on the electrochemical environment. Research by Delor *et al.* [65] was then studied rubber durability in long term behavior.

Influence factors that affecting durability such as temperature, UV exposure, carbon black, or stress, as well as the oxidation profile across the materials, have been examined. As expected, these factors were decreased the mechanical properties and the total life of the rubber. Latest investigations on rubber durability were published by [66]–[68] conducted on the key parameter to the accelerated aging fatigue. The work of Ruellan *et al.* [66] focused on the high thermo-sensitive phenomena roles in reinforcing fatigue life and temperature affects to improve the durability of rubbers. The strain-induced crystallization (SIC) was introduced and investigated the temperature effects on the fatigue life reinforcement due to SIC for non-relaxing loadings. This version of the fatigue durability test was campaigned due to the lack of experimental results in this section. Besides, the results published pointed out the reason for the required new fatigue tests. Fatigue damaged was then further investigated at the microscopic scale. The works were contributed to the influenced of SIC damaged mechanism details of rubber durability under fatigue conditions at 90-110°C temperature. An example of durability studies on the rubber product application was recently reported by Nyaaba *et al.* [67]. The cracking energy density theory was implemented in this study to predict the nucleation life of selected components of a tire. Finite Element Analysis (FEA) was the key platform that providing the assumed parameters for the computed cracks driving force. The combined effect of thermal and mechanical loads accounted for a negative effect on the tire fatigue durability and performance. As mentioned in the earlier section, natural and accelerated aging test methods are commonly used for evaluating durability [58], [69]–[81]. The accelerated aging test method can predict the lifespan of materials under normal use conditions in a short period and has received extensive attention. Recently studied by Liu *et al.* [68] incorporated the modeling method for parameter identification in the analysis of rubber-accelerated aging test. The data acquired then provides a scientific basis for the prediction of rubber durability. The results showed that the predicted values were consistent with the measured values, and the accuracy of the parameter identification results was verified.

III. DURABILITY TEST SPECIMEN

Failure due to durability has complex characteristics, but it has immensely benefited in the dynamic engineering applications. A variety of test methods have been designed over the past 15 years to quantify the durability of MRE materials. These tests are identified by the type of loading applied, number of cycles, temperature effects, aging process, frequency dependence, the magnitude of the external magnetic field, and the environmental parameters concerning the durability performance. Of these considerations, a trivial amount of research work has been done on the durability of MRE due to the concern over the intrinsic weakness of the structure failure to durability over a certain period. Nevertheless, data collected from durability tests have shown a tendency to be specimen dependent. This problem, however, does not write off the importance of durability data and, contrary to that, an increasing number of attempts are being made to apply various modes of problems in structures. Therefore, the widespread interest in these failure modes is creating an impressive data bank, resulting in improved understanding, especially of durability failure mechanisms.

This overview exclusively deals with MRE durability testing of particular interest in this research which is an experimental method. Due to the fast response, reversible state, and low energy requirement, the MRE system is an economically viable alternative to the traditional system and material. However, long term performance of MRE systems is affected not only by the constituent materials, but also by the processes used during fabrication, which has been difficult to quantify. Hence, there is a lack of generally accepted fabrication specification and process control procedure for the MRE system and researchers are heavily dependent on MRE manufacturers to provide fabrication process control. In common, certainly, no standard test geometry recommended by established standard organizations to be used for characterization of MRE durability. In the view of the experimental approach, few organizations suggested guidelines and procedures in conducting durability tests, such as ASTM Standard, Chinese National Standard, and ISO Standard. However, no established test standards available for the MRE durability test. The best practice was to employed test standards for rubber into MRE due to considerable similarity, especially in the matrix system. Though, agreed by Tee *et al.* [13] that these standards not sufficient to test materials under real service condition, in particular, the multi-axial loading. Available standards constricted specimen geometry for durability tests such as the dumbbell type specimen was the only design recommended for the fatigue test.

Among the most celebrated test standards for rubber durability test was ASTM D4482- Standard Test Methods for Rubber Property – Extension Cycling Fatigue [82]. This test method covers the determination of fatigue life of rubber compounds undergoing a tensile-strain cycle at various extension ratios. Specimen design recommended in this test standard is the dumbbell test specimen. Environmental durability can be evaluated using ASTM D1149-Standard Test Method for Rubber Deterioration – Cracking in an Ozone Controlled Environment [83]. These test methods are used to estimate the effect of exposure in an atmosphere containing specified levels of ozone concentration. The specimen design in this test procedure is characterized according to six sub-test methods. For the tensile elongation test, the specimen recommended is in a rectangular strip at 10 mm width and 25 mm length. In the belt flex test, rubber specimen has adhered to 25 mm width and 2300 mm length of square woven cotton ply-belt. In the method of exposure to straight specimens, the test specimens shall be rectangular strips 25 mm in width by 150 mm in length and having a thickness from 1.9 mm minimum to 2.5 mm maximum. The same specimen criteria recommended for the method of exposure of bent loop specimens. Slightly different can be found in the design on the exposure of tapered specimen method, which the design shall be die-cut tapered strips having outside dimensions of 25 mm width and 95 mm length. The thickness of the specimen is from 1.9 mm to 2.5 mm. Nevertheless, most of the available data published on MRE durability evaluations entirely was not following the established test standards. Researchers proposed the specimen design according to the suitability and ability to meet the complexity of the testing condition.

Table 1 shows the currently available types of samples prepared by recent researchers for MRE durability evaluation. The test samples were prepared based on the requirement of the test apparatus. According to the literature surveyed on the durability of MRE, circular disk design was the highest employed geometry for the MRE durability test. The radius of ranged between 13 mm [34] to 60 mm [36] was used, however 50 mm [14], [16], [17], [19], [24], [31] was the commonly been practiced. This may due to the requirement of the sample mounting devices from the test machine itself, such as the Modular Compact Rheometer (MCR) and the bi-axial test device. The second highest shape that has been chosen for the MRE durability test was the dumbbell design, also called as dog bone by Lokander *et al.* [35]. Dumbbell design was used in the fatigue tensile test by [15], [19], [23], [26], [35]. The sample was applied with tensile load at an increasing number of cycles reached to 10×10^5 cycles [26]. In MRE durability testing, this type of sample was the only design found being practiced according to the established test standard in the Chinese National Standard and ISO Standard [15], [23]. Contrary, the other sample designs were not per any test standards, which purely modification of sample geometry limited to the analysis consideration.

In the MRE durability test, the Beam-liked specimen was then the closest following number of geometries that have been used. Researchers [16], [19] used this specimen for

TABLE 1. MRE samples details and test conditions currently available for MRE durability evaluation conducted by referred researchers.

Ref.	Type of Matrix	Type of Particle	Particle Size (μ)	Content of Particle (%)	MRE Type (ANISO/ ISO)	Sample Type (mm)	On-State Value
[14]	Cis-polybutadiene rubber (BR) and Natural rubber (NR) 100:0, 80:20, 60:40, 40:60, 20:80, and 0:100	carbonyl iron particles CN	NA	60	ANISO 800mT	Circular disc 50mm radius X 1mm thick	0-800mT
[15]	Natural rubber (NR)	Carbonyl iron (type CN), S_iC nanoparticles	6	60	ANISO NA	Dumbbell shapes, 6 mm wide and 5.5 mm thick (GB 528-82)	0-1000mT,
[26]	(cis-polybutadiene rubber (BR) and natural rubber (NR) BR and NR were 100:0, 80:20, 60:40, 40:60, 20:80 and 0:100	carbonyl iron particles	7	60	ANISO 0-1T	Dumbbell 6 mm x 3 mm Beam-like 6 mm x 6 mm x 3 mm	0-900mT
[31]	Silicone rubber (SR), catalyst (10:1)	Soft carbonyl iron (CS)	6-7	20	ISO ANISO 400mT	Circular disc 50mm radius 1mm thick	Off-State
[32]	Silicone rubber (wetted with silicone oil)	carbonyl iron power	5	10-90 (best at 60)	ISO	Circular disc 20mm radius 1mm thick	0-750mT
[33]	Silicone rubber (SR) (HTV)silicone oil, and vulcanizing agent	Iron powders (CN)	NA	3.5, 6, & 21	ISO	Cube, 10mm x 10mm x 3mm	0-1T
[34]	Polydimethyl siloxane (PDMS)	Carbonyl iron particles (SL) Modification with TEOS layer	NA	30-60 (best at 60)	ISO ANISO 250mT	Circular disc 13mm, 20mm & 30mm radius 1-1.2mm thick	0-850mT
[35]	Natural rubber (NR)	Iron particles irregularly shaped Spherical (CM)	<60 ≈10	0, 9 & 37	ISO	Dog bones cross section 2mmx3mm	Off-state
[36]	Silicone Rubber RTV (10:1) silicone oil	Carbonyl iron powder CN uncoated & coated	8	70	ISO	Circular disc 60mm radius 3mm thick	0-0.62T
[37]	Synthetic rubber Urethane product (blend of two polyols)	Carbonyl iron	6-9	33	ISO ANISO 100-300mT	Cylinder type Radius 20mm Thick 20mm	0-127mT
[16]	Natural rubber (NR) Carbon black filled	Carbonyl iron	NA	18.3	ISO	Beam type 70mmx20mmx1mm Circular disc 50mm rad. x 1mm	0-200mT
[17]	RTV silicone rubber (SR) Catalyst 10:1	soft carbonyl iron (CI)	6-7	15, 20, 25, 30 & 35	ISO	Circular disc 50mm rad. x 1mm	Off-state
[18]	Natural rubber (NR), Plasticizer 10, 13, 16 & 20% Silicone rubber (SR) (RTV) Silicone oil 10, 15, 20 & 25%	Carbonyl iron (CN)	3.5	(NR) 60, 70, 80 & 90 (SR) 50, 60, 70 & 80	ANISO (NR) 0-1.5T (SR) 0-1.5T	Circular disc (dimension NA)	(NR) 0, 300, 600 & 900mT (SR)
[19]	Vulcanized natural rubber (NR) Carbon filled (1.65%)	Carbonyl iron	NA	18.3	ISO	Strips 70mmx20mmx1mm Circular disc 50mm radius 1mm thick	0-235mT
[20]	Thermoplastic matrix Plasticizer (13%)	Iron powder (irregular particles)	60	35	ISO ANISO 0.5T	Rectangular 40mmx40mmx4mm	0-130mT
[21]	Silicone rubber (SR)	Carbonyl iron	10	80	ISO	Cube 25mmx25mmx10mm	5-300mT
[22]	Natural rubber (NR)	Carbonyl iron	6	85	ANISO 1.5T	Cube 10mmx10mmx5mm Cylindrical 10mm radiusx20mm height	0-800mT
[23]	Cis-polybutadiene rubber Plasticizer	Carbonyl iron particles	7	60, 70 & 80	ANISO 150mT	Dumbbell 6mmx5.5mm Fatigue sample 5mmx5mmx3mm	0-800mT
[24]	Silicone rubber (SR) (RTV), Catalyst 10:1	Soft carbonyl iron (CS)	6-7	15, 20, 25, 30 & 35	ISO	Circular disc 50mm radius 1mm thick	Off-state
[25]	Thermoplastic elastomer, Plasticizer	Iron powder	42-60	82.8	ISO ANISO 0.5T	Rectangular 40mmx40mmx4mm	0-125.4mT
[27]	Natural rubber (NR)	Irregular shape iron particles	38-63	33	ISO	Rectangular 15mmx20mmx2mm	0-0.8T

the uniaxial tensile fatigue test in the method for specifying the magnetic field applied during MRE durability testing. The other researchers worked in MRE durability test, however used unfamiliar test geometry such as cube [21], [22], [33], rectangular [20], [25], [27] and cylindrical [22]. Fig. 3 shows various types of sample designs that have been used in the MRE durability test and it is represented by the percentage, which summarized in detail the sample design specifically according to the condition of the test either on-state or off-state. It is also considered the isotropic or anisotropic arrangement of carbonyl iron particles in the samples.

A. CHEMICAL COMPOSITIONS

A successful preparation process in MRE fabrication yields outstanding properties to meet requirements for designing certain specimen geometry in testing and analysis. A standard curing duration and pressure is applied to produce the MRE pieces for evaluations of its physical properties. Varying or changing process parameters during the fabrication process can easily manipulate or affect the material properties of the MRE samples. Therefore, special attention must be given to the fabrication process in producing a sample so that the full potential of MRE is readily achievable. The basic composition of MRE includes the matrix, magnetizable particles, and

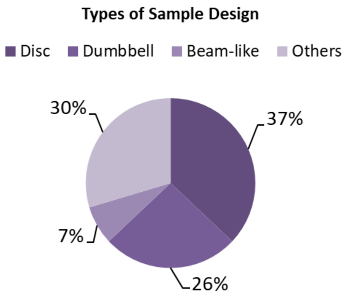
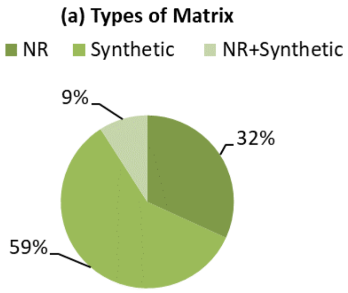


FIGURE 3. Type of sample design in durability literature.



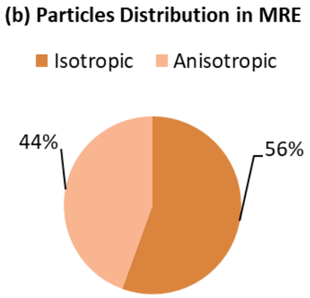


FIGURE 4. MRE durability samples based on (a) matrix materials and (b) particle distribution.

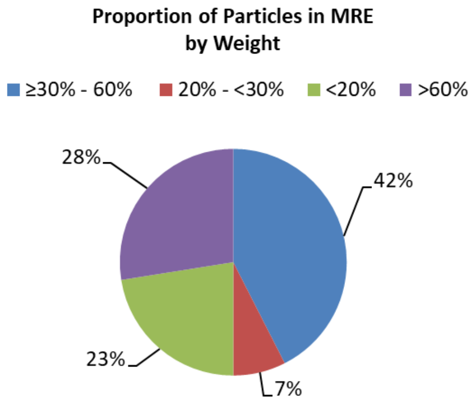


FIGURE 5. Carbonyl iron particles content in MRE durability samples.

curing agent. The matrix has a big influence on the MRE properties and therefore a suitable matrix should be employed to yield materials with a desirable magnetic field induced storage modulus and MR effect [1].

In the literature as summarized in Table 1, the matrix used for durability evaluation can be categorized into three categories, inclusive of natural rubber (NR), synthetic rubber (SR) or the combination of NR and SR. Fig. 4 (a) shows the type of matrix used in MRE durability samples. The synthetic rubber matrix seems to have attracted the highest amount of interest among researchers with about 59%. The contribution was due to the liquid state in the preliminary step, which made the sample easily fabricated. In contrast, dealing with natural rubber is much complex and involves more equipment since the matrix is in solid form. Mixture of synthetic and NR received the lowest interest at less than 10%, however, the matrix proven to have better mechanical properties and heat resistance than other matrices. Fig. 4 (b), however, illustrates in the durability test of MRE, isotropic arrangement has 56% interest, in both natural rubber and synthetic matrices. Even though this arrangement disclosed as less performance, nevertheless better effect can be achieved when particles have a relatively low concentration for touching each other or low volume concentration. In isotropic MRE, iron particles were distributed uniformly in the matrix.

MR effect can also be affected by the particle distribution in the MRE element. Reported from the previous work by Zhou *et al.* [24], the anisotropic arrangement provides a better performance than the isotropic arrangement. Anisotropic can be considered as a pre-structured MRE and possess strictly directed particle orientation. Research conducted by Lai *et al.* [84] reported that the performance of MRE depends not only on the matrix and type of magnetic particles, but also on the columnar structures in anisotropic MRE. To date, the weight fraction of iron particles aligned within the matrix to reach a good MR effect is about 70% [1], [85]. The only issue during fabrication is the equipment setup for applying the external magnetic flux to the MRE during the curing process.

B. CARBONYL IRON PARTICLES

Magnetizable particle chosen for durability test samples was typically iron particles, especially for its high permeability, low remnant, and saturated magnetization. These were agreed and reported in the previous work of Ubaidillah *et al.* [1]. According to the summarized Table 1, the entire durability test was conducted using carbonyl iron particles at various ranges of sizes, overall less than 100 μm of grain size. The proportion of carbonyl iron particles plays an important role in achieving a better MR effect. A higher fraction of iron particles in the matrix will decrease the amount of matrix carrier and caused problems to the sample toughness. In certain cases, as reported from previous work of Ubaidillah *et al.* [52], and imprudent increase of particle content in the samples increased the stiffness of the MRE though the total MR effect exhibited hardly any increment and usually decreased.

Accordingly, MRE samples used in durability studies were mostly 30-60 wt% of particle content and this has contributed

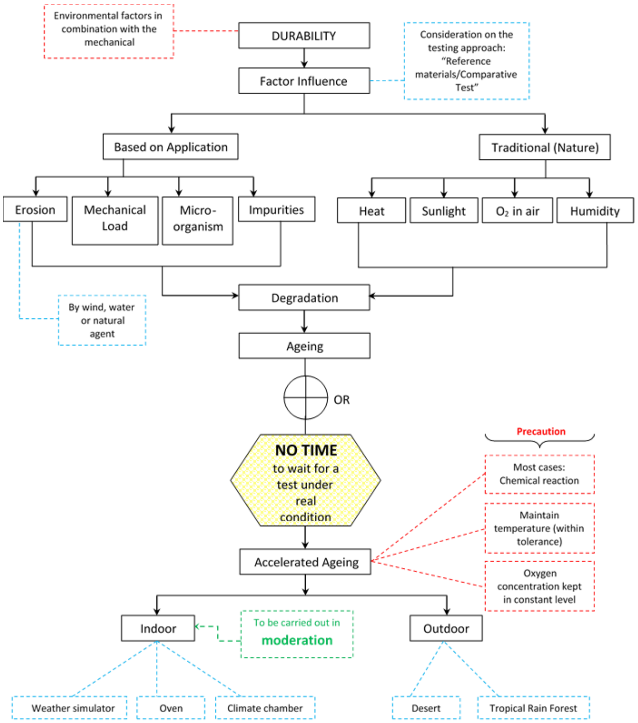


FIGURE 6. Aging process of MRE durability.

the highest 42 wt% from overall ratios as the particle ratios summary illustrated in Fig. 5. In general, most of the works conducted for MRE durability employed above 60 wt% particle content limited to the highest at 90%. However, agreed by [14], [15], [26], [32], [34] that 60 wt% particles content in MRE sample for durability test is the best ratio. Particle content ranged 20 – 30 wt% have a little interest compared to particles below 20% in the MRE durability test sample.

IV. DURABILITY EVALUATION

Presently, evaluation of MRE durability can be categorized into less than ten types of analyses compared to the rubber or its similar off-state behavior materials. Among the analyses, cyclic loading was the most employed by researchers [15], [16], [19]–[23], [25], [26], [35], [37] in evaluating MRE durability. The cyclic loading applied to the sample was in tensile, compression, and shearing continuously for various increasing numbers of cycles. Another example, DMA was used by [15], [18], [22], [26], [33] to evaluate and measure the mechanical and viscoelastic properties of MRE. In the application of DMA, the sample is subjected to periodic stress at several different modes of deformation.

Material aging is the critical aspect of investigating the durability of MRE. Aging can occur in various ways, practically due to nature and during application. Fig. 6 shows the aging mechanism to the MRE durability evaluation. The upper part of the chart shows the aging process by mechanical and nature, which the degrading rates are gradually progressive. Degrading studies formerly dealt with the complexity of material lifetime prediction and extrapolation.

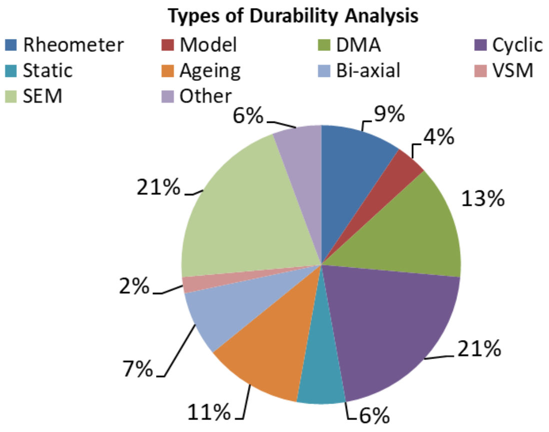


FIGURE 7. Ongoing types of MRE durability analysis.

The trend for over the years advances to more comprehensive studies to tackle the insufficient data to match the observed aging process. As reported by Celina *et al.* [86], the lifetime prediction of materials will require extrapolation of accelerated aging data with the suitability approaches. The accelerating aging process as shown in the bottom part of the chart yet requires moderate formulation to prevent extreme aggravated of the materials. Exhaustive aging application and evaluation of the test sample of rubber-like materials have been thoroughly discussed and guided in the established test standards [87]–[91]. Current durability studies on MRE with ageing process conducted by [14], [26], [27], [34]–[36]. These involved the aging process by high temperature, extreme low temperature, acidic environment, oxidation, and high pressure respectively.

Fig. 7 illustrates the percentage of the MRE durability evaluation method by recent researchers. Static analysis on the MRE sample was conducted by [23], [35], [37] and these involved with Chemiluminescence (CL) and mostly quasi-static tensile loading. Another promising durability evaluation carried by [16], [17], [24], [31] using equi-biaxial fatigue. This method focused on determining the effect of altering strain limits on the MR effect. Among the popular evaluation, few researchers used a vibrating-sample magnetometer (VSM) [34], Fourier transform infra-red (FTIR) [36], and shaker testing device [27] for durability analysis. Despite of encouraging number of researchers investigated MRE durability by conducting an experimental work, however, fewer were working on the theoretical modeling. The works of [13], [14], [29], [30] seems impressive and huge potential in enhancing the knowledge related to long-term durability. However, modeling is still needed to be elaborated and accompanied by accelerated tests for more timely experimental validation studies [29]. The scanning electron microscopy (SEM) studies were conducted by [15], [17], [21]–[23], [25], [26], [31]–[34], [36]. Before the test, the use of SEM was to justify the homogeneity of the mixture and monitor the interphase material bonding. Subsequently, SEM was useful for morphology studies.

Microscopic analysis through the studies is the art and science of examining the surface of a failed component to determine the cause of failure. Morphology analysis is one of the major steps in the process of post-failure analysis to determine the cause of failure, initiation site, the direction of the failure, state of stress or loading conditions, effect of environmental exposure, material defects, or processing deficiencies. It is agreed that it will be the main reason MRE durability studies using SEM contributed to the largest percentage.

Table 2 shows the summary of the MRE durability test results in a specific condition. The researches were carried out since 2004 and conducted by [14]–[27], [31]–[37]. MRE durability test by Zhang *et al.* [14] under different temperatures was compared the theoretical and experimental results. The theoretical results were a little higher than experimental results, which due to the assumption that all particles in the MRE samples obey the Gaussian distribution and no defect in the matrix. The results revealed that the storage modulus and loss modulus of the sample decreased linearly with the temperature increment. Through the research, [14] has developed an improved constitutive equation.

The dynamic behavior of MRE under compressive loading was captured using an artificial neural network-based phenomenological model with a multi-layer perception network. Modeling studied by Cantera *et al.* [29] comprehended the modeling for long-term durability that considers creep, fatigue, and other modes of failure are needed to provide greater reliability in engineering designs of MRE-based system. Also, the dynamic properties of MRE under cyclic loadings were investigated by Wang *et al.* [15]. The study found maximum storage modulus, the MR effect, and the magneto-induced storage modulus changed regularly with the content of Silicon Carbide (SiC) nanoparticles. The test was conducted up to 10×10^4 cyclic loading and incorporated of SiC nanoparticles, the decrement in mechanical performance that was less obvious due to fatigue. The overall magneto-induced mechanical performances of the sample after cyclic loads were better in the samples incorporated with SiC than in those without SiC nanoparticles.

Durability of MRE due to aging as discussed in the previous section was carried by Zhang *et al.* [26], in which the sample aged at three different temperatures reached to 150°C. MR effects for all samples decreased with the increment of aging time at 100°C. It is also noted that the samples were fractured when the number of cycles was above 10^5 cycles.

From the studies, they found that natural rubber had better durability properties because their MR effect was higher and decreased slower than that samples contained synthetic rubber. Dynamic store energy criterion can be used as a plausible predictor in determining the fatigue life of MRE. The work by Zhou *et al.* [31] discovered complex modulus of MRE samples decreased under fatigue test and failure took place at identified limiting value. This discovery was led to the presentation of the first Wöhler curves for isotropic and anisotropic MRE. However, the test conducted only at off-state condition. In another study, shear strain – stress evaluation for the MR effect of MRE durability was conducted by Li *et al.* [32]. Shear modulus found to be increased with the applied magnetic field and stiffness of the system showed a slowly increasing trend with the frequency. The MRE material exhibited a feature that its modulus and damping capability was both field-dependent. The study has proposed a four-parameter viscoelastic model to describe the performance of MRE.

Following the fabrication, work by Wei *et al.* [33] studied two vulcanization methods to describe the durability of MRE. Heat vulcanization (HV) and radiation vulcanization (RV) were compared for its MR effect and tested every week for a total of three weeks. The RV sample has good MR affect durability. In the case of HV, the sample has air gaps for the movement of plasticizer. Thus, the speed of plasticizer migratory of the HV sample was large, contributed the zero-field modulus increased quickly with the storage period.

Durability investigation conducted by Cvek *et al.* [34] concentrated on the particles of MRE. Particles were modified with a thin layer of tetraethoxysilane (TEOS) to enhance the wettability of their surface in hydrophobic media. Through the corrosion test, the MRE based on bare (uncoated) carbonyl iron particles exhibited dramatically decreased relative MR effect and mechanical properties when compared with its analog containing carbonyl iron – TEOS. Various analyses were also included in the studies such as VSM, FTIR, tension-metric analysis, wash-burn method, and for the first-time dielectric relaxation spectroscopy (DRS) was used for MRE microstructure studies. FTIR confirmed that a thin layer of TEOS successfully formed on the surface of the carbonyl iron particles and increased the durability of MRE. Besides, VSM analysis revealed negligibly decreased magnetization due to TEOS coating.

Durability of MRE due to aging as performed by Zhang *et al.* [26] was also conducted by Lokander *et al.* [35] with a slightly longer period of aging time, up to 14 days. Oxidation was introduced to the samples as part of the aging process. The mechanical strain at break decreased with the increasing aging time, whereas the stress at break and tensile modulus initially decreased due to chain scission within the matrix before it increased rapidly due to the formation of cross-linked oxidized skin. A large number of iron particles incorporated in the matrix, contributed to the excess of oxygen on the surface of the particles. Hence, the oxidative stability of MRE decreased dramatically. Similar research by Fuchs *et al* [36] on oxidized iron particles (up to 72 hours) of MRE was conducted using a high pressure and high-temperature reactor for the aging process. The coated particles indicated superior mechanical properties respected to the oxidation stability test agree with Lokander *et al.* [35]. MRE with surface coated iron particles required approximately 15% lesser force to achieve 20% strain compared to the uncoated.

Static and cyclic compression tests were conducted by Kukla *et al.* [37] to accomplish the durability characteristic of MRE under compression load. The cyclic test was established

TABLE 2. Result analysis of durability test conducted by referred authors.

Condition	Shear Modulus		Loss Modulus		Storage Modulus		Complex Modulus		MR Effect		Mechanical Performance		Stiffness		Fatigue Life	
	+	-	+	-	+	-	+	-	+	-	+	-	+	-	+	-
Isotropic MRE	[32] [33] [18] [27]	[21]	[26]		[26] [33] [36] [24]	[22]	[17]	[26] [31] [34]	[18]	[26] [33] [34] [35] [16] [19] [21]	[36] [17]	[26] [35] [22] [27]	[32] [37] [17] [21]	[26] [35]		[26] [35] [16] [17] [20] [22]
Anisotropic MRE	[18]		[26]	[14] [23]	[15]	[14] [23]		[26] [31] [23]	[18]	[26] [34]		[15]	[37]			[17] [23]
Particles coated/mixture					[15] [36]		[17]			[34]	[36] [17]	[15] [34]	[17]			[17]
Off-state	[14][15][26][31][32][33][34][35][36][37][16][17][18][19][20][21][22][23][24][25][27]															
On-state	[14][15][26] [32][33][34][35][36][37][16][18][19][20][21][22][23][25][27]															
Increasing magnetic field	[32] [33] [18] [27]	[21]	[21]	[14]	[26]	[14]		[26]	[18]	[26] [16] [19] [29] [21]		[15] [26]	[32] [37] [21]	[26]		[15] [26]
Increasing temperature	[27]			[14]		[14]										
Decreasing temperature												[27]				
Increasing particles %	[18]			[23]		[23]			[18]							
Increasing fatigue cycles		[21]		[23]	[24]	[22]		[26] [31]		[26] [16]		[15] [26] [22]		[26]		[15] [26] [16] [17] [20] [21] [22] [23]
Aging time			[26]		[26] [33]			[35]		[26] [33]		[35]		[35]		[35]
Increasing frequency												[27]	[32]			

Note: (+) = Increased and (-) = Decreased

at low frequency and the maximum strain level ranged 10 to 30%. The required strain work increased with the magnetic field strength and concluded that the effective content of iron particles in the matrix should be about 76 wt%. An interesting cyclic loading on tensile mode was proposed by Gorman *et al.* [16], focused on the effect of altering strain limits on the MR effect. The influence of flux density was introduced to the sample at every 50 cycles and off magnetic for the next 50 cycles. The pattern continued and ended at 500 cycles. A similar pattern of magnetic field influence has applied to the equi-biaxial bubble inflation test but introduced at every 20 cycles and ended at 109 cycles. In the case of both uniaxial and equi-biaxial, overall strain has the greatest influence on the magnetic response of an MRE sample subjected to a magnetic field and cyclic loadings [16].

Zhou *et al.* [17] conducted equi-biaxial fatigue on various carbonyl iron particles percentage to the matrix materials. Five different ratios were introduced and tested at off-state condition. Increasing of filler contributed to a proportionally smaller distance between iron particles. As stress amplitude increased, fatigue life of MRE decreased irrespectively to the particle content. However, according to $S-N$ curve characteristics, fatigue life of MRE with lower particle contents was more rapidly decreased. The rubber matrix reported to be dominantly controlled the fatigue of MRE when they contained fewer magnetic particles. Higher magnetic particle content expected to produce higher elastic modulus. The important finding from the study was the identification of limiting value for complex modulus between 1.2 MPa and 1.38 MPa regardless of the particle content and the stress amplitude applied.

Curing of MRE samples at a strong magnetic field was investigated by Gong *et al.* [18] and this practice led to the high magneto-induced modulus. As high as one Tesla magnetic field induced, the relative MR effect reached 878% and was the highest reported ever. Magnetic field effect to the MRE durability was also considered by Gorman *et al.* [19], has introduced electromagnetic array to the MRE biaxial test system. The studies produced the first comparative results for uniaxial and biaxial testing under high strain fatigue test conditions at magnetic flux density up to 206 mT.

Kaleta *et al.* [20] performed cyclic shearing at 5 Hz frequency intending to analyze the MRE durability. It was marked as a necessary step before the introduction of MRE based devices into the market. The cyclic shear test was conducted for 1,296,000 of loading cycles per specimen. Surprisingly, the MRE sample maintained stable in terms of mechanical properties over long periods of cyclic work has offered a high application potential. Fatigue shearing test on MRE for durability evaluation was conducted by Lian *et al.* [21] Following ASTM E143-13, Standard Test Method for Shear Modulus at Room Temperature. In this study, the shear modulus was found to decrease as the number of fatigue cycles increased for both with and without magnetic fields. However, the hardness of the MRE sample increased, leading to a low hysteresis loss. The test was conducted up to 129,600 cycles. The authors concluded that as the number of fatigues increased, carbonyl iron particles underwent a slight movement, which led to a loose internal structure. Nevertheless, Wang *et al.* [22] concluded the depreciation of shear modulus from fatigue loading at different perspectives. First, the destruction of the microstructure and slippage happened, while second, with the degree of the fatigue increased, the plastic deformation was more obvious. The study was conducted on the MRE sample under increasing cyclic loading reached 1×10^4 cycles. The method practiced from the test claimed to be useful to detect the MRE microdamage and predict the service life (durability).

Research by Zhang *et al.* [23] was conducted on considerably high carbonyl iron particles ratio MRE at 60, 70, and 80 wt%. The cyclic tensile loading was performed in accordance to the Chinese National Standard (GB 1688-86). Strain amplitudes applied were 50, 75, and 100% of the length of the MRE samples. At 60 wt% iron particles, the storage and loss modulus MRE were almost independent of the strain amplitude and number of cycles. However, at 80 wt% particles, it is contrariwise behaved. The study summarized that the change of magneto-induced modulus of MRE was related to the evolution of microstructure of filled networking.

The work by Zhou *et al.* [31] and later [24] has established a general equation for fatigue life prediction for MRE subjected to complex loading. The maximum engineering stress of cycles after the material has been conditioned was introduced according to typical value applied in industry, which agreed at 10 cycles. In their research, few considerations were presented in conducting MRE durability analysis. Maximum strain cannot be used as a general fatigue life predictor for a common range of particle content. Similarly, for a tensile minimum stress, total energy was an unreliable predictor. However dynamic stored energy remained a credible predictor of MRE fatigue life. The study observed on isotropic silicone based MRE with a range of different particles contents. The stored energy density was found to be increased with the increasing number of cycles over ranged of constant stress amplitude. It was reported that maximum engineering stress and stored energy density can be used as credible fatigue life predictor for MRE subjected to equi-biaxial loading.

Comparison studies on both isotropic and anisotropic MRE materials were conducted by Kaleta *et al.* [25] under cyclic shearing conditions. The performance was compared in terms of magneto-mechanical properties at increasing values of the magnetic field. The field strength infused to the system with value increment at every 100 cycles and reached to 0.125 T at the final 2000 cycles. Concurrently, at every 500 cycles the strain amplitude was increased, resulted in the force amplitude signal fluctuated. MR effect for anisotropic MRE in most cases observed to be slightly larger. The study reported that changes in magneto-mechanical parameters were contributed by particle orientation and chemical composition. An appropriate amount of magnetic field stimulated to the MRE was part of the influence too.

Durability of MRE and its behavior in extremely low temperatures was investigated by Lejon and Kari [27] with the utilization of liquid hydrogen. The study was concentrated on the influence of low-temperature conditions to the shear modulus of MRE, accompanied by magnetic field and frequencies. Shear modulus was increased with the applied magnetic field at 10% for 0.3 T and a maximum of 20% for 0.8 T on average. However, shear modulus magnitude behaved diametrically different as temperature decreased to the coolest state, −31.15°C. The MRE was reached to the transition phase and approached to the end of it. Temperature was concluded as a greater influence than the other parameters. This establishment was contributed to summarize that the influence of temperature to the MRE has improved the possibilities to construct tunable mounts and isolators that meet that design criteria.

In overall, this study set out to review in detail the available information on MRE durability evaluation. These findings draw our attention to the importance of considering some key technological issues beforehand MRE characteristic advantages became a popular choice of materials for structural and engineering applications. The technical issue that remains to be addressed is illustrated in Fig. 8 and manifest shortcoming in sample design, fabrication process, and test apparatus. Therefore, a complete understanding of MRE particularly durability, and the influence of production methods (fabrication and curing) on their performance is vital in achieving the full potential of these materials. Ubaidillah *et al.* [92] suggested future investigations will possess ample opportunity to ameliorate the rheological properties of MRE towards device applications. In a particular example, Khairi *et al.* [93] performed experimental work to show that MRE fabrication issues in which degraded rheological performance of MRE can be resolved by incorporating plasticizer into the matrix. Consequently, the improved properties of MRE will be validated by adopting application devices for future investigation.

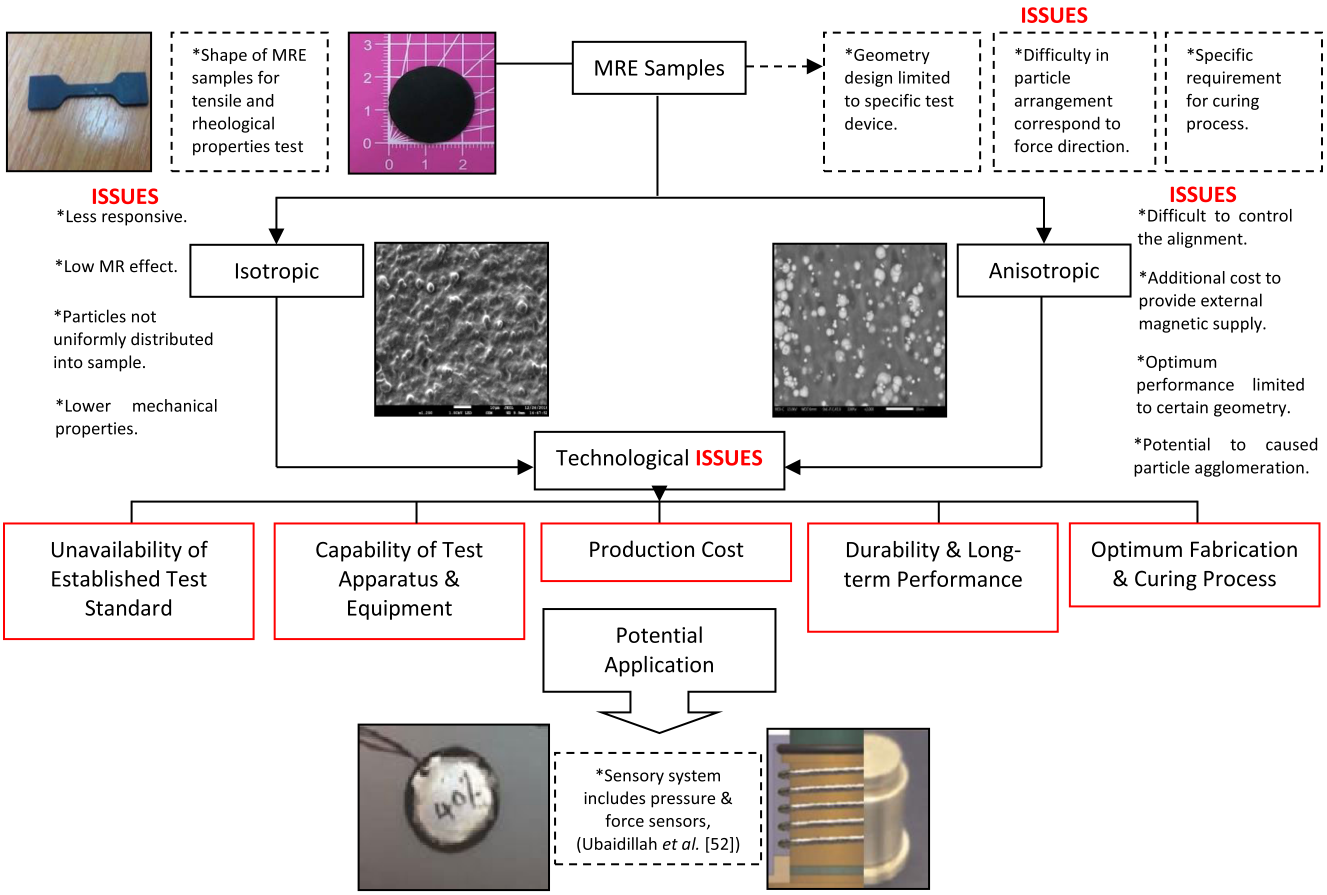


FIGURE 8. Key technological issues of MRE.

V. CHALLENGES AND FUTURE TRENDS

The durability characterization in this study can be further expanded by considering and exploring other condition factors for durability evaluation. From the author's point of view, the starting phase could be consideration of the fabrication method. The selection of new ranges of raw materials should be carefully performed to achieve a novel kind of MRE, which able to withstand even better durability challenges. Better form of matrix materials and special fillers, for example, may increase the performance. The idea of green MRE for example, was an eye-opener to the MRE technology and should be solemnly considered. The new evolution of MRE may have a better resistance to heat, cold, acidic, surface degradation, and various factors that physically affect its durability. The importance of durability studies on MRE has comprehensively agreed and concluded that it is an important step before commercialized and implementing the materials in potentially dynamic applications. The preparation of desirable materials is hardly to be realized by overlooking raw materials, manufacturing methods, and performance evaluation.

Various environmental effects upon durability failure can also be investigated. Existing environmental effect studies were conducted by [14], [27], [34]–[36], [26], however, it was accelerated under lab environment control. The conditions were mimicked to the realistic condition to develop aging and yet, the possibility of over-aging to the sample was undeniable. Researchers should come up with more representational data and a moderate accelerated aging process should be comprehended. Various weathering conditions should be considered to establish a complete environmental effect on the durability performance. The environment durability factor, most of which are non-mechanical, have an influence on failure initiation and degradation both under cyclic and sustained mechanical loadings. Temperature, moist air, water, salty water, and other active reagent intensifies the process of degradation. Concentration of these active agents and temperature conditions are among the most important factors in environment fatigue durability.

Presently, most of the durability studies were focused on the load at tensile, which was the mode-I of failure inclusive compression [23], [35], [37]. Other explorations on different modes of failure load such as torsional, oscillating, and sliding load directions to durability of MRE could also be investigated. In particular case, tearing shear mode (mode-III of failure) deformation perpendicular to the load direction could be crucial to investigate. Moreover, regular materials were forced to its static limit and continued with durability characterization. These practiced seem not to represent the real initiation (linear stage) and the total value of the sample under durability loading. Beyond this linear limit, the control strategies turn out to be ineffective. Consideration should be given to the condition, in which the sample is still in the linear characteristics. In the case of MRE, durability evaluation should begin at the strain value in the linear viscoelastic (LVE) region. This is the point where storage and loss modulus become dependent on the strain. Identification of this LVE limits was briefly discussed by Olabide *et al.* [94]–[96] and Karrabi *et al.* [97]. Durability investigation at the condition that strain is constantly within LVE limits will be a great challenge. As MRE properties in a long-term operation are still in the early stage, the data of MRE durability at the LVE region will be interesting and indisputably crucial.

Developing durability performance with Finite Element Analysis (FEA) could also be carried out to simulate and model complex analysis due to durability characteristics, especially on MRE. Preliminary works were conducted by many researchers [28]–[30] on MRE durability modeling. Experimental data on various related parameters to the durability behavior can be manipulated into modeling equations. The long-term behavior of MRE is obligatory to be modeled towards the implementation of MRE in actual applications. The analytical and computational results could thus be compared with the experimental value, inaugurate for future durability problems to be anticipated.

Micrography analysis is an important factor in the study of failure surfaces of material. Partially work on microstructure evaluation has been discussed in [98]–[107]. Considering MRE can be microscopically failed because of various factors during the durability process, micrographic studies are potentially crucial. Morphological analysis on failed MRE materials, specifically due to durability is never been explored using micrography analysis. A micrographic analysis of the durability failure mechanism is supposed to be included in the investigation of the failed surface of MRE by using SEM and atomic force microscopy (AFM). Introductory studies on MRE microstructural analysis by using the AFM method has previously attempted but restricted to surface roughness and size distribution of particles [108], [109]. Furthermore, identification of particles and matrix failure can be established including micrographic characterization of failed surfaces for various cyclic loadings. Eventually, patterns and mechanisms of the failure can be proposed.

Last but not least, as the Fourth Industrial Revolution (Industry 4.0) greatly important for the future advancement and smart manufacturing system, MRE simultaneously should along with its smart behavior to develop the physical of this Industry 4.0 revolution's system. MRE durability research aspect in the future will contribute to the establishment and development of a higher material quality via the important failure mechanics approach. Therefore, durability performance being complex in characteristic dictating failure and has immense importance to engineering applications. Durability failure during routine services becomes a major concern in material structural design. Resistance to durability being one of the most important mechanical properties of MRE occurs once failure grows causing progressive stiffness reduction, and even material degradation.

VI. CONCLUSION

This overview has contributed to the introduction of present durability studies conducted by numerous researchers. This investigation summarized based on the profound review related to the durability studies by the availability of scientific and technical reports published on MRE. Pertinent information along this overview could anticipate researchers to identify gaps in the MRE durability studies, which thus far immense. The reliable results for durability evaluation depending upon the correct method and techniques that must be carried out for characterizing the durability failure behavior. The material and specimen preparation is a critical factor for obtaining a meaningful result. All concepts and methodologies of material handling have been analyzed to ensure a representative scientific investigation. Material composition and its mechanical properties had been investigated as necessary parameters important to the basic formulation of the durability characteristic model. Throughout the available literature on MRE durability, experiment procedures, apparatus, scope, and interpretation of results are barely following the prerequisite of established test standards. To the apprehension of authors, most researchers do not adopt the available standards. Many researchers proposed several specimen geometry and procedures to meet the complexity of the durability test. In the final section of this paper, the summary of future trends derived from previous durability researches is also presented. The potential future improvement and development were attentively identified.

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MOHD AIDY FAIZAL JOHARI received the B.Eng. degree in mechanical engineering and the M.Eng. degree in advanced materials from the School of Engineering and Information Technology, Universiti Malaysia Sabah, in 2004 and 2007, respectively. He is currently pursuing the Ph.D. degree in smart materials research focused on the synthesis, characterization, and durability performance evaluation of magnetorheological (MR) solids especially MR elastomer, with the Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia. His research interests include material durability, fatigue toughness, microstructure characterization, and fracture mechanics.

SAIFUL AMRI MAZLAN received the Ph.D. degree from Dublin City University, Ireland. He is a registered Professional Engineer with the Board of Engineers Malaysia. He is currently an Associate Professor with the Malaysia-Japan International Institute of Technology, Universiti Teknologi Malaysia. His research is primarily in the area of magnetorheological (MR) Materials, where these materials undergo significant responses leading to consequent rheological changes upon the influence of the magnetic field. The materials can offer tremendous opportunities for variable stiffness devices. He published his research works at several international journals and conference proceedings.

UBAIDILLAH (Member, IEEE) received the master’s degree from Universiti Teknikal Malaysia (UteM), Melaka, Malaysia, in 2010, majoring in a semi-active automotive suspension system using magnetorheological (MR) dampers, and the Ph.D. degree from the Malaysia Japan International Institute of Technology, Universiti Teknologi Malaysia, in 2016. He is currently an Assistant Professor in mechanical engineering with the Faculty of Engineering, Universitas Sebelas Maret, Indonesia. He started to study MR technologies, since 2007, starting from the development of device-based MR such as MR damper, MR brake, MR clutch, as well as MR engine mounting. He began research on MR materials, since 2012, which focused on MR elastomers, MR grease, MR foam, and MR fluids. He has managed to publish about 75 indexed articles in MR fields.

HARJANA received the M.Sc. and Ph.D. degrees from SUNY University, Albania, USA. He acts as the Dean of the Faculty of Mathematics and Science, Universitas Sebelas Maret. He is currently an Associate Professor with majoring in waves and vibration. His research focuses on the sound and vibration fields, especially on acoustic materials. He has managed some prestigious projects in sound absorption panels for classrooms, auditoriums, and theaters. He also developed some techniques for robust sound absorption in low frequency. Some articles were published based on his research findings on the sound and vibration of materials.

SITI AISHAH ABDUL AZIZ received the Ph.D. degree in engineering (smart materials) from Universiti Teknologi Malaysia (UTM), in 2017. She is currently a Research Officer with UTM. Her research mainly focuses on the fabrication, and properties evaluation as well as the development of magnetorheological elastomers with nanoparticles. She has presented papers at several international conferences. She also has published in several publications in ISI journals and book chapters with her research group.

NUR AZMAH NORDIN was born in Ipoh, Malaysia, in 1989. She received the B.Eng. degree in mechanical-materials engineering and the Ph.D. degree in mechanical engineering from Universiti Teknologi Malaysia (UTM), Johor, in 2012 and 2017, respectively. She is currently a Senior Lecturer in one of the faculty of Universiti Teknologi Malaysia, namely the Malaysia-Japan International Institute of Technology (MJIIT), which held in campus Kuala Lumpur, Malaysia. Her research interest is about modification of structure and properties of polymer composites, known as magnetorheological materials (smart materials), synthetization of magnetic particles, corrosion study, and development of coating on magnetic particles. Besides, she also involves the modification of structure and mechanical properties of metal composite via addition elements melt treatment, superheating, and thermal analysis of CCTA.

NORHASNIDAWANI JOHARI received the degree, master’s, and Ph.D. degrees in materials engineering (nanotechnology) from the International Islamic University (IIUM), Malaysia. She is currently the Staff with the Malaysia Japan International Institute of Technology (MJIIT), Universiti Teknologi Malaysia, Kuala Lumpur. She served in nanotechnology, materials, composites, and corrosion, where she also holds several awards in international exhibition. she is a member of Board Engineer Malaysia, Nano Malaysia, and Technologists.

NURHAZIMAH NAZMI received the B.Sc. and M.Sc. degrees in mathematics from Universiti Sains Malaysia and Universiti Teknologi Malaysia (UTM), respectively, and the Ph.D. degree in biomedical engineering from the Malaysia-Japan International Institute of Technology (MJIIT), UTM, in 2018. She is currently a Senior Lecturer with MJIIT, UTM. Her research interest includes artificial intelligence, signal processing, and smart materials for assistive devices in rehabilitation.

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