SEMARAK ILMU PUBLISHING
202103268166(003316878-P)

Journal of Advanced Research in Applied Mechanics

Journal homepage:
https://semarakilmujournal.com.my/index.php/aram/index
ISSN: 2289-7895

Ageing Effects on the Properties of Radiation Cross-Linked PVC Cable

Nur Alia Rizani[1], Norazrina Mat Jali[1,*], Nor Azwin Shukri[2], Norzaima Nordin[1], Sri Rizki Putri Primandari[3]

[1] Faculty of Engineering, National Defence University of Malaysia, Sungai Besi Camp, 57000 Kuala Lumpur, Malaysia
[2] Polymer Processing Division, Malaysian Nuclear Agency, 43000 Kajang, Selangor, Malaysia
[3] Department of Mechanical Engineering, Faculty of Engineering, Universitas Negeri Padang, Padang, Sumatera Barat 25171, Indonesia

ARTICLE INFO

Article history:
Received 21 March 2025
Received in revised form 24 April 2025
Accepted 1 May 2025
Available online 30 May 2025

Keywords:
PVC; insulation cables; electron beam irradiation

ABSTRACT

In this study, the impact of ageing on radiation cross-linked PVC cables, using electron beam irradiation within 0-100kGy radiation doses was investigated. Accelerated thermal ageing was performed in a vacuum oven to simulate real-time ageing and shelf life. Tensile test was then conducted using Universal Instron machine to evaluate the ultimate tensile strength (UTS) while electrical conductivity tests using impedance analyser was carried out to assess the insulation properties of the radiation crosslinked PVC. Results indicated that higher radiation doses generally increased UTS values, enhancing the mechanical performance of the cables. However, UTS values varied across different ageing durations, indicating an inconsistent ageing effect on mechanical properties. From this experiment, the data shows that the higher radiation doses increased the gel content and ultimate tensile strength (UTS) as well as the higher percentage of elongation. Lower conductivity values were observed for unaged specimens as compared to aged specimens, indicating better insulation properties. These findings offer valuable insights for optimizing cable design and selection, facilitating performance improvements and early detection of failures in PVC cables across industries. The study contributes to predicting PVC cable lifespan and enhancing reliability in critical applications.

1. Introduction

The current population uses a variety of devices and equipment that are wired and cabled in various ways. Most of the insulation of the electric wire and cable is generally made up of rubber or plastic. In addition, a lot of modern living involves electrical devices with wires and cables. These circumstances increase the number of lives lost and property lost because of an electrical fire caused by a cable or wire with poor insulation if it is not properly design or manage. Poor insulation used in wires and cables can release harmful gases and smoke that can harm the health permanently. Therefore, wire and cable insulation must meet both mechanical and electrical requirements.

* *Corresponding author.*
E-mail address: norazrina@upnm.edu.my

https://doi.org/10.37934/aram.137.1.122133

Researchers have recently been involved in improving the physical, electrical insulation and mechanical properties of these wires and cables, which are polymers, due to rising demand in the polymer sector and applications.

Furthermore, according to study by Coaker *et al.,* [1], Merzouk *et al.,* [2], Zaharescu *et al.,* [3], Abdel-Gawad *et al.,* [4] and Mendizabal *et al.,* [5] polymers such as polyvinylchloride (PVC) compounds are among the best materials for use as wire and cable insulation due to their excellent mechanical and electrical properties because it is proven product performance, material processability and economic cost-effectiveness. In addition, as mentioned before, PVC is very susceptible to thermal degradation where it produces a sequence of double bonds (polyene) and has poor thermal stability that can delay fire from starting and from spreading due to the flame-retardant properties inherent in its chlorine content.

It is necessary to use polyfunctional monomers that can encourage the crosslinking of the polymerization since PVC exhibits a low yield of mechanical crosslinking when exposed to radiation. A study conducted by Facio *et al.,* [6] the most efficient substances for this use are polyfunctional acrylates and methacrylate, particularly trifunctional monomers like Trimethylolpropane triacrylate (TMPTA), a common crosslinking agent that generates a lot of radicals when exposed to radiation.

Polyvinyl chloride (PVC) is a widely used polymer in the cable industry due to its good mechanical and electrical properties. However, the inherent properties of PVC can be improved through the process of radiation crosslinking, which involves exposing the polymer to high-energy radiation, such as electron beam irradiation. This process leads to the formation of crosslinks between the polymer chains, resulting in a material with enhanced properties, including improved mechanical strength, thermal stability and resistance to environmental stress [7].

The study of the ageing effects on the properties of radiation cross-linked PVC cable provides valuable insights into the durability and performance of this specific type of PVC material. Several research conducted the effect of aging shows different properties reduction to the materials [8-13]. In comparison, the research conducted by Jakubowicz *et al.,* [14], focuses on the effects of accelerated and natural ageing on plasticized polyvinyl chloride (PVC). While not directly investigating radiation cross-linked PVC cable, this study shares relevant aspects related to the ageing behaviour of PVC and examined the changes in mechanical and thermal properties of plasticized PVC under accelerated and natural ageing conditions. Their findings highlighted the degradation mechanisms and subsequent effects on properties such as tensile strength, elongation at break, glass transition temperature (Tg) and thermal stability. Although specific to plasticized PVC, the research by Jakubowicz *et al.,* [14] provides valuable insights into the general ageing behaviour of PVC-based materials, which can be informative for understanding the potential ageing effects on radiation cross-linked PVC cable.

Electron beam irradiation is a widely used method for crosslinking polymers, including polyethylene, polypropylene, polyamide and polyvinyl chloride (PVC). There are various studies on the effect of electron beam irradiation on polymer properties [15-19]. The crosslinking of wire and cable insulation has significant commercial advantages. In this process, polymer molecules make chemical interactions with one another to create a three-dimensional insoluble network. Most often, ionisation results in the abstraction of hydrogen from a polymer. This produces active sites along a polymer chain that are able to form bonds. Electron Beam (EB) crosslinked wire and cable insulation has various advantageous qualities. It won't melt and flow in hot environments, nor will it melt and flow if a shorted electrical circuit causes the conductor to heat up. EB crosslinking protects wire and cable insulation during soldering, when a short circuit occurs or at high temperatures, such as near an automobile's engine or exhaust pipe. If a fire breaks out in electrical equipment, EB crosslinking lessens the chance of flame spread. Abrasion resistance, stress fracture resistance, solvent resistance and tensile strength are all improved, especially at high temperatures.

The study of radiation crosslinking in polyvinyl chloride (PVC) cable insulation is crucial due to the significant enhancements it imparts to the material's properties. Electron-beam processing, a common method for inducing crosslinking, transforms thermoplastic materials like PVC into thermosets by creating a three-dimensional network of bonds between polymer chains. This transformation leads to improved thermal resistance, mechanical strength and chemical stability, making the cables more durable and reliable in various applications. Additionally, crosslinked PVC exhibits increased resistance to temperature variations, aging and environmental stress cracking, which are essential characteristics for ensuring the longevity and safety of electrical wiring systems.

Furthermore, understanding the aging effects on radiation crosslinked PVC cables is vital for assessing their long-term performance. Research indicates that while crosslinking enhances properties such as tensile strength and abrasion resistance, it also influences the material's behaviour under prolonged environmental exposure. Studies have shown that factors like thermal aging can affect the mechanical and thermal properties of crosslinked PVC, leading to changes in tensile strength and elongation at break over time. By investigating these aging mechanisms, the study provides valuable insights into the durability of crosslinked PVC cables, guiding the development of more robust materials for electrical insulation applications

2. Methodology

2.1 Materials Under Consideration

2.1.1 Sample preparation

Polyvinyl chloride (PVC) in this study was supplied by Wonderful Ebeam Cable SDN BHD. PVC was mixed with TMPTA as crosslinking agent and mix together in HAAKE internal mixer. In this procedure, a roller rotor was used with a mixture temperature of 160˚ C and speed range of 50 rpm for 10 minutes. Then, resulting mixture were compressed using hot press machine. Prior for testing, irradiation process was carried out under electron beam radiation dose of 60,80 and 100 kGy using the EPS-3000 3.0 MeV high-energy machine. Thermal aging of samples was performed using Memmert VO 200-230V Vacuum Oven (see Figure 1). Aging temperature was 50°C and the duration was 3,5 and 7 days.

Fig. 1. Irradiation PVC sample placed evenly spaced inside the Memmert VO200 oven

2.2 Gel Content Testing

Gel content testing is a method used to determine the degree of crosslinking in PVC. It involves dissolving a sample of the PVC in a solvent that can dissolve the uncrossed linked polymer chains but not the crosslinked chains. Before being solubilized in a solvent, the specimen is dried and weighed. A weight of 0.20 g was cut from the respective samples and the put into a single-use stainless steel wire mesh pouch (size 4cm x 4cm). The wire mesh containing the sample was then fitted into a 30 mL Soxhlet extractor and extracted for 24 h using Tetrahydrofuran (THF) as a solvent. The gel is collected after the solvent solution has been filtered. Five samples per formulation were measured. Once dried, it is weighed and the resulting number is divided by the original weight to yield a gel percentage

2.3 Tensile Testing

The tensile test was performed in order to determine mechanical properties of un-irradiated and irradiated PVC specimen by apply a tensile force to a test specimen until the specimen is pulled to failure using Universal Testing Machine, Shimadzu AG-X. The standard test method is ASTM D1882-L (Figure 2). All five different sample irradiations with PVC doses (0, 60, 80 and 100kGy) were tested at constant strain rates between 3 and 10 mm/min^{-1}. Specimens after being aged and ready for tensile testing are shown in Figure 2. The data obtained from tensile tests are collected and Young's modulus and yield stress are compared in a stress-strain diagram.

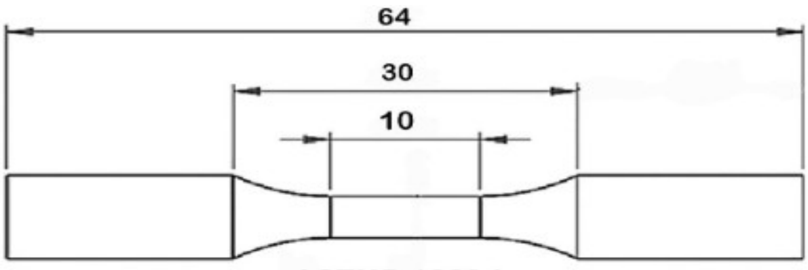


Fig. 2. Detail measurement for tensile test sample (ASTMD 1822-L)

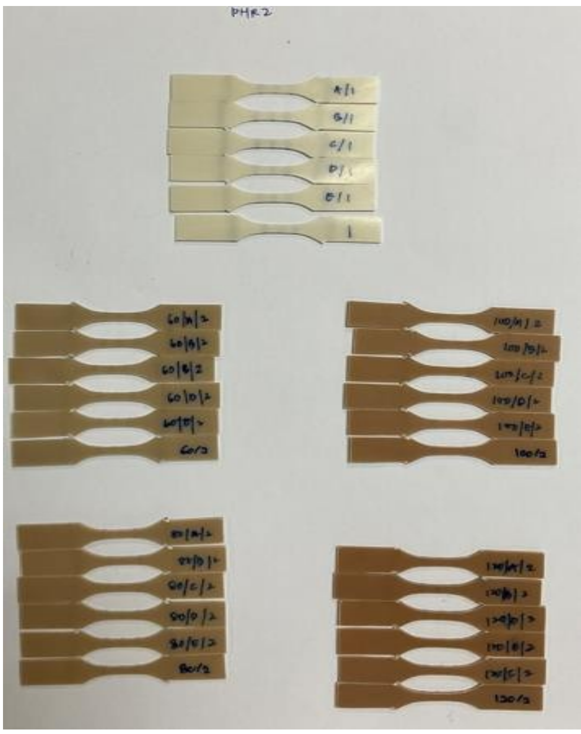


Fig. 3. Specimens for tensile testing after being thermally aged

2.4 Conductivity Testing

Impedance Analyzer 16451B was used to measure the conductivity of the. This is important to study the effect its conductivity after undergo ageing process. Dielectric properties will also be measured for all samples including under new and aged conditions. The irradiated PVC samples were prepared and cut to the desired dimensions. The samples were placed in the analyser and measurements were taken at specific frequencies or within a frequency range, depending on the requirements of the analysis.

3. Results

3.1 Gel Content

Gel content is important test because it determines the crosslinked fraction of PVC materials. The degree of crosslinking is affected by the amount of irradiation dose passed the electron beam. Table 1 tabulated the data for the gel content test for different radiation dose.

It is found that for both blends, the amount of gel content increases with radiation dose and the higher value of gel content suggests the formation of highly crosslinked network structure. The ionizing radiation produced by electron beam accelerator generates extremely reactive species like free radicals and ions which modify the molecular structure of polymeric material by the formation of insoluble chemical crosslinks between molecular chains through radical combination and degradation or chain scission which destroys the molecular structure to some extent. Although both processes occur simultaneously, one plays the major role mainly dependent on the chemical structure of the polymer and applied radiation dose.

Table 1
The result of Gel Content for different dose of electron beam irradiation

Irradiation dose (kGy)	Wt. of sample (g)	Wt. Of sample + net (g)	Wt. Of net (g)	Wt. Of sample + net after boiling (g)	Wt. of sample after boiling	Gel content (%)
PHR 5						
0	0.2041	0.7509	0.5468	0.5516	0.0048	3.28
60	0.2022	0.6771	0.4750	0.5596	0.0846	55.42
80	0.2046	0.8694	0.6648	0.8120	0.1472	70.98
100	0.2028	0.8534	0.6507	0.8023	0.1516	75.91

The percentage of polymer chains that are linked determines the degree of crosslinking that occurs, chain also known as the density of the gel component. More connections per length of polymer result in greater property changes with higher crosslink density. Figure 4 shows the effect of irradiation dose to the degree of crosslinking. Based on Figure 4, degree of crosslinking value, 100 kGy PVC has the highest degree of crosslinking value which means more crystalline structure were formed after the irradiation. This crystalline structure which linked together plays an important role to change the properties of the polymer (in our case the PVC).

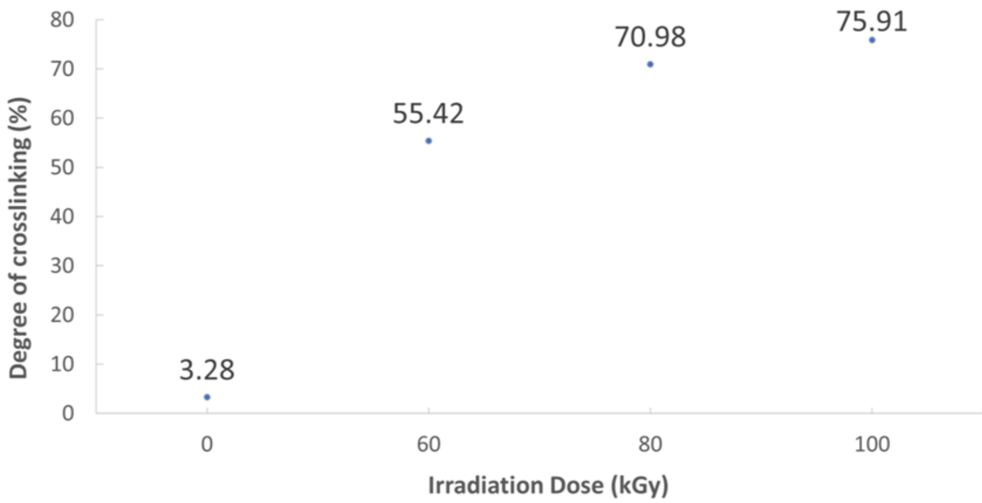


Fig. 4. Effect of irradiation dose to the degree of crosslinking of PVC

3.2 Tensile Strength

The tensile strength is a key parameter that can be obtained from the stress-strain curve in a tensile test. The stress-strain curve represents the relationship between the applied stress (force per unit area) and the resulting strain (deformation) in a material subjected to tensile forces. The correlation between irradiation doses and tensile strength may vary for aged and non-aged PVC due to natural ageing processes. Additionally, colour differences can occur during ageing. Tensile tests were performed on non-aged PVC (0day) and PVC aged for 3, 5 and 7 days to determine the tensile strength values for each condition. Ageing PVC may involve degradation mechanisms like chain scission, cross-linking or chemical degradation. This study has examined the impact of different irradiation doses on both non-aged PVC and ageing PVC samples. This experiment was carried out at room temperature with a constant of 50 mm/min strain rate. Figure 5 shows the PVC sample after ageing process at 50 Degree Celsius for 7 days.

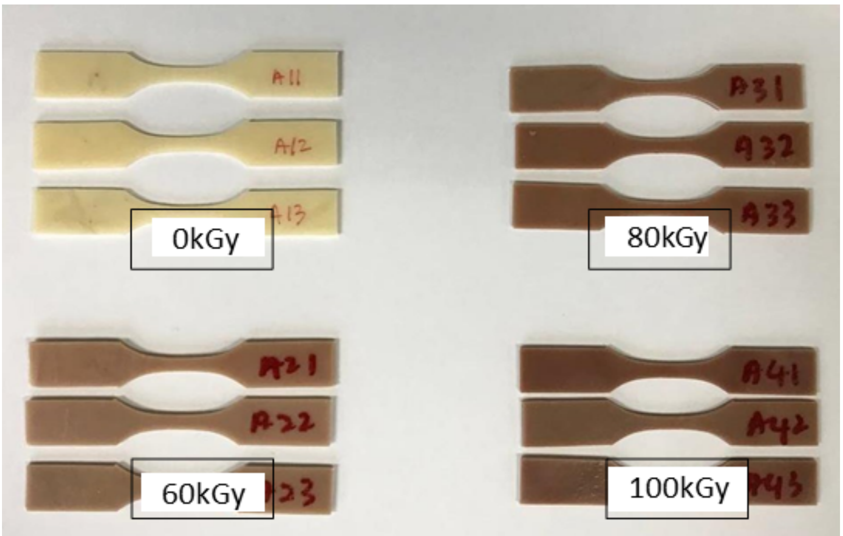


Fig. 5. PVC sample after ageing (50˚C for 7 days)

3.3 Ultimate Tensile Strength (UTS) and Elongation at Break

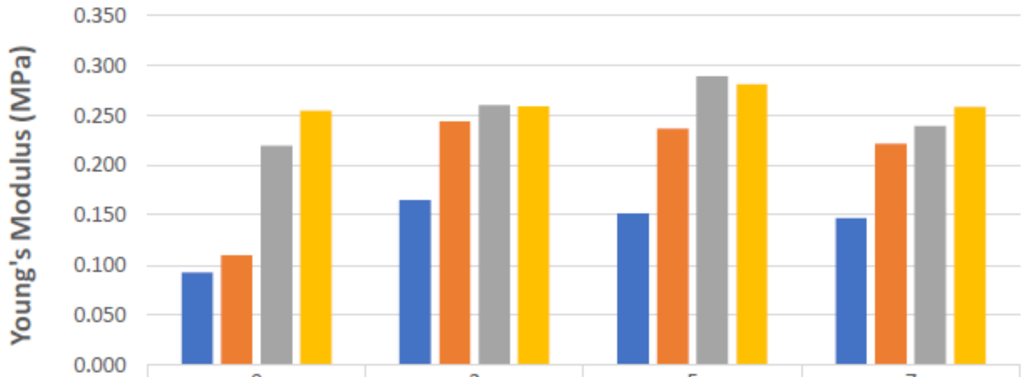
The results for ultimate Tensile Strength can be seen in Table 2. According to Table 1, the UTS of the PVC samples generally increased with higher irradiation doses. As proved by the gel content test, higher dose results in higher degree of crosslinking and hence higher strength. In 2% of increasing and decreasing obtain value for each dose, there were variations in UTS values across different ageing durations. Moreover, the effect of ageing on the mechanical properties varied. In some cases, the UTS increased with ageing (3 days and 5 days), while in others, it decreased (7 days). Moreover, elongation at break followed a similar pattern, with variations observed across different doses and ageing durations. In other words, this indicates that the PVC samples became less stretchable and less ductile as the irradiation dose and ageing period increased. However, the effect was not always linear, as the UTS values varied for different doses and ageing durations. Ageing does gives effect as also investigated by Merzouk *et al.,* [21].

Table 2
Comparison value of mechanical properties for non-aged PVC and ageing PVC at different doses of irradiation on 0,3,5 and 7 days

PVC sample								
	0 days		3 days		5 days		7 days	
Dose of irradiation (kGy)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)	Ultimate Tensile Strength (MPa)	Elongation at Break (%)
0	20.65	3.60	19.96	2.16	19.97	2.18	19.69	2.43
60	20.78	3.05	20.77	1.55	21.52	1.57	21.50	1.70
80	20.89	1.66	21.25	1.43	20.95	1.16	21.52	1.60
100	21.12	1.42	22.24	1.49	21.74	1.35	22.50	1.45

3.4 Young' Modulus

Young's modulus (or Elastic Modulus) is, in fact a material rigidity. In other words, how easy it is bent or stretched. Therefore, based on experiments that have been carried out, the value of Young's Modulus can be obtained through this experiment. Based on Figure 6 this data was obtained by the tensile test machine software, the data show at low to moderate electron beam doses, the Young's modulus of PVC increased by 19.56% (At 0 days, the value increased as much 0.092 to 0.110). This increase can be attributed to the formation of additional cross-linking within the PVC polymer chains. Generally, higher doses of irradiation tend to increase the Young's modulus of PVC due to the cross-linking effect by 19.56% after irradiation. The cross-linking reactions induced by irradiation lead to a higher degree of cross-link formation, resulting in a stiffer material. Other than that, Irradiation has been found to have an impact on the tensile stress at break of PVC, which refers to the stress level at which the material fractures during a tensile test. The effect of irradiation on PVC is dependent on various factors, including the irradiation conditions and the duration of ageing.



	0	3	5	7
0kgy	0.092	0.165	0.151517146	0.147
60kgy	0.110	0.244	0.23717195	0.222
80kgy	0.220	0.260	0.289604423	0.240
100kgy	0.255	0.259	0.281503016	0.258

Ageing (days)

Fig. 6. Graph of Young's Modulus against durations of ageing PVC at 0, 3, 5 and 7days

When PVC is exposed to higher doses of irradiation, it can lead to changes in the polymer structure. As a result, the tensile stress at break can either increase or decrease, depending on the specific conditions. This means that the material may exhibit either enhanced or reduced resistance to fracture under tensile forces.

3.5 Dielectric Test (Conductivity Measurement)

Four samples of 7 days aged PVC with various doses of irradiation (0 kGy, 60 kGy, 80 kGy and 100 kGy) were consider as a function of the frequency of this dielectric test. The conductivity results for all types of samples as a function of frequency are shown in Figure 7. Conductivity is an inverse for the insulation properties. Hence, lower conductivity means higher insulation properties which is the requirement for an insulation cable. Figure 7 shows the behaviour of the PVC from low to high frequency. The result shows that PVC behaves differently at higher frequency but quite similar properties at lower frequency.

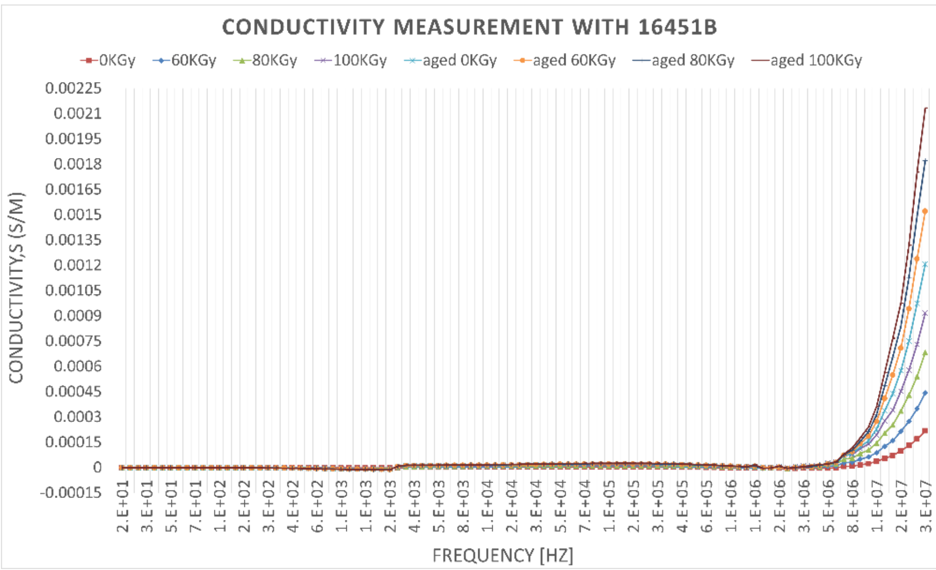


Fig. 7. Graph of conductivity measurement versus frequency

Based on Figure 7, non-aged PVC has higher electrical conductivity than the 7-day aged PVC samples. This is attributed to the ageing process, which modifies PVC's molecular structure through chemical reactions and degradation sample formation, restricting charge carrier mobility and reducing conductivity. Moreover, irradiation dose plays a significant role in these results. Higher doses of irradiation have been reported to increase PVC's conductivity due to enhanced crosslinking and reduced formation of conjugated double bonds. This finding is consistent with Youssef *et al.,* [20], which reports that crosslinking improves PVC stability, minimizing the formation of conjugated double bonds that enhance electronic mobility and increase conductivity. Ageing can also introduce structural defects like microcracks, further impeding charge movement and lowering conductivity. Hence, the decrease in electrical conductivity in aged PVC can be attributed to the effects of ageing on molecular structure, degradation products and structural defect formation.

The conductivity values were observed at 50Hz, as depicted in Figure 8 providing insights into the electrical characteristics of PVC wire and cable. This frequency was chosen because it is the common electricity frequency for most of the building in the world and Malaysia. The data reveals that in the 0-day (unaged) condition, the conductivity is 1.5E-8 and after 7 days, the conductivity increases up to 4.5E-8. These increases of conductivity values indicate a reduction of insulation properties of PVC. This is also reported by Merzouk *et al.,* [2], Similar trends were observed for higher dose of radiation. However, the conductivity values decrease with higher radiation doses. According to this, increasing the radiation dose causes conductivity to decrease and may ultimately enhance insulation efficiency. It shows that ageing and irradiation dose affects the insulation properties of PVC cables and crosslinking through irradiation contribute to longer insulation ability/property of PVC cable.

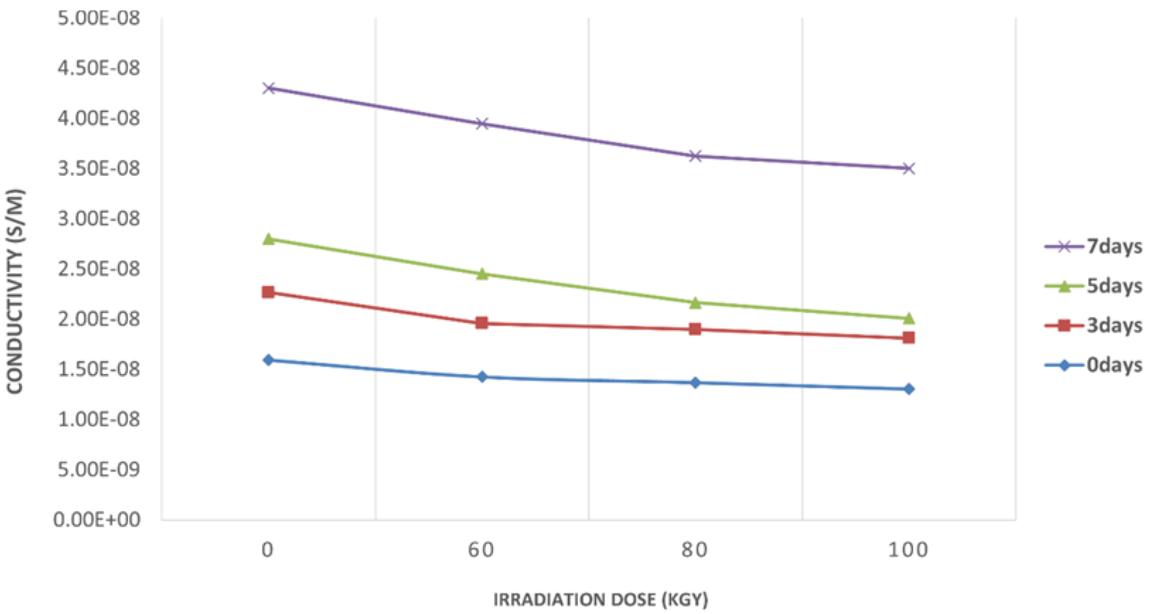


Fig. 8. Comparison of electrical conductivity at 50Hz for radiation crosslinked PVC after 0days (unaged), 3 days, 5 days and 7 days of ageing duration for 0KGy, 60KGy, 80KGy and 100KGy

When considering the effect of increasing the dose of irradiation on the insulation properties of PVC, it's important to remember that there are different factors at play. As mentioned earlier, the study by Merzouk *et al.,* [21], found that the electrical conductivity of PVC initially increased with ageing, but then decreased with increasing radiation dose. This suggests that ageing can degrade the insulation properties of PVC, while irradiation can improve them. The authors also found that the optimal irradiation dose for achieving the best insulation properties was dependent on the type of PVC and the intended application.

However, the subsequent decrease in conductivity with higher radiation doses could ultimately lead to improved insulation properties in the irradiated PVC samples compared to the non-radiated PVC samples. This is because the decrease in conductivity indicates a reduction in the movement of charge carriers, which enhances the insulating characteristics of the material.

It's worth noting that the optimal irradiation dose for achieving the best insulation properties might not necessarily be the highest dose. There could be an optimal dose at which the balance between increased crosslinking and reduced conductivity leads to the most favourable insulation performance.

Thus, when the dose of irradiation is increased, the insulation properties of the irradiated PVC sample could potentially be better than those of the non-radiated PVC sample. However, achieving the optimal insulation performance would require finding the right balance between the initial increase in conductivity due to crosslinking and the subsequent decrease in conductivity with higher radiation doses. Proper testing and evaluation are essential to determine the most suitable irradiation dose for the desired insulation properties in a specific application.

However, Insulation properties of radiation cross-linked PVC cables would likely be better than non-irradiated PVC cables. The process of radiation cross-linking introduces additional cross-links between polymer chains, creating a more interconnected and stable structure. These cross-links enhance the mechanical strength and resistance to deformation of the cables, making them more durable and less susceptible to damage. With increased cross-linking, the polymer chains become more rigid and less able to move freely. This rigidity results in improved electrical insulation properties, as there are fewer charge carriers (electrons) that can move through the material, reducing electrical conductivity. As a result, radiation cross-linked PVC cables tend to have lower electrical conductivity compared to non-irradiated PVC cables, making them more effective insulators.

Furthermore, radiation cross-linking can also improve the thermal stability of the PVC material, making it better suited to withstand high temperatures and harsh environmental conditions. This enhanced thermal stability contributes to the long-term reliability of the cables as insulating materials. In summary, due to the increased cross-linking and improved mechanical and electrical properties, radiation cross-linked PVC cables generally offer better insulation properties compared to non-irradiated PVC cables, making them more suitable for various applications where reliable and efficient electrical insulation is essential.

4. Conclusion

The study demonstrates that increasing electron beam irradiation dose enhances PVC gel content through cross-linking between polymer chains. The optimal crosslinking dose is 100 kGy, aligning with prior research. In summary, electron beam irradiation effectively crosslinks PVC, offering control over the degree of crosslinking, with 100 kGy identified as optimal for improved mechanical and chemical properties.

The impact of ageing duration on crosslinked PVC cable is also explored. Longer ageing reduces tensile strength due to polymer chain degradation. Dielectric tests show improved insulation properties with higher radiation doses, but aged PVC exhibits higher conductivity, likely due to molecular changes and structural defects. This helps to understand the correlation between ageing duration and properties, providing insights into the long-term performance of PVC cables.

Moreover, the relationship between irradiation dose and insulation properties can be complex and dependent on various factors, such as the type of PVC, the intended application and specific environmental conditions. Therefore, careful experimentation and testing would be necessary to determine the ideal irradiation dose for a particular PVC application.

Overall, the investigation highlights the positive effect of higher irradiation doses on crosslinking for improved mechanical properties. Ageing, however, leads to degradation and the relationship between irradiation dose and insulation properties requires further exploration. However, with the aid of irradiation, effect of aging can be reduced. These insights advance understanding for developing enhanced PVC cable designs for diverse applications.

Acknowledgement
The author would like to extend sincere appreciation to Faculty of Engineering National Defence University of Malaysia and Malaysian Nuclear Agency for providing materials and equipment's for this project.

References

[1] Coaker, A. W. and Marcelo M. Hirschler. "New low fire hazard vinyl wire and cable compounds." *Fire safety journal* 16, no. 3 (1990): 171-196. https://doi.org/10.1016/0379-7112(90)90032-A
[2] Merzouk, Djelloul Saïh and Nor Azwadi Che Sidik. "Assessing and quality tests of new PVC electrical cables outer sheath by accelerated thermal ageing." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 44, no. 1 (2018): 73-84.
[3] Zaharescu, Traian, E. Nemeş, M. Râpa and E. Grosu. "Radiation modification of functional properties in PVC/mica electrical insulations." *Polymer Bulletin* 57, no. 1 (2006): 83-90. https://doi.org/10.1007/s00289-006-0536-0
[4] Abdel-Gawad, Nagat MK, Adel Z. El Dein, Diaa-Eldin A. Mansour, Hanaa M. Ahmed, Mohamed MF Darwish and Matti Lehtonen. "PVC nanocomposites for cable insulation with enhanced dielectric properties, partial discharge resistance and mechanical performance." *High Voltage* 5, no. 4 (2020): 463-471. https://doi.org/10.1049/hve.2019.0116
[5] Mendizabal, E. B. A. U. D. G., L. B. A. U. D. G. Cruz, C. F. Jasso, G. B. A. U. N. A. D. M. Burillo and V. I. Dakin. "Radiation crosslinking of highly plasticized PVC." *Radiation Physics and Chemistry* 47, no. 2 (1996): 305-309. https://doi.org/10.1016/0969-806X(94)00183-K
[6] Facio, A. Castañeda, R. Benavides Cantú, ME Martínez Pardo and H. Carrasco Abrego. "Radiation-induced modifications of PVC compounds stabilized with non-lead systems." *Radiation Physics and Chemistry* 71, no. 1-2 (2004): 247-252. https://doi.org/10.1016/j.radphyschem.2004.04.051
[7] Ahmed, Jawad and Yong Zhang. "Effect of electron beam irradiation on the thermal and mechanical properties of ethylene-vinyl acetate copolymer/polyamide blends." *Polymers and Polymer Composites* 29, no. 6 (2021): 714-723. https://doi.org/10.1177/0967391120930108
[8] Xiao-Kai, M., H. Pei-Jie, L. Xinyuan and J. Tao. "The aging degree analysis of EPR cable insulation based on hardness retention rate measurement." *Journal of Electrical & Electronic Systems* 7 (2018): 2332-0796. https://doi.org/10.4172/2332-0796.1000260
[9] Mergos, John A., Maria D. Athanassopoulou, Theodore G. Argyropoulos, Constantine T. Dervos and Panayota Vassiliou. "The effect of accelerated UV-ageing on the dielectric properties of PVC, PTFE and HDPE." In *2010 10th IEEE International Conference on Solid Dielectrics*, pp. 1-4. IEEE, 2010. https://doi.org/10.1109/ICSD.2010.5568019
[10] Real, Luis Pimentel and Jean-Luc Gardette. "Ageing and characterisation of PVC-based compounds utilised for exterior applications in the building construction field: 1: Thermal ageing." *Polymer Testing* 20, no. 7 (2001): 779-787. https://doi.org/10.1016/S0142-9418(01)00033-2
[11] Frigione, Mariaenrica. "Assessment of the Ageing and Durability of Polymers." *Polymers* 14, no. 10 (2022): 1934. https://doi.org/10.3390/polym14101934
[12] He, Dongxin, Tao Zhang, Meng Ma, Wenjie Gong, Wei Wang and Qingquan Li. "Research on Mechanical, Physicochemical and Electrical Properties of XLPE-Insulated Cables under Electrical-Thermal Aging." *Journal of Nanomaterials* 2020, no. 1 (2020): 3968737. https://doi.org/10.1155/2020/3968737
[13] Hemmerich, Karl J. "General aging theory and simplified protocol for accelerated aging of medical devices." *Medical Plastic and Biomaterials* 5 (1998): 16-23.
[14] Jakubowicz, Ignacy, Nazdaneh Yarahmadi and Thomas Gevert. "Effects of accelerated and natural ageing on plasticized polyvinyl chloride (PVC)." *Polymer degradation and stability* 66, no. 3 (1999): 415-421. https://doi.org/10.1016/S0141-3910(99)00094-4

[15] Faltermeier andreas, Michael Behr, Claudia Reicheneder, Peter Proff and Piero Römer. "Electron-beam irradiation of polymer bracket materials." *American Journal of Orthodontics and Dentofacial Orthopedics* 139, no. 1 (2011): e7-e11. https://doi.org/10.1016/j.ajodo.2009.10.038

[16] Ng, Hon-Meng, Soo-Tueen Bee, C. T. Ratnam, Lee Tin Sin, Yee-Yao Phang, Tiam-Ting Tee and A. R. Rahmat. "Effectiveness of trimethylopropane trimethacrylate for the electron-beam-irradiation-induced cross-linking of polylactic acid." *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms* 319 (2014): 62-70. https://doi.org/10.1016/j.nimb.2013.10.027

[17] Youssef, H. A., Z. I. Ali and A. H. Zahran. "Electron beam structure modification of poly (vinyl chloride)-wire coating." *Polymer degradation and stability* 74, no. 2 (2001): 213-218. https://doi.org/10.1016/S0141-3910(01)00062-3

[18] Behjat, Abbas and Djafar Gheysari. "10 MeV electron beam cross-linking of plasticized PVC in presence of EHPTM and TAC additives." *Nukleonika* 53, no. 2 (2008): 57-62.

[19] Basfar, A. A. "Flame retardancy of radiation cross-linked poly (vinyl chloride)(PVC) used as an insulating material for wire and cable." *Polymer degradation and stability* 77, no. 2 (2002): 221-226. https://doi.org/10.1016/S0141-3910(02)00037-X

[20] Youssef, H. A., Z. I. Ali and A. H. Zahran. "Electron beam structure modification of poly (vinyl chloride)-wire coating." *Polymer degradation and stability* 74, no. 2 (2001): 213-218. https://doi.org/10.1016/S0141-3910(01)00062-3

[21] Merzouk, Djelloul Saïh and Nor Azwadi Che Sidik. "Assessing and quality tests of new PVC electrical cables outer sheath by accelerated thermal ageing." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 44, no. 1 (2018): 73-84.